Appendix A: Task 1 - Application Selection

A.1 Applications and Mapplets

A.1.1 Application Categories

Eighty-four applications were identified that were either enabled or enhanced by a map database. An initial description and first estimate of the input data requirements for each of the applications was made, but is not included in this Appendix. A final list consisting of 33 grouped applications was compiled. Applications were divided and referred to as application systems based on their mode of operation. For each application, the number of derived application systems depends on the various modes of operation that are possible. The following three modes of operation were considered:

- **Advisory**
  In this mode of operation, the application system assists the driver by providing relevant information without additional processing.
- **Warning**
  In this mode of operation, the application system provides warning to the driver when a crash scenario is likely or when the driver is operating outside of a defined operating region.
- **Control**
  In this mode of operation, the application system alters the vehicle speed and/or trajectory in order to prevent a crash or to mitigate a crash. Application systems also may be developed that control the vehicle in order to perform a specific non-crash related task.

The advisory mode is the simplest mode of operation of an application. No decision is made by the system to determine if the vehicle is really in a crash scenario before providing advisory information to the driver. An example of an advisory system is one that informs the driver of upcoming stop signs in the vehicle's path. As one might imagine drivers could consider this as nuisance and therefore the application system may be turned off. Hence, it may not be effective in all situations.

In the warning mode, some decision is made by the system based on sensor inputs to determine if the vehicle is really in a crash scenario before providing warning information to the driver. An example of a warning system is one that warns the driver if the vehicle is approaching a stopped vehicle in its lane, and the distance to the stopped vehicle, vehicle speed, weather condition, road surface type, etc. indicate that aggressive braking is required to prevent collision. Although a warning system can be developed to be very effective in preventing or mitigating crashes, it might not be effective in certain situations – an example is the case of drowsy or impaired driver. A warning system may also be designed to provide a warning to the driver when the vehicle operates outside the defined operating area. An example of this is a lane departure warning system that provides a warning to the driver when the vehicle path crosses over the lane boundary.

In the control mode, the vehicle is controlled by the system, generally, to prevent or mitigate a crash. An example of a control system is one that controls the vehicle approaching a stop sign, where the distance to the stop sign, vehicle speed, road surface type, etc. indicate that aggressive braking is required to prevent collision. The control mode may also be designed for a specific

non-crash related task. An example is a speed limit control system that regulates the maximum vehicle speed to match the speed limit of the road. In many situations the control mode of operation is usually preceded by a warning mode and is activated only when the driver does not respond to the warning. When warning precedes control mode of operation, sufficient time would elapse before the system realizes the driver is not reacting to the warning provided. In such a situation collision avoidance may not be feasible and therefore the role of the control mode would be to perform an action altering the vehicle speed and/or trajectory in order to mitigate the severity of collision. There are some exceptions where the control mode of operation need not be preceded by warning first. An example is the lane keeping control system that need not be preceded by warning before control action.

For each application, application needs were described. These needs included information to be provided by a map database, and information to be obtained from other sensors or sources. The term “mapplet” was created to represent the data items to be provided by the map database.

A mapplet is information derived from a map database that is used by EDMap applications. It serves as an application interface to the map database. Each mapplet is independent of specific applications. The same mapplet can be used by multiple applications.

A.1.2 Mapplet Categories

The map information can be grouped into a few categories:

- **Road Geometry**
  These mapplets provide data about the shape, size, and location in three dimensions of the road. Examples are curvature, grade, superelevation, and width.
- **Road Characteristics**
  These mapplets provide data about other, non-geometric attributes of the road. Examples are surface type, traffic statistics, lane marking type, and overhead clearance.
- **Location Specific**
  These mapplets provide information about the location of objects and places along the road. Examples are bridge abutments, guard rails, school zones, no passing zones, signs, and traffic signals.

A.1.3 Mapplets by Application

The following table, which extends across two pages, shows which mapplets are required for each application. The applications are listed horizontally across the top. The mapplets are listed vertically along the left edge. Within each cell, ‘a’ means used in the advisory version of the application, ‘w’ means used in the warning version, and ‘c’ means the control version.

Table A-1: Required mapplets for each application

(table continued across two pages)

Application	Adaptive Drivetrain Management	Adaptive Headlight Aiming	Adaptive Transmission Management	Approaching Emergency Vehicle Assistant	Lateral & Longitudinal Control	Cooperative Vehicle System - Platoon	Cooperative Collision Warning	Curve Speed Assist	Enhanced Route Planning and Guidance	Extended Lane Change Advisory	Forward Collision Warning/Avoidance	Improved ABS	Improved Stability Control	Improved Traction Control	Infrastructure Based Traffic Management - Probes	Infrastructure Based Traffic Management - Road Sensors
Clutter Reduction				c	c	c										
Freezing Characteristics					c							c		c		
Guidance Instruction									a							
Hospital Zone																
Information Signs									a							
Intersection Complexity									a							
Intersection Geometry																
Intersection Location											w c					
Landscape Information																
Lane Change Restriction Signs																
Lane Directions					c				a							
Lane Geometry					c	c	w			a	w c					
Lane Markings Types					c											
Lane Width					c	c	w				w c					
Multimodal Transit Information																
Number of Lanes				w c	c		w		a		w c					
Overhead Clearance									a							
Park and Ride									a							
Parking Lot Map																
Parking Restrictions																
Parking Spot Geometry																
Passing Restrictions									a	a						
Preferred Routes		a							a							
Railroad Crossing Information									a							
Ramps					c					a						
Regulation Signs						c			a							
Road Class					c			a w c								
Road Condition					c		w				w c	c	c	c		
Road Curvature	a c	a	a c		c	c	w	a w c			w c		c			
Road Grade	a c		a c		c	c	w	a w c	a		w c	c	c	c		
Road Side Barriers				w c							w c					
Road Surface Type											w c	c	c	c		
Route				w c		c		w c							a	a
School Zone																
Shoulder Type				w c												
Shoulder Width				c							w c					
Signaled/Gated Intersection	a c															
Special Instruction									a							
Speed Limit	a c				c	c		a w c								
Spot Attributes																
Stationary Roadway Objects						c					w c					
Stationary Roadway Structure					c	c					w c					
Stop Sign Locations	a c			c												
Superelevation	a c		a c		c	c	w					c	c	c		
Traffic Restrictions															a	a
Traffic Signal Location	a c			c											a	a
Traffic Signs						c									a	a
Traffic Statistics									a							
Tunnels					c						w c					
Turn Information									a							
Turn Path Geometry																
Warning Signs						c			a							
Yield Sign Locations				c												

Application	Intersection Collision Warning/Avoidance	Intersection Turn Assistant	Lane Change Assistant	Lane Following Assistant	Merging Traffic Assistant	Optimal Speed Advisory	Parking Assistant	Parking Spot Locator	Passing Assistant	Railroad Collision Avoidance	Ranging/Imaging Sensor Calibration	Road Maintenance Aid	Selective Disable for ACC	Speed Limit Assistant	Stop Light Assistant - Infrastructure	Stop Light Assistant - Vision	Stop Sign Assistant
Clutter Reduction	w c		w c		a w c								c				
Freezing Characteristics	c									c							
Guidance Instruction																	
Hospital Zone													c				
Information Signs																	
Intersection Complexity	w c																
Intersection Geometry	w c	a w c															
Intersection Location		a w c															
Landscape Information																	
Lane Change Restriction Signs			w c		a w c												
Lane Directions																	
Lane Geometry			w c	a w c	a w c								c				
Lane Markings Types			w	a					w			a					
Lane Width		w c	w c	a w c							c						
Multimodal Transit Information																	
Number of Lanes	c				c												
Overhead Clearance																	
Park and Ride																	
Parking Lot Map								a									
Parking Restrictions							a w c										
Parking Spot Geometry							a w c										
Passing Restrictions			w c						a w c								
Preferred Routes																	
Railroad Crossing Information			w							a w c							
Ramps					a w c								c				
Regulation Signs													c				
Road Class	c												c				
Road Condition										c				c	c	c	w c
Road Curvature	w c			a w c					w c		c						
Road Grade	w c			a w c			a w c		w c	c	c						
Road Side Barriers	c																
Road Surface Type	c		w							c		a		c		c	w c
Route		a w c															
School Zone													c				
Shoulder Type				w													
Shoulder Width				w													
Signaled/Gated Intersection										a w c							
Special Instruction																	
Speed Limit	c				c	a			w				c	a c			
Spot Attributes								a									
Stationary Roadway Objects											c						
Stationary Roadway Structure																	
Stop Sign Locations	w c																a w c
Superelevation	w c			c					c		c						
Traffic Restrictions	c																
Traffic Signal Location	w c					a									a w c	a w c	
Traffic Signs											c		c				
Traffic Statistics																	
Tunnels																	
Turn Information	w c																
Turn Path Geometry		w c															
Warning Signs																	
Yield Sign Locations	w c																

A.2 Database Formation and Structure

This chapter describes the structure of the EDMap application database, how to calculate potential benefits for different map-enhanced safety applications, and how to use the database as a data-mining tool.

A.2.1 Database Structure

An outcome of the EDMap project was to demonstrate the potential safety benefits of the database for map-enhanced or enabled safety applications. Therefore, the applications were ranked in several ways, including the position accuracy needed, map building issues, communication needs, and the deployment timeframe.

To demonstrate the greatest potential safety benefits, the applications were connected to the 44 Crash scenarios that were used as the basis for all calculations.

The applications function in one of three operating modes: advisory, warning, or control. Each application may require different levels of position accuracy, deployment timeframe, or other attributes. In addition, an application may need different map-derived information (mapplets), such as position of a stop sign or other sensor data. The effectiveness of the specific application can vary based on different system types.

Application attribute information is maintained in a set of tables within the database. In addition, there is a need for additional quantitative data such as how many cars are on the roads, how many new cars are bought every year, and the total cost of car accidents within the United States. Two additional tables contain this information. The database tables are listed and described in Table A-2 and the relationships among the tables are diagrammed in Figure A-1.

Table A-2: Database tables

AppFamily	Applications can be logically combined into application families. This table describes the different families, such as ACC, Stop, or Lane.
AppFamilyApp	This table defines the connection between the different applications and their related families.
Application	This table contains the definition of the application itself.
ApplicationCrash	This table connects the applications and their subsystems to specific 44 Crashes. The effectiveness could be different for each system. (see SystemCrashEffectiveness)
ApplicationNHTSA	This table contains the connection between the applications and the NHTSA crash subcategories. Subcategories are connected to only one category.
CarData	This table contains the numbers of cars on the roads in the United States and a replacement percentage for new cars every year.

Crashes	This table contains the name, description, and crash cost in terms of vehicles crashed, percent functional years lost, and percent direct costs to each of the 44 Crash scenarios.
CrashTotal	This table contains the total value of crash costs from the 44 Crashes. These values are used to calculate the potential benefits as the total crash costs for all police reported car accidents within the United States.
Mapplet	All information needed by the system is defined in mapplets or applets. The database can distinguish between those types by the connection to the MappletType table.
MappletSystem	This table defines the connection between systems and their mapplets and applets.
MappletType	This table contains the name and description of the different types of applets. Currently, MappletType can be mapplet, applet, communication, or sensor
NHTSACrashCategory	This table contains the main NHTSA crash categories, e.g., rear-end.
NHTSACrashSubcategory1	This table contains subcategories for the main crash categories. Not all of the main categories contain subcategories. For those cases, the database contains empty entries.
System	Every application could have different working levels. Currently, the advisory, warning, or control levels of each application are used (see SystemNames). The attributes of each subsystem are saved in this table. It is also possible to add system specific comments.
SystemCrashEffectiveness	Although the application is already connected to its specific 44 Crashes data, the effectiveness to prevent each type of crash could be different for each system. The effectiveness values are saved in this table.
SystemNames	This table contains the names of the different system types: advisory, warning, or control.

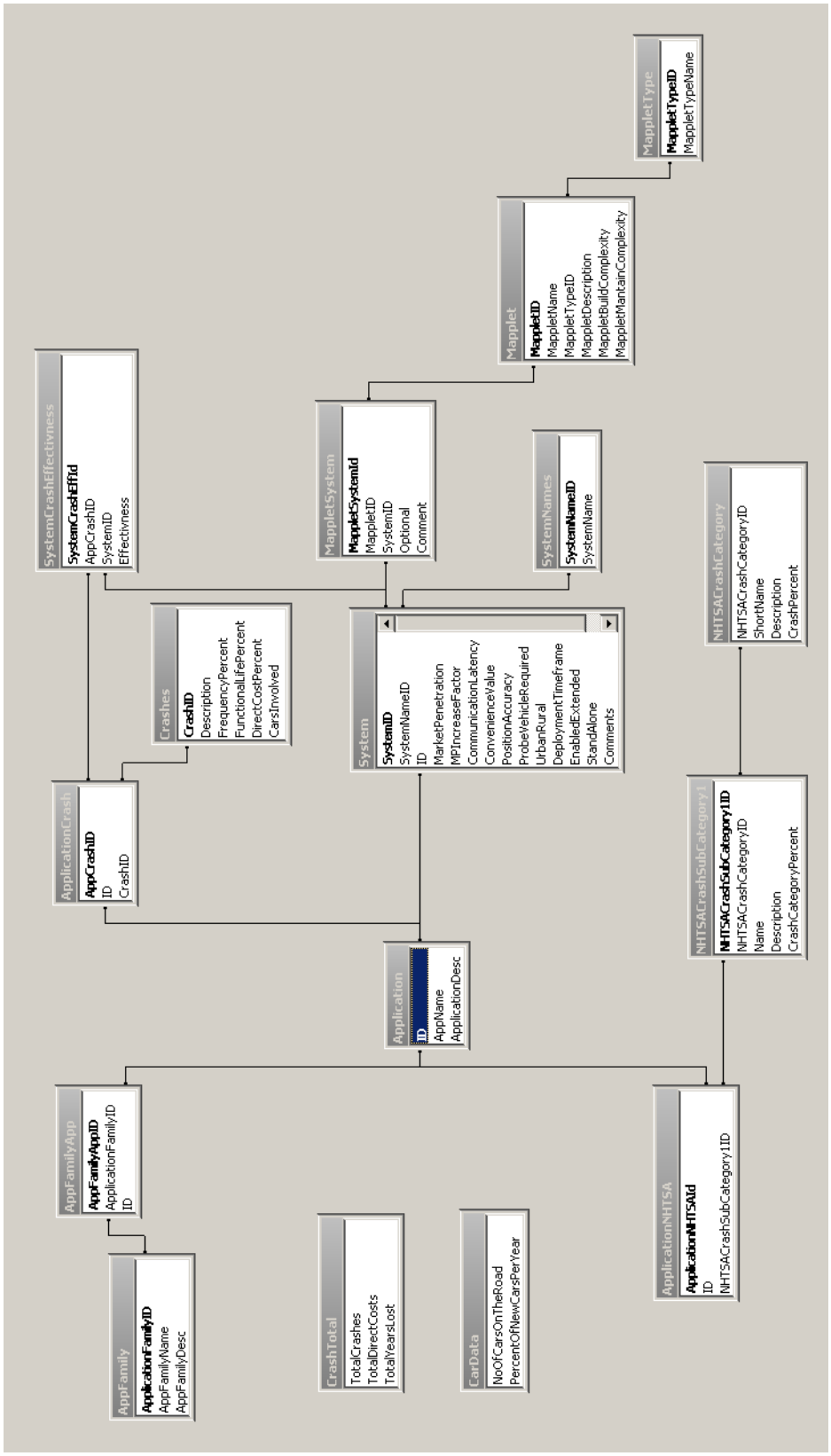

Figure A-1: Relationships between the database tables

A.2.2 Estimated Benefits Calculation

The EDMap application database can be used to estimate potential benefits for the various map-enhanced safety applications. To calculate benefits, a base data set with all possible crashes and their cost to society is needed. The 44 Crashes study from General Motors provides this data in terms of “functional years lost”, “vehicle crashes”, and “direct cost lost”. The connection between the applications and the 44 Crashes data is established in form of “This application could prevent accidents of this 44 Crash type”. Since no application will prevent all accidents of all the crash types, an "effectiveness value" was established for each application-crash type relation.

The 44 Crashes data include crashes caused by inexperienced, drowsy, or inattentive drivers. The effectiveness value was adjusted for these situations. For example, a warning system would have a lower effectiveness value for an aggressive driver than for an observant driver.

Finally, a probability factor was added to the estimated benefits calculation to consider how many cars are equipped with a safety application and the probability of having a safety-application equipped car involved in an accident. Also considered was the probability of two-car accidents where both cars are equipped with a safety application.

The NHTSA Benefit Working Group has used a different approach to calculating the estimated potential benefits of vehicle safety applications. NHTSA starts with crash categories that describe the state of the cars directly before the accident. As an example, for rear-end crashes there are two scenarios described in the report *Preliminary Crash Scenarios* (NHTSA Benefits Working Group, 1996): “Lead Vehicle Decelerating Rear-End Pre-crash Scenario” and “Lead Vehicle Not Moving Rear-End Pre-crash Scenario”. Starting from these scenarios, NHTSA simulates different speeds and road conditions using a large number of Monte Carlo trials and assumptions on system usage and market penetration.

As a comparison of the estimated benefits calculation based on the EDMap application database and the results of the NHTSA Safety Benefits Group study, consider the estimated benefit numbers published by NHTSA in terms of “reduction in policed-reported, rear-end crashes” for various safety applications. For Forward Collision Warning (FCW), NHTSA estimated a reduction of 791,000 police-reported, rear-end crashes with 100% market penetration. The EDMap application database does not use a rear-end crash category. However, since a rear-end crash means that two cars are involved in the accident, multiplying the NHTSA result (791,000) by two yields 1,582,000 reduction in crashes. The EDMap calculation for the benefit from FCW with 100% market penetration is 1,800,000 reduction in crashes. The difference in the two estimates is only about 15%. The difference is probably less since the EDMap estimate does not focus only on rear-end crashes only and FCW reduces the number of accidents with pedestrians or deer as well.

Combining the EDMap estimated benefits calculation for FCW with its calculation for the Lane-Following-Assistant Warning and the Curve Speed Assistant Warning applications, results in a category similar to that used by NHTSA for its Road Departure Warning application. Here, the difference in estimates between the EDMap calculation and the NHTSA calculation is even smaller.

Based on the existing data in the database, the calculation of the benefits is simple. First, it is important to know if both cars, or any car, need to be equipped with the application to avoid an accident. Based on this definition, we get different probability values to avoid a possible crash (Equation 1-1). Then we multiply the probability, the effectiveness, the crash frequency and the total cost of one specific crash of the 44 Crashes (Equation 1-2).

$$P = \begin{cases} MP \ \ for\ any\ car \\ MP^2 \ \ for\ a\ specific\ car \end{cases}$$

Equation 1-1: Probability of having a car involved in a crash situation equipped with a safety system to prevent the crash

$$benefit = P * E * F * T$$

Equation 1-2: Benefit for an application to a crash type

Where:

MP = Market Penetration of a safety application in cars as a percentage of all cars

P = Probability of having a car equipped with a safety application involved in an accident

E = Application effectiveness for a specific application to a specific crash in percent

F = Crash frequency in percent of all crashes

T = Total cost of this crashtype

A.2.3 Use of the Database as a Data Mining Tool

A.2.3.1 Hardware and Software Requirements

The EDMap application database is based on Microsoft Access 2000. The software will not work with older versions of Microsoft Access. The software was not tested on newer versions of Access. The minimum hardware and software requirements are:

Computer/Processor	PC with Pentium II 400 MHz or higher processor
Memory	64 MB RAM
Display	1280 x1024 recommended minimum resolution
Microsoft Access 2000	Service Pack 2

A.2.3.2 Installation

The EDMap application database is delivered in two files: EDMap.mde and EDMap_Database.mdb. The first one is an executable file and the second one is the data file. For installation, create a new directory and copy both files into the directory.

It is recommended that some of the settings of Microsoft Access 2000 be changed before using the database. If these settings are not changed, each mouse-click selection must be confirmed and the data could be corrupted if any operation is cancelled. To change the Access database settings, select Start Microsoft Access 2000, create a new, blank database with any name and then Tools> Options>Edit/Find. Uncheck all three options in the Confirm box: Record Changes, Document Deletions, and Action Queries. Press OK, and exit Access.

A.2.4 Using the EDMap Application Database

A.2.4.1 The Main Screen

The main screen (Figure A-2) shows the available Applications (left panel). After selecting one of the applications, additional data displays in one or more of the other panels: System, NHTSA Crash Categories, 44 Crashes, and Application Family.

Below each panel are “Add” and “Delete” buttons and, if applicable, an “Edit” button. Before editing any data, a specific entry has to be selected.

The "Mapplets" button in the System window shows specific applets and mapplets needed by an application system type. The "Confirm System" button is used to agree with the current data of a system. The last state of a system is shown in the History box. The “View Log” button is used to display the complete data editing history for one system.

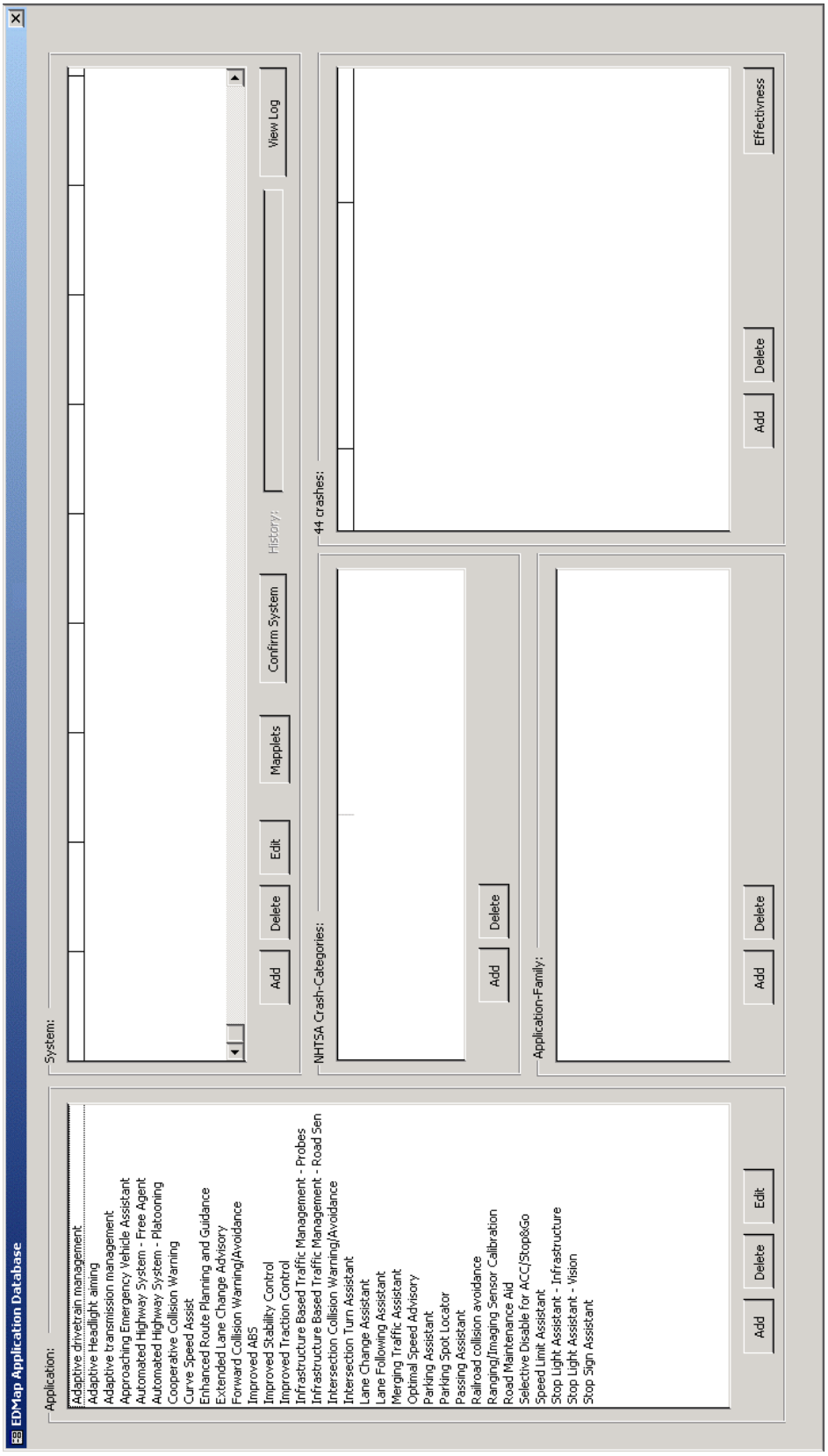

Figure A-2: EDMap application database main window

A.2.4.2 Edit System Type

Select an application from the Main Screen. Click "Edit" under the Application or System window to display the System Description (Figure A-3). The user can chose from a set of specific values by clicking on the arrow to the right of dialog box or entering specific attributes for a system. There is no limit for data entries in the comments box.

Click "OK" to change the attribute permanently. The History dialog box entry indicates that the user made changes. Click "Cancel" to undo any changes made.

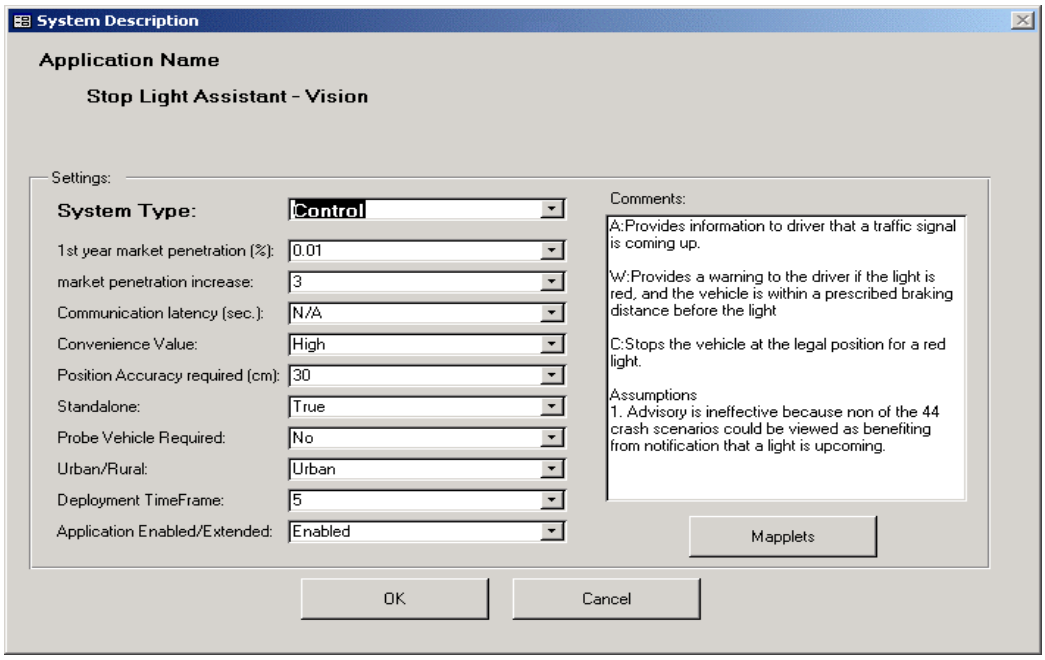

Figure A-3: Editing a system

A.2.4.3 Edit Applets/Mapplets

Click "Mapplets" on the Main Screen or the System Description screen after selecting an application to display the System-Mapplets screen (Figure A-4). A list of applets and mapplets connected with the specific system display in the Mapplets dialog box.

Select a mapplet and click "Add" to add mapplet information, "Edit" to change the information, or "Delete" to remove the selected mapplet for this system after confirmation. Click "OK" to accept changes and to have an opportunity to add additional comments for this mapplet and/or mark it as optional.

Mapplets and applets can be edited under the “Base Data – Mapplets” in the menu bar. It is possible to add, change, or delete data and to enter additional information that is valid for this applet in all applications.

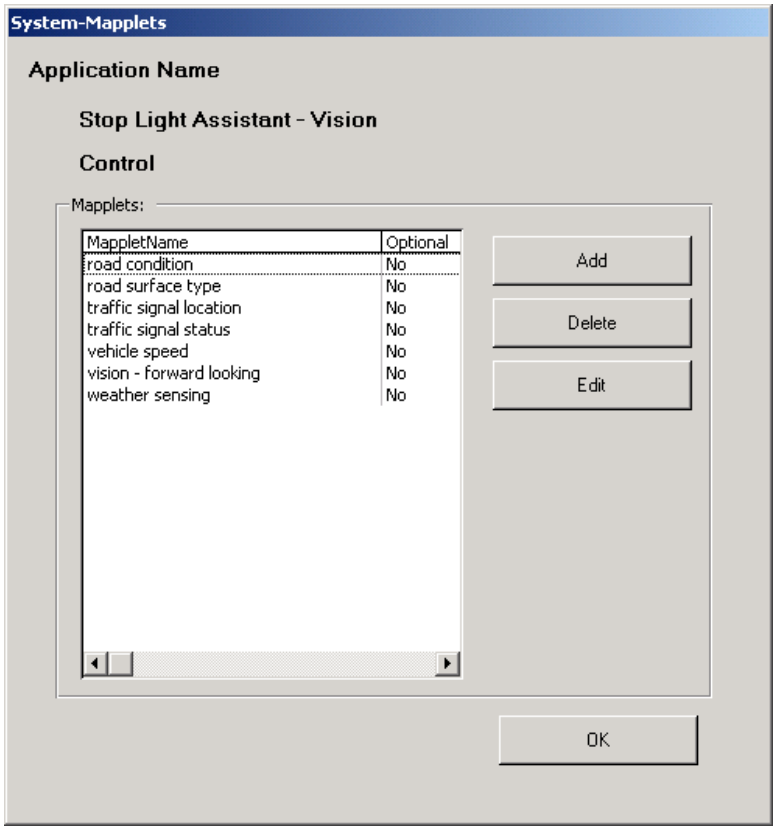

Figure A-4: Mapplets and applets of one system type of one application

A.2.4.4 Edit 44 Crash Scenarios

Adding a 44 Crash scenario to an application makes a valid connection between all of the system types of one application and the selected crash scenario. To make the connection, the effectiveness of all system types to this crash is set to zero. Then, after adding the suitable scenario to an application, the user has to change the effectiveness value for each of the different system types to each of the crashes. The idea behind this is that the control system of an application could have a different effectiveness on a specific crash type than a warning version.

A.2.4.5 Edit NHTSA Crash Categories

Adding a NHTSA crash category to an application makes a valid connection between this category and all of the system types of one application.

A.2.4.6 Edit Application Families

In addition to different instantiations of the applications (the different system types like warning and control), there are also groups of applications, called application families. Currently, there are five families: ACC, Cruise/Follow, Intersection, Lane, and Stop. Under “Base Data – Application Families” in the menu bar, these families can be edited and more families can be created. It is possible for one application to be part of more than one family.

A.2.5 Reports

There are 10 different reports available. In addition, some of the reports have different options to choose from as well.

- **Application Mapplets**: This report shows all applications, the different systems and their mapplets and applets they need to work.
- **Application Number of Mapplets**: This report counts the number of mapplets and applets needed by the different applications.
- **Application Families**: This report shows the application families and their members.
- **Mapplets Used in Application**: This report counts the number of applications that are using the different mapplets and applets.
- **44 Crashes and Number of App**: This report counts the number of applications that help to prevent each of the 44 Crashes scenarios.
- **NHTSA vs. 44 Crashes**: This report shows a histogram of the connection between the 44 Crashes and the NHTSA crash categories. For every application in a specific NHTSA crash category x and prevents 44 Crash number y increases the cell x/y in the report by one.
- **Applications vs. 44 Crashes**: The user can choose to see a report either for all system types or just for a specific system type. If the user selects for all system types, every connection between the 44 Crashes and an application is marked with an X. If the user selects for a specific system type, the report will show the effectiveness of the X.
- **Application Benefits**: The user has to decide how to look at cumulative potential benefits of the different applications (see Figure A-5). First, the user must enter a year in a range of 1 to 50, meaning the number of years after the EDMap project ends. In the Report Options section, there are three different ways to use market penetration values: the first one uses the estimated market penetration values included to every application and every system type in the database. The next option uses estimated values based on the number of cars in the US in 1998, if every new car gets the systems installed. The third option is like using a magic wand—every car on the street immediately gets the system installed and the market penetration is set to 100%. In addition to the market penetration, the user also can decide either to use the estimated system effectiveness on the 44 Crashes or to set this effectiveness to 100%. The numbers, if set to 100%, will just show a potential – the real values must be much lower. In the last section, the user can group the applications in different ways. This will not change the estimated benefit numbers but the way the report looks and the sorting of the applications. Finally, the user can use the magic wand again. In the database, there are expected deployment timeframe values included. To see a potential, the user can set these values to one and therefore can make every technology needed by all applications available now.

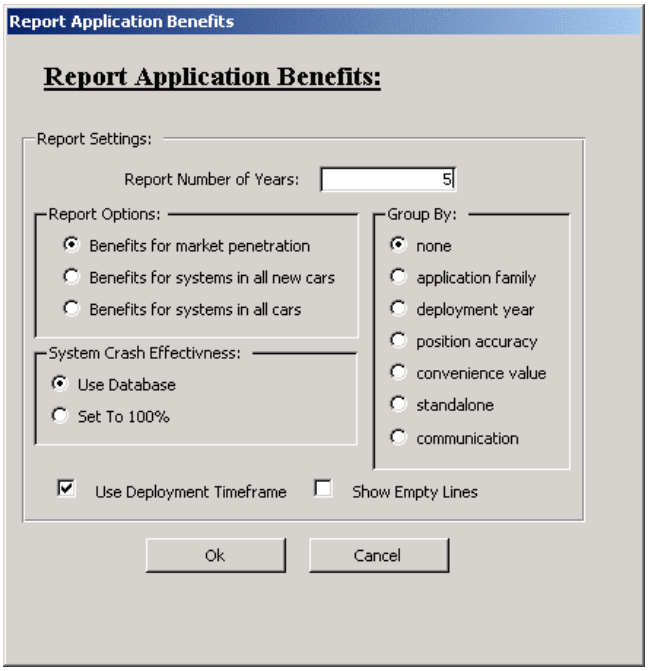

Figure A-5: Report print choices for estimated benefit reports

- **Application Family Benefits**: This report shows cumulated estimated benefits for the application families. The user has to decide again which market penetration estimation and which effectiveness values of the applications to the 44 Crashes to be used. In addition, the deployment timeframe can be set to one again. In this report, the benefit values of the different applications in one family are accumulated. In the case that two or more applications benefit the same of the 44 Crashes, the maximum of those effectiveness values is used. This results in underestimating the potential benefit numbers.
- **5 Year Benefit Overview**: This report shows estimated benefit values, not cumulated values. After choosing the market penetration and crash effectiveness estimates to use and the start year (1 to 50) produces a five-year overview for the functional years saved, direct costs benefit, or vehicle-crashes benefit report.

All benefit values are based on estimated effectiveness and estimated market penetration numbers—there is no guarantee for these values.

A.3 Applications Ranking

A methodology for analysis and ranking of application systems was developed in Task 1 of the EDMap project. Our primary goal in application analysis has been to develop a methodology for estimating the relative ranking of the application systems. Based on such a ranking, Toyota, DaimlerChrysler, General Motors and Ford will each select two application systems, one near-term and one mid/long-term, for demonstration at the end of the EDMap project. NAVTEQ will provide enhanced map databases of two locations based on the requirements of the demo application systems selected by the OEMs.

A.3.1 Near-, Mid-, and Long-term Application Systems

The application systems were first grouped based on expected deployment time frame. Table A-3 shows the deployment time frame for each application.

- **Near-term Application Systems**
  Near-term application systems are considered to be deployable in the U.S. market in about one year after the conclusion of the EDMap project.
- **Mid-term Application Systems**
  Mid-term application systems are considered to be deployable in the U.S. market in about five years after the conclusion of the EDMap project.
- **Long-term Application Systems**
  Long-term application systems are considered to be deployable in the U.S. market in about ten years after the conclusion of the EDMap project.

Table A-3: Application deployment time frame

		Deployment Time Frame		
Application	**System**	**Near-term**	**Mid-term**	**Long-term**
Adaptive Headlight Aiming	Advisory	X		
Approaching Emergency Vehicle Assistant	Advisory		X	
	Warning		X	
	Control			X
Cooperative Collision Warning	Warning			X
Cooperative Vehicle System - Platooning	Control			X
Curve Speed Assist	Advisory	X		
	Warning	X		
	Control		X	
Enhanced Route Planning and Guidance	Advisory	X		
Forward Collision Warning/Avoidance	Warning		X	
	Control			X
Improved ABS	Control		X	
Improved Stability Control	Control		X	
Improved Traction Control	Control		X	

		Deployment Time Frame		
Application	**System**	**Near-term**	**Mid-term**	**Long-term**
Infrastructure Based Traffic Management - Probes	Advisory		X	
Infrastructure Based Traffic Management - Sensors	Advisory		X	
Intersection Collision Warning/Avoidance	Warning		X	
	Control			X
Intersection Turn Assistant	Advisory	X		
	Control		X	
	Warning		X	
Lane Change Assistant	Warning		X	
	Control			X
Lane Following Assistant	Warning		X	
	Control			X
Lateral and Longitudinal Control	Control			X
Merging Traffic Assistant	Advisory		X	
	Warning			X
	Control			X
Optimal Speed Advisory	Advisory		X	
Passing Assistant	Advisory	X		
	Warning		X	
	Control			X
Railroad collision avoidance	Advisory	X		
	Warning		X	
	Control			X
Road Maintenance Aid	Advisory	X		
Speed Limit Assistant	Advisory	X		
	Control		X	
Stop Light Assistant - Infrastructure	Control		X	
	Warning		X	
Stop Light Assistant - Vision	Control		X	
	Warning		X	
Stop Sign Assistant - Infrastructure	Advisory	X		
	Warning	X		
	Control		X	

Considering the fact that the EDMap project will be completed in April 2004, the near-, mid-, and long-term application systems are considered as being deployable in the U.S. market by middle of calendar years 2005, 2010, and 2015 respectively. It should be understood, e.g., that a mid-term time frame covers the time span of three to seven years given the one, five, and ten year increments used in the ranking. The deployment time frames for near-, mid-, and long-term application systems are realistic and can be achieved provided that there is significant impetus from Department of Transportation, automakers, and map database suppliers. Independent of the EDMap project, there is ongoing work by map database suppliers to provide the next generation of map database that has several enhancements and attributes of road geometry.

A.3.2 Application Ranking

Ranking was done separately for near-term, mid-term, and long-term application systems respectively. Application systems were primarily ranked based on benefits derived with respect to 44 Crashes. The relevant crash types from 44 Crashes that could benefit from an application system were determined. For each of the relevant crash types that benefit from an application system, the EDMap team estimated the percent effectiveness of the application system to that particular crash type.

Estimates for market penetration were used to determine the estimated number of vehicles in the U.S. market that would be equipped with the application system in each year after initial deployment. The market penetration model is described in Chapter 2. It should be pointed out that the EDMap market penetration estimates depended on various application analysis categories such as position accuracy required, standalone, communications latency, convenience value, urban/rural value, etc. that have been described in Chapter 2.

44 Crashes was used to estimate three types of benefit distributions that are potentially obtained with each of the application systems –direct costs saved, functional years saved and vehicles saved.

- **Direct Costs Saved**
  44 Crashes defined Direct Costs as the actual dollar expenditures related to the damage and injury caused by the crash, annually. Direct Costs Saved is hence defined as the value of crash incurred direct costs that are saved, potentially, by the deployment of a specific application system.
- **Functional Years Saved**
  44 Crashes defined Years of Functioning and Life Lost as the number of years lost to fatal injury plus the number of years of functional capacity lost to nonfatal injury, annually. Functional Years Saved is hence defined as the Years of Functioning and Life that is potentially saved by the deployment of a specific application system.
- **Vehicles Saved**
  44 Crashes defined Vehicles Crashed as the number of vehicles in the U.S. involved in each of the crash types, annually. Vehicles Saved is hence defined as the vehicles that are potentially saved from crashes by the deployment of a specific application system.

The benefit distributions of an application system with respect to 44 Crashes were computed based on two perspectives: benefit opportunity and estimated benefits.

A.3.2.1 Benefit Opportunity

Benefit opportunity provides an estimate of the potential benefits derived by deployment of an application system in all new vehicles for each year after initial deployment. The percent effectiveness of the application system with respect to 44 Crashes is based on the EDMap team estimates:

Market Penetration = All New Vehicles per production year,

44 Crashes Percent Effectiveness = EDMap Estimates.

A.3.2.2 Estimated Benefits

Estimated benefits provides an estimate of the potential benefits derived by deployment of an application system using the EDMap estimates for market penetration and the market penetration model described in Chapter 2. The percent effectiveness of the application system with respect to 44 Crashes is based on the EDMap team estimates:

Market Penetration = EDMap Estimates,

44 Crashes Percent Effectiveness = EDMap Estimates.

In order to rank the near-term, mid-term, and long-term applications, functional years saved was used as the most important benefits distribution. The fifth year after deployment was used for computation of benefit opportunity and estimated benefits of the application systems.

The application database presented in Chapter 4 was developed primarily in Task 1 of the EDMap project to be used as a tool for performing the application analysis and ranking.

The following figures show benefits (functional years saved) for fifth year after deployment, and the ranking for the near-term, mid-term, and long-term application systems. The letter designator within parentheses indicates the mode of operation of the application:

a = Advisory mode
w = Warning mode
c = Control mode.

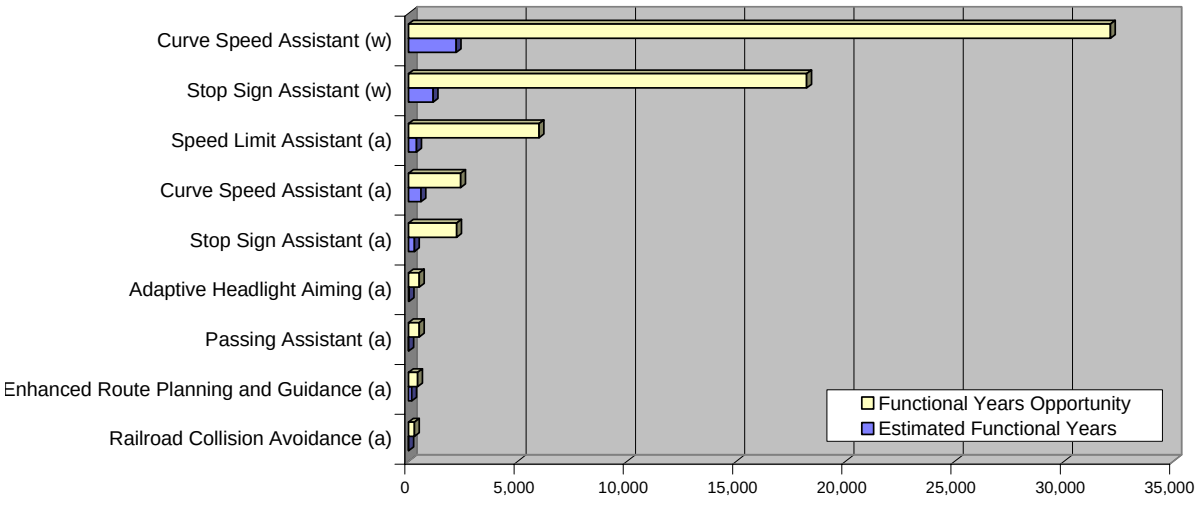

Figure A-6: Near-term ranking by benefit opportunity

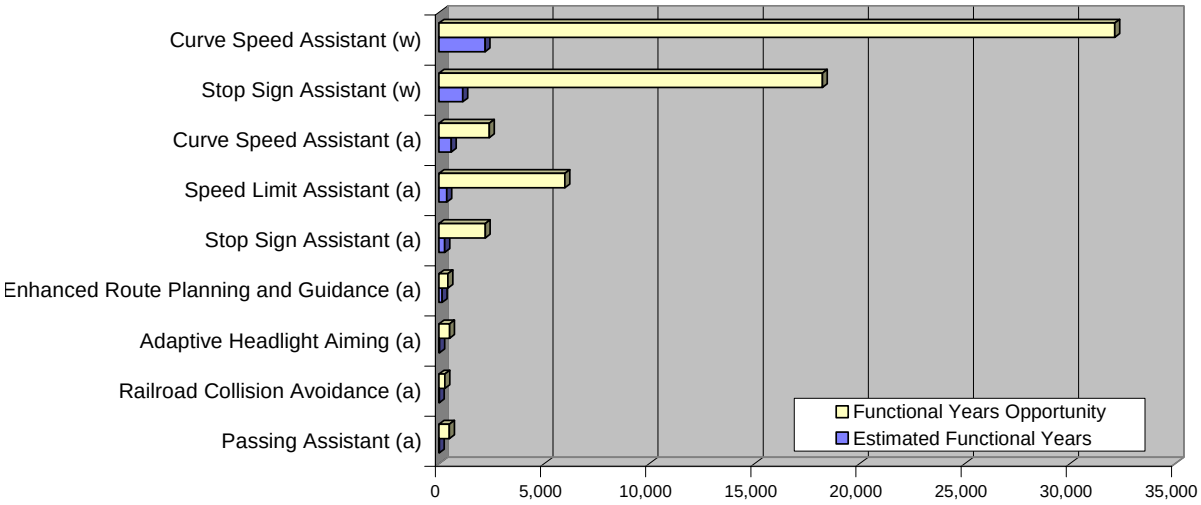

Figure A-7. Near-term ranking by benefit estimate

Figure A-7 provides ranking of near-term application systems based on benefit opportunity (market penetration based on all new cars) for fifth year after deployment. Figure A-8 provides ranking of near-term application systems based on estimated benefits (market penetration based on EDMap estimates) for fifth year after deployment.

As shown in Figure A-7 and Figure A-8, the benefit opportunity and estimated benefits of Curve Speed Warning and Stop Sign Warning are significantly greater than those of Curve Speed Advisor and Stop Sign Advisor respectively. Hence, Curve Speed Advisor and Stop Sign Advisor are not considered any further. Based on the remaining application systems, the Curve Speed Warning, Stop Sign Warning, and Speed Limit Advisor provide the best benefit opportunity as well as best estimated benefits. The remaining application systems shown in Figure A-7 and Figure A-8 provide significantly low benefit opportunity and estimated benefits in relative comparison to Curve Speed Warning, Stop Sign Warning, and Speed Limit Advisor.

Based on the analysis of near-term application systems, the EDMap team selected Curve Speed Warning, Stop Sign Warning, and Speed Limit Advisor as the highest rated near-term application systems. Table A-4 provides the benefit opportunity and estimated benefits (i.e. functional years saved based on 44 Crashes) that can be achieved with the selected application systems in the fifth year after deployment. The percentage value shown in Table A-4 indicates the functional years saved as a percentage of functioning and life lost per year according to 44 Crashes.

Table A-4: Benefits of highest rated near-term applications in 5th year after deployment

Application System	**Benefit Opportunity** (Functional Years Saved)	**Estimated Benefits** (Functional Years Saved)
Curve Speed Warning	32,126 (1.5 %)	2,191
Stop Sign Warning	18,226 (0.9 %)	1,130
Speed Limit Advisor	5,984 (0.3 %)	371

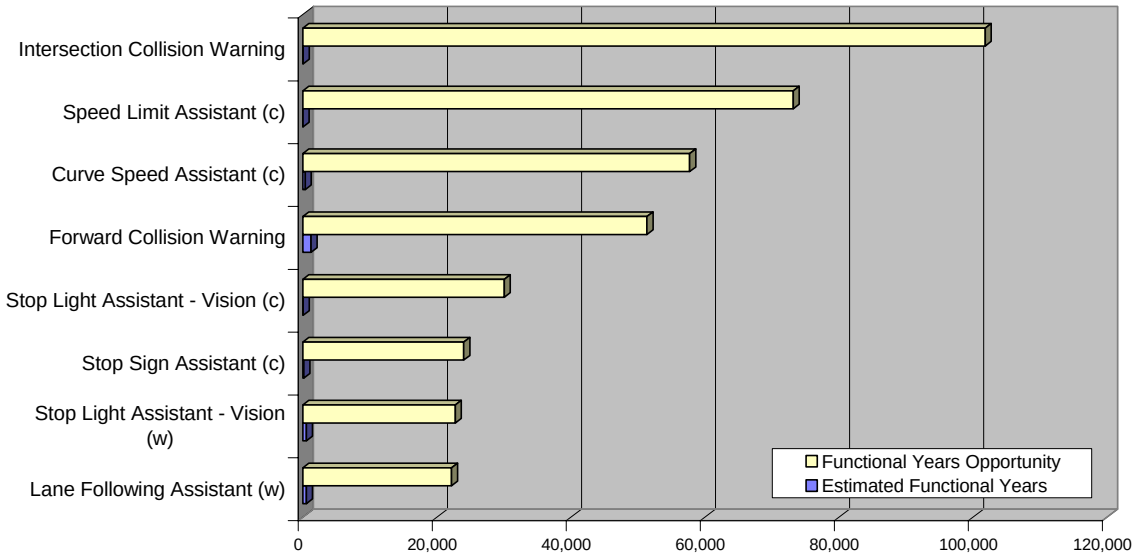

Figure A-8: Mid-term ranking by benefit opportunity

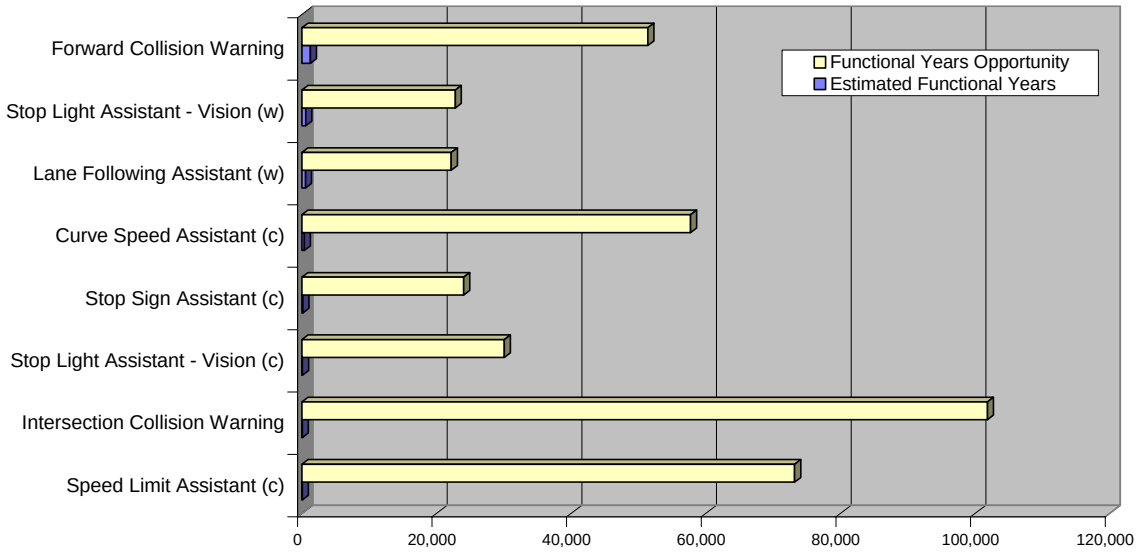

Figure A-9: Mid-term ranking by estimated benefits

Figure A-8 provides ranking of mid-term application systems based on benefit opportunity for fifth year after deployment. Figure A-9 provides ranking of mid-term application systems based on estimated benefits for fifth year after deployment.

Figure A-8 shows that the benefit opportunity for Intersection Collision Warning is the highest. However, Intersection Collision Warning is a cooperative application system and requires infrastructure-to-vehicle communication. The cost of equipping intersections with infrastructure communication capability is reflected in low market penetration of this application and hence the estimated benefits in the fifth year after deployment is significantly low. Hence, Intersection Collision Warning is not considered any further.

Figure A-8 shows that the benefit opportunity for Speed Limit Control is high. However, Speed Limit Control will not be a popular application system as reflected in low market penetration of this application. Hence, the estimated benefits in the fifth year after deployment is the lowest and Speed Limit Control is not considered any further.

Based on the remaining application systems, we find that Forward Collision Warning, Stop Light Warning, Lane Following Warning, and Curve Speed Control provide the best estimated benefits. The remaining application systems shown in Figure A-9 provide significantly low estimated benefits in relative comparison Forward Collision Warning, Stop Light Warning, Lane Following Warning, and Curve Speed Control.

Based on the analysis of mid-term application systems, the EDMap team has selected Forward Collision Warning, Stop Light Warning, Lane Following Warning, and Curve Speed Control as the highest rated mid-term application systems. Table A-5 provides the benefit opportunity and estimated benefits (i.e. functional years saved based on 44 Crashes) that can be achieved with the selected application systems in the fifth year after deployment. The percentage value shown in Table A-5 indicates the functional years saved as a percentage of functioning and life lost per year according to 44 Crashes.

Table A-5: Benefits of highest rated mid-term applications in 5th year after deployment

Application System	**Benefit Opportunity** (Functional Years Saved)	**Estimated Benefits** (Functional Years Saved)
Forward Collision Warning	51,364 (2.5 %)	1,243
Stop Light Warning	22,785 (1.1 %)	551
Lane Following Warning (Lane Departure Warning)	22,190 (1.1 %)	537
Curve Speed Control	57,742 (2.8 %)	358

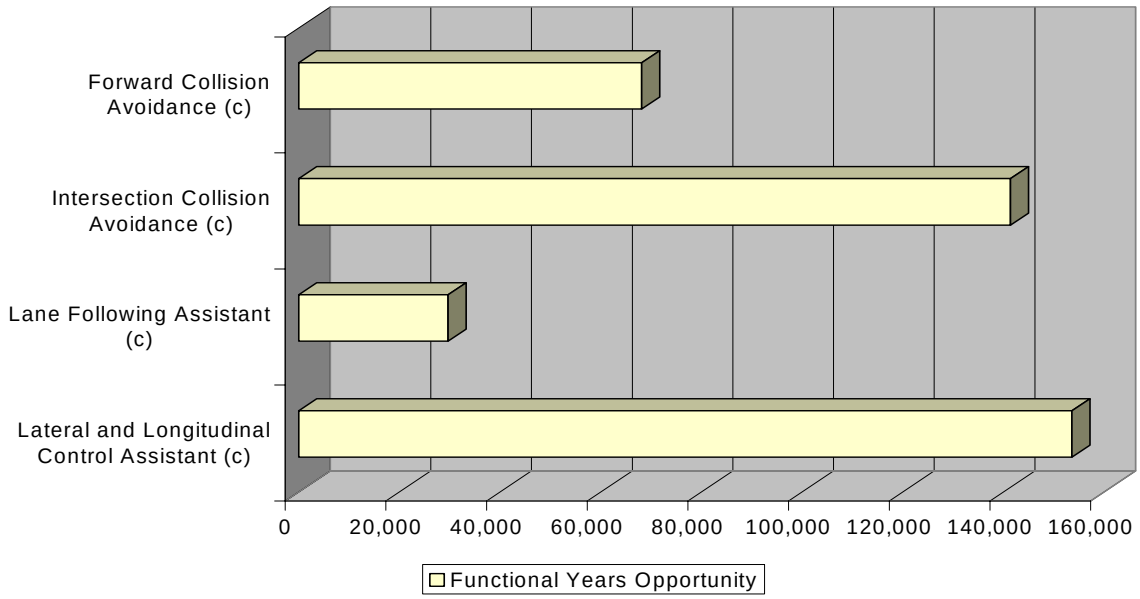

Figure A-10: Long-term ranking by benefit opportunity Figure A-10 provides ranking of long-term application systems based on benefit opportunity for fifth year after deployment. The estimated benefits of long-term application systems are very noisy and therefore the estimated benefits here are not considered.

Based on the analysis of long-term application systems, the EDMap team has selected Lateral and Longitudinal Control, Intersection Collision Avoidance, Forward Collision Avoidance, and Lane Following Control as the highest rated long-term application systems. Table A-6 provides the benefit opportunity (i.e. functional years saved based on 44 Crashes) that could be achieved with the selected application systems in the fifth year after deployment. The percentage value shown in Table A-6 indicates the functional years saved as a percentage of functioning and life lost per year according to 44 Crashes.

Table A-6: Benefits of highest rated long-term applications in 5th year after deployment

Application System	**Benefit Opportunity** (Functional Years Saved)
Lateral and Longitudinal Control	153,615 (7.3 %)
Intersection Collision Avoidance	141,414 (6.7 %)
Forward Collision Warning	68,135 (3.2 %)
Lane Following Assistant	29,694 (1.4 %)

Appendix B: Task 2 - Data Analysis Tools

B.1 Absolute and Relative Accuracy

The geometry of the road/lane that is represented in the map database typically contains some error. The error arises due to methods used in measurement of the ground truth geometry to be represented and due to data reduction algorithms used in the representation of the geometry in the map database. In what follows, definitions of absolute and relative accuracy for a road/lane segment represented in the map database are presented. Only a two-dimensional representation of the road/lane geometry is considered. Methods for validating the absolute and relative accuracy of the road/lane geometry are also discussed.

B.1.1 Absolute Accuracy

Consider the left-hand portion of Figure B-1, representing a segment of a road/lane. The unknown is the black line that represents the ground truth of the road/lane geometry. In the map database, a representation of the road/lane geometry is subject to two major sources of errors—errors introduced by the measurement system used to collect the data and errors introduced by data reduction algorithms used to provide a representation of the geometry.

Upper bounds that limit these errors are defined by the absolute accuracy specification for the geometry. The absolute accuracy specification of the lane geometry representation is defined as a circle of radius $E_{absolute}$. The envelope of the accuracy circles (area between the dotted red lines) defines the accuracy zone for the road/geometry representation in the map database. Therefore, the absolute accuracy specification enforces the requirement that the geometry representation of the road/lane in the map database must be fully contained within the indicated accuracy zone.

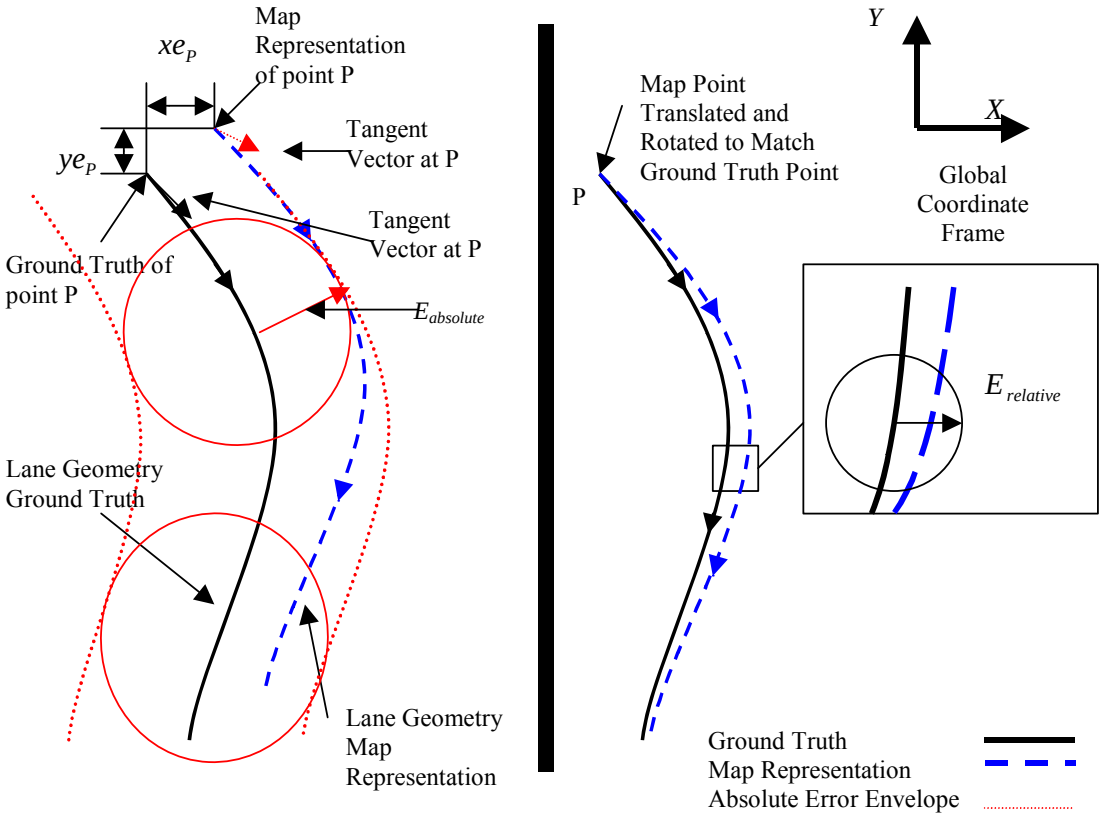

Figure B-1: Absolute and relative map accuracy

Consider the left-hand portion of Figure B-1, where P represents a reference point on the road/lane segment. The map representation of this point P must be represented in the map database within the circle of radius $E_{absolute}$, as shown. In Figure B-1, the map representation of point P is shown to have an absolute position error given by xe_P and ye_P in the two-dimensional world coordinates. Similarly, the entire road/lane segment shown in the figure can be represented in the map database, which is indicated by the dashed blue line in the left portion of Figure B-1.

B.1.2 Relative Accuracy

To define relative error, a reference point needs to be selected first. Consider the left portion of Figure B-1 and the reference point P on the segment represented in the map database and on the ground truth segment. Relative error is invariant to translation and rotation, and so after the absolute position error at P and the heading error at P are compensated for, the error between the segments is the relative error with reference to P. The heading error at P is defined as the angle between the tangent vectors at P in the map database segment and the ground truth segment. Similarly, relative error can be defined for any reference point on the segment. Relative error is a continuous function and changes at each reference point along the segment.

The right portion of Figure B-1 shows the relative errors present in the map database with reference to point P. The relative map error is determined by translating the point P in the map database to the corresponding ground truth point, and by rotating the map database segment by an angle corresponding to the heading error at P about the pivot point P, as shown. The error between the ground truth and the map database defines the relative map error with reference to point P.

The relative accuracy specification $E_{relative}$ provides an upper bound and limits the relative errors to be within the specified accuracy. If no relative accuracy specification is provided, then the relative error of the lane geometry is bounded by twice the absolute accuracy specification. However, if applications require an upper bound on relative errors that need to be tighter than this, then the relative accuracy specification must be explicitly provided in the requirements.

It is important to realize that relative accuracy for Advanced Driver Assistance Systems (ADAS) is typically specified with respect to the forward road geometry up to a certain distance with reference to the current vehicle position. The applications should define the distance of the forward geometry up to which the relative accuracy specification is valid with reference to any point on the road/lane segment.

B.1.3 Validation of Absolute and Relative Accuracy

The road/lane geometry represented in the map database must be validated to ensure that the required absolute and relative accuracy specification are satisfied. This task is not easy since the ground truth is an unknown. The following approaches may be used as a basis for validation.

B.1.3.1 Ground Truth Validation

The first step is to identify the ground truth to be used for the validation process. Post-processed data from the GPS/INS measurement system that is used to collect the road/lane geometry data can potentially be used as ground truth specification. However, independent initial testing is essential in order to verify that the post-processed data from the GPS/INS measurement system is accurate and meaningful. This may be done by mapping a small test area accurately, based on measurements using surveying techniques or other independent methods. The test area should also be mapped using post-processed GPS/INS measurements. If the errors between the road/lane geometry segments produced by both methods are significantly small, then the post-processed data from the GPS/INS measurement system that is used to collect the road/lane geometry data may be used as ground truth specification.

B.1.3.2 Absolute Accuracy Validation

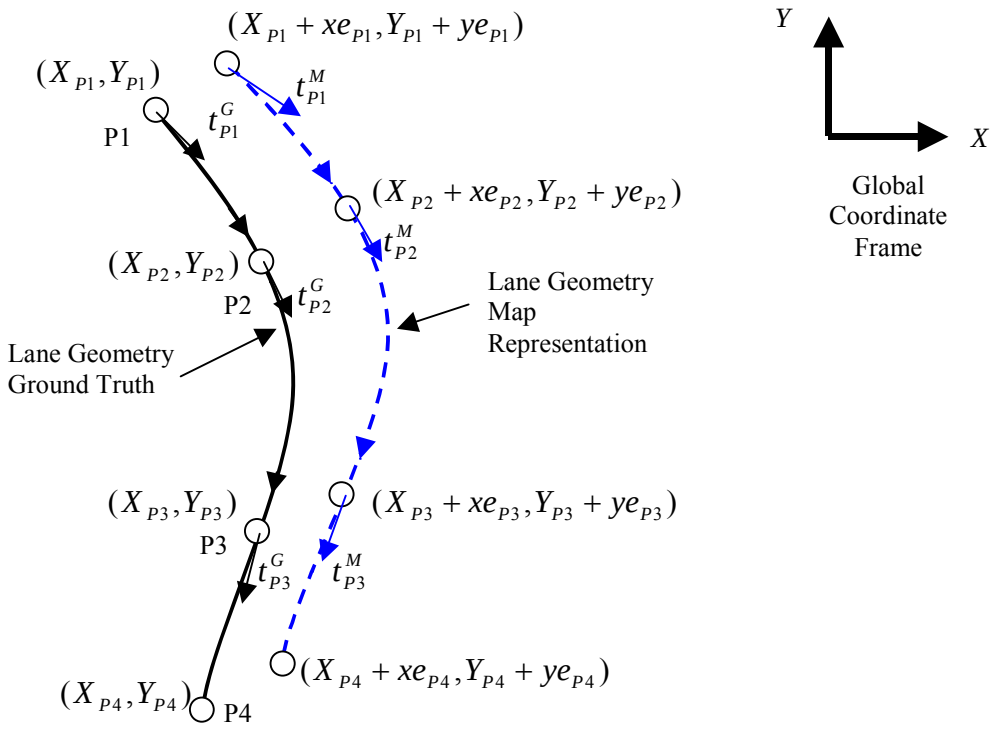

Figure B-2: Absolute and relative map accuracy validation

Figure B-2 represents the ground truth and the map representation of a road/lane segment. The following procedure may be used to validate the absolute accuracy of the segment:

1. Scale the segments to unit length (or to equal length).
2. Compute the maximum deviation between the two segments. The metric derived from this assessment is the absolute accuracy corresponding to the particular segment.
3. For each segment, report this value as the absolute accuracy attribute.

B.1.3.3 Relative Accuracy Validation

Figure B-2 represents the ground truth and the map representation of a road/lane segment. The following procedure may be used to validate the relative accuracy of the segment.

1. Scale the segments to unit length (or to equal length). Designate reference points on each segment that are equidistant along the segments. These would be points with index P1, P2, P3, and P4 in Figure B-2.
2. Compute tangent vectors between corresponding reference points on both segments. The ground truth tangent vectors are labeled t^G_{Pi} and the map tangent vectors are labeled t^M_{Pi} at reference point *Pi*, as shown.

3. Compute the angle between corresponding tangent vectors (heading errors) for each reference point. The angle between each pair of ground truth and map segment tangent vectors is defined as the angle through which the tangent map segment must be rotated, so that it aligns with the corresponding tangent to the ground truth segment. Without loss of generality, let a clockwise rotation be defined as positive and a counterclockwise rotation be defined as negative. The angle is given by:

$$\theta_i = \cos^{-1}\left(\frac{\overline{t_{Pi}^{G}} \cdot \overline{t_{Pi}^{M}}}{\left\|\overline{t_{Pi}^{G}}\right\|\left\|\overline{t_{Pi}^{M}}\right\|}\right)$$

4. Translate the map segment so that a reference point coincides with the corresponding reference point on the ground truth segment. Then rotate it by the heading error θ_i corresponding to that reference point with pivot as the reference point. Once this is done, determine the maximum deviation between the two segments (up to a certain specified forward distance). The metric derived from this assessment is the relative error corresponding to the particular reference point chosen.

5. Repeat Step 4 for each reference point that is defined along the segment. Thus, the relative errors corresponding to every chosen reference point along the segment are computed.

6. For each segment, report a single value of relative accuracy which can be defined as the maximum of all the relative errors computed at the reference points along the segment, as described above.

B.2 Description of Mapplets

B.2.1 Road/Lane Geometry

Definition: The representation of the road/lane center according to appropriate mathematical equations.

Near-term map databases have representations of road geometry, and mid-term and long-term map databases have representations of lane geometry.

B.2.1.1 Road Center

For near-term map databases, road center is the center of the roadbed, as defined by the outer edges of traffic lanes. For bi-directional roads, this includes all traffic lanes plus any dividers, shoulders, or special-use lanes (center turn, HOV, bus lane, etc.) between the directions of travel.

B.2.1.2 Lane Center

For mid-term and long-term databases, lane center is the midpoint of a virtual line **A** that extends orthogonally from one lane edge to the opposite lane edge, as shown in Figure B-3.

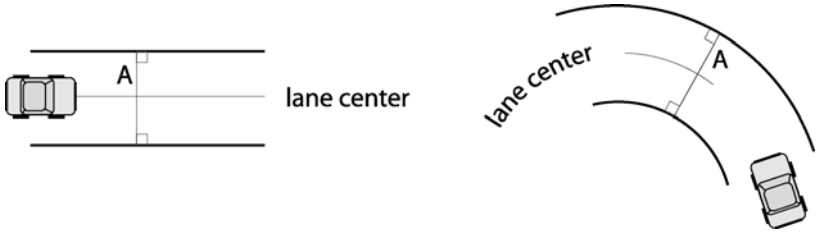

Figure B-3: Basic lane center

B.2.1.3 Lane Edge

The lane edge is the inner edge of each lane stripe, where the inner edge is defined as that closest to the vehicle travel lane. Figure B-4 shows lane edges for solid, double solid, and dashed lane stripes. The lines perpendicular to the lane edge are directed toward the center of the vehicle travel lane. "Botz dots" are treated the same as paint; the outermost portion of each dot defines the lane edge.

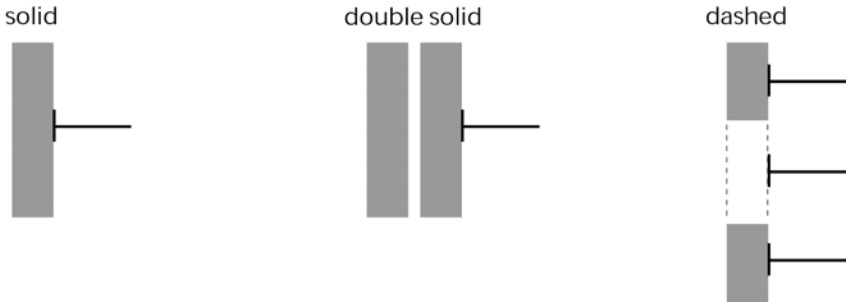

Figure B-4: Solid, double solid, and dashed lane stripes

In areas where the striping changes frequently between single and double striping, the edge will be deemed to be the leading edge of the double stripe, if present, or where it "would be", if not present. This will keep the lane centerline from "jogging" due to shifting positions of the stripe, as indicated in Figure B-5.

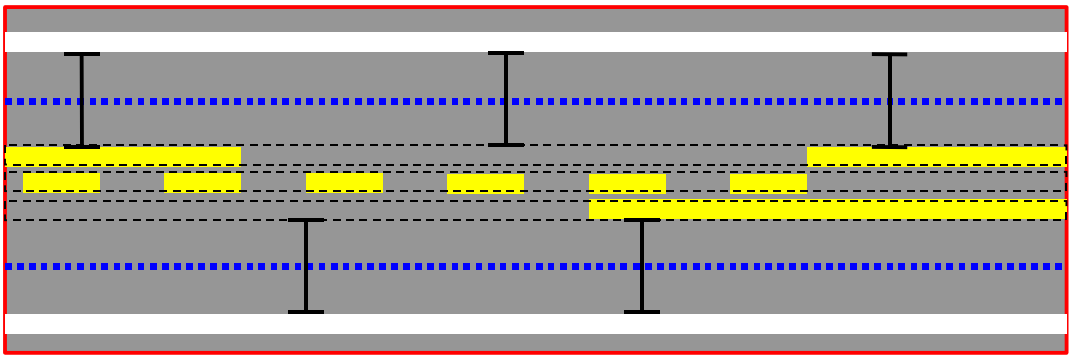

Figure B-5: Lane edge with passing/no-passing stripes

If a stripe is absent, a virtual lane stripe is to be constructed. Lane stripes can be absent for a number of reasons. In such cases, the physical edge of the lane/road will be used when discernable. This may be the base of a curb or wall, transition from pavement to curb/gutter, or edge of pavement. When a roadway has one surface material and the curb/gutter has another, the lane edge will be considered to be the transition to the curb/gutter material. When a roadway has one material and the shoulder has another, the lane/shoulder edge will be considered to be the transition between materials.

A very wide lane (wide enough for more than one car) but with no discernable lane marking will be considered to be a single, wide lane–not two or more lanes–unless probe vehicle data is available, and it indicates that there is more than one parallel lane present.

B.2.2 Lane Width

Definition: The distance **A** between the two inner edges of the lane, as in Figure B-3.

B.2.3 Transition Zone

Definition: A location on a roadway where lanes are added or subtracted.

An example of a two-lane segment transitioning into a three-lane segment is shown in Figure B-6.

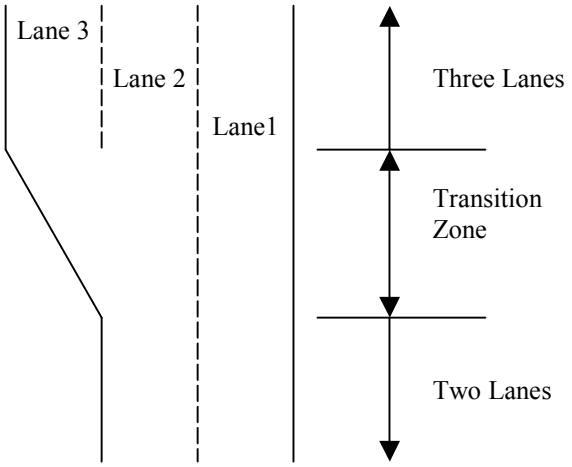

Figure B-6: Roadway merge/lane creation area

Transition lanes do not have width. There will be a line connecting the lanes on either end, but it is not necessarily the geometric centerline of the pavement (see Figure B-7). Until probe vehicle data is available, the transition lane centerline position will be estimated. After probe vehicle data is available, transition lane "centerlines" will follow probe data traces.

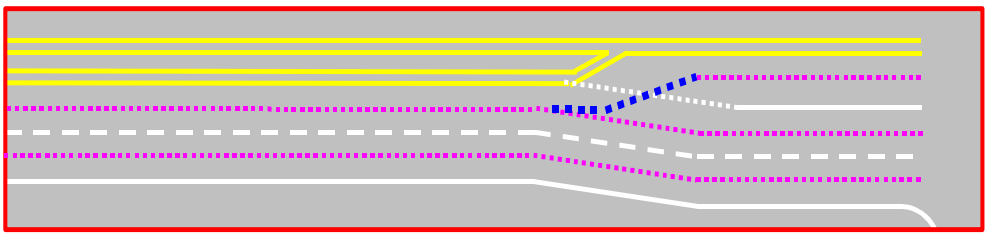

Figure B-7: Transition lane "centerlines"

B.2.4 Road/Lane Heading

Definition: The angle of the unit tangent vector at any point on the road/lane center, as shown in Figure B-8.

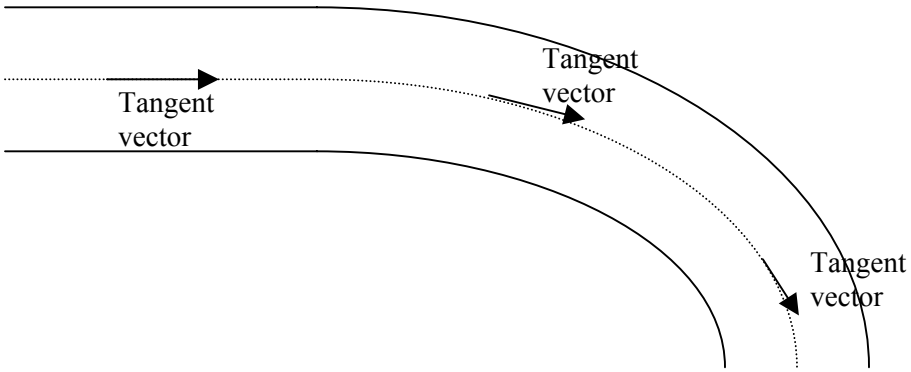

Figure B-8: Road/lane heading

Near-term map databases will have road heading, whereas mid-term and long-term map databases will have lane heading as accessible attributes. Road and lane heading may be computed based on the road and lane geometry equations, respectively.

For an arc $y = f(x)$, the heading is:

$$\theta(x) = \tan^{-1}\frac{dy}{dx}.$$

B.2.5 Road/Lane Curvature

Definition: The instantaneous change of the unit vector tangent (shown in Figure B-8) per unit arc length at any point on road/lane center.

Near-term map databases will have road curvature, whereas mid-term and long-term map databases will have lane curvature as accessible attributes. Road and lane curvature may be computed based on the road and lane geometry equations, respectively.

For an arc $\mathbf{r} = f(t)\mathbf{i} + g(\mathbf{t})\mathbf{j}$ defined parametrically in t, the curvature is:

$$\kappa(t) = \frac{g'(t)f''(t) - f'(t)g''(t)}{\left(f'^2(t) + g'^2(t)\right)^{3/2}}$$

For an arc $y = f(x)$, the curvature is:

$$\kappa(x) = \frac{\dfrac{d^2y}{dx^2}}{\left(1 + \left(\dfrac{dy}{dx}\right)^2\right)^{3/2}}.$$

B.2.6 Shoulder Type

Definition: The classification of the road shoulder into two categories: paved and unpaved.

B.2.7 Shoulder Width

Definition: The width of the roadway shoulder, calculated as the distance between the shoulder edges.

If the shoulder is separated from a lane by a stripe, the shoulder is deemed to begin at the outside edge of the lane stripe. If the shoulder or roadway edge is erratic or not discernable, the edge will be considered to be a "virtual edge" such that it is parallel to other lane edges/markings. These virtual edges will change only if the road shoulder changes beyond a stretch of 20 m or more to avoid making too many unnecessary changes in shoulder width (see Figure B-9).

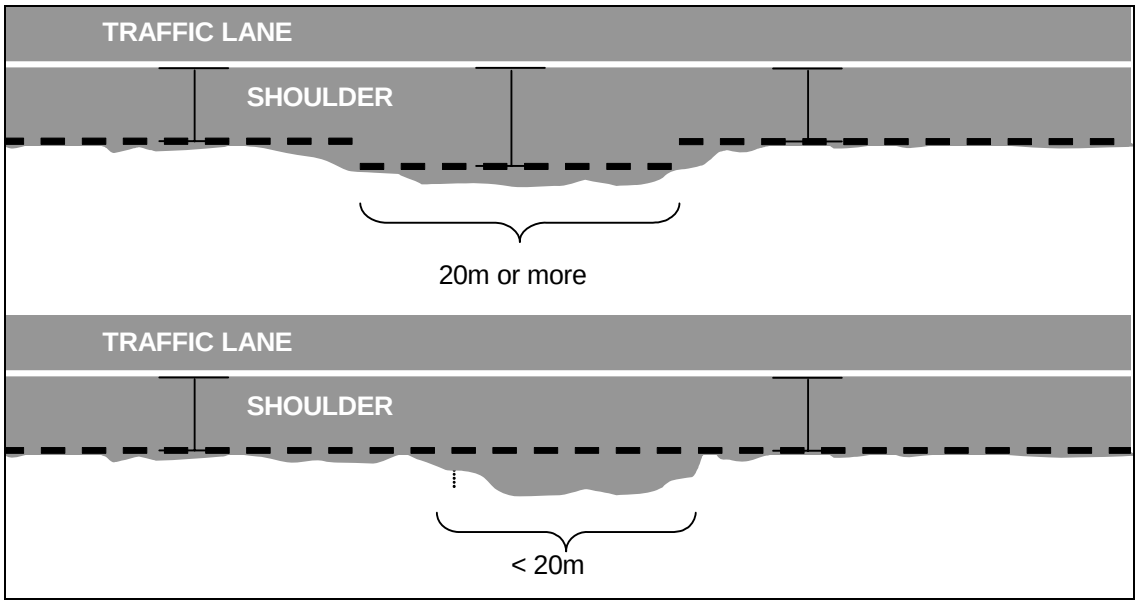

Figure B-9: "Virtual edge" and shoulder width

B.2.8 Lane Markings Type

Definition: The painted or raised markers that designate the edge(s) of lanes.

Lane marking types are typically solid, dashed, dotted, none, and erratic. Lane marking "medium" will be "paint" or "Botz dots." "Reflectors present" will be a yes/no attribute for each marker. This pertains to reflectors present in addition to paint, not reflective paint or Botz dots. When double stripes are present, each of the two stripes can have a unique type (solid, dashed, dotted) and color.

B.2.9 Lane Direction

Definition: The legal direction of travel of the lane.

Each lane in the map database will have one direction of travel identified for the lane. Lanes used for reverse-flow operation and center turn lanes, where both directions of travel are common, shall be identified as such.

B.2.10 Number of Lanes

Definition: The number of lanes in each direction ("from" the reference end, "to" the reference end).

This mapplet represents the number of through traffic lanes on the road, in each direction. Turn lanes, shoulders, and lanes not available to autos (e.g., bus/taxi lanes) are not included in the count. Transition lanes do not affect the count.

B.2.11 Road Condition

Definition: An indication of the condition of the road surface.

Typical road condition types will be "smooth," "rippled," and "uneven."

B.2.12 Road Surface Type

Definition: An indication of whether the road surface is paved or unpaved or metal grating. Paved roads are further divided into asphalt, concrete, or block.

Typical types are rigid (concrete), flexible (asphalt), metal grating, blocks, and "mixed" when no surface type predominates. Road surface type will be applied to roads in the near-term database, and to lanes in the mid-term and long-term databases.

B.2.13 Road Grade

Definition: The change in *rise* over *run* of a road section, as shown in Figure B-10.

The *rise* is straightforwardly defined as the change in elevation. The *run*, on the other hand, is the horizontal travel component as shown. Grade is then computed based on the equation:

$$\%G = 100\frac{rise}{run} = 100\tan\theta$$

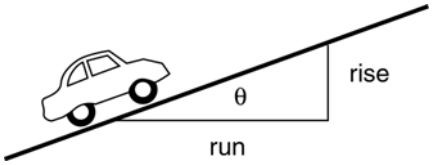

Figure B-10: Road grade

Grade is often expressed as a percentage. As an example, for a road that rises 5 m in 100 m of run, the %G = 5%. Grade can also be negative for down-sloping road segments.

In the strict definition, the vehicle travel distance is not the *run* length, but it is sometimes practical to substitute the travel distance for *run*. For roads, the error introduced is not significant for small θ where $\tan\theta$ can be approximated by $\sin\theta$. For 10% grade, the error is 0.05% where the reported %Grade would be calculated (using $\sin\theta$) as 10.05% instead of 10%. The error, therefore, is biased to overstate the grade.

B.2.14 Superelevation

Definition: Superelevation, often called banking, is used to help keep the vehicle from leaving the road in a turn by *increasing* the centripetal force.

Superelevation is defined in a manner similar to grade. In Figure B-11, the road (or lane) cross-section is shown with terminology similar to grade. The superelevation *e* is calculated by

$$\%e = 100\frac{rise}{run} = 100\tan\theta$$

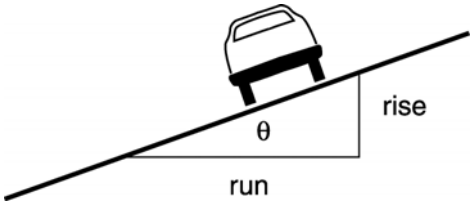

Figure B-11: Superelevation

B.2.15 Road Class

Definition: Road class is made up of a number of discrete attributes that can be used to classify roads.

These discrete attributes will include the following:

- Ramp (yes/no)
- Bifurcation (yes/no)
- Types of traffic allowed (autos, pedestrians, bicycles, buses, trucks, taxis, carpools, deliveries, through traffic, emergency vehicles)
- Controlled Access (yes/no)
- Tollway (yes/no)
- Multiple-digitized carriageways (yes/no)
- Ramp (yes/no)
- Frontage Road (yes/no)
- POI Access Road (yes/no)
- Turn Lane (yes/no)
- "Functional class" (logical hierarchical usage ranking, 1-5, where 1 is a primary high-volume, maximum speed artery, and 5 is a side street)

B.2.16 Speed Limits

Definition: The posted speed for a section of roadway.

Typical speed limit examples include general posted speed limits, default speed limits, advisory posted speeds, and dependent speeds (school, hospital zones, and weather-related speed advisories).

B.2.17 Stopping Location

Definition: The legal stopping position for stop signs and traffic signals.

In near-term databases, the stopping location will be provided as a point along the roadway (distance from end of road segment). If the stopping location position varies between lanes, the earliest encountered location is used. In mid-term and long-term databases, the stopping location will be provided as a point along each lane.

A stopping location will not be present for yield signs unless a painted line actually exists, since often a yield will not normally result in a stop, but rather an adjustment in speed.

B.2.17.1 For Stop Sign

For stop signs, the stopping location is typically indicated as a white line painted on the pavement. If no line is present, a virtual stop line may indicate where traffic should stop.

B.2.17.2 For Traffic Signal

For traffic signals, the stopping location is typically indicated as a white line painted on the pavement. If no line is present, a virtual stop line may indicate where traffic should stop.

B.2.17.3 For Railroad Crossing

For railroad crossings, the stopping location is typically indicated as a white line painted on the pavement. If no line is present, a virtual stop line may indicate where traffic should stop.

B.2.18 Stop Sign Location

Definition: The position of stop signs on the road.

An indication that a road has a stop sign at an intersection will be required, with the longitudinal position of the first encountered stop sign. This may be before or after the stopping position. There will be a logical relationship established between the stop sign and its stopping location.

B.2.19 Stop Ahead Sign Location

Definition: The position of stop ahead signs on the road.

Stop ahead signs will be included only if actually present. These signs can provide the application an indication that the actual stop sign may be hard to see, because the path is twisted or hilly. Applications can use the presence of a stop ahead sign to optimize the timing for warning or control.

B.2.20 Traffic Signal Location

Definition: The location (latitude/longitude) of each traffic signal on the road.

There will be a logical relationship established between the traffic signal and its stopping location. Each traffic signal will be associated with one or more lanes that it controls. These lanes will all be part of the same road. If there are two or more traffic signals at the same location, but facing different roads, they will be maintained separately.

There will be an indication if a traffic signal is a "left turn signal", i.e., that it only controls left turns. This will not be applied to signals that have a left-turn arrow but also have a round green light for through traffic. A "left turn signal" will only be associated with left turn lanes.

B.2.21 Yield Sign Location

Definition: The position of yield signs on the road.

An indication will be provided if the road has a yield sign at an intersection, with the longitudinal position of the first encountered yield sign. This may be before or after the stopping position (if present). There will be a logical relationship established between the yield sign and its stopping location (if present).

B.2.22 Intersection Location

Definition: Point at which the center of a lane intersects with the crossing lane edge, as shown in Figure B-12.

Right turn lanes will be marked with intersection location at the point where the centerline crosses the lane edge of the destination lane (i.e., same as through lanes and left turn lanes). Note that this may be outside the perceived "bounding box" of the intersection (see Figure B-12).

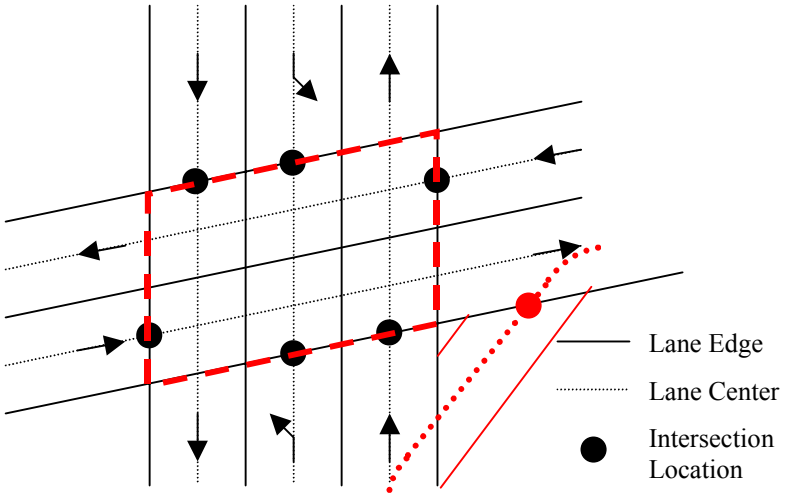

Figure B-12: Intersection location with right turn lane

B.2.23Intersection Geometry

Definition: Representation of lane geometry specifically at intersections.

Figure B-13 illustrates potential variability in actual intersection lane paths. At turns, there may be multiple destination lanes as well as variable paths while making the turn. Variability is likely even in the case of multiple dedicated turn lanes, as in the right-side drawing.

An indication is provided for every lane entering an intersection as to what the expected lane(s) can be leaving the intersection. This will cover any configurations present–single and multiple turn lanes, lanes that are "through plus turn," situations where the number of through lanes increases or decreases across an intersection, etc. There may be one-to-many or many-to-one situations, if consistent with reality.

Because turn maneuvers within an intersection are variable, no attempt will be made to determine intersection lane "centerlines" until probe vehicle data is available. At that time, intersection lane "centerlines" will follow nominal probe data traces.

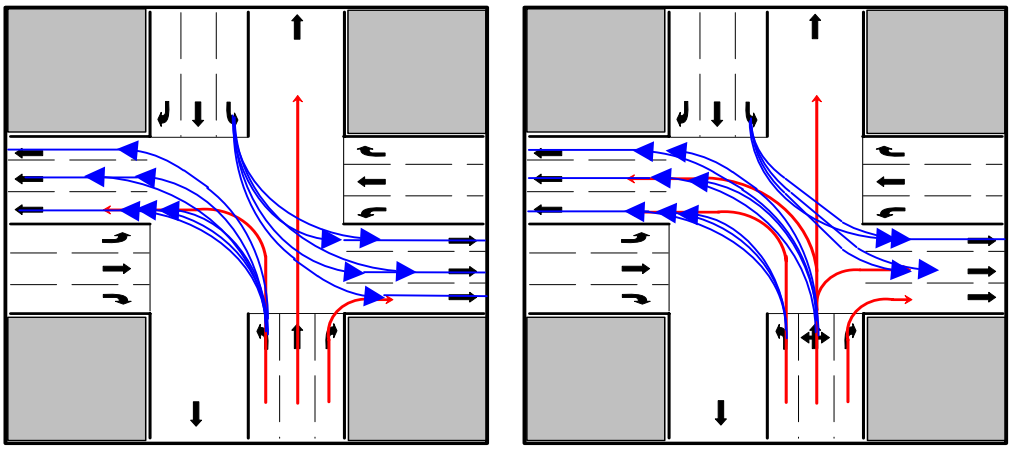

Figure B-13: Variability of intersection lane paths

B.2.24 Overhead Stationary Roadway Structures

Definition: The location of structures that cross over the roadway.

Typical examples include bridges, overpasses, tunnels, pedestrian walkways, and overhead signs. Structures that begin more than 10 m over the road will not be included. This includes very high overpasses, power lines, etc.

The location and posted heights will be included. If there is no height posted, the database will say "unposted" (rather than a default height, which may not resemble reality).

B.2.25 Stationary Roadside Objects

Definition: Qualitative measure of stationary objects that exist within 4 m of the edge of the travel way.

Typical examples include mail boxes, light poles, and trees. If stationary objects exist within 2 m of the roadway, some qualitative measure can be used to score the segment in terms of the density of objects within 2 m of the roadway.

Stationary roadside objects will be coded as follows:

"0" - Closest object is >2 m from roadway (distance provided)

"1" - Sparsely placed objects within 2 m of roadway

"2" - Low density of objects within 2 m of roadway

"3" - Significant density of objects within 2 m of roadway

"4" - Very dense placement of objects within 2 m of roadway

This will be provided as a segment attribute (not point-by-point). If no objects in the segment exist within 2 m of the roadway ("0" on qualitative scale), an indication as to the distance of the closest object within 4 m of the roadway could be provided.

B.2.26 Stationary Roadside Barriers

Definition: Start and end locations of stationary barriers on the roadside, such as guard rails, Jersey barriers, and bridge abutments.

Guard rails, bridge abutments, and walls will be coded as such. There is no minimum length for inclusion of bridge abutments, guard rails, or walls. Metal guard rails of any length will be included when within 10 m of the road edge (outer travel lane). Walls (not metal) of any length will be included when within 5 m of the road edge (outer travel lane).

B.3 Mapplet and Vehicle Positioning Requirements

This appendix presents the mapplet and vehicle positioning requirements for the 12 safety applications identified in Task 1 (Table 1-1). Engineering analysis was performed to capture these requirements based on kinematic and geometric calculations.

B.3.1 Forward Collision Warning/Avoidance: Map Database and Vehicle Positioning Requirements

B.3.1.1 Introduction

In the past and on current production navigation systems, GPS-measured vehicle position and the map database are combined with map-matching techniques to identify the roadway on which the vehicle is traveling and determine the longitudinal position of the vehicle on the roadway. The EDMap project is intended to reflect positioning and map capabilities in the future, so the Forward Collision Warning (FCW) application will utilize vehicle positioning and the map database that reflect production potential in the years 2006 through 2010, and the Forward Collision Avoidance application will utilize vehicle positioning and the map database that reflect production potential in the years 2011 through 2015.

Using accurate vehicle positioning and the map database, the map-matching problem becomes one of matching the vehicle position onto the correct travel lane on the road. The high accuracy vehicle positioning systems and map databases expected to be available in the future will be used by the application to identify the roadway and lane on which the vehicle is traveling without need for elaborate map-matching techniques.

For the application, the map database must provide the system with roadway information containing lane geometry of all its lanes and other map attributes. The accuracy of the lane geometry specification in the map database should be good enough in order to correctly classify the radar targets ahead of the host vehicle as in-path or out-of-path targets. Incorrect classification of in-path and out-of-path targets leads to false alarms and missed detections in the system, which would limit deployment and user acceptance.

This analysis attempts to develop error bounds for the map database attributes in order to assist the system in correct prediction of forward road/lane geometry and thereby limit the errors in target classification as in-path and out-of-path, and to improve the performance of the system.

B.3.1.2 Brief Description

The Forward Collision Warning application will typically use a forward-looking radar sensor mounted at the front of the host vehicle that detects targets (other vehicles or objects) ahead of the host vehicle and in its field of view. An accurate prediction of the forward lane geometry ahead of the host vehicle travel lane (up to 120 m) is necessary in order to properly classify the radar targets as in-path or out-of-path. The system would typically use a GPS receiver for vehicle position measurement along with a map database, a vision system that detects lane markers, a vehicle speed sensor, and a yaw-rate sensor to predict the forward road geometry ahead of the host vehicle.

An EDMap project goal is to develop an enhanced map database with necessary map attributes and accuracy to use as a primary source for predicting the forward path. To accurately predict the path of the host vehicle, map database software uses the current vehicle position to create an electronic horizon. The electronic horizon includes a list of possible paths determined by the structure of the road system. Once host vehicle position is established, the host vehicle is

associated with a map-matched point on the travel lane. From this reference point, map information provides the forward geometry of the lane and other possible paths the driver may choose.

Errors introduced by the map database, the radar sensor, and the host vehicle position measurement accumulate, resulting in ambiguity in determining whether an object is in-path or out-of-path. In the following sections, accuracy specifications are derived for map database attributes based on an analysis of cumulative lateral target position errors that may lead to correct classification of radar targets as in-path or out-of-path targets by the system.

The Forward Collision Avoidance application will be a natural progression of the warning application in the long-term timeframe. The Forward Collision Avoidance application will use automated braking to prevent or mitigate rear-end crashes in situations where the driver does not take appropriate action based on the warning provided by the system. The map database attribute requirements for the Forward Collision Warning application would be sufficient for the Forward Collision Avoidance application as well. However, since the Forward Collision Avoidance application is deployable in the long-term timeframe, the accuracy specifications that have been made for the map database attributes for the Forward Collision Warning application in the mid-term timeframe are expected to only get better as the map database progresses from mid-term to long-term timeframe.

B.3.1.3 Requirements for Forward Collision Warning/Avoidance

The following is an attempt to identify the positioning and map attribute requirements for a forward collision warning/avoidance application. First, positioning requirements are provided, followed by requirements for road/lane geometry, road/lane attributes, and roadway clutter. Where appropriate, sensor errors are introduced in an effort to identify all sources of error in the system. The effect of sensor errors and map errors are used in order to determine whether a target identified by the radar is in-path or out-of-path.

B.3.1.3.1 Positioning Requirements

The Forward Collision Warning application will use vehicle position sensing capabilities that reflect the mid-term timeframe. A typical mid-term vehicle position sensor should be able to limit the vehicle heading error to within 0.15 degrees and the longitudinal and lateral position error to within 0.5 m.

The Forward Collision Avoidance application will use vehicle position sensing capabilities that reflect the long-term timeframe. A typical long-term vehicle position sensor should be able to limit the vehicle heading error to within 0.15 degrees and the longitudinal and lateral position error to within 0.2 m.

The error bounds stated are for the worst case, typically after a 30 second GPS outage. The positioning system should indicate to the application the estimated 1-σ error in the heading and position measurements so that the application can determine when the error bounds are being exceeded. Typical values of the errors should be smaller than the worst case bounds stated here. The update rate for vehicle positioning should be greater than 10 Hz for good performance.

B.3.1.3.2 Road/Lane Geometry

Road/Lane geometry is defined in Appendix B, Section B.2.1. For the Forward Collision Warning/Avoidance application, representation of the lane center of each travel lane should be provided in the map database. Furthermore, equations should be provided that represent the center of each travel lane of the road for at least 120 m ahead (forward geometry) of the current vehicle position on the road.

Absolute and relative accuracy definitions for road/lane geometry are provided in Appendix B, Section B.1. The accuracy requirements of the representation of the road/lane geometry are discussed here. In defining accuracy for the road/lane geometry, the effects of the vehicle position, map database, and radar errors on in-path or out-of-path classification of the radar target are determined. An analysis of lateral error introduced in the target location relative to the lane center provides an estimate of errors that may be tolerated in map database representation of road/lane geometry.

Effect of Travel Road/Lane Heading Error

Road/lane heading is defined in Appendix B, Section B.2.4. The accuracy for road/lane heading for the application is derived here. In this application, vehicle heading and travel road/lane heading are used to transform radar targets represented in the vehicle coordinate frame to the road/lane frame of reference (i.e., a reference frame with x-axis along the road/lane tangent and y-axis orthogonal to it at the vehicle location). The transformation is necessary to correct for the deviation in vehicle heading from the road/lane heading at the vehicle position.

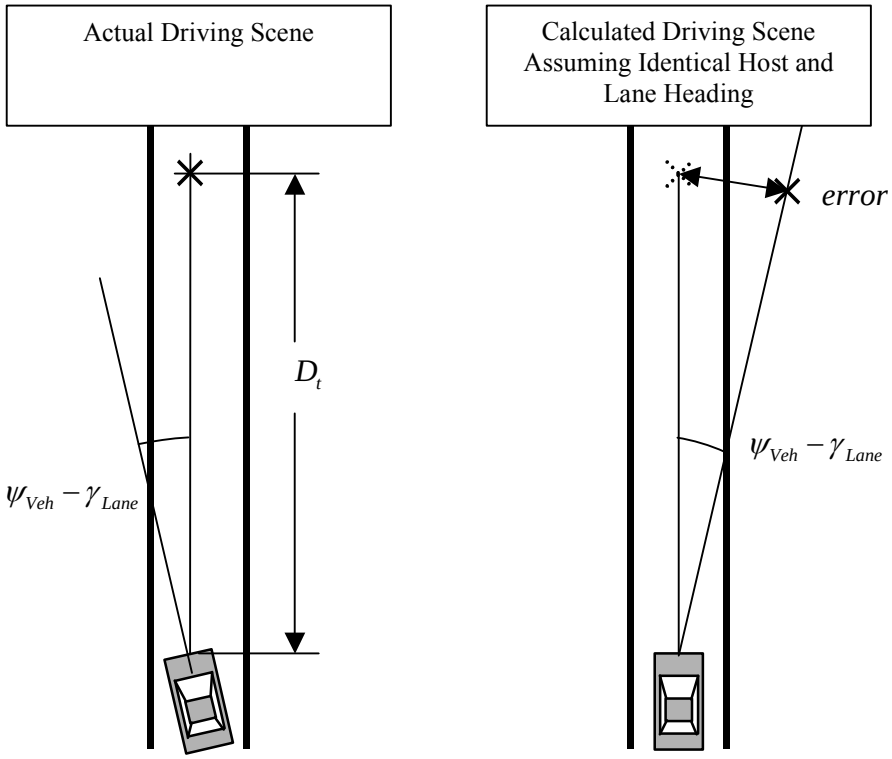

Figure B-14: Vehicle heading correction

Figure B-14 shows a driving scene in which the host vehicle is traveling along the lane center with a heading that is different from the travel lane heading. A radar target is shown at the lane center at a range D_t ahead of the vehicle. $\psi_{Veh} - \gamma_{Lane}$ represents the difference between vehicle heading and travel lane heading. The effect of assuming the vehicle heading is identical to travel lane heading is shown. Directly transforming radar targets into lane coordinates without compensating for the difference in vehicle and travel lane heading results in a lateral target position-in-lane error that is given by:

$$error = 2D_t \sin(\frac{\psi_{Veh} - \gamma_{Lane}}{2}) \cong D_t(\psi_{Veh} - \gamma_{Lane})$$

The errors introduced by not compensating for the vehicle heading result in errors in the lateral position of the target with respect to the lane center which could lead to inaccurate classification of targets as in-path or out-of-path, as the case may be.

For example, a target identified at a range of 120 m and a host relative heading of 1 degree with respect to the lane heading will result in a lateral target position-in-lane error of 2.1 m. The magnitude of the error indicates that correction for vehicle heading in lane is required in order to classify radar targets as in-path or out-of-path targets at ranges up to 120 m.

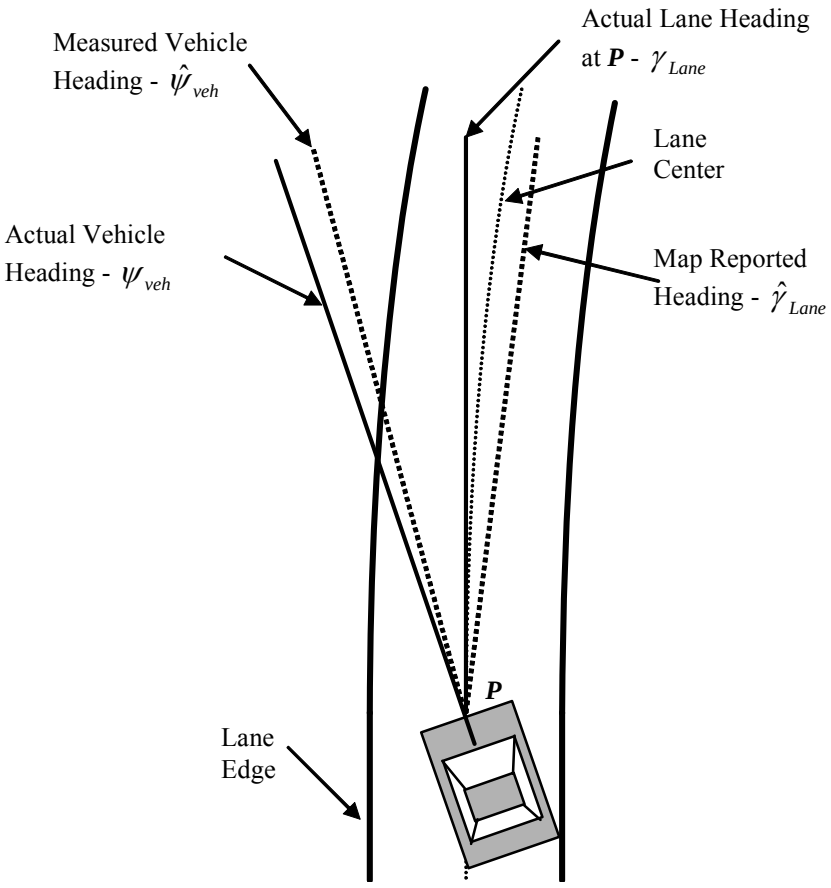

Figure B-15 Vehicle and road heading errors

Figure B-15 identifies the variables used for vehicle heading and road/lane heading. ψ_{Veh} represents actual vehicle heading while $\hat{\psi}_{Veh}$ represents measured vehicle heading. $\psi_e = \psi_{Veh} - \hat{\psi}_{Veh}$ is the error associated with the measurement of the vehicle heading and originates from the GPS/INS system used for vehicle positioning.

γ_{Lane} represents the actual travel road/lane heading at point ***P*** while $\hat{\gamma}_{Lane}$ represents the travel road/lane heading represented in the map database. $\gamma_e = \gamma_{Lane} - \hat{\gamma}_{Lane}$ is the error associated with the representation of road/lane heading in the map database.

The errors associated with measured vehicle heading and map represented travel road/lane heading result in a lateral target position-in-lane error given by:

$$error = 2D_t \sin(\frac{\psi_e - \gamma_e}{2}) \cong D_t(\psi_e - \gamma_e)$$

For example, a target identified at a range of 120 m, a host vehicle heading error of 0.15 degrees, and a lane heading error of 0.15 degrees will result in a lateral target position-in-lane error of 0.63 m. The magnitude of the error indicates that vehicle heading error and lane heading error must be small in order to classify radar targets as in-path or out-of-path targets at ranges up to 120 m.

Alternatively, a vision system may be used to determine host vehicle heading relative to the travel road/lane heading. If a vision system is used in the FCW system, travel road/lane heading will be not be required from the map database, but representation of lane markings on the road surface will be required. Therefore, the vision system cannot provide reliable vehicle heading information relative to road/lane center in the absence of clear lane markings on the road surface. The effect of error in the measurement of vehicle heading relative to road/lane heading using a vision system would be similar to the lateral target position-in-lane error introduced by a GPS/INS system and map database with road/lane heading information.

Effect of Radar Sensor Error

In FCW, a forward-looking radar is the primary sensor for determining the position of target vehicles and objects relative to the host vehicle. The radar sensor measures the range, range-rate, and azimuth angle, the angle between the heading of the host vehicle and target location, of targets in its field-of-view. Figure B-16 shows the azimuth angle, θ_t, between host vehicle heading and target location. The radar measures the target azimuth as $\hat{\theta}_t$.

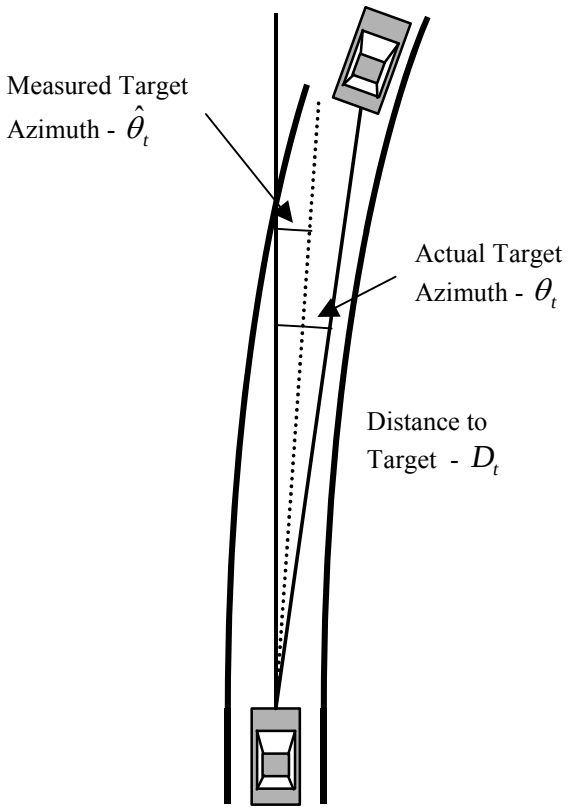

Figure B-16: Radar azimuth error

$\theta_e = \hat{\theta}_t - \theta_t$ is the error between the actual and measured azimuth angle of the target. The lateral target position-in-lane error associated with the radar azimuth error can be approximated as:

$$error \cong D_t \sin(\hat{\theta}_t - \theta_t) \cong D_t \theta_e$$

The approximation in the above equation can be made due to small values of θ_t, $\hat{\theta}_t$, and θ_e. For example, a target identified at a range of 120 meters and an azimuth angle error of 0.167 degree will result in a lateral target position-in-lane error of 0.35 m. The magnitude of the error indicates that consideration of azimuth error is important in order to classify radars targets as in-path or out-of-path targets at ranges up to 120 m.

Although an error exists in the radar measurement of the distance to the target, D_t, this has little impact on the lateral position error of the target with respect to lane center. Hence, the error in radar range is ignored in this analysis.

Effect of Vehicle Positioning and Absolute Map Errors

Consider a vehicle traveling along the lane center as shown in Figure B-17. The GPS/INS system reports a position, (x_{INS}, y_{INS}), that differs from the actual position, (x, y), of the vehicle. Figure B-17 shows the longitudinal and lateral errors in vehicle position that are due to the measurement of the GPS/INS system. The x-axis is along the tangent of the road/lane and the y-axis is orthogonal to it and to its right. The longitudinal and lateral

(along the road/lane and orthogonal to it, respectively) errors introduced by the GPS/INS system are given by:

$$(x_{INSerror}, y_{INSerror}) = (x, y) - (x_{INS}, y_{INS})$$

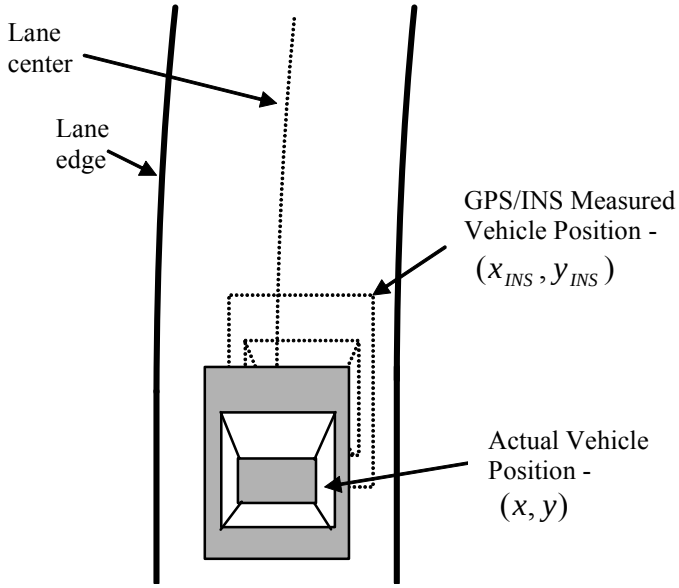

Figure B-17: Vehicle position and absolute map errors

A map-matching algorithm uses the measured vehicle position (x_{INS}, y_{INS}) along with the map database to identify the appropriate location of the vehicle on the map database. The map-matched vehicle position is used to generate the forward path of the vehicle. The forward path predicted from the map database will have errors with respect to the ground truth due to absolute longitudinal and lateral errors present in the map database. These absolute map errors in the longitudinal and lateral errors are essentially given by $(x_{Maperror}, y_{Maperror})$, respectively.

The longitudinal position errors introduce errors in the lateral target position-in-lane with respect to the lane center. Three scenarios are described below, and the error identified in each case has direct impact when determining lane position of targets. In these cases, it is assumed that map matching will not be able to detect and eliminate the error in x_{INS} due to the expectation that the errors will be less than one meter.

The lateral errors will have little effect when estimating the forward path of the host vehicle, assuming that the host is identified in the correct lane. However, the lateral errors will introduce errors in determining the lateral host vehicle position-in-lane and hence the lateral target position-in-lane with respect to the lane center. This is discussed below in *Effect of Positioning and Map Absolute Lateral Error*.

Effect of Absolute Longitudinal Error When Host Vehicle on Straight Road Approaches Curve

The vehicle position measurement error, $x_{INSerror}$, and the absolute map database error, $x_{Maperror}$, project onto longitudinal and lateral errors of the lane geometry when the host is approaching a curve. As shown in Figure B-18, the host vehicle is traveling on a straight section of road approaching a curve. The map-matched vehicle position is shown to be closer to the start of the curve but, in reality, it could also be further away. This error is due to the vehicle positioning error.

The absolute map error is shown to decrease the distance to the curve, resulting in the vehicle being closer to the beginning of the curve, but it could also increase the distance. The absolute map error is shown in the direction tangent to the lane path, where it has the maximum effect on lateral error.

The absolute map error is shown to decrease the distance to the curve, resulting in the vehicle being closer to the beginning of the curve, but it could also increase the distance. The absolute map error is shown in the direction tangent to the lane path, where it has the maximum effect on lateral error.

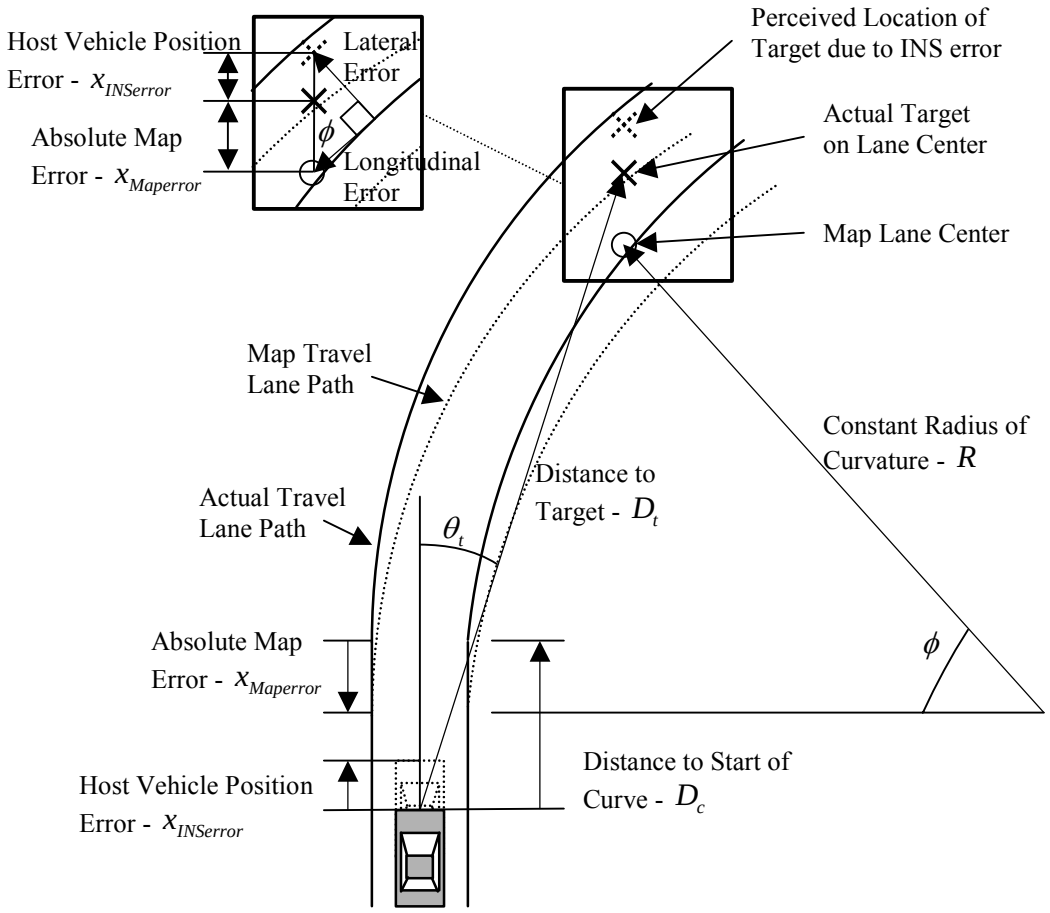

Figure B-18: Host vehicle approaching curve

As a result of the positioning and absolute map errors, the perceived location of the target combined with the calculated path may have large lateral errors with respect to the actual path. The calculated target lateral error for this scenario is given by:

$$error = (x_{INSerror} + x_{Maperror})\sin(\phi) = x_e \frac{D_t \cos(\theta_t) - D_c}{R} \cong x_e \frac{D_t - D_c}{R}.$$

Values of θ_t being less than 7.5 degrees allow the approximation in the equation above.

Effect of Absolute Longitudinal Error When Host and Target Vehicles on Curved Paths

Figure B-19 shows another scenario where the host vehicle is traveling along a constant curvature path with a target vehicle ahead on the same constant curvature path. The host longitudinal error, $x_{INSerror}$, causes the host vehicle to be matched to a different point on the curved path.

The absolute map error, $x_{Maperror}$, causes the path of the host vehicle to be perceived incorrectly. The direction of the absolute map error is consistent with the direction of the longitudinal error in order to maximize the effect on target lateral error.

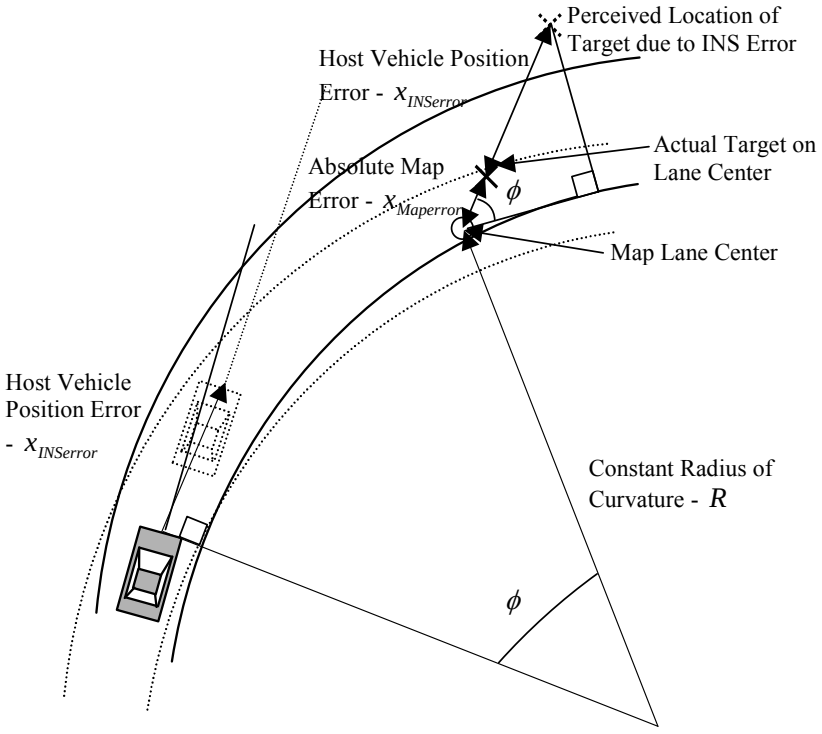

Figure B-19: Host and target vehicles on constant curvature

By matching the host vehicle position with errors along the curved path, errors similar to those discussed above (in "Effect of travel road/lane heading error") may occur depending on the sensor used to determine host heading in the lane. If a GPS/INS system is used to determine vehicle heading and is compared to the path heading in the map database, a position error around the curve yields an incorrect path heading measurement from the map. The resulting target position-in-lane error is:

$$error = (x_{INSerror} + x_{Maperror})\sin(\phi) \cong D_t \frac{x_{INSerror} + x_{Maperror}}{R} = D_t \frac{x_e}{R}$$

The error introduced in this scenario is essentially caused by the improper identification of road heading and may result in small errors. For example, a target identified at a distance of 120 m on a 480 m radius of curvature will result in 25 centimeters of lateral error for every meter of host longitudinal error and absolute map error.

If a vision system is determining the heading in the lane, the measurement is independent of the map and vehicle heading and results in zero target position-in-lane error.

Effect of Absolute Longitudinal Error When Host Vehicle on Curve Approaches Straight Road

Figure B-20 shows another scenario where the host vehicle is traveling along a constant curvature path with a target vehicle ahead on a straight segment. The host longitudinal error causes the host vehicle to be matched to a different point on the curved path.

The absolute map error in this figure maximizes the lateral target error when the map error direction is consistent with the vehicle's heading.

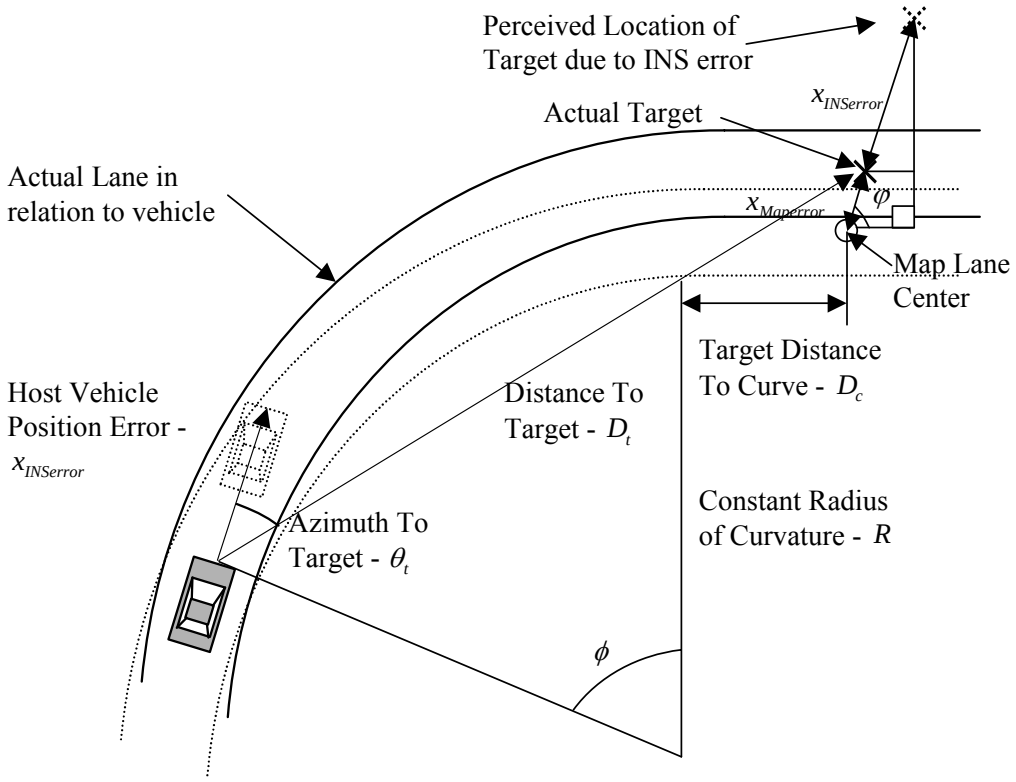

Figure B-20: Host on curved segment and target vehicle on straight segment

By matching the host vehicle position with errors along the curved path, target lateral offset occurs depending on the sensor used to determine host heading in the lane. In the figure, is equal to the angle between the current map position heading and the heading at the end of the curve. Clearly, a GPS/INS system will observe the following target lateral error:

$$error = (x_{INS} + x_{Maperror})\sin(\phi) \cong x_e \frac{D_t \cos(\theta_t) - D_c \cos(\phi)}{R} \cong x_e \frac{D_t - D_c \cos(\phi)}{R}$$

For example, a target at a distance of 120 m around a 480 m radius curve will result in approximately 0.25 m for one meter combined positioning and map error. In general,

curves with radius less than 480 m will result in greater lateral error while curves with radius greater than 480 m will yield smaller lateral error.

Effect of Relative Map Error

The relative map accuracy has been defined in Appendix B, Section B.1.2. Relative map accuracy is required to be small as it has an additive effect on target lateral position-in-lane error. The target lateral position-in-lane error introduced by relative map error is given by:

$error = E_{relative}$.

Cumulative Errors Affecting In-path Target Classification

The previous sections outline errors that occur in the estimate of the lateral target position with respect to the estimated path along the lane center of the travel lane. In order to identify a target as in-path or out-of-path, the system must identify each target's lateral distance relative to the estimated path along the lane center of the travel lane. A threshold on the lateral distance is used to classify whether a target is in-path or out-of-path.

As discussed in the previous sections, the errors are linear and superposition can be used to determine the cumulative errors that accumulate in the target's lateral position estimate to the estimated path along the lane center of the travel lane as follows:

- When host vehicle approaching a curve:

  Total target position lateral $Error \cong D_t(\theta_e + \psi_e - \gamma_e) + x_e \frac{D_t - D_c}{R} + E_{relative}$

- When host and target vehicle are on a curve:

  Total target position lateral $Error \cong D_t(\theta_e + \psi_e - \gamma_e) + D_t \frac{x_e}{R} + E_{relative}$

- When host is on curve and target vehicle is on straight:

  Total target position lateral $Error \cong D_t(\theta_e + \psi_e - \gamma_e) + x_e \frac{D_t - D_c \cos(\phi)}{R} + E_{relative}$

In order to specify accuracies for the absolute longitudinal map error, $x_{Maperror}$; map heading error, γ_e; and relative map geometry error, $E_{relative}$, estimates must be made for the other errors in the equations. In the worst case, the target's lateral position error relative to the estimated path lane center should not exceed one-half of a lane's width. Lane widths of 2.7 to 3.6 m are generally used, with a 3.6 m lane predominant on most high-type highways [AASHTO]. 3.6 meter lanes limit the worst-case error bound to 1.8 m.

A host vehicle traveling at 70 miles per hour typically requires correct identification of a stopped, in-path target at a range of 120 m. Hence, the FCW application requires target classification to be effective up to a range, , of 120 m from the host vehicle. In order to identify targets at 120 m, the radius of curvature must be larger than 480 m due to the limited-radar field of view. For this reason, 480 m will be chosen for the radius of curvature in the following example.

The standard deviation of error for the radar, θ_e, is 0.206 degrees. A typical mid-term vehicle sensor should be able limit the vehicle heading error, ψ_e, to 0.15 degrees and the

longitudinal vehicle position error to within 0.5 m. A map database with longitudinal absolute map error, $x_{Maperror}$, within 0.5 m; road/lane heading error, γ_e, within 0.15 degrees; and relative map error, $E_{relative}$, within 0.5 m at a distance of 120 m could result in a target position lateral error approximately equal to 1.69 m. This worst-case error is approximately one-half the lane width for a lane 3.6 m wide.

Effect of Positioning and Map Absolute Lateral Error

Absolute lateral vehicle positioning and map accuracy are required to be small in order to correctly place the host vehicle on the correct roadway and the correct lane in the roadway with respect to the lane center. Figure B-21 shows a vehicle traveling down a two-lane roadway with a GPS antenna mounted in the lateral center of the vehicle.

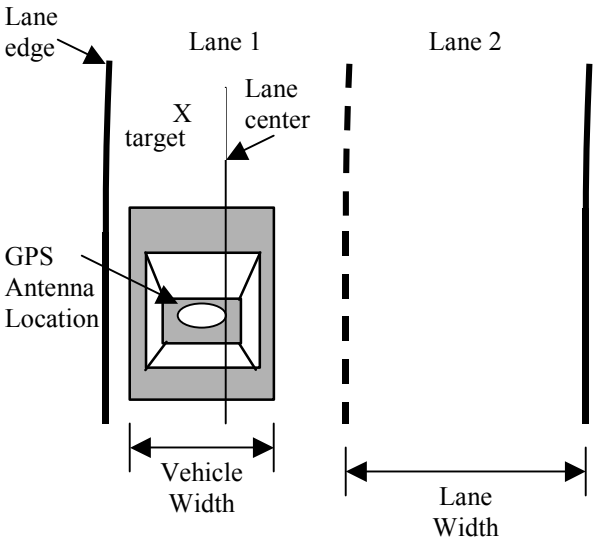

Figure B-21: Vehicle lane identification

The absolute lateral errors due to GPS/INS and map, $y_{INSerror}$ and $y_{Maperror}$, have an approximately one-to-one effect on vehicle lateral position-in-lane error. The vehicle lateral position-in-lane error introduced is given by

$$error = (y_{INSerror} + y_{Maperror}) \cong y_e$$

The absolute lateral error introduced by positioning and map matching will introduce a direct error in vehicle lateral position-in-lane. Assuming that the lateral vehicle positioning error is 0.5 m, an absolute lateral map error within 0.5 m is required so that the sum of the two lateral errors are bounded to be within one half of a typical vehicle width of 2 m.

Summary

Definition of road/lane geometry is given in Appendix B, Section B.2.1. For the Forward Collision Warning/Avoidance application, a representation of every lane center of the road is required that satisfies the following specifications:

- Map absolute accuracy within 0.5 m
- Map relative accuracy within 0.5 m up to 120 m ahead

- Map road/lane heading accuracy within 0.15 degrees

An equation representing the lane center from the host vehicle location up to a distance of 120 m ahead is required. The equation must be a smooth fit to the lane geometry representation in the map database.

B.3.1.3.3 Road/Lane Attributes

The following outlines how specific attributes can be used in the Forward Collision Warning/Avoidance application and the accuracies required for the EDMap project.

Lane Width

Lane width is defined in Appendix B, Section B.2.2. Lane width should be accurately identified to within 0.3 m.

Transition Zone

Appendix B, Section B.2.3 shows a roadway where the number of lanes changes. As shown in the figure, the transition zone should be identified. The position accuracy of the transition zone should be within 3 m.

Depending on the direction of travel, Appendix 2, Figure 2-4 shows a merge or lane creation. The width for Lane 2 in the transition zone should be determined by the width of the lane outside of the transition zone. Width and lane geometry for Lane 3 should not be defined in the transition zone.

Road /Lane Heading

Road/lane heading, as defined in Appendix B, Section B.2.4 may be calculated from equations used to represent the road/lane centerline. Accuracy of road/lane heading should be within 0.15 degrees. Heading must be represented in the map database as an accessible attribute. The heading vector is orthogonal to the vector used to define curvature and so accuracy specification of any one has a direct effect on the other.

Road /Lane Curvature

Definition of road/lane curvature is given in Appendix B, Section B.2.5. Road/lane curvature may be calculated from equations used to represent the road/lane centerline. An explicit specification for curvature will conflict with the relative accuracy specification for road/lane geometry. The equation for road/lane geometry must be obtained with curvature fairness as an important consideration. Curvature must be represented in the map database as an accessible attribute.

Shoulder Width

Shoulder width is defined in Appendix B, Section B.2.7. The width of the shoulder can be used by the application to determine whether a stationary object is in the travel lane or off the roadway. Shoulder width on roadways ranges from 0.6 m to 3.6 m, depending on the type of roadway and its environment. A map-reported value, in discrete values of 0.05 m with an accuracy within 0.5 m, should be sufficient to support the system. Shoulder width changes need to be made only if the change is for a stretch longer than 20 m.

Lane Directions

Each lane in the map database should have one direction of travel identified for the lane, as defined in Appendix B, Section B.2.9. Lanes used for reverse-flow operation and

center turn lanes, where both directions of travel are common, should be identified as such.

Number of Lanes

This attribute is defined in Appendix B, Section B.2.10. The number of lanes in a roadway is required to determine whether vehicles are in-path or out-of-path.

Road Condition

Road condition is defined in Appendix B, Section B.2.11. This attribute can be used by the application in calculating the appropriate braking distance of the host vehicle and determining the optimal distance at which a warning should be issued to the driver. Accuracy for the road condition mapplet should be within 10 m.

Road Surface Type

Road surface type is defined in Appendix B, Section B.2.12. Road surface type is important in order to determine the type of road on which the vehicle is traveling. Paved roadways generally have lane markings, and vehicles may potentially travel at high speeds. Unpaved roadways generally do not have any lane markings, possess characteristics that may cause incorrect radar target identification, and are traveled at low speeds. Roadways composed of steel grating can cause false identification of non-existent radar targets.

This attribute can also be used by the application in calculating the appropriate braking distance of the host vehicle and determining the optimal distance at which a warning should be issued to the driver.

Accurate identification of paved, unpaved, and steel grating roadways is required to be ±3 m for lengths greater than 10 m.

Road Grade

The Forward Collision Warning/Avoidance application has to make optimal changes to the warning distance to compensate for the road grade. Road grade is defined in Appendix B, Section B.2.13. This attribute can be used by the FCW application in calculating the appropriate braking distance of the host vehicle and determining the optimal distance at which a warning should be issued to the driver.

Road grade contributes an additional force on the vehicle given by:

$$R_g = W \sin\theta \cong W\theta ,$$

where W is the weight of the vehicle and θ is the inclination angle as shown in Figure 2-8. In addition, θ can be approximated by the actual road grade itself. As a result, to maintain the same stopping distance as in a flat road, a -4% (-0.04) grade results in an additional requirement of 0.04 g of braking effort.

The distance required to stop a vehicle is governed by the kinematic equation given by:

$$d = \frac{v^2}{2a},$$

where is the stopping distance in meters, is the vehicle speed in meters per second, and is the vehicle's deceleration in meters per second squared. A braking force generating 0.5 g of deceleration on a flat roadway will only generate 0.46 g of deceleration on a decline with -4% grade. Initially traveling at 70 mph, the resulting stopping distance is 7.4 m longer on the decline.

Although the stopping distance is longer when the same braking force is applied, it is unknown how a typical driver responds to grade when applying the braking force. If a driver is unable to determine the effect of road grade on stopping distance and applies the same braking force as that applied on a flat road, a warning system must warn earlier on declined roadways. Conversely, if a driver perceives the effect of grade on stopping distance, the system should warn later on inclined roadways in order to reduce the chance of a false alarm. Whether the driver perceives the effect of grade on stopping distance or not, grade will have an effect on the performance of the system.

It is important that the system calculates the effect of grade and warns the driver appropriately. An error in calculation of 5 m, 0.16 seconds traveling at 70 mph, is tolerable. This indicates an accuracy of ±2% grade in discrete values of 2% is required. For example, acceptable recordings for a grade of 1.7% are 0% or 2% grade.

A change of grade should be reported if the travel length of the grade exceeds 10 m. Bumps, patches, and small segments of grade change less than 10 m in travel length may be ignored.

Road Class

Road class is defined in Appendix B, Section B.2.15. This map attribute can be used to enhance the performance of the Forward Collision Warning/Avoidance application based on the road classification. Accuracy for road class mapplet attributes should be within 10 m.

Ramps, bifurcations, etc. should be modeled as lanes using the same lane geometry specifications identified for lane requirements. A flag in the map database should identify any lanes that are considered ramps transitioning from one roadway to another. The flag will assist in identifying when an in-path vehicle is transitioning to an out-of-path vehicle and vice versa.

Intersection Location

Intersection location, defined in Appendix B, Section B.2.22, may be calculated from the crossing of travel lanes along with lane width. Each lane in each direction may have a unique intersection location. Figure 2-10 recognizes intersection locations of a three-lane roadway, with a turn lane intersecting with a two-lane roadway. Accuracy of intersection location should be within 1 m.

B.3.1.3.4 Roadway Clutter

Overhead Stationary Roadway Structures

Overhead structures can be detected by the forward-looking radar sensor as in-path objects. These are defined in Appendix B, Section B.2.24. In order to avoid the false identification of overhead structures as in-path objects, the location of overhead objects needs to be identified.

For this application, stationary structures on the roadway, such as bridges, overpasses, tunnels, pedestrian walkways, and overhead signs that may be a radar target, need to be

identified. Structures that begin more than 10 m over the road need not be recorded. Location and posted heights (if present) of structures should be recorded. Start and end points of the structures should be recorded to within 3 m.

Stationary Roadside Objects

For this application, the presence of stationary roadside objects needs to be identified qualitatively, as defined in Appendix B, Section B.2.25, within 2 m on either side of the travel way (portion of the road used for travel). Stationary roadside objects close to the roadway, such as mail boxes, light poles, trees, etc., would be a source of radar targets. They should be identified only qualitatively. If there are roadside objects within 4 m of the travel way edge and none within 2 m, only the location of the closest roadside object in each segment is needed.

Stationary Roadside Barriers

Roadside barriers, defined in Appendix B, Section B.2.26, may be identified as in-path vehicles at long ranges due to the errors associated with the system. Pre-identification of stationary roadside barriers can help to eliminate false identification of in-path vehicles and reduce "ghost" targets returned by the radar.

For this application, stationary barriers on the roadside, such as guardrails, jersey barriers, bridge abutments, etc. that may be a radar target need to be identified. They should be identified using different classifications. Locations of both start and end points are needed to an accuracy within 3 m.

B.3.2 Curve Speed Assistant: Map Database and Vehicle Positioning Requirements

B.3.2.1 Introduction

The instances of single vehicle roadway crashes comprise approximately 20 percent of all light vehicle crashes annually in the U.S. Within the single vehicle roadway departure crash category, crashes result from four basic categories:

- Lane drifting
- Control loss
- Evasive maneuvers
- Driver incapacitation

Countermeasures that can attempt to address these crash categories are derived from a variety of sensor systems. Lane drift warning is conventionally addressed by computer vision lane trackers that perform best when the vehicle is slowly drifting toward or across the road edge.

There are two primary failure modes with lane tracker-based drift warning. The first is due to not always being able to visually track the lane markers. This deficiency is being addressed by the Lane Keeping Assistant application within EDMap, where the map database and vehicle positioning aid the computer vision lane tracker (Section B.3.3). The other failure mode is not really a failure of the lane tracker to track the road edge marks, but rather the situation where the vehicle crosses the road edge with high lateral speed such that a warning is of little use to the driver. The high relative lateral speed is usually the result of vehicle control loss or driver evasive maneuvers. Evasive maneuvers, like driver incapacitation, are difficult to address with countermeasures since the driver is occupied or otherwise distracted.

Control loss, on the other hand, is often the result of excessive speed for the road or road conditions. Control loss in curved road sections, and the resulting road departure crashes, could be mitigated by a system that aids the driver in entering a curve at a passable speed. The required forward sight distance is prohibitive for reliable computer vision-based detection of upcoming curves (Pape et al. 1995).[1] A reliable source of upcoming preview information can be gathered from a digital map database that can "look" ahead into the road network ahead of the vehicle, detect upcoming road curvature, and then take action appropriate to aid the driver in negotiating the curve. A map-derived preview is the motivation for the Curve Speed Assistant application.

B.3.2.2 Brief Description

The Curve Speed Assistant (CSA) aids the driver in approaching curves at speeds appropriate to navigate the curves.

In the context of the EDMap application descriptions used in the Task 1 report, the list below summarizes the roles of the CSA with respect to advisory, warning, and control modes of operation.

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1 Pape, D., D. Pomerleau, V. Narendran, J. Hadden, J. Everson, and M. Koenig, "Run-Off-Road Collision Avoidance Countermeasures Using IVHS Countermeasures," NHTSA report DTNH22-93-C-07023, September 5, 1995.

- **A** - The advisory role of the application informs the driver when the vehicle is approaching a curve. The driver is also notified of a suggested speed at which to navigate the curve.
- **W** - The warning role of the application warns the driver when the vehicle is approaching a curve at a speed greater than the recommended speed for the curve.
- **C** - The control role of the application regulates the speed of the vehicle to the recommended speed for the curve before entering the curve.

The warning and control roles were identified in Task 1 as having potential safety benefit. The advisory role in the CSA is a subset of the Speed Limit Advisor (Section B.3.7).

The basic functional components of the CSA are a vehicle positioning system, a digital map database, and a decision-making algorithm that takes either warning or control actions.

The CSA application must have information about curve locations, road/lane geometry, vehicle speed, and the advised speed limits at the curves. The CSA needs to be able to reliably place the vehicle along a road and provide proper curvature prediction based on the expected vehicle path. When the path is unambiguous, e.g., following a road with no upcoming road splits, curvature prediction can be reliable. When the upcoming path contains splits, e.g., an exit ramp, the preview path is ambiguous due to not knowing with certainty which path the driver will take. The CSA will need to behave appropriately under these conditions. The unambiguous path is expected to be the predominant operational CSA mode.

The intended route of the vehicle could be used to avoid nuisance information or actions. In a similar fashion, vehicle turn indicators could provide additional intended route information, but are not considered completely reliable or available. Road surface type and weather conditions may be useful for the control mode of operation. Road surface type could be, in part, provided in the map database, with other augmenting information. Weather conditions are anticipated to come from non-map derived sources.

B.3.2.3 Requirements for Curve Speed Assistant

The requirements defined in this section are intended to provide guidance in the mapplet development and subsequent data collection. The requirements also describe the commensurate vehicle positioning needs of the CSA. CSA needs described here are for both the warning and control operational modes.

The CSA requirements are justified using an analysis of acceptable curvature and vehicle positioning error in the map on the overall operational expectations of the CSA. Other road/lane attribute effects are also developed.

B.3.2.3.1 Positioning Requirements

Task 1 evaluation of Curve Speed Assistant vehicle positioning needs is 5 m for both warning (near-term) and control (mid-term). The 5 m requirement comes from the predominant operational mode where a vehicle is approaching a rural road curve that the driver must negotiate.

The 5 m requirement is viewed as an average value for the near-term (warning) and an upper bound for the mid-term (control). The positioning error is . For near-term, the positioning requirement includes the combined positioning error of GPS and INS. For mid-term, it is expected that positioning will be better than 5 m with nominal accuracy in the 1 to 2 m range with some form of code-based DGPS. For the near-term, GPS outages should be detected, and 5 m maintained by the INS for 30 seconds. For the mid-term, it is

expected that code-based DGPS will be used. DGPS outages of up to 30 seconds can then degrade to GPS to aid INS to not exceed 3 m. Primary positioning sensitivity is in the along the road positioning error (longitudinal error).

Rationale

Average rural road speed is 50 to 60 mph (22.8 to 26.8 mps). Five meters provides for at least a 0.25 second detection zone for curve geometry changes (equivalent to 4 Hz), which is twice the 2 Hz yaw response of a vehicle. For warning, this should be adequate. For control, 5 m may be sufficient, but there may be some uses for accuracy to 1 meter for freeway ramp detection, and quicker response in other ambiguous situations.

Subsequent to the completion of Task1, it is believed that sub-meter positioning in the mid-term is possible–mainly due to earlier than expected improvements to IMU capability at a low cost (see the Task 8a report for details). With this improved accuracy outlook comes the opportunity to place the vehicle in a lane. In-lane placement could provide for increased error handling, especially in ambiguous situations. The CSA will be developed to take advantage of the increased accuracy, but will also work toward satisfying functional capability described from Task 1. Therefore, 1 meter will be the mid-term positioning goal, with 5 m also being considered.

GPS outage INS survival is based on a maximum 500 m preview, which at 50 mph (22.8 mps) is a 23 second operational window. If longer than 500 m, the driver can be informed accordingly or the system can perform at a reduced effectiveness. Mid-term outage performance is driven by the need to detect lane change onto a ramp. A 5 meter lateral positioning bound would provide for no more than a 1 second delay in placing the vehicle on a ramp. One meter positioning would permit lane identification.

Orientation information in the form of heading is also desirable for ramp detection. Here, the heading is used to determine vehicle heading angle comparison with respect to two potential road path angles. Accuracy required is a function of the map database road geometry-derived heading. It is anticipated that 2 degree heading accuracy at 10 Hz is reasonable.

Positioning Summary

Positioning can be summarized as follows:

- 5 m for near-term warning after 30 second D/GPS outage.
- 1 m after 30 second outage for mid-term control.
- Heading accuracy should be at least 2 degree.
- All positioning data at 10 Hz near-term, 40 Hz mid-term.

B.3.2.3.2 Road/Lane Geometry

Absolute Accuracy

Absolute accuracy is defined in Appendix B, Section B.1.1. For the CSA system, the map database should be at least as good as expected vehicle positioning. Absolute accuracy concerns, while important, must be considered in their effect on curvature (see Appendix B, Section B.2.5). Near-term accuracy should be 5 m in the 2 sense. Mid-term accuracy can range from the same as near-term to that which will ensure lane identification. This would put mid-term absolute accuracy in the range of 5 m drms to 1 (2). One meter is based on permitting lane location identification on a 3.5 m lane width.

Relative Accuracy

Relative accuracy is defined in Appendix B, Section B.1.2. For the CSA system, relative accuracy should be such that the curvature error described in Section 0 is maintained. In a longitudinal sense, the error is to be bounded by absolute accuracy requirements. Both near-term and mid-term relative accuracy needs to be addressed by not only meeting curvature requirements, but by also meeting absolute accuracy at the same time.

B.3.2.3.3 Road/Lane Attributes

The following outlines how specific attributes can be used in a CSA application and the accuracies required for the EDMap project.

Curvature

The primary geometry representation affecting the CSA is curvature. Curvature has an explicitly defined mathematical meaning based on the instantaneous change of the direction of travel along a path (in this case, a road or lane). The curvature vector points along the normal direction (perpendicular to the path), and its length is an indication of how much the road bends. When the road or lane path is described parametrically, is defined, as in Appendix B, Section B.2.5.

Curve Fairness

The accuracy, by which the path is represented, however, has direct consequences on the shape of the curve. If the path accuracy requirement (see Appendix B, Section B.1) is such that lane edge undulations are closely tracked, then the resulting curvature vector based on the lane representation will undulate as well. The resulting curvature changes, while an accurate representation based on the road position, are detrimental to CSA performance. An example of the effect of subtle road position variations on the curvature is shown in Figure B-22.

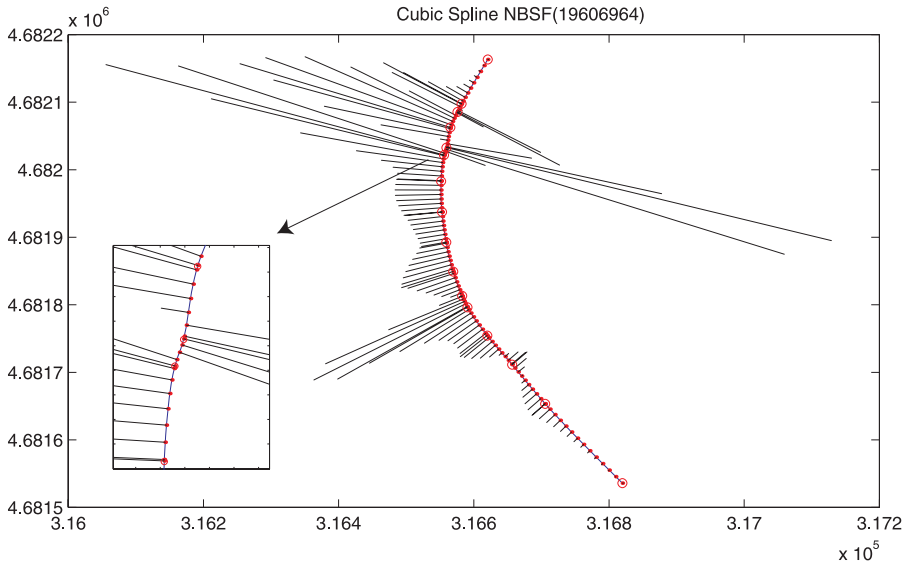

Figure B-22: Cubic spline fit to a road segment that has subtle position variation

It is clear that the overall shape of the curve is captured in one's mind; however, the road position, shown here as discrete coordinates, does not behave in a "fair" manner.

The issue of curve fairness is widely researched in the computer graphics modeling community (Farin and Sapidis 1989),[2] providing a good introduction to the idea of *curve fairing*. Curve fairing introduces metrics to allow trade-offs to the off-setting goals of road position accuracy versus curve shape. There can be many approaches to curve fairing. The analysis presented below attempts to take the first steps in defining curvature requirements for CSA. Curve fairing will need to be taken up as part of an effort involving both the CSA application along with those responsible for the geometric representation of lane models and position accuracy.

Steady State Curvature

The approach taken to determine curvature requirements is based on an examination of steady state curvature and vehicle speed through the curve. The key element is to determine the sensitivity of curvature error on the target vehicle speed. The steps taken are:

1. Use highway minimum radius calculation as a function of superelevation, *e*, and side friction, *f*, guidelines from AASHTO Green Book (AASHTO 1994).
2. Invert equation to get equivalent $\Delta V/\Delta\rho$ sensitivity where ρ is road radius of curvature and V is vehicle speed.
3. Vary radius of curvature to determine change in velocity.
4. Set acceptable curvature error based on acceptable target velocity variation.

The AASHTO Green Book provides conservative minimum radius of curvature tabulations based on the equation:

$$\rho_{\min} = \frac{V^2}{g\left(\frac{e_{\max}}{100} + f_{\max}\right)}$$

Equation B-1

where e_{man} is the maximum superelevation expected, and $f_{\max}$ is the maximum expected road friction. The lower expression, along with gravity g, serve to limit the radius of curvature. If superelevation or side friction are increased, then the minimum radius is decreased, allowing sharper curve radius.

The AASHTO has general recommendations for the relationship between vehicle speed, superelevation, and side friction. An example is shown in Table B-1 for $e = 8$ percent.

2 Farin, G. and N. Sapidis, "Curvature and the Fairness of Curves and Surfaces," *IEEE Computer Graphics and Applications*, V2(9), March 1989, pp. 52-57.

Table B-1: AASHTO Table III-6

Speed (km/hr)	*e*_max	*f*_max	Radius (m)
30	8.00	0.17	30
40	8.00	0.17	50
50	8.00	0.16	80
60	8.00	0.15	125
70	8.00	0.14	175
80	8.00	0.14	230
90	8.00	0.13	305
100	8.00	0.12	395
110	8.00	0.11	500
120	8.00	0.09	665

Figure B-23 is the output of Equation B-1, showing the values used for side friction as a function of vehicle speed. In order to use Equation B-1, it was necessary to generate $f_{\max}$ as a function of V. This relationship was curve fit based on Figure B-23 using a first order polynomial fit. Using vehicle speed in the range 10 to 70 mph (4.5 to 31.3 m/s), the vehicle speed and minimum radius relationship is generated as shown in Figure B-23.

Based on Equation B-1, it is also possible to determine a "maximum" radius of curvature that can be considered a straight road (equivalent to κ =0). The approach would depend on the highest straight road posted speed limit, e.g. 75 mph, along with worst case side friction estimates. The threshold may have use in reducing curve fitting numerical issues.

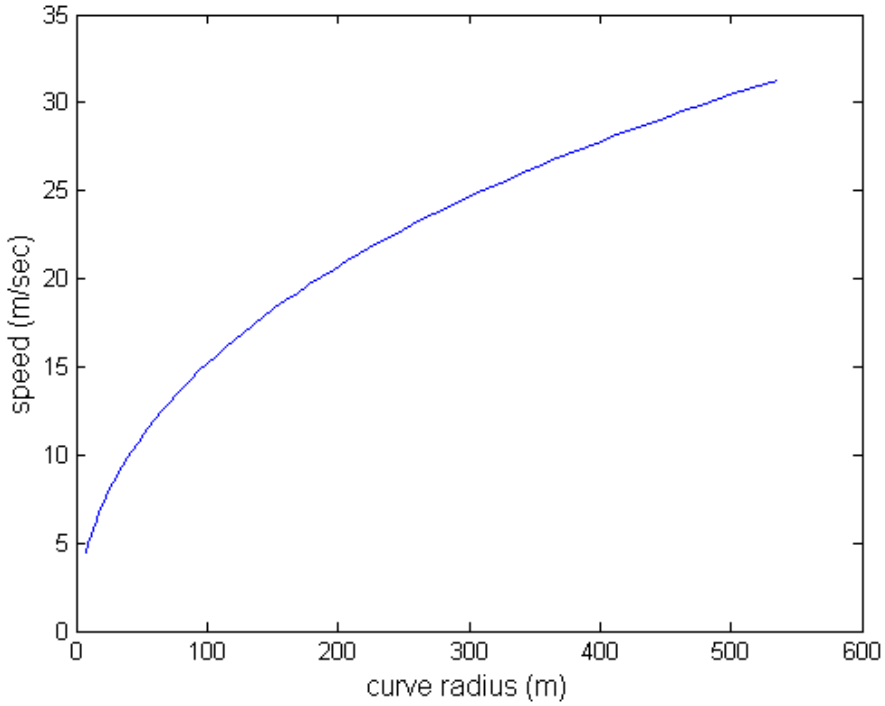

Figure B-23: Steady state speed vs. curve radius using Equation 3.1

The sensitivity of a change in radius with respect to a change in steady-state speed was determined by taking piecewise-small portions of the data in Figure B-23 using:

$$S = \frac{\Delta V}{\Delta \rho}$$

Equation B-2

The plot of Equation B-2 is shown in Figure B-24.

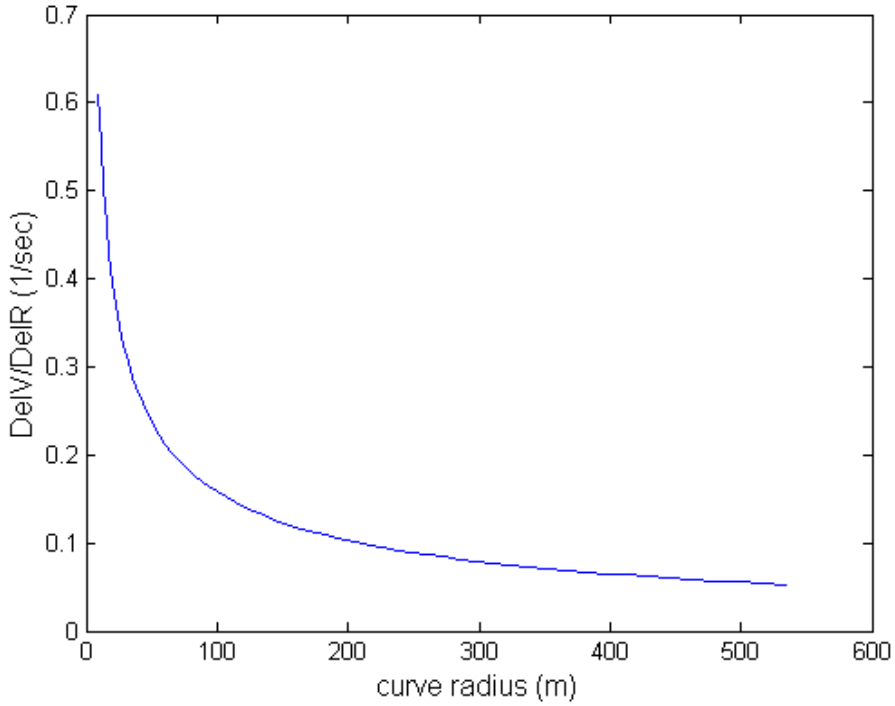

Figure B-24: Sensitivity of velocity with a change in curve radius

Figure B-24 shows that the sensitivity to a change in radius is relatively flat in curve radii over 200 m. This is a promising result, which suggests that curvature error can be expressed as a generalized error, and not as a function of the radius itself. The sharp peak at low curve radius can be expected, and is not a cause for concern.

As a comparison, the lateral acceleration was computed using:

$$a_{lat} = V^2 / \rho$$

Equation B-3

The plot, shown in Figure B-25, has a shape similar to Figure B-24.

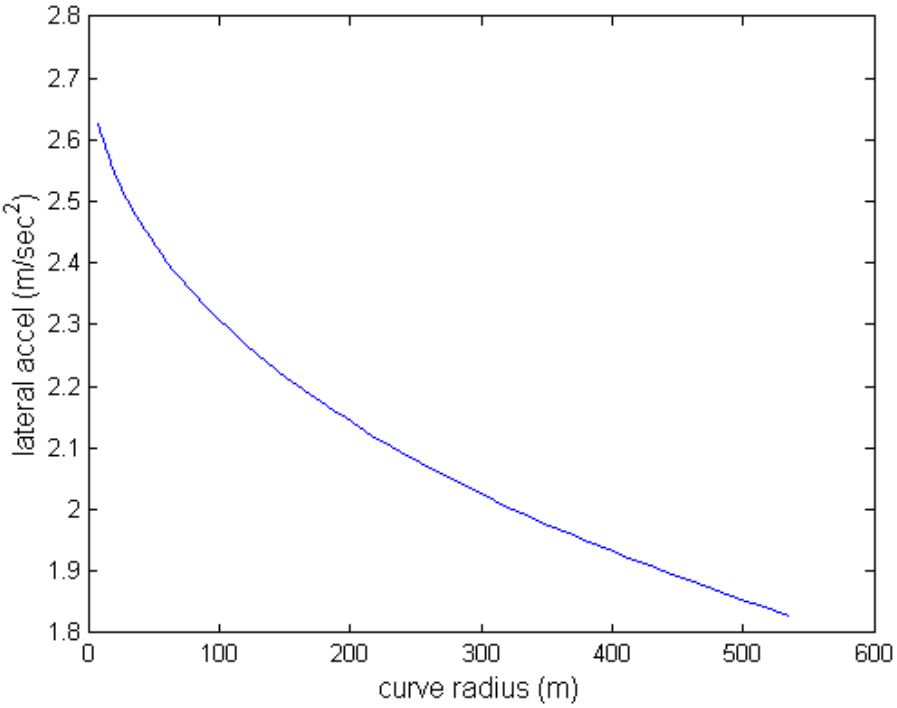

Figure B-25: Lateral acceleration profile for Equation B-2

Now that the sensitivity of vehicle speed to a change in radius of curvature has been established, it is possible to examine the effect on vehicle speed when a radius of curvature error is introduced. Figure B-26 shows the results on steady state vehicle speed when the radius of curvature is allowed to vary in increments of 5%, 10%, 15%, and 20%.

The traces in Figure B-26 were created by:

$$V_{error} = \frac{\Delta V}{\Delta \rho} \rho_{\pm error}$$

Equation B-4

The original speed/radius relationship from Figure B-23 is shown in Figure B-26 as the baseline with no radius of curvature error. The speed units were converted to mph units for ease of readability. All calculations were performed with SI units to ensure dimensional correctness.

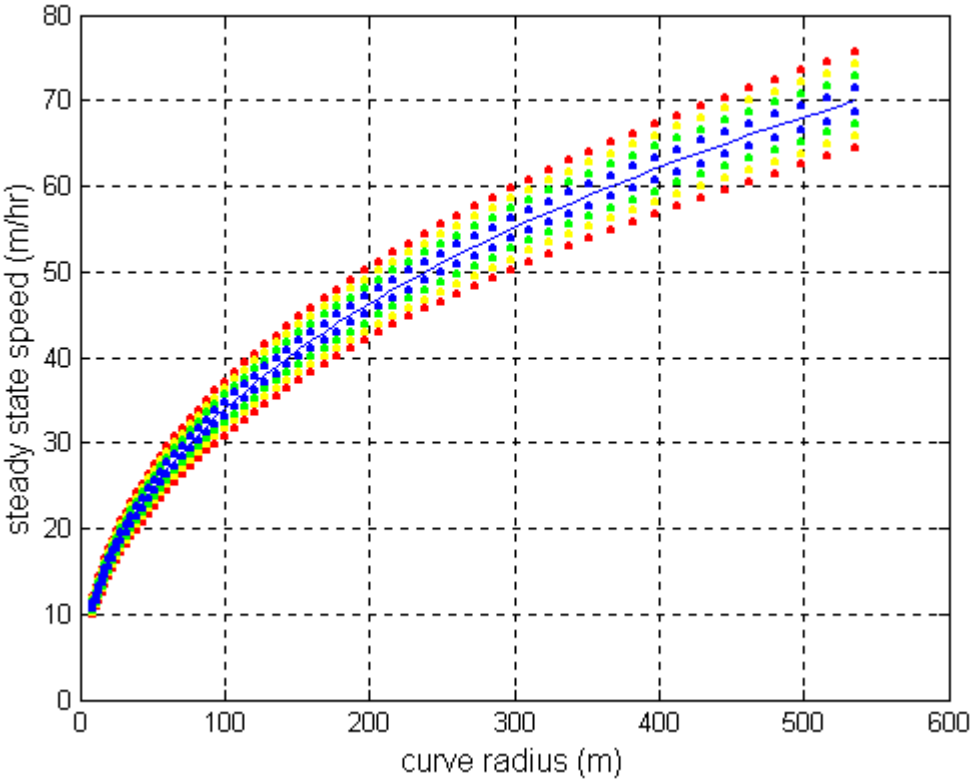

Figure B-26: Speed effect of 5%, 10%, 15%, and 20% radius of curvature error on steady state velocity

The final step in the determination of acceptable curvature error is provided by computing the percent error in vehicle speed as a function of a percent error in radius of curvature. The view shown in Figure B-27 uses the same data as in Figure B-26; however, in this view, the plots are determined by the percent change in vehicle speed.

$$\%V_{error} = \frac{V_{error}}{V} 100$$

Equation B-5

Figure B-27 shows that a 20% error in curve radius results in approximately 9% to 10% error in the vehicle speed in the 200+ meter range, as calculated by Equation B-5. On the other end of the errors tested, a 5% curve error results in just over 2% error in steady state velocity. The other attribute of the plot traces is the consistent percentages of speed error as a function of curve radius. Just as in Figure B-24, the speed equation (Equation B-5) lends to the conclusion that, all other factors being consistent, the target vehicle speed of a CSA system is affected equally at most all radius of curvature ranges.

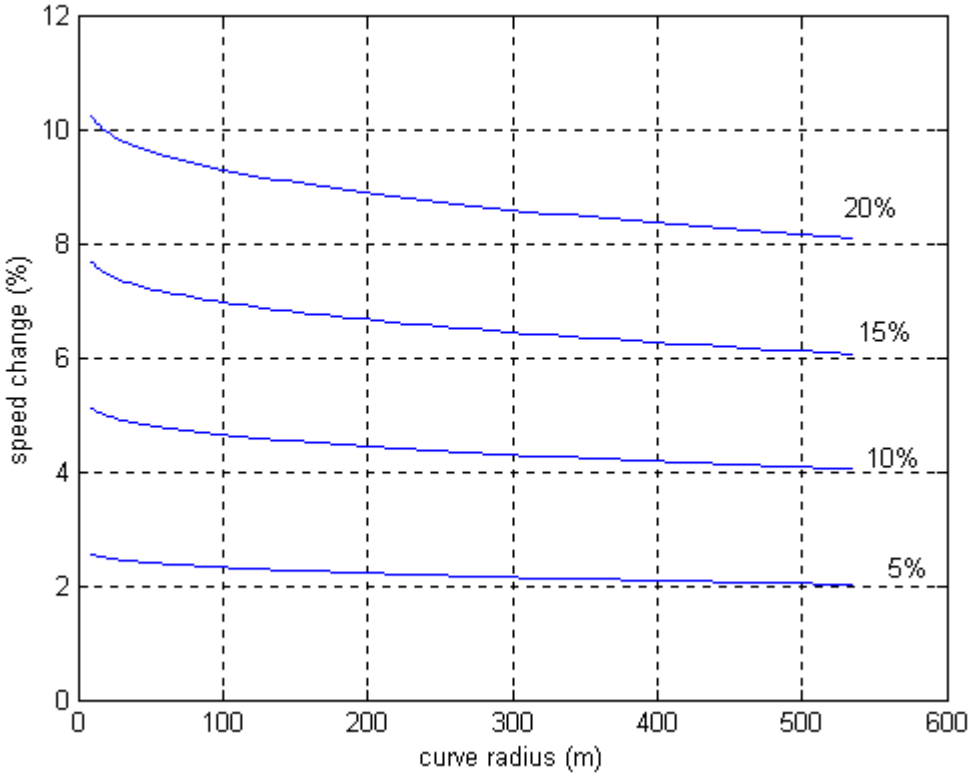

Figure B-27: Percent change in vehicle speed when radius of curvature has steady error

The connection has been made with steady state curvature error to steady state vehicle speed variation. It is now necessary to associate an acceptable tolerance for the error in radius of curvature.

It is reasonable that the near-term CSA application allow a 10% curvature error. The resulting vehicle speed error is approximately 4%, making the error within a 5 mph bound (2.5 mph), which is acceptable.

The mid-term CSA application should expect to see less than 5% curvature error. The mid-term CSA is expected to perform speed control in a curve, thereby increasing the tolerances with regard to driver acceptance over the speed threshold that will be performed by the CSA warning mode.

Number of Lanes

Near-term and mid-term should include the number of lanes, as defined in Appendix B, Section B.2.10 (excluding transitions).

Road Condition

Road condition is defined in Appendix B, Section B.2.11. This attribute can be used by the CSA application to add reliability to the deceleration zone computation as well as to possibly bias the curve speed calculation. Position accuracy for this attribute is 75 m for warning and 25 m for control, respectively.

Road Surface Type

Position accuracy for this attribute is 75 m for warning and 25 m for control, respectively.

Road Grade

Road grade is defined in Appendix B, Section B.2.13. It is anticipated that road grade will be used in two stages in the CSA. Firstly, grade will be used to determine "effective sight distances" to allow the warning algorithm to adjust to the driver not being able to see the curve for which braking may be required.

The second use is directed at deceleration zones where the goal is to go from the initial velocity to the curve speed in time *t* according to:

$$v_2 - v_1 = a\,t$$

Equation B-6

where the achievable acceleration, *a,* is affected linearly by grade.

Given that acceptable deceleration is in the range of 0.3 , 2% grade increments (to the nearest 2%) should be sufficient.

A minimum grade sensitivity is suggested at 10 m. There is a concern that vehicle de-weighting may occur on roller coaster-like whoops. This 10-meter value needs to be compared with the heave mode in a vehicle.

Superelevation

This attribute is defined in Appendix B, Section B.2.14. For near-term, it is sufficient to report whether a road is banked properly, has no banking, or is banked improperly (negative or off-camber banking). For mid-term, it is requested to have superelevation in the form similar to grade, but in the range [-3, 0, 3, 6, 9] %.

Rearranging Equation B-6 and solving for *V,* using superelevation e of 6% instead of 8%, results in a lower expected vehicle speed by approximately 4% to 6 % in over the 10 mph to 70 mph speed range. The error in superelevation is large (25%), but the effects are less than half those of curvature errors.

While the superelevation difference is 25% and sounds large, it is interesting to note that if one assumes a 4-meter lane width, the difference in road height (in cross section) from one lane edge to the other is only 8 cm. Scaling linearly, the difference across two lanes would be approximately 16 cm. This will make it challenging to record road survey information. Three percent increments provide a 24 cm vertical threshold in road altitude across two lanes.

Road Class

Road class is defined in Appendix B, Section B.2.15. Accuracy must be within 10 m.

Speed Limit

This attribute is defined in Appendix B, Section B.2.16. In the context of the CSA, speed limits provide a potential reliability check to the curve speed that is determined from the road curvature and other artifacts. Of particular use are the yellow curve speed advisory signs that are supposed to be at the curve entrance. For the control CSA mode, the speed limit at the curve exit would be useful as the vehicle resumes speed after the curve.

For the near-term, the posted speed going into corners is requested (mph). Posted refers to the advised speed presented to the driver on a sign. The position along the link where the sign is placed should be within 5 m. The same tolerance for the curve advisory signs is also acceptable for the mid-term CSA control application. In addition, the CSA control mode needs the posted speed limit coming out of the curve. Tolerance for CSA is 15 m. Even if there is no speed limit posted, there should be an exit speed defined if the speed after the curve is slower than the speed limit before the curve. There is expected overlap with the Speed Limit Assistant with regard to speed limits.

B.3.3 Lane Following Assistant: Map Database and Vehicle Positioning Requirements

B.3.3.1 Introduction

The Lane Following Assistant (LFA), as defined in the EDMap Task 1 report, contains two different modes of operation: warning and control modes. In this section, the warning application, which is also called Lane Departure Warning (LDW), is described. The control version is also known as Lane Keeping.

In today's market, there are a few LDW applications commercially available[3,4]–Freightliner in the U.S. and the Mercedes-Benz truck division in Europe are offering the AutoVue system from Iteris as an option. The applications from Iteris and AssistWare both are based on a monocular grayscale camera mounted in the middle and at the highest point of the windshield, and are looking ahead for lane markings on the road. However, this type of LDW application can result in shortcomings in the following cases:

- No lane markings on the road
- Bad contrast values between the marking and the pavement
- Repaired lane surface
- Darkness
- Heavy rain or snow

These cases are also difficult for human drivers; therefore they need to get support in these cases.

The Enhanced Digital Map (EDMap) project is working on using highly accurate digital maps and positioning for car safety application in the near, mid, and long-term timeframe. Based on the assumption that there will be lane-level information in future digital maps, it could be possible to extend today's LDW applications with this type of information. The combination of a map and positioning with a vision system should improve the overall performance compared to a system just based on computer vision.

For the Lane Departure Warning application, the map database must provide road geometry information, including lane information for all the lanes on the road. This information must be good enough to find the exact position of the car in the lane. If the information is not accurate enough, the system will produce too many false alarms and then the driver will simply turn it off.

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3 AssistWare Technology: SafeTRAC™.

4 Iteris, Inc: AutoVue™.

Since the application used is based on positioning, digital maps, and computer vision, there is no need for centimeter-level accuracy in the map for this application. By using additional map attributes, such as lane width, lane markings type, and other attributes, the EDMap system has a great advantage over today's vision system, which has to figure out all these attributes by itself.

This study tries to determine the accuracy needed for the map attributes to assist the LDW application in finding the correct position of the car with respect to the lane and reduce the number of false alarms to a minimum.

B.3.3.2 Brief Description

The Lane Following Assistant (LFA) consists of two grayscale cameras mounted behind the windshield. In addition to using the lane markings, such as stripes or Botz dots, the application will use other features provided by the cameras as well. By using a stereo camera system, it is possible to give a good estimate of the height of the features and therefore to reduce the number of false positive lane markings. In addition, the system will use a GPS system for vehicle positioning, a digital map, the vehicle speed, and a yaw-rate sensor.

The application as described in this document is defined within the EDMap project as a mid-term application. This means the positioning and map requirements should be available for a reasonable price within five to seven years after the end of the project.

To determine the current position of the car in the lane and to predict the future position of the car, the system will use the position to get the map attributes, such as centerline information, lane width, lane markings type, and road pavement type, from the digital map. Knowing this, the vision system will search the image to confirm that information. By using gathered information, predictions based on the past and present information from the image sensor, it could be possible to get a proper solution even if the map and vision system do not agree.

For streets without lane markings or in cases where it is impossible to see the lane markings, the system has to rely on the positioning system and on the map. Based on the expected accuracy of positioning systems (better than 30 cm) in the five to seven year timeframe,[5] this will probably not be possible at all times. However, depending on the accuracy of the map, the time of the vision system outage and the accuracy of the positioning system, it could still be possible to have a proper system to warn the driver before lane departure. If these conditions do not match anymore, the system has to turn itself off and tell the driver that it is not working in this kind of environment. However, the combination of different systems should allow this to be done more gracefully.

Errors are introduced from all sensors used for this application. However, as a result of using a combination of a vision system and a positioning system, not all of these errors are accumulated. The errors within the positioning system (accuracy of the map attributes and accuracy of the positioning sensor) are accumulative and the errors within the vision system (calibration errors, false positives, and false negatives for the lane marking recognition) add up as well. Nevertheless, the errors of both systems are orthogonal to each other and not necessarily accumulative.

5 EDMap Task 8a Positioning Study by Honeywell.

B.3.3.3 Requirements for Lane Following Assistant (Warning)

B.3.3.3.1 Positioning Requirements

As described above, the LFA application is based heavily on the vision system and uses the positioning system as well as the digital map mainly to assist the lane marking detection algorithms. Nevertheless, in the case where either the street has no proper lane markings or where the markings are not visible due to weather conditions, the system has to rely on the positioning system. Therefore, it is necessary to get a positioning system with a reasonable performance. This means, even with a GPS outage of about 30 seconds, the accuracy of the positioning system should not be worse than ±0.3 m.

B.3.3.3.2 Road/Lane Geometry

For an LFA, not only is it important to know the actual position of the car on the road, it is also important to know the predicted lane geometry ahead. Using this information, it is possible to predict and warn the driver even before the car is about to leave the lane.

The red line in Figure B-28 shows the warning corridor for different cases of lane width and shoulder width. In the left image, the shoulder width is increasing whereas in the right image, the shoulder size is constant at less then 0.3 m but with increasing lane width.

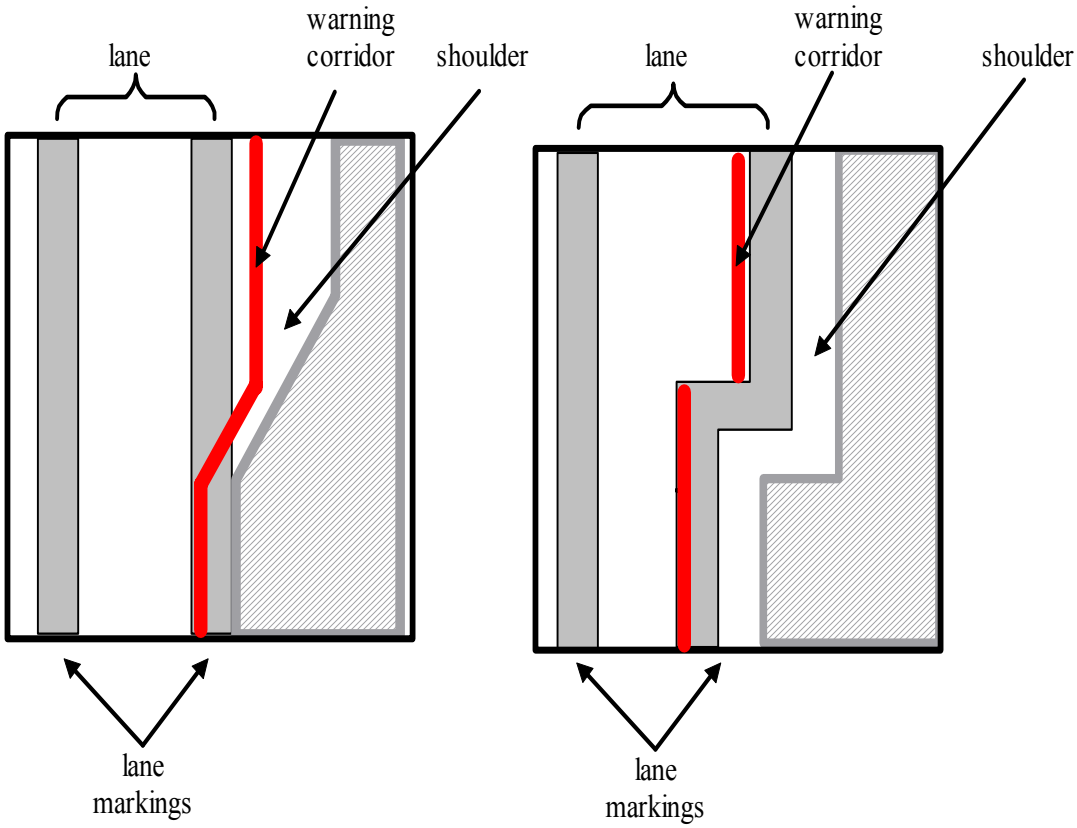

Figure B-28: Warning corridor for LFA

To get a good estimate of the position of the car in the lane, the lane centerline as well as the width of the lane need to be known. This information should meet the definitions in Appendix B, Section B.2. The combined accuracy of attributes should be within ±0.3 m (for centerline information at intersections, see *Intersection Geometry* later in this section).

For the lane geometry prediction, the accuracy constraints are not as hard as for the position of the car in the lane. Here a linear increasing error that goes up to 2 m for the 50 m prediction can be tolerated.

The described LFA is based on a vision system and a positioning system. With the knowledge of the lane centerline, the lane width, and the lane marking types (described below), it is possible to aid the vision system to recognize the lane markings properly. The error of these attributes is within ±0.3 m and the positioning system error is smaller than 0.3 m. This adds up to a maximum error of ±0.6 m. However, this already reduces the time needed to set up the vision system to find the proper lane markings and therefore results in a much better application performance.

B.3.3.3.3 Road/Lane Attributes

Shoulder Type

Shoulder type, defined in Appendix B, Section B.2.6, is also very important for warning applications such as the Lane Following Assistant. In this case, it helps to determine when to warn the driver that he or she is about to leave the road and not just the lane. The shoulder should be classified into two categories: paved and unpaved shoulder. In the case where a shoulder starts paved and changes (laterally) to unpaved, it should be categorized as paved but the shoulder width information should just be given for the paved area. Otherwise, the shoulder type has to be set to unpaved.

It is very important to know the change of the shoulder type from paved to unpaved. The reason and the accuracy constraints are the same as for the case where the shoulder width gets smaller. If it is still OK for a driver to drive on or next to the lane markings with a big and paved shoulder, it is dangerous in the case where the shoulder width changes to zero or the shoulder becomes unpaved. For this reason, a change from paved to unpaved or a declining shoulder width has to be reported within 10 m before the change.

On the other hand, an increasing shoulder width or a change from unpaved to paved is not as important to know immediately. These attributes should be updated within 10 m after the change occurs.

Shoulder Width

The shoulder width information is used to determine the timing for warning the driver that he is about to leave his lane. In the case with a wide shoulder, the driver does not have to be warned as early as with a very narrow shoulder. The accuracy needs for the shoulder width depends on the shoulder width itself. For a shoulder width less than 1 m, the information should be stored in 0.1 m steps with an accuracy of ±0.3 m. For a shoulder width of ≥1 m, information should be stored in 0.5 m steps with an accuracy of 0.5 m.

Based on the shoulder and lane width information, it is possible to use a dynamic warning corridor. For streets without a shoulder or with a shoulder width of less than 0.3 m, the driver will get a warning whenever he is about to touch the lane marking. With a growing shoulder size, there is more time to warn the driver.

In addition, the shoulder width information is important for vision system outages. If the lane width plus the shoulder width (in the case of being on the lane next to the shoulder) are smaller than the width of the car plus the accumulated errors of the positioning system and the digital map, the system will not work. In this case, a positioning system and a map with an accuracy of a few centimeters would be needed.

If the positioning and map error plus the width of the car are smaller than the lane width, it is possible to use the system–but with a worse performance than in combination with the vision system. In this case, there will be either some false positives or late warnings. However, it could still be possible for the driver to go back to the center of the lane safely.

The most common lane width in the United States is 12 feet.[6] Most highways have a lane width of at least 11 feet and a typical width does not fall below 10 feet. With these values, the system will still work even without the vision system–but the performance will be degraded. There will be false warnings and in addition, the driver will sometimes be warned late.

The discussion on Shoulder Type (above) describes how to handle the case where the shoulder type is changing. For the shoulder width, it is possible to use the same accuracy constraints as for the change in shoulder type. If the shoulder narrows, then the same accuracy requirements should be used as for the case where the shoulder type changes to unpaved. If the width gets wider, then accuracy constraints from the unpaved to paved section apply.

Lane Markings Type

Lane markings type is defined in Appendix B, Section B.2.8. The digital map should contain the marking types of each lane marking on the road. Hereby, it should distinguish between Botz dots, paint markings, and none. Paint markings shall be divided into solid and dashed lines, with double lines either both solid or one solid and the other dashed. The same attributes need to be collected for Botz dots. A line of Botz dots should be called solid if dots on a constant line are not further apart than 0.3 m.

A vision system for an LFA is usually looking ahead about 40 m. Moreover, depending on the grade, curvature, and weather, the system usually can see very well for the first 30 m; beyond this point the quality of the signal gets worse. To have an advantage of the knowledge of the lane markings type, it is important that this attribute is correct for the majority of the area the vision system can see ahead. This results in the requirement of knowing the change from one lane markings type to another, if the new marking type is used for more than 10 m. For the same reason, the map should report a change of the lane markings type within 5 m before or after the marking change (see Figure B-30). An example can be seen in Figure B-29, which contains two broken solid lane markings. Both of them are broken for less than 10 m, so they still should be called solid.

6 Federal Highway Administration, Highway Statistics, 1996.

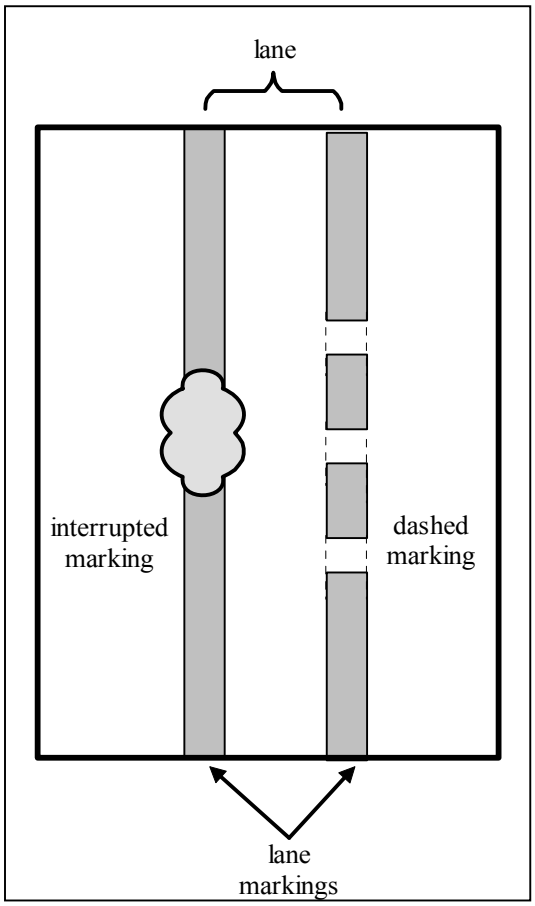

Figure B-29: Solid lane markings

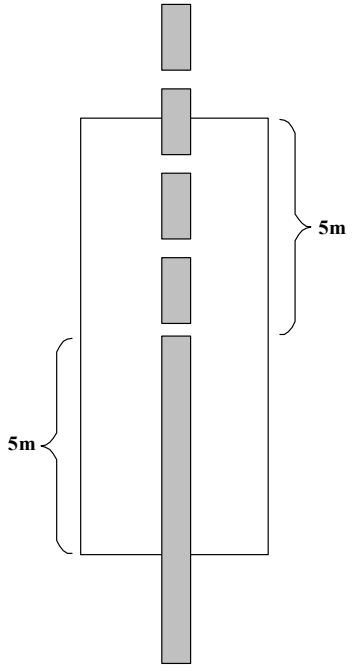

Figure B-30: Region in which to change the lane marking attribute in the map after a lane marking change

Road Surface Type

Road surface type is defined in Appendix B, Section B.2.12. For a vision system that tries to gather information about the lane markings of a road, it is important to determine the pavement type. This information can be used to set initial contrast values needed for the detection of edges at the marking. The contrast for a marking on a cement road is very poor in comparison to the contrast of a white marking on a dark pavement. The attributes needed for this application are asphalt, concrete, metal grating, blocks, and mixed. However, adaptive algorithms could make this information dispensable.

The accuracy needs for a pavement type change is similar to a lane marking change as described above. A change between one pavement type, another type, and back within 10 m does not need to be reported. A segment should get the attribute 'mixed' for lanes with frequent changes in the pavement type.

Intersection Geometry

Intersection geometry is defined in Appendix B, Section B.2.23. Within intersections, it is important to know the centerline and lane width information as well. It is important not to leave the lane, especially for multi-lane turns. Therefore, the following connections between incoming and outgoing lanes have to be included in the map:

- For straight lanes, a lane centerline should connect all legal connections between incoming and outgoing lanes. If there are no markings within the intersection, the typical vehicle path has to be included in the map. The map data should include a flag, indicating that the centerline information is based on the typical vehicle path. For intersections with lane markings, the rules and accuracy constraints for lane geometry apply.
- For turn lanes, the incoming lanes should be connected to the adjacent number of outgoing lanes. For intersections with lane markings, the accuracy requirement for lane geometry applies. For intersections without lane markings, the connections should start with the left-most outgoing lane for left turns and with the right-most outgoing lane for right turns. In this case, the map should include the most typical vehicle path.

There is no need to include U-turn centerlines in the map. Figure 2-11 (in Appendix 2) shows two typical examples for possible lane centerlines.

B.3.3.4 Requirements for Lane Following Assistant (Control)

The Lane Following Assistant (Control) is an enhancement to the described warning application. In addition to warning the driver when he or she is about to leave the lane, the control application controls the steering and tries to keep the car in the lane. This application is also known as "Lane Keeping." Based on the Task 1 results of the long-term application within the EDMap project, the application will not be demonstrated here. However, a short overview is given to show the possible future positioning and map attribute accuracy needs.

B.3.3.4.1 Positioning Requirements

The LFA control application, like the warning application, is based heavily on a vision system; however, it may also need additional sensor input, such as radar or other sensors. To keep the car in the lane, the positioning requirements are stricter for the control application than for the warning version. Therefore the position accuracy requirements are between 0.1 m and 0.2 m.

B.3.3.4.2 Road/Lane Geometry

In addition to better positioning capabilities, the map should provide more accurate road and lane geometry information. For this, it is expected that an accuracy of 0.2 m and a worst case of 0.3 m should be sufficient.

It is preferable to have better accuracy for the other map attributes as well, but it is not expected that stricter requirements are needed here.

B.3.4 Stop Sign Assistant: Map Database and Vehicle Positioning Requirements

B.3.4.1 Introduction

In Task 1, eleven EDMap application systems were chosen based on potential safety benefits. The Stop Sign Assistant system is one of the selected applications. According to the traffic safety statistics, inappropriate attention to stopping at intersections is one of the primary causes of traffic accidents. Therefore, steps should be taken to reduce "inattentive driving," "poor attention," or "poor judgment" as drivers approach stop signs. Prescribed or previewed information provided by a map database will help to make a "safer decision" to prepare for stopping at the regulated position.

B.3.4.2 Brief Description

The system aids the driver in stopping at the legally prescribed location. Typically, the system will operate at intersections with posted stop and yield signs. As a Driver Assistant System (DAS), three basic functionalities are defined as follows:

B.3.4.2.1 Advisory Functionality of the System

The system will simply notify the driver of the existence of posted stop and yield signs when the subject vehicle approaches within a certain distance of the sign. This system will help to avoid unintentional over-run at intersections or will help to recognize those signs which may be difficult to identify, such as limited visibility due to road side structures (trees, leaves); road geometries (hills, curves); weather conditions (heavy rain, snow); and/or altered/damaged signs (facing wrong way, corrupted).

B.3.4.2.2 Warning Functionality of the System

The system will warn the driver if the required stopping maneuver is predicted to be more aggressive than normal. The system observes legal stopping point, vehicle position, behavior (speed, yaw rate, heading), road geometry, and road condition. For yield signs, recognizing the context will provide greater ability for reducing annoying warnings.

Reaction force, where the gas pedal is used to warn drivers of excessive speed by pressing against the driver's foot, may be considered a human-machine interface for warning the driver to reduce speed before the situation becomes dangerous. This type of system, known as Intelligent Speed Adaptation (ISA), is now under development in Europe and Australia. This system will use either a positioning system with map

databases or Dedicated Short-Range Communication (DSRC) to identify any restrictions along the direction of travel. While DSRC may become an essential element for this type of application, it is not part of the application to be demonstrated.

The ISA may enforce not only speeding/stopping but also zones such as “School Zone”, “Residential Zone”, and “Construction Zone” as well (see *Curve Speed Assistant Speed Limit*).

B.3.4.2.3 Control Functionality of the System

When the vehicle needs to stop and the system predicts that the vehicle might not be able to stop at the legally prescribed position based on observed situation, the control system will help apply appropriate brake force to mitigate excessive intrusion beyond the expected stopping point. A more intelligent control methodology could be applied if devices for observing the subject vehicle’s environment were employed in conjunction with communication devices such as Dedicated Short Range Communication (DSRC) for vehicle-to-vehicle(s) or vehicle to infrastructure communication.

The SSA is mainly focused on legally posted stop signs along the road. As the basic functionality of the “EDMap Application System”, location of the stop sign will be provided from the “EDMap database” based on the position data provided by a positioning system such as an Inertial Navigation System (INS). An integrated system with GPS and Inertial Measurement Unit (IMU) is, in general referred to as an INS. Vision Systems and DSRC also have potential for positioning system capability in the future as well.

The map database can provide ”stored information” with respect to the current vehicle position or the requested position in terms of preview information. Supporting and verifying current environmental information will be useful for safer driving.

“Accuracy” and “Confidence” are important considerations in a database for a driver assistance system. The map database can provide application specific non real-time information but it is not capable of providing information on conditions that occur randomly in time. Therefore, other sensing systems such as forward-looking radar/vision are needed in order to obtain this type of information. So, while the EDMap database may be very accurate, defining the center of the lane to within several centimeters, there is little confidence in the information if the driving environment is not completely defined, such as the existence of a stalled vehicle ahead in the lane.

As an application system, the system consists of a vehicle positioning system, EDMap database, driver interface, actuators on the vehicle, and forward-looking obstacle sensors (radar and/or vision sensor) that detect preceding vehicles or objects ahead of the host vehicle to sense obstacles that will not be predicted from the EDMap database.

The warning functionality is expected to perform under relatively poor positioning accuracy environments in terms of the expected deployable period (i.e., 2004 - 2006).

Once the host vehicle position is established, the associated data will be provided from the map database. If there is a stop sign for instance, the SSA will aid the driver in achieving a gentle and normal stop at the regulated stopping point.

B.3.4.3 Requirements for Stop Sign Assistant

The following is an attempt to identify the map related requirements for an SSA warning application in the "near-term" 2004 - 2006 timeframe, and a control application in the "mid-term" 2006 - 2010 timeframe as well.

B.3.4.3.1 Positioning Requirements

Assumptions:

- Driving speed: 55 mph (88Km/h) 24.444 m/s - Maximum speed at non-posted section
- Maximum Deceleration: 0.3G (2.94 m/s^2)
- Stop line width: 0.3 m

Positioning Requirements for Stop Sign Assist (Warning)

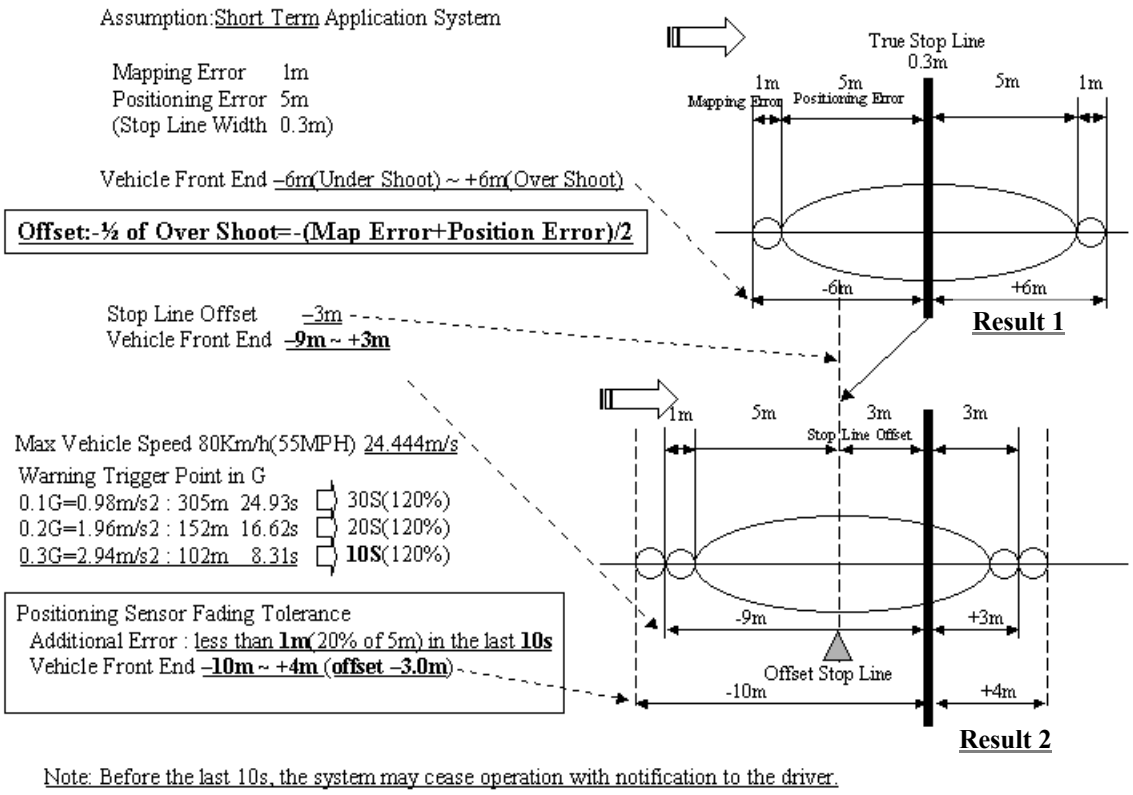

Figure B-31: Estimated stop location for warning

From analysis of Figure B-31 above regarding both map database accuracy and the vehicle positioning accuracy, 1m was chosen for the map position error and 5m was chosen for the positioning error.

- Absolute map position error in longitudinal direction: 1 m
- Vehicle positioning error in longitudinal direction: 5 m
- 10Hz data update rate will cause up to 2.5 m additional errors.

Result 1 (upper part of Figure B-31)

- Vehicle front end stopping point deviation: -6 m (under shoot) ~+6m (over shoot)
- As a driver assistant system, under shoot is more preferable compared to over shoot, however, to minimize the over shoot, "Stop Line offset" was developed.
- For the warning system, ½ of over shoot (-3 m) was chosen as Result 2 (w/offset –3 m).

Result 2 (lower part of Figure B-31)

- Vehicle front end stopping point deviation: -10 m (under shoot) ~+4 m (over shoot)

Positioning Requirements for Stop Sign Assist (Control)

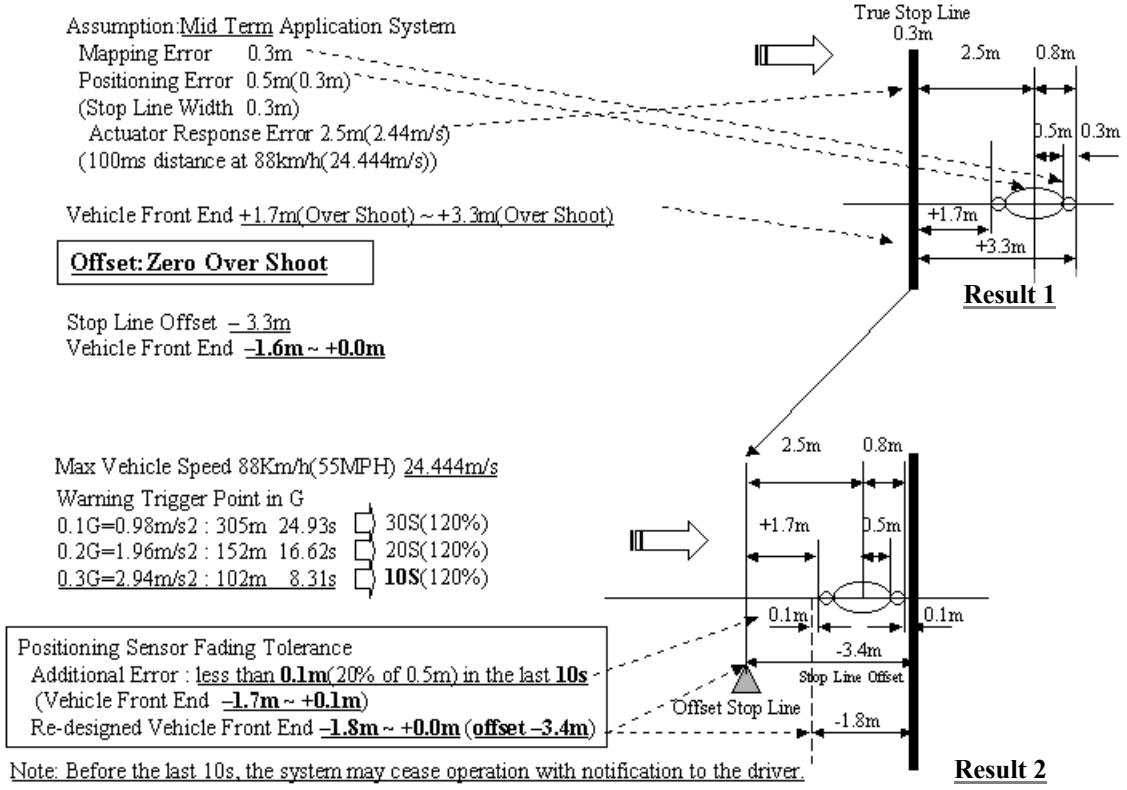

Figure B-32: Estimated stop location for control

From analysis illustrated by Figure B-32 above regarding both map database accuracy and the vehicle positioning accuracy, 0.3 m was chosen for the map position error and 0.5 m or the positioning error. For this application system, lane-by-lane stop line data would be required because the stop line position for each lane may be different. The lane-by-lane data needs to be accurate to at least ½ of the lane width that is assumed to be 3.6 m.

- Absolute Map position error in longitudinal direction: 0.3 m
- Vehicle positioning error in longitudinal direction: 0.5 m
- GPS outage error: 0.1 m (in last 10 s prior to reaching the stopping point)
- Brake Actuator Response delay: 100 ms 2.5 m at 24.444 m/s
- Data update rate will directly relate to the response delay. At least 50 Hz is expected.

Result 1 (upper part of Figure B-32)

- Vehicle front end stopping point deviation: +1.7 m (over shoot) ~+3.3 m (over shoot)
- To minimize the over shoot, "Stop Line offset" was developed. For a control system, an additional error of 0.1 m (20% of 0.5 m) in last 10 s was assumed for GPS outage.
- For the control system, -3.4 m (-3.3 m -0.1 m) was chosen as Result 2.

Result 2 (lower part of Figure B-32)

- Vehicle front end stopping point deviation: -1.8 m (under shoot) ~+0.0 m
- The biggest difference between the two timeframes is that "Near-Term" EDMap is not expected to have lane-by-lane data due to limitations of the current map database.

Summary of Vehicle Positioning Requirements

Vehicle Positioning Accuracy

Longitudinal absolute positioning error for SSA:

- Less than 5 m for warning. (Refer to Figure B-31.)
- Less than 1 m for control. (Refer to Figure B-32.)

Lateral absolute positioning error for SSA:

- Less than 1.8 m for control. (Refer to Figure B-32.)

GPS outage error

- Less than 0.1 m for control. (Refer to Figure B-32.)

Data update rate

- At least 10 Hz for warning. (Refer to Figure B-31.)
- At least 50 Hz for control (Refer to Figure B-32.)

B.3.4.3.2 Road/Lane Attributes

Lane Direction

The mid-term map database will contain the mapplet Lane direction as defined in Appendix B, Section B.2.9. This mapplet is required to allow the driver to select the appropriate lane in terms of driving direction. Prohibited/permissible directions should be reported along with applicable conditions such as days of week, time dependent rules, rights of way, and so on posted as sub captions.

Road Condition

This mapplet is defined in Appendix B, Section B.2.11. If the road condition is not smooth, the SSA may change system parameters to a more moderate setting.

Length: at least 5 m, from start to end positions (with 1m accuracy) should be reported

Road Surface Type

Road surface type is defined in Appendix B, Section B.2.12. Estimated maximum deceleration may be changed based on changes in the road surface type.

This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.)

Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported

Road Grade

Road grade is defined in Appendix B, Section B.2.13. During moderate deceleration, Road Grade affects vehicle deceleration. To achieve an expected deceleration, compensation should be applied based on the value of the Road Grade. Both up and down hill grades should be considered.

Stopping Distance will be affected by Grade.

Vehicle velocity: V

Deceleration: Xg G

Slope angle: θ degrees (up hill (+))

Stopping Distance: $d\ (Xg,\ \theta)$

$$* d\left(X_g, \theta\right) = \frac{V^2}{2G \cdot \left(X_g + \sin(\theta)\right)}$$

*$\sin\theta$ is used for calculation purposes only.
Road construction codes define grade in terms of $\tan\theta$.

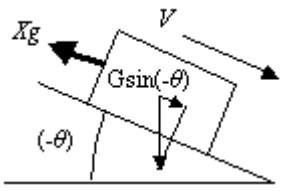

Figure B-33: Effect of grade

Figure B-33 shows a down hill case:

- Grade 1% corresponds to 0.573 degree
- G sin (0.573°) = 0.01G is 5% on 0.2G deceleration situation
- Expected accuracy: 1% (+/- 0.5%)

Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported

Stopping Location

Stopping location mapplet is defined in Appendix B, Section B.2.17. This is the most important mapplet for SSA. The stopping point refers to the edge of the stop line nearest the approaching vehicle. The location of the stop line is described in section 3B.16 on page 3B-34 of the Manual of Uniform Traffic Control Devices (MUTCD) (2000 Edition) as being placed 4 ft (1.2 m) in advance of and parallel to the nearest crosswalk line. In the absence of a marked crosswalk, the stop line is placed no less than 4 ft (1.2 m) nor more than 30 ft (9 m) from the nearest edge of the intersecting roadway.

Also, according to the Michigan Driver's Manual, in the event there is no crosswalk or stop line, drivers must stop at a point before entering the intersection where traffic coming from all directions is visible. No objective reference is provided in this case therefore the mapplet must define the stopping point within the constraints of the MUTCD section 3B.16. Locations where traffic is prohibited from stopping or standing should be addressed i.e. "No Blocking", "Cross walk", etc.

The SSA observes the given stopping point data and vehicle behavior data to determine the system output to achieve system functionality.

The SSA is one of the basic applications that utilize real-time positioning data and stopping point data. An issue is how the system could minimize error for shifting target stopping point, based on estimating both positioning error of the vehicle and the mapping error of the stopping point on the map database. The following is a discussion regarding stopping point error associated with assumed vehicle positioning error and map data positioning error.

Case A

Figure B-34 shows the system recognized vehicle position at the front most positioning error region in the travel direction and mapping error around the true stopping point. The distance between the actual vehicle stopping point and the true stopping point (Actual Distance) should be in the range of (- Positioning Error - Mapping Error) to (-Positioning Error +Mapping Error).

In this case, the actual vehicle stopping point would be before the true stopping point, due to both the magnitude of the position error and the direction of the position error being in the direction of travel.

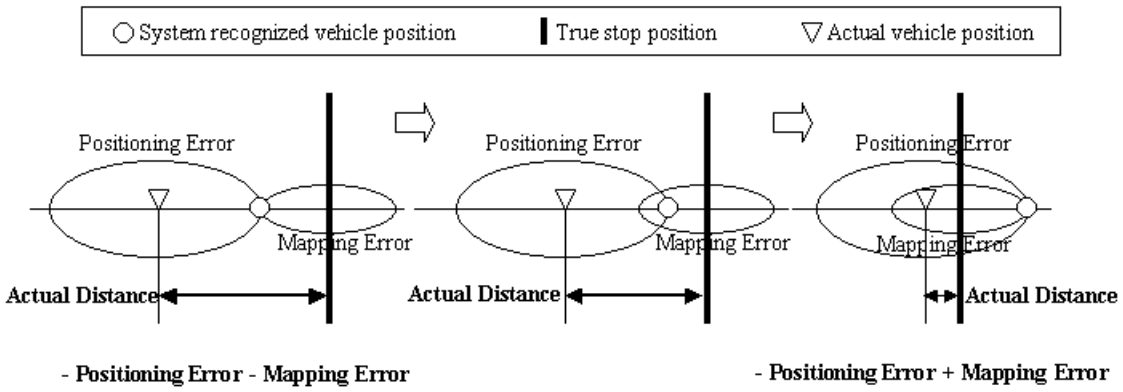

Figure B-34: Actual distance to the true stopping point Case A

Case B

Figure B-35 shows the system recognized vehicle position at the front most positioning error region in the travel direction and mapping error around the true stopping point. The distance between the actual vehicle stopping point and the true stopping point (Actual Distance) should be in the range of (Positioning Error - Mapping Error) to (Positioning Error + Mapping Error). However, in this case, actual vehicle stopping point would be behind of the true stopping point (over run), due to both the magnitude of the position error and the direction of the position error being in the direction of travel.

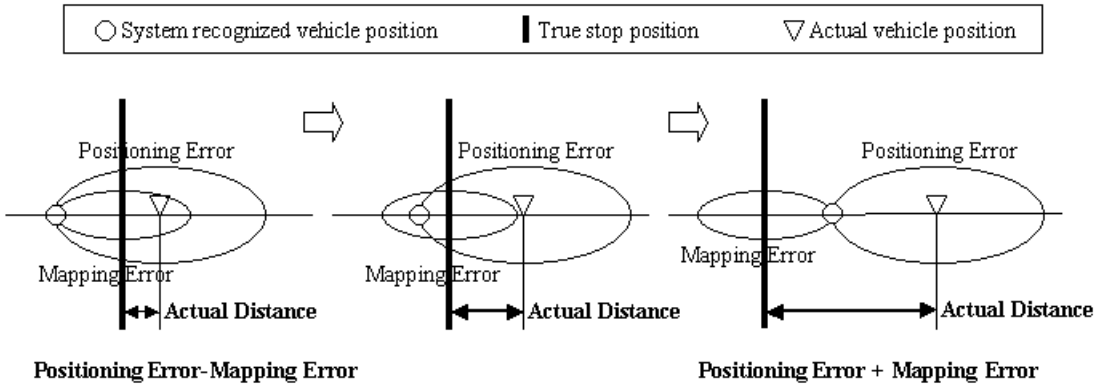

Figure B-35: Actual distance to the true stopping point Case B

Conclusion

For either Case A or Case B where the positioning error is greater than the mapping error, the actual vehicle stopping point would be in the range of (- Positioning Error - Mapping Error) to (Positioning Error + Mapping Error).

Expected absolute accuracy: 1 m for warning, 0.3 m for control.

Stop Sign Location

This mapplet is defined in Appendix B, Section B.2.18. Stop signs are usually posted just before the entrance of intersections. This attribute is a secondary reference if the stopping point is well defined by a stop line. If there are additional restrictions such as time dependent restrictions, they should be reported.

Expected absolute accuracy: 1 m in longitudinal direction along the direction of travel. (before the cross-section)

Stop Ahead Sign Location

"Stop Ahead Signs" should be considered as defined in Appendix B, Section B.2.19, with only a difference in accuracy. This sign location should be posted to support situations where Stop Signs are difficult to see.

Expected absolute accuracy: 5 m in longitudinal direction along the direction of travel

Yield Sign Location

This mapplet is defined in Appendix B, Section B.2.21. Yield Sign location should be posted in the map database.

Expected absolute accuracy: 5 m in longitudinal direction along the direction of travel

B.3.4.3.3 Summary for SSA

For the control functionality of the SSA, lane-by-lane representation of each Mapplet will be required because differences in the location of the stop lines may exist.

For the warning functionality of the SSA as a near-term application, it is assumed that map data won't have a lane-by-lane attribute due to limitations in the current map database.

The warning application of the SSA is a longitudinal application. Even though absolute accuracy is not good, appropriate map matching techniques will support the utilization of a current map database resource.

The stopping point location along the road is the most important attribute for the SSA. Table B-2 provides a summary of map database requirements for SSA.

Table B-2: Summary of mapplets requirements for SSA

Mapplet	Requirement
Stopping Location	Expected absolute accuracy: 1 m for warning, 0.3 m for control in longitudinal direction along the direction of travel.
Stop Sign Location	Expected absolute accuracy: 1 m in longitudinal direction along the direction of travel.
Stop Ahead Sign Location	Expected absolute accuracy: 5 m in longitudinal direction along the direction of travel (5 m assumed a vehicle length)
Yield Sign Location	Expected absolute accuracy: 5m in longitudinal direction along the direction of travel.
Road Condition	Length: at least 5 m, from start to end positions (with 1m accuracy) should be reported.

Mapplet	Requirement
Lane Direction	This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.)
Road Surface Type	This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.) Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported
Road Grade	Expected accuracy: 1%(+/- 0.5%) Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported

B.3.5 Traffic Signal Assistant (Warning): Map Database and Vehicle Positioning Requirements

B.3.5.1 Introduction

One of the major reasons of car accidents at intersections are cars running a red light. This happens either because the driver was distracted and did not notice the light or he or she thought that it was still possible to make it or intended to run it.

A warning system as described below will at least reduce the number of accidents for the first case to a minimum. For the second case it should be at least possible, to reduce the number of accidents – as long as the driver has to make the decision to stop or not to stop, there will be people who do not care about this kind of warning system.

B.3.5.2 Brief Description

The application described here will warn the driver approaching a red light at a traffic signal controlled intersection with three-color traffic signals. For the initial stage, it is not planned to warn at stop signals, yield, or stop signs (either yellow or red blinking lights). However, this could definitely be a very useful extension and could be implemented in the future. Therefore, it is useful to include these signals in future digital maps as well.

The traffic signal assistant (TSA) is based on a stereo grayscale camera system installed behind the windshield of the car, a vehicle positioning system and a precise digital map. With today's image processing and classification capabilities, it is possible to develop a traffic signal assistant to detect the position of the traffic signal and then to find out the status[7]. The problem is that a system just based on a vision sensor is not reliable enough to find all traffic signals and to make the connection between different lanes with different traffic signals.

To solve these problems, a high precision digital map and a vehicle positioning system can help. If the application knows where traffic signals are installed at an intersection, and the connection between the different signals and lanes are known, a warning system can successfully warn a driver when he or she is about to run a red light.

7 Franke et. al: *Autonomous Driving Goes Downtown*, IEEE Intelligent Systems, vol. 13, nr. 6, 1999

Based on the *x*/*y* position of all traffic signals and the vehicle position, the application can use the stereo information to select a specific area in a given distance. In this area, the application will look for the signals, define a bounding box, and feed the content of the bounding box to a classification system, such as a neural network, a polynomial classifier[8], or a support vector machine[9], to find out about the state of the signal.

Based on the state of and distance to the signal and the vehicle speed the driver gets a warning to slow down the car in order to not run the red light.

B.3.5.3 Requirements for Traffic Signal Assistant

B.3.5.3.1 Positioning Requirements

For finding the traffic signal with its known position, the positioning system should have an accuracy of 1 m to 2 m. However, it is important to get this positioning capability reliable even in cities with high buildings around.

B.3.5.3.2 Road/Lane Attributes

Traffic Signal Location

For a vision based Traffic Signal Assistant there are three problems to solve. The first is to find all traffic signals at an intersection. After finding the signal itself, a direction/lane has to be connected to each signal and as a last point, the color of the signal has to be determined. Various statistical pattern classification algorithms can solve the last problem. For the first and second problem, a highly accurate digital map is valuable. A vision system can search for traffic signals on its own, but there is no guarantee that it will find them all. In addition, it is very difficult to determine which traffic signal is responsible for which direction.

The mapplet Traffic Signal Location is defined in Appendix B, Section B.2.20. The digital map should provide the *x*/*y* position (lateral/longitudinal) of all traffic signals. The accuracy needed in the x-direction is 2 m, and in the y-direction 3m. The restriction for the accuracy is in the order of the traffic signals: the relative position of the traffic signals have to be retained. Based on this accuracy requirements the vision system can extract the needed information very well and therefore it is possible to classify the status of the signal reliably.

There is no need in providing the height of the signal. With the *x*/*y* position, the area to search for the signal is already very small, so it should be possible to determine the z position automatically.

Each traffic signal should be connected to a lane and/or driving direction. In addition, it is very useful to know especially about left turn signals, when the driver has to yield for oncoming traffic. A green arrow within the traffic signal usually provides this information. However, with today's camera technology it is almost impossible to see the difference between a plain green light and green arrow. Therefore, this should be included in the map as well.

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8 Schuermann: Pattern Classification : *A Unified View of Statistical and Neural Approaches*, Wiley, 1996

9 N. Vapnik: *The Nature of Statistical Learning Theory*. Springer, 1995

Stopping Location

This mapplet is defined in Appendix B, Section B.2.17. For calculating the exact time to warn the driver it is important to know the position, where the car should stop. This information should be provided for each lane and the accuracy needs for this are within +0 and -2 m of the position of the stop line. If there is no marking on the road/lane, then the attribute should be within the edge of the intersection going backwards.

B.3.6 Lateral and Longitudinal Control: Map Database and Vehicle Positioning Requirements

B.3.6.1 Introduction

This application functions only in the control role and provides both lateral and longitudinal control of the vehicle. The automated operation will be driver selectable. Longitudinal control of the vehicle is provided as in adaptive cruise control for headway distance following and cruising. Lateral control via automated steering provides lane keeping of the vehicle in the intended lane of travel. Longitudinal control of the vehicle maintains a safe headway distance to the lead vehicle. Therefore this application has the potential to reduce the frequency and severity of rear-end collisions between vehicles. Vehicle-to-vehicle communication and infrastructure-to-vehicle communication is not considered in this application. Using vehicle communications, this application could be enhanced very much. For instance, the headway distance for following the lead vehicle could be reduced significantly if lead vehicle dynamics can be obtained via communication. Lateral control feature of this application maintains the vehicle position in the travel lane via automated steering. Therefore, the frequency and severity of crashes due to lane departures caused by driver error can be minimized. Automated lane change maneuvers are not part of this application requirement.

B.3.6.2 Brief Description

Longitudinal vehicle control requires at least one forward-looking sensor. Vision sensors and laser ranging sensors (lidars) can be used for forward object detection, but the automotive radar sensor is currently being widely used due to its advantages. The longitudinal control feature of this application will typically use a fusion of a forward-looking radar sensor mounted on the front of the host vehicle and a stereo vision system mounted behind the windshield for detecting targets (other vehicles or objects) ahead of the host vehicle and in its field of view. This sensor fusion approach would use the advantages of both systems and their results could be combined for the full range. The vision sensors usually have a range of about up to 50 m ahead of the vehicle, radar sensors of up to 120 m. For smaller distances, the vision system then gets a higher priority in voting about obstacles, with larger distances this changes slowly to a higher priority of the radar system. Target selection then reports the closest-in-path moving and closest-in-path stationary vehicle or object based on results of the sensor fusion algorithm and estimated forward lane geometry ahead of the host vehicle. Based on the driver-selected timed-headway, the longitudinal vehicle controller controls the vehicle so that it maintains the desired headway distance with respect to the lead vehicle. When the lead vehicle is beyond the radar sensor's maximum detection range, the host vehicle will maintain the set cruise speed selected by the driver.

An accurate prediction of the forward lane geometry ahead of the host vehicle travel lane (up 50 m for the vision system and up to 120 m for the radar) is necessary in order to properly classify targets as in-path or out-of-path. This application would typically use multiple sensors to predict the forward geometry – GPS/INS system for vehicle position measurement along with a map database, a vehicle speed sensor with yaw-rate sensing, and vision-based lane markings tracking system.

An EDMap project goal is to develop an enhanced map database with necessary map attributes and accuracy, to use it as one of the sources for predicting the forward path. To accurately predict the path of the host vehicle, map database software uses the current vehicle position to create an electronic horizon. The electronic horizon includes a list of possible paths determined by the structure of the road system. Once host vehicle position is established, the host vehicle is associated with a map-matched point on the travel lane. From this reference point, map information provides the forward geometry of the lane. Accuracy specifications are made for map database attributes that may lead to an accurate forward geometry representation.

Lateral vehicle control requires a reference trajectory to be specified which can be followed closely via automated steering. Reference trajectories can be generated using magnetic pucks or tapes placed along the travel lane center. The vehicle detects the lane center magnets using a magnetometer mounted underneath the vehicle that is used for lateral vehicle control. The disadvantage of this method is that the roadway infrastructure needs to be modified to install magnets along the lane center, which could be very difficult in practice.

In this application, a lane markings tracking system based on vision sensors would be used for lateral vehicle control. Lane center geometry estimated using the measured lane markings are used as reference trajectories for lateral control. However, the vision system would not be reliable in the following situations:

- No lane markings on the road
- Bad contrast values between the marking and the pavement
- Repaired lane surface
- Darkness
- Heavy rain or snow

This long-term application will also use the map database in addition to the lane markings tracking system based on vision. An accurate map database in the long-term timeframe would complement the vision system by offering redundancy for lane geometry information and would result in much better performance of this application. The system would work better even under bad weather condition or during the night. For lateral control, the map database must provide lane geometry information, for all the lanes on the road. In addition, the map database must have information about lane width, lane markings types, etc. If the information is not accurate enough, the system will not be reliable. An accurate map database that has the lane center representation is an excellent source of reference trajectory and if integrated with vehicle positioning can be used to complement the vision-based lane markings tracking system for reliable lateral vehicle control. It would result in reduced infrastructure cost (in comparison to installing magnetic markers along the lane center), provide redundancy for safety (in conjunction with the vision system), higher bandwidth, higher sample rate and would provide better preview information of the road than any other source.

The lateral control system will use the lane geometry representations in the map database along with the lane geometry estimation based on the vision-based lane markings tracking system and use them both in intelligent data fusion using confidence measures to generate the required reference trajectories for the vehicle to follow. The map database information can also be used to increase or decrease the confidence of the outputs from the lane tracking system. For example, high confidence can be assigned to the lane markings system outputs if the lane markings attribute is present in the map database and poor confidence can be assigned to the lane markings system outputs if the lane markings attribute is absent in the map database. Automated steering will try to maintain the vehicle lateral position close to the reference trajectories.

Errors introduced in the map database representation of lane center and the host vehicle position measurement, accumulate resulting in ambiguity in determining the accurate position of the vehicle within the lane. Accuracy specifications are made for map database attributes that may lead to a good lateral vehicle control system.

B.3.6.3 Requirements for Lateral and Longitudinal Control

The following is an attempt to identify the positioning and map attribute requirements for the lateral and longitudinal control application. First, positioning requirements are provided followed by requirements for road/lane geometry, road/lane attributes and roadway clutter.

B.3.6.3.1 Positioning Requirements

For longitudinal control, the positioning requirements are similar to that for forward collision warning / avoidance application described in Section B.3.1. Heading accuracy of 0.15 degrees, longitudinal position accuracy of 0.5 m would be sufficient for the longitudinal controller.

The positioning requirements for the lateral control are much more stringent than for longitudinal control. Heading accuracy of 0.15 degrees, longitudinal accuracy of 0.2 m, and lateral accuracy of 0.2 m would be required for proper functioning of the lateral control system.

In summary, the lateral and longitudinal control application requires a vehicle positioning system with heading accuracy within 0.15 degrees, lateral and longitudinal position accuracy within 0.2 m. The error bounds stated are for the worst case, typically after a 30 sec GPS outage. Typical values of the errors should be smaller than the worst case bounds stated here. The update rate for vehicle positioning should be greater than 50 Hz for good vehicle control response.

B.3.6.3.2 Road/Lane Geometry

Definition of road/lane center is provided in Appendix B, Section B.2.1. For the lateral and longitudinal control application, representation of the lane center of each travel lane should be provided in the map database. Furthermore, equations should be provided that represent the center of each travel lane of the road for at least 120 m ahead (forward geometry) of the current vehicle position on the road.

Absolute and relative accuracy definitions for road/lane geometry is provided in Appendix B, Section B.1. Accuracy requirements of the longitudinal controller for the road/lane geometry are discussed first. In defining accuracy for the road/lane geometry, the effects of the vehicle position, map database, and radar errors on in-path or out-of-path classification of the radar targets are determined. An analysis of lateral error introduced in the target location relative to the lane center provides an estimate of errors that may be tolerated in map database representation of road/lane geometry. The analysis is similar to that carried out for the forward collision warning / avoidance application (see Section B.3.1) and the worst-case lateral error happens when the host and target vehicle are both traveling on a curve. The worst-case lateral error in target position relative to the true lane center is given by:

$$\text{Total target position lateral } Error \cong D_t(\theta_e + \psi_e - \gamma_e) + D_t \frac{x_e}{R} + E_{relative}$$

where, D_t is the range of the target, $\theta_e, \psi_e, \gamma_e$ are the azimuth error of the radar, heading error of vehicle positioning, heading error of the road/lane in the map database

respectively, x_e is the longitudinal absolute accuracy of the map lane geometry, $x_{Maperror}$, plus the longitudinal vehicle position accuracy, $x_{INSerror}$, $E_{relative}$ is the relative accuracy of the map lane geometry.

In order to specify accuracies for the absolute longitudinal map error, $x_{Maperror}$; map heading error, γ_e; and relative map geometry error, $E_{relative}$, estimates must be made for the other errors in the equation. In the worst case, the target's lateral position error relative to the estimated path lane center should not exceed one-half of a lane's width. Lane widths of 2.7 to 3.6 m are generally used, with a 3.6 m lane predominant on most high-type highways.

A host vehicle traveling at 70 mph hour typically requires correct identification of a stopped, in-path target at a range of 120 m. Hence, the longitudinal control feature of this application requires target classification to be effective up to a range, D_t, of 120 m from the host vehicle. In order to identify targets at 120 m , the radius of curvature must be larger than 480 m due to the limited radar field of view. For this reason, 480 m will be chosen as the radius of curvature in the analysis.

The standard deviation of error for the radar, θ_e, is 0.206 degrees. A typical long term vehicle sensor should be able limit the vehicle heading error, ψ_e, to 0.15 degrees and the longitudinal vehicle position error to within 0.2 m. A map database with longitudinal absolute map error, $x_{Maperror}$, within 0.2 m; road/lane heading error, γ_e, within 0.15 degrees; and relative map error, $E_{relative}$, within 0.2 m at a distance of 120 m could result in a target position lateral error approximately equal to 1.31 m. This worst-case error is approximately one-half the lane width for a lane 2.7 m wide.

The accuracy requirements for the lateral controller are considered next. Absolute lateral vehicle positioning and map accuracy are required to be small in order to correctly place the host vehicle on the correct roadway and the correct lane in the roadway with respect to the lane center.

The vehicle's lateral position controlled by the lateral controller is subject to the absolute lateral errors due to GPS/INS, $y_{INSerror}$, absolute lateral errors in the lane center geometry specified in map, $y_{Matperror}$, and the tracking accuracy specification of the controller. The vehicle lateral position-in-lane error relative to the true lane center is given by

$$error = (y_{INSerror} + y_{Maperror} + controller\ tracking\ accuracy) \cong y_e .$$

The tracking accuracy specification for the controller should not be very small because this will cause discomfort in ride since the controller will have to work hard to correct for the error at each sample time. Assuming the lateral vehicle positioning error is 0.2 m, and a tracking accuracy of the controller to be 0.1 m, and an absolute lateral map error within 0.2 m bounds the vehicle lateral position-in-lane error relative to the true lane center to be 0.5 m on straight roads. This error would be higher on curved roads due to the effect of longitudinal map errors and longitudinal GPS/INS errors on the tracking capability of the lateral controller. However, such error estimates are not easy to obtain analytically. The lateral controller requires a much smaller accuracy specification for relative map errors. A relative map accuracy specification prevents the vehicle from high frequency lateral movements about the lane center and thereby provide a smooth, comfortable ride for the

driver. Relative accuracy specification for good lateral control motion must be within 0.1 m, up to 30 m longitudinally from the vehicle position along the lane.

Definition of road/lane geometry is given in Appendix B, Section B.2.1. For the lateral and longitudinal control application, a representation of every lane center of the road is required that satisfies the following specifications:

- Map absolute accuracy within 0.2 m
- Map relative accuracy within 0.1 m up to 30 m ahead
- Map relative accuracy within 0.2 m from 30 m to 120 m ahead
- Map road/lane heading accuracy within 0.15 degrees

Equation representing the lane center from the host vehicle location up to a distance of 120 m ahead is required. The equation must be a smooth fit to the lane geometry representation in the map database.

B.3.6.3.3 Road/Lane Attributes

The following outlines how specific attributes can be used in the lateral and longitudinal control application and the accuracies required.

Lane Width

Lane width is defined in Appendix B, Section B.2.2. Lane width should be accurately identified to within 0.2 m.

Transition Zone

Appendix B, Section B.2.3 defines the roadway mapplet Transition Zone where the number of lanes changes. The Transition Zone should be identified. Within the transition zone, lane center representations of most likely driver paths (based on probe data) must be provided so that the lateral controller may control the vehicle to follow the most likely path through transition zones. Accuracy of transition zone lane centerlines must be the same as for lane geometry.

Road /Lane Heading

Road/lane heading as defined in Appendix B, Section B.2.4 may be calculated from equations used to represent the lane centerline. Accuracy of road/lane heading should be within 0.15 degrees. Heading must be represented in the map database as an accessible attribute. The heading vector is orthogonal to the vector used to define curvature and so accuracy specification of any one has a direct effect on the other.

Road /Lane Curvature

Definition of road/lane curvature is given in Appendix B, Section B.2.5. Road/lane curvature may be calculated from equations used to represent the road/lane centerline. The equation for lane geometry must be obtained with curvature fairness as an important consideration. Curvature must be represented in the map database as an accessible attribute.

Shoulder Type

Shoulder type is defined in Appendix B, Section B.2.6. Shoulder type should be identified as paved or unpaved within 10 m. Lateral control system will use the vision system to detect that the vehicle is probably entering the shoulder and will warn the driver to take control or to stop the vehicle safely in the shoulder. The type of the

shoulder will be used to determine how fast the warning should be given. Lateral control system should not be used on roadway shoulders.

Shoulder Width

Shoulder width is defined in Appendix B, Section B.2.7. Lateral control system must not be used on road shoulders. Shoulder width should be reported to an accuracy within 0.3 m if the shoulder width is less than 1 m. Otherwise the accuracy could be 0.5 m. Lateral control system will use the vision system to detect that the vehicle is probably entering the shoulder and will warn the driver to take control or to stop the vehicle safely in the shoulder. Shoulder width will be used to determine how fast the warning should be given. Shoulder width changes need to be made only if the change is for a stretch longer than 20 m.

Lane Markings Type

The definition for lane markings type is provided in Appendix B, Section B.2.8. This attribute should be accessible in the map database. A lane markings tracking system based on vision system will typically be used in this application to increase reliability. Changes in type should be represented for a stretch longer than 10 m to an accuracy within 5 m.

Lane Direction

Each lane in the map database should have one direction of travel identified for the lane as defined in Appendix B, Section B.2.9. Lanes used for reverse-flow operation and center turn lanes, where both directions of travel are common, should also be identified as such.

Number of Lanes

The number of lanes in a roadway is required as defined in Appendix B, Section B.2.10.

Road Condition

Road condition is defined in Appendix B, Section B.2.11. This attribute can be used by the application in order to make optimal adjustments to the lateral and longitudinal controller gain constants to maintain good performance. Accuracy for road condition mapplet should be within 10 m.

Road Surface Type

This attribute is defined in Appendix B, Section B.2.12. Road surface type is important in order to determine the type of road on which the vehicle is traveling. Paved roadways are generally good for lateral control and vehicles may potentially be controlled by the longitudinal controller to travel at high speeds. Lateral control on unpaved roadways generally do not have good tracking accuracy, possess characteristics that may cause incorrect radar target identification, and the vehicle must be controlled by longitudinal controller to travel at low speeds. Roadways composed of steel grating can cause false identification of non-existent radar targets.

Accurate identification of paved, unpaved, and steel grating roadways is required to be ±3 m for lengths greater than 10 m.

Road Grade

Both the lateral controller and longitudinal controller has to make optimal changes to compensate for road grade variations in order to ensure good performance. Road grade is defined in Appendix B, Section B.2.13. An accuracy of ±2% grade in discrete values of

2% is required. For example, acceptable recordings for a grade of 1.7% are 0% or 2% grade.

A change of grade should be reported if the travel length of the grade exceeds 10 m. Bumps, patches, and small segments of grade change less than 10 m in travel length may be ignored.

Superelevation

Superelevation is defined in Appendix B, Section B.2.14. Superelevation affects lateral controller performance in the sense that tracking accuracy of the controller becomes better with consideration of correct super elevation value in the controller. An accuracy of ±2% grade in discrete values of 2% is required for this application.

Road Class

Definition of road class is given in Appendix B, Section B.2.15. The importance of this map attribute is to enhance the performance of the application based on the road classification provided from the map database. This attribute can also be used to enable / disable this application based on the road classification. For e.g. the application could be disabled in dense urban roads if it perceived that human control of the vehicle is more appropriate in such situations. Accuracy for this mapplet should be within 10 m.

Speed Limits

Speed limits of roadway segments as defined in Appendix B, Section B.2.16 should be provided. The applicable roadway segment must be identified within 10 m accuracy. This attribute could be used by the application to limit the cruising speed of the vehicle to the legal limits.

Intersection Geometry

An example of intersection lane geometry is shown in Appendix B, Section B.2.23. At intersections, it is important to know the centerline and lane width information as well. Especially for multi-lane turns, it is important not to leave the lane. Therefore, the following connections between incoming and outgoing lanes have to be included in the map:

- For straight lanes, a lane centerline should connect all legal connections between incoming and outgoing lanes. If there are no markings within the intersection the typical vehicle path has to be included in the map. The map data should include a flag, that the centerline information is based on the typical vehicle path. For intersections with lane markings, the rules and accuracy constraints for lane geometry applies.
- For turn lanes, the incoming lanes should be connected to the adjacent number of outgoing lanes. For intersections with lane markings, the accuracy requirement for lane geometry applies. For intersections without lane markings, the connections should start for left turns with the left most outgoing lane and for right turns with the right most outgoing lane. In this case, the map should include the most typical vehicle path.

B.3.6.3.4 Roadway Clutter

Overhead Stationary Roadway Structures

Overhead structures can be detected by the forward-looking radar sensor as in-path objects. These are defined in Appendix B, Section B.2.24. In order to avoid the false identification of overhead structures as in-path objects, the location of overhead objects needs not be identified.

For this application, we need to identify stationary structures on the roadway such as bridges, overpasses, tunnels, pedestrian walkways, and overhead signs that may be a radar target. Structures than begin more than 10 m over the road need not be recorded. Location and posted heights (if present) of structures should be recorded. Start and end points of the structures should be recorded to within 3 m accuracy.

Stationary Roadside Objects

For this application, we need to identify the presence of stationary roadside objects qualitatively as defined in Appendix B, Section B.2.25, within 2 m on either side of travel way (portion of the road used for travel). Stationary roadside object close to the roadway such as mail boxes, light poles, trees, etc. would be a source of radar targets. Identify them only qualitatively. If there are roadside objects within 4 m of travel way edge and none within 2 m, only the location of the closest roadside object in each segment is needed.

Stationary Roadside Barriers

Roadside barriers, defined in Appendix B, Section B.2.26, may be identified as in-path vehicles at long ranges due to the errors associated with the system. Pre-identification of stationary roadside barriers can help to eliminate false identification of in-path vehicles and reduce “ghost” targets returned by the radar.

For this application, we need to identify stationary barriers on the roadside such as guardrails, jersey barriers, bridge abutments, etc. that may be a radar target. Identify those using different classifications. Locations of both start and end points are needed to an accuracy within 3 m.

B.3.7 Speed Limit Assistant: Map Database and Vehicle Positioning Requirements

B.3.7.1 Introduction

It is estimated that speeding – exceeding the posted speed limit or driving too fast for conditions - is a prevalent factor contributing to vehicle crashes. According to the NHTSA 29% of all fatal crashes had speeding as a contributing factor in 2000 [NHTSA 2001][10]. In addition, 703,000 people were injured in speeding related crashes. In all, the NHTSA estimates speeding to have an estimated societal cost of $27.4 billion.

There are several related factors that affect the potential benefits of a system that can help a driver maintain proper vehicle speed. The first has to do with alcohol. 70% of fatal crashes had drivers with 0.01% to 0.1%+ blood alcohol content, and 13% of the fatal crashes did not involve alcohol. Another related factor is driver age. Speeding related fatal crashes are predominant in younger age drivers (<24 years). 85% of speed related fatalities occurred on non-freeway, e.g., non Interstate, roads.

The EDMap project SLA application seeks not to solve confounding issues of speeding, but rather provide an in-vehicle extension to speed limit signs.

B.3.7.2 Brief Description

The Speed Limit Assistant (SLA) aids the driver in maintaining the vehicle near legal speed limits.

In the context of the EDMap application descriptions used in the Task 1 report, the list below summarizes the roles of the SLA with respect to advisory, warning, and control modes of operation.

> **A** - The advisory role of the application warns the driver when the vehicle speed exceeds the legal speed limit of the road.
>
> **C** - The control role of the application regulates the speed of the vehicle so that the legal speed limit is not exceeded (unless countermanded by the driver).

The advisory role was identified in Task 1 as having potential safety benefit. The SLA is related to the Curve Speed Assistant (Section 3.2). It is noted here that only the advisory mode of the SLA was identified as having potential safety benefit that was deployable. The opportunity benefit for the control mode is positive, but the estimated benefits are low due to estimated market penetration of such an application. The Curve Speed Assistant addresses control issues more directly, and was viewed as more deployable. Please see the EDMap Task 1 report for details.

The basic functional components of the SLA are a vehicle positioning system, a digital map database, and an interface to present driver information. The primary database need is posted speed information; with variations described below. It is assumed that the physical speed limit signs will take precedence over any database "posted" speed limit.

One proposed method to present information to the driver would be to provide a speedometer interface that indicates the legal or advised speed limit.

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10 Traffic Safety Facts 2000, National Center for Statistics & Analysis, NHTSA, USDOT HS 809 329, 2001.

B.3.7.3 Requirements for Speed Limit Assistant

The requirements defined in this section are intended to provide guidance in mapplet development and subsequent data collection. The requirements also describe the commensurate vehicle positioning needs of the SLA. SLA needs described here are for the advisory operational mode.

The SLA requirements are justified using an examination of posted speed limit rules as described in the Manual on Uniform Traffic Control Devices [MUTCD, 2000][11].

B.3.7.3.1 Positioning Requirements

Task 1 evaluation of Speed Limit Assistant vehicle positioning needs are 10 m for the near term timeframe. The 10 m requirement comes from the predominant operational scenario where a vehicle is approaching a physical speed limit or speed advisory sign, and needs to correlate vehicle position with position in the map and the respective sign.

The 10 m requirement is viewed as an average value in a sense. The positioning requirement includes the combined positioning error of GPS + INS. Primary positioning sensitivity is in the along the road positioning error (longitudinal error), and correct road placement.

Rationale – Average rural road speed is 50 to 60 mph (22.8 to 26.8 mps). 10 m provides for at least a 0.5 sec detection zone for "triggering" a speed limit revision (equivalent to 2 Hz).

Subsequent to the completion of Task1, it is now believed that sub-meter positioning in the mid term is possible – mainly due to earlier than expected improvements to IMU capability at a low cost. Please see the Task 8a report for details. With this improved accuracy outlook comes to opportunity to place the vehicle in a lane. In-lane placement could provide for increased error handling, especially in ambiguous situations. The SLA can be developed to take advantage of the increased accuracy, but will also work toward satisfying functional capability described from Task 1.

GPS outage INS survival requirements are based on the need to keep track of the vehicle's longitudinal progress along a road. Longitudinal tracking is needed to match up the distance along the map road segment with speed limit/advisory sign placement. It is expected that longitudinal positioning error could grow to 30 m over a 30 second GPS outage. Such error, while not preferred, is about two seconds at vehicle travel speed of 35 mph (15.6 mps). Toward this goal, it is reasonable that near term dead reckoning and map matching are sufficient.

Update rate should be not less than 2 Hz.

B.3.7.3.2 Positioning Summary

Positioning: 10 m for Near Term Warning, 30 m after 30 second GPS outage. All positioning data at least 2 Hz.

11 MUTCD, Millennium Edition, USDOT FHWA, http://mutcd.fhwa.dot.gov/

B.3.7.3.3 Road/Lane Geometry

Absolute Accuracy

Absolute accuracy is defined in Appendix B, Section B.1. For the SLA system, the map database should be at least as good as expected vehicle positioning. Near term accuracy should be 10 m in the 2 sense. SLA as proposed for the near term does not require lane level information.

The primary role of the SLA is on non-freeway scenarios. As such, it is assumed that close parallel road situations that cause errors in road segment placement in typical navigation systems are not a primary error concern. If parallel road situations are to be addressed, Figure B-36 shows that less than 5 m road center positioning is needed (with commensurate vehicle positioning).

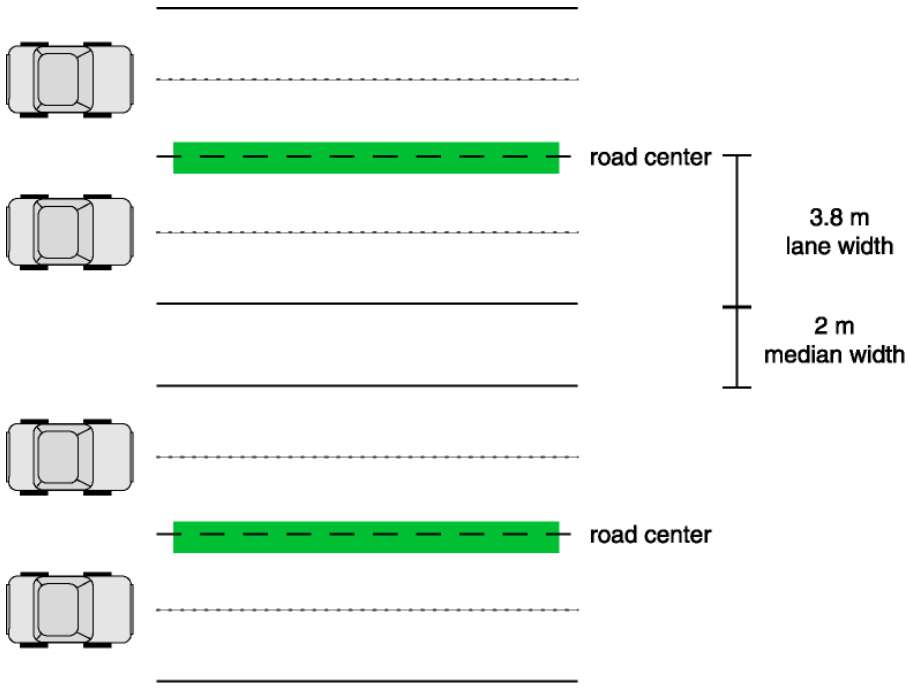

Figure B-36: Road center accuracy for parallel lane placement

Relative Accuracy

Relative accuracy, as defined in Appendix B, Section B.1.2, plays a minor role in the SLA as long as the absolute error between the speed limit/advisory sign location in the map is maintained as described below.

As with the above discussion of parallel road positioning placement error, reliable road placement could be achieved using 5 m absolute positioning error. In a relative sense, as seen in Figure B-36, the errors between parallel road segment geometry should be contained within 1 m. It is restated here that parallel road error handling is a secondary issue. If it can be addressed it would be a benefit, but not a requirement.

B.3.7.3.4 Road/Lane Attributes

The following outlines how specific attributes can be used in a SLA application and the accuracies required for the EDMap project.

Speed Limits - Regulatory

In the context of the SLA, speed limit postings provide the primary attribute information to the system. As described in the MUTCD Chapter 2b, the posted legal speed limit, in the regulatory sense, is to be determined by local officials as the 85th percentile speed of free flowing traffic, rounded to the nearest 5 mph. As defined the location of the speed limit sign becomes the instantaneous speed transition point from the prior posted speed limit sign.

The speed limit needs to be included as a road attribute such that the position along the road (in the longitudinal sense) needs to be within 10 m of the physical sign. The attribute can be expressed in an absolute position sense, or it can be expressed as a distance along the link in the direction of travel. See MUTCD 2B-15 for details on sign placement. As stated in MUTCD, the speed limit attribute is expected to take on values of 5 mph increments.

There are variations of the speed limit attribute that are considered of interest to the SLA application. The first variation is a flag (or some other indication) for day/night time speed limit difference. If there is a nighttime speed limit, it should also be tagged in the database. Second, if the posted speed limit is time dependent in a manner other than day/night, a flag should be set indicating that the speed limit can be modified, and then include any temporal information. The third variation is information relating to "reduced speed ahead" information. Reduced Speed Ahead sign position information should also be included as with the posted speed sign. MUTCD 2B-16 describes when Reduced Speed Ahead signs can be expected. A fourth variation is a road class assigned speed limit. Road class speed limits are sometimes defined for a road type (typically on main rural roads) within a region such that all roads of this type are set to the same speed limit unless otherwise posted. In a sense, this is a "default" speed. The default speed needs to be assigned in the database.

Other speed limit information as the result of circumstances, such as school zones, are assumed to be addressed as if it was a posted speed limit. There is understandably a great deal of latitude in defining other circumstances, and these will have to be addressed as the application is developed.

Speed Limit - Advisory

Advisory speed limit signs are those that provide speed warning information. For the SLA the primary warning sign is that for curve speeds. Placement of the curve warning speed signs is described in MUTCD Table 2C-4 and related documentation. Sign placement is based on assumed deceleration profiles between the posted speed limit (regulatory) and the appropriate curve speed. It is noted here that the map database need only contain curve speed warnings that are physically posted and that the advisory speed limit attribute is the same value as that posted on the sign. The Curve Speed Assistant is specifically described to address curve speed issues for all curved road segments.

Database attributing for warning speed signs should follow that of the regulatory signs with 10 m position accuracy along the path.

As with regulatory signage, there is understandably a great deal of latitude in defining other circumstances, and these will have to be addressed as the application is developed.

B.3.8 Intersection Collision Avoidance System: Map Database and Vehicle Positioning Requirements

B.3.8.1 Introduction

Intersection Collision Avoidance System (ICAS) is considered a "long-term" application within EDMap. This application requires the addition of communications infrastructure at intersections for communicating between the ICAS and vehicles present in and/or approaching the intersection.

B.3.8.2 Brief Description

ICAS utilizes infrastructure-to-vehicle communication devices to aid drivers in avoiding collisions at intersections. The ICAS employs a number of sensors that detect the positions, velocities and driving behavior of all vehicles approaching the intersection[12]. It uses the information collected from the sensors to continuously predict the possibility of a collision for any given point in time. High-speed processing capability ensures that the system generates predictions in time to be of value in avoiding/mitigating collisions. The ICAS employs communication devices to both receive data from vehicles and transmit data/commands to activate vehicle functionalities such as braking, steering, and acceleration as necessary. Dedicated Short-Range Communication (DSRC) is one option for providing the communication function[13]. More information concerning communication technologies applicable for this type of Driver Assistant System will be discussed in the Task 8 report.

Functions suitable for the ICAS include reducing inattentive/aggressive intrusions into intersections, speed control for vehicles approaching intersections and giving priority to emergency vehicles.

Collision prediction, determining the proper countermeasure and how to interact with vehicles are major issues concerning ICAS.

B.3.8.3 Requirements for Intersection Collision Avoidance

ICAS is considered a "long-term" application, but the physical structure of intersections is assumed to remain unchanged. Each vehicle needs to be equipped with communication devices in order for the ICAS to communicate with vehicles in and/or approaching the intersection. Vehicle behavior can be sensed by either infrastructure or on-vehicle sensors. In the case of on-vehicle sensors, information is transmitted from the vehicle to the infrastructure via vehicle-infrastructure communications. The ICAS must possess a sophisticated level of intelligence to 1) observe traffic conditions within the intersection and the approaches to the intersection and 2) accurately predict the likelihood of collisions. The status of the traffic signal should be addressed and could be optimized by the ICAS.

Communication between the infrastructure and vehicles is the essential element in an ICAS however, the map database will provide an important function as well. It could for example be used to provide accurate distance between vehicle and intersection and driver intent in terms of turning left, right or proceeding forward. This information is then used to determine rate of

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12 Smart Cruise 21 Demo 2000 Panel Sessions / Technical Sessions presentation materials, The Demo2000 Secretariat, Nov, 2000

13 Analysis of an Infrastructure Collision Avoidance Concept for Straight Crossing Path Crashes at signalized Intersections. Robert A. Ferlis, FHWA, Aug 1, 2001

approach to the infrastructure, the presence of crossing path maneuvering, etc. which is key to predicting collisions. By providing this type of information, the map database serves to relieve the sensor burden on the infrastructure and/or act as a backup to infrastructure based sensors, both of which will result in a more reliable infrastructure.

B.3.8.3.1 Positioning Requirements for ICAS

The infrastructure is stationary but vehicles are not, therefore, positioning requirements should be a concern for vehicles. ICAS assists in avoiding "inattentive" or "aggressive" driving. To do so, the ICAS will transmit warnings/control commands to vehicles to stop/reduce speed and/or control the drive path when the vehicle is likely to run past defined stopping locations or likely to get into a collision.

The functionality of the ICAS is quite similar to the "Stop Sign Assistant (Control)" (see Section 0) in terms of making a stop. The ICAS is also similar to the "Lateral and Longitudinal Control"(see Appendix 2, Section B.3.6) in terms of following lane direction in the intersection. The key difference is the interaction with the infrastructure. Regarding communication capability, shorter communication latency would be required (ex. the distance traveled in 20ms corresponds to 0.2 m when driven at 40 km/h (25 mph).

B.3.8.3.2 Summary of Vehicle Positioning Requirements

Vehicle Positioning Accuracy (refer to Appendix 2, Section B.3.6.3):

- Longitudinal absolute positioning error for ICAS:

  Less than 0.5 m for control

- Lateral absolute positioning error for ICAS

  Less than 0.2 m for control

- GPS outage error:

  Less than 0.1 m for control

Data update rate: at least 50 Hz

Communication latency: less than 20 ms (at least 50 Hz)

B.3.8.3.3 Road/Lane Geometry

The travel distance to the stopping point or road signs could be obtained from this attribution.

The ICAS is capable of providing precise lane guidance. Lane-by-lane representations of each mapplet would be required because restrictions are lane dependent. The centerline represents the lane.

Expected absolute accuracy: 0.3 m

B.3.8.3.4 Road/Lane Attributes

Lane Direction

This mapplet is required for intersection approaches to allow the driver to select the appropriate lane in terms of driving direction (refer to Appendix B, Section B.2.9). Prohibited/permissible directions should be reported along with applicable conditions such as days of week, time dependent rules, rights of way, and so on posted as sub captions.

Lane direction data should be provided to assist drivers in choosing the appropriate lane of travel.

Road Condition[14]

The ICAS may revise system parameters to fit the conditions present.

Length: at least 5 m from start to end positions (with 1 m accuracy) should be reported

Road Surface Type

Estimated maximum deceleration may be modified based on changes in the "Road Surface Type".

This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection).

Length: at least 5m, from start to end positions (with 1m accuracy) should be reported

Road Grade

Needed for reducing stopping distance error. (Reference to Section 0)

Expected accuracy: 1% (+/- 0.5%)

Length: at least 5 m from start to end positions (with 1 m accuracy) should be reported

Road Class

This mapplet, defined in Appendix B, Section B.2.15, is necessary for identifying the rights of way or priorities.

This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.)

Speed limit[15]

In order to determine whether or not a vehicle is likely to violate the signal, the ICAS needs to know the posted speed limits for traffic approaching and leaving the intersection in the "Green" direction.

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14 Analysis of an Infrastructure Collision Avoidance Concept for Straight Crossing Path Crashes at signalized Intersections. Robert A. Ferlis, FHWA, Aug 1, 2001, pg 8

15 Analysis of an Infrastructure Collision Avoidance Concept for Straight Crossing Path Crashes at signalized Intersections. Robert A. Ferlis, FHWA, Aug 1, 2001, pg 9

Stopping Location

ICAS needs to predict vehicle behavior in the intersection to evaluate the possibility of traffic violations. Locations where traffic is prohibited from stopping or standing should be addressed, e.g., "No Blocking", "Cross walk", etc. (see Appendix B, Section B.2.17)

Expected absolute accuracy: 0.3 m for control

Intersection Geometry

Intersection Lane Geometry is described in Appendix B, Section B.2.23.

Required for predicting vehicle behavior as it travels through the intersection. Provided lane geometry are the paths vehicles should trace as they proceed through the intersection.

Accuracy requirements for vehicle path are defined by lane keeping functional applications because the path is the same as the centerline.

Expected absolute accuracy: 0.3 m (as the same as the centerline)

This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage, i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.)

B.3.8.3.5 Summary for ICAS

Table B-3: Summary of mapplets requirements for ICAS

Mapplet	Requirement
Stopping Location	Expected absolute accuracy: 1 m for warning, 0.3 m for control in longitudinal direction along the direction of travel.
Speed Limit	Posted speed limits for vehicles entering and leaving the intersection.
Intersection Lane Geometry	Refer to Appendix B, Section B.2.23. Expected absolute accuracy: 0.3 m
Road Class	Identify the rights of way or priorities.
Road Condition	Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported.
Lane Direction	This data should be provided at least 60 m (200 ft) before the stopping point. (200 ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.)
Road Surface Type	This data should be provided at least 60 m (200ft) before the stopping point. (200ft is the maximum length for center lane usage i.e. the driver starts changing lanes from this point to prepare for maneuvering in the intersection.) Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported
Road Grade	Expected accuracy: 1%(+/- 0.5%) Length: at least 5 m, from start to end positions (with 1 m accuracy) should be reported
Road/Lane Geometry	Expected absolute accuracy: 0.3 m

B.4 Summary of Map Database and Vehicle Positioning Requirements

This chapter is a collection of database mapplet and vehicle positioning requirements drawn from Appendix B, Section B.3. The EDMap applications covered are those safety applications short-listed in Task 1. Mapplet and vehicle positioning needs are shown for the EDMap high safety potential applications in the near, mid, and long term time periods. Map Database Requirements

The application map database requirements described in this section are based on the EDMap Task 1 applications.

B.4.1 Summary Tables

The following data table are presented:

- Mapplet Requirements for Near-term EDMap Applications
- Mapplet Requirements for Mid-term EDMap Applications
- Mapplet Requirements for Long-term EDMap Applications

Table B-4: Mapplet requirements for near-term EDMap applications

	Near-term		
	Curve Speed Assistant	**Stop Sign Assistant**	**Speed Limit Assistant**
Mapplet	**Warning**	**Warning**	**Advisory**
Road Geometry	Absolute accuracy: 5 m.		Absolute accuracy: 5 m.
Road Curvature	Accuracy: 10%, fair curve.		
Number of Lanes	Required except at transitions.		
Road Condition	Position accuracy: 75 m.	Position accuracy: 1 m for length > 5 m.	
Road Surface Type	Position accuracy: 75 m.	Position accuracy: 1 m for length > 5 m (within 60 m of stop sign).	
Road Grade	Accuracy: 2% grade increments (to the nearest 2%) for length > 10 m.	Accuracy: 0.5%, resolution 1%. Position accuracy: 1 m for length > 5 m.	
Superelevation	Values: yes, no, incorrect banking.		
Road Class	Position accuracy: 10 m.		
Speed Limits	Position accuracy: 5 m.		Position accuracy: 10 m.
Stopping Location		Position accuracy: 1 m.	
Stop Sign Location		Position accuracy: 1 m.	
Stop Ahead Sign Location		Position accuracy: 5 m.	
Yield Sign Location		Position accuracy: 5 m.	

Table B-5: Mapplet requirements for mid-term EDMap applications

	Mid-term				
	Curve Speed Assistant	**Forward Collision Warning/Avoidance**	**Lane Following Assistant**	**Traffic Signal Assistant - Vision**	**Stop Sign Assistant**
Mapplet	**Control**	**Warning**	**Warning**	**Warning**	**Control**
Lane Geometry	Absolute accuracy: 1 m.	Absolute accuracy: 0.5 m. Relative accuracy: 0.5 m for forward geometry up to 120 m.	Absolute accuracy + lane width accuracy: 0.3 m. Relative accuracy: linearly increasing to 2 m for forward geometry up to 50 m.		
Lane Width		Accuracy: 0.3 m.	See above.		
Transition Zone		Position accuracy: 3 m.			
Lane Heading		Accuracy: 0.15^{o}.			
Lane Curvature	Accuracy: 5%, fair curve.	Fair curve.			
Shoulder Type			Position accuracy: 10 m.		
Shoulder Width		Accuracy: 0.5 m, resolution 0.05 m for length > 20 m.	Accuracy: 0.3 m, resolution 0.1 m (if shoulder width < 1 m). Accuracy: 0.5 m, resolution 0.5 m (otherwise).		
Lane Markings Type			Position accuracy: 5 m for length > 10 m.		

Table 2-5 (continued): Mapplet requirements for mid-term EDMap applications

	Mid-term				
	Curve Speed Assistant	**Forward Collision Warning/Avoidance**	**Lane Following Assistant**	**Traffic Signal Assistant - Vision**	**Stop Sign Assistant**
Mapplet	**Control**	**Warning**	**Warning**	**Warning**	**Control**
Lane Direction		Required.			Required.
Number of Lanes	Required except at transitions.	Required except at transitions.			
Road Condition	Position accuracy: 25 m.	Position accuracy: 10 m.			Position accuracy: 1 m for length > 5 m.
Road Surface Type	Position accuracy: 25 m.	Position accuracy: 3 m for length > 10 m.	Position accuracy: 5 m for length > 10 m.		Position accuracy: 1 m for length > 5 m (within 60 m of stop sign).
Road Grade	Accuracy: 2% grade increments (to the nearest 2%) for length > 10 m.	Accuracy: 2%, resolution 2% for length > 10 m.			Accuracy: 0.5%, resolution 1%. Position accuracy 1 m for length > 5 m.
Superelevation	[-3, 0, 3, 6, 9]%.				
Road Class	Position accuracy: 10 m.	Position accuracy: 10 m.			
Speed Limits	Position accuracy: 5 m.				
Stopping Location				Position accuracy: 0 to 2 m.	Absolute accuracy: 0.3 m.
Stop Sign Location					Absolute accuracy: 1 m.
Stop Ahead Sign Location					Absolute accuracy: 5 m.

Table 2-5 (continued): Mapplet requirements for mid-term EDMap applications

	Mid-term				
	Curve Speed Assistant	**Forward Collision Warning/Avoidance**	**Lane Following Assistant**	**Traffic Signal Assistant - Vision**	**Stop Sign Assistant**
Mapplet	**Control**	**Warning**	**Warning**	**Warning**	**Control**
Yield Sign Location					Absolute accuracy: 5 m.
Traffic Signal Location				Longitudinal accuracy: 2 m. Lateral accuracy: 3 m.	
Intersection Location		Position accuracy: 1 m.			
Intersection Geometry			Required.		
Overhead Stationary Roadway Structures		Position accuracy: 3 m for height < 10 m.			
Stationary Roadside Objects		Qualitative density score: 0, 1, 2, 3, 4.			
Stationary Roadside Barriers		Position accuracy: 3 m.			

Table B-6: Mapplet requirements for long-term EDMap applications

	Long-term			
	Forward Collision Warning/Avoidance	**Lane Following Assistant**	**Intersection Collision Avoidance**	**Lateral and Longitudinal Control**
Mapplet	**Control**	**Control**	**Control**	**Control**
Lane Geometry	Absolute accuracy: 0.5 m. Relative accuracy: 0.5 m for forward geometry up to 120 m.	Absolute accuracy + lane width accuracy: 0.2 m. Relative accuracy: linearly increasing to 2 m for forward geometry up to 50 m.	Absolute accuracy: 0.3 m.	Absolute accuracy: 0.2 m. Relative accuracy: 0.1 m for forward geometry up to 30 m. Relative accuracy: 0.2 m for forward geometry 30 m up to 120 m.
Lane Width	Accuracy: 0.3 m.	See above.		Accuracy: 0.2 m.
Transition Zone	Position accuracy: 3 m.			Requires lane geometry.
Road/Lane Heading	Accuracy: 0.15^{o}.			Accuracy: 0.15^{o}.
Road/Lane Curvature	Fair curve.			Fair curve.
Shoulder Type		Position accuracy: 10 m.		Required for length > 10 m.
Shoulder Width	Accuracy: 0.5 m, resolution 0.05 m for length > 20 m.	Accuracy: 0.3 m, resolution 0.1 m (if shoulder width < 1 m). Accuracy: 0.5 m, resolution 0.5 m (otherwise).		Accuracy: 0.3 m, resolution 0.1 m (if shoulder width < 1 m). Accuracy: 0.5 m, resolution 0.5 m (otherwise).
Lane Markings Type		Position accuracy: 5 m for length > 10 m.		Position accuracy: 5 m for length > 10 m.

Table 2-6 (continued): Mapplet requirements for long-term EDMap applications

	Long-term			
	Forward Collision Warning/Avoidance	**Lane Following Assistant**	**Intersection Collision Avoidance**	**Lateral and Longitudinal Control**
Mapplet	Control	Control	Control	Control
Lane Direction	Required.		Required.	Required.
Number of Lanes	Required except at transitions.			Required except at transitions.
Road Condition	Position accuracy: 10 m.		Position accuracy: 1 m for length > 5 m.	Position accuracy: 10 m.
Road Surface Type	Position accuracy: 3 m for length > 10 m.	Position accuracy: 5 m for length > 10 m.	Position accuracy: 1 m for length > 5 m (within 60 m of stop sign).	Position accuracy: 3 m for length > 10 m.
Road Grade	Accuracy: 2%, resolution 2% for length > 10 m.		Accuracy: 0.5%, resolution 1%. Position accuracy: 1 m for length > 5 m.	Accuracy: 2%, resolution 2% for length > 10 m.
Superelevation				Accuracy: 2%, resolution 2% for length > 10 m.
Road Class	Position accuracy: 10 m.		Position accuracy: 10 m.	Position accuracy: 10 m.
Speed Limits			Position accuracy: 10 m.	Position accuracy: 10 m.
Stopping Location			Accuracy: 0.3 m.	

Table 2-6 (continued): Mapplet requirements for long-term EDMap applications

	Long-term			
	Forward Collision Warning/Avoidance	**Lane Following Assistant**	**Intersection Collision Avoidance**	**Lateral and Longitudinal Control**
Mapplet	**Control**	**Control**	**Control**	**Control**
Stop Sign Location			Absolute accuracy: 1 m.	
Stop Ahead Sign Location			Absolute accuracy: 5 m.	
Yield Sign Location			Absolute accuracy: 5 m.	
Intersection Location	Position accuracy: 1 m.			
Intersection Geometry		Required.	Required.	Required.
Overhead Stationary Roadway Structures	Position accuracy: 3 m for height < 10 m.			Position accuracy: 3 m for height < 10 m.
Stationary Roadside Objects	Qualitative density score: 0, 1, 2, 3, 4.			Qualitative density score: 0, 1, 2, 3, 4.
Stationary Roadside Barriers	Position accuracy: 3 m.			Position accuracy: 3 m.

B.4.2 Vehicle Positioning Requirements for EDMap Applications

The application positioning requirements summarized in this section are based on the EDMap Task 1 applications. In Task 1, applications were assigned rough positioning requirements in order to determine timeframes in which applications could be deployed. As part of Task 2, positioning requirements for each application were closely examined using information contained in the Task 8a report. The derivation of the positioning requirements for each application is contained in Appendix B, Section B.3.

B.4.2.1 Near-term Positioning

Table B-7: Positioning requirements for near-term EDMap applications

	Near-term		
	Curve Speed Assistant	**Stop Sign Assistant**	**Speed Limit Assistant**
	Warning	**Warning**	**Advisory**
Position Error	5 m	5 m	30 m
Heading Error	2°		
Update Frequency	10 Hz	10 Hz	2 Hz

B.4.2.2 Mid-term Positioning

Table B-8: Positioning requirements for mid-term EDMap applications

	Mid-term				
	Curve Speed Assistant	**Forward Collision Warning/ Avoidance**	**Lane Following Assistant**	**Traffic Signal Assistant - Vision**	**Stop Sign Assistant**
	Control	**Warning**	**Warning**	**Warning**	**Control**
Position Error 1	1 m	0.5 m	0.3 m	1-2 m	0.6/1.5 m 2
Heading Error	2°	0.15°			
Update Frequency	40 Hz	10 Hz			50 Hz

[1]Position error after 30 second GPS outage

[2]Longitudinal/Lateral position error after 10 second GPS outage

B.4.2.3 Long-term Positioning

Table B-9: Positioning requirements for long-term EDMap applications

	Long-term			
	Forward Collision Warning/ Avoidance	**Lane Following Assistant**	**Intersection Collision Avoidance**	**Lateral and Longitudinal Control**
	Control	**Control**	**Control**	**Control**
Position Error[1]	0.2 m	0.2 m	0.6/0.3 m [2]	0.2 m
Heading Error	0.15°			0.15°
Update Frequency	>10 Hz			50 Hz

[1]Position error after 30 second GPS outage

[2]Longitudinal/Lateral position error after 10 second GPS outage

B.5 Assessment of Existing Database Capabilities and Application Needs

This section describes the capabilities of current map databases, as of the start of the EDMap project, and compares these map capabilities to EDMap applications.

B.5.1 Existing Database Capabilities

B.5.1.1 Position Accuracy

NAVTEQ Corporation (formerly Navigation Technologies Corporation) data specifications refer to two kinds of positional accuracy: absolute and relative. A position in the database is defined by its latitude and longitude. "Absolute" positional accuracy is the distance between the map position and true position on earth. "Relative" positional accuracy refers to whether each database node and shape point is located in the correct relative position to each other in order to accurately represent the shape of a road.

The NAVTEQ database has the following specification levels:

- Detailed City coverage, present in the most populated counties in the USA (contiguous states and Hawaii). All roads are included. This coverage is primarily based on USGS 1:24000 (7.5 minute) quadrangles. Specified accuracy is 15 m absolute position accuracy and 3 m relative position accuracy. Figure B-37 illustrates the extent of Detailed City coverage as of the second quarter of 2002, as EDMap database construction began. (Figure B-38 updates this to the first quarter of 2004.) Figure B-39, from the National Geophysical Data Center, National Oceanic and Atmospheric Administration16, illustrates the correlation of Detailed City coverage to population centers.
- Inter-town coverage, present in the remaining counties in the contiguous states and Alaska. This coverage is primarily based on USGS 1:100000 quadrangles. Primary roads are included; generally, any road that is included in an AAA state-level map is included in this coverage. Specified accuracy is 100 m absolute position accuracy.

Many arterial roads in both Detailed City and Inter-town areas have been field-collected with differential GPS (DGPS) data collection, providing 5 m absolute and 1 m relative accuracy. During this field collection effort, some additional attributes have been collected, including specific speed limits and number of lanes.

16 Image taken from http://dmsp.ngdc.noaa.gov/images/usa_small.gif, on page http://dmsp.ngdc.noaa.gov/html/night_light_posters.html .

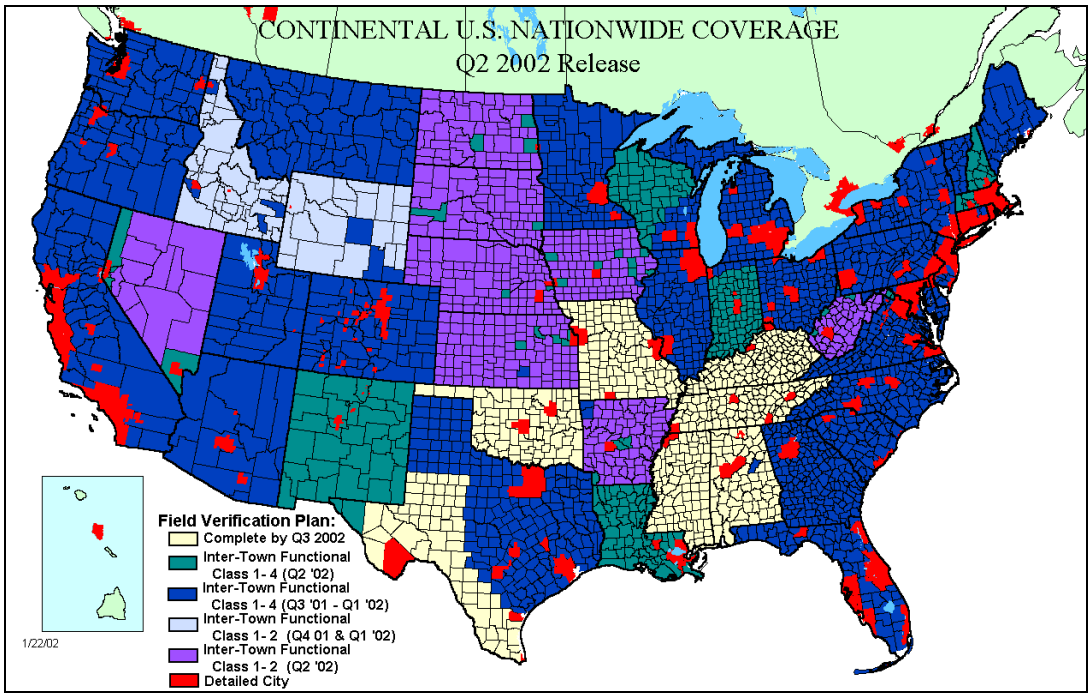

Figure B-37: Detailed city and inter-town extent (2nd Quarter 2002)

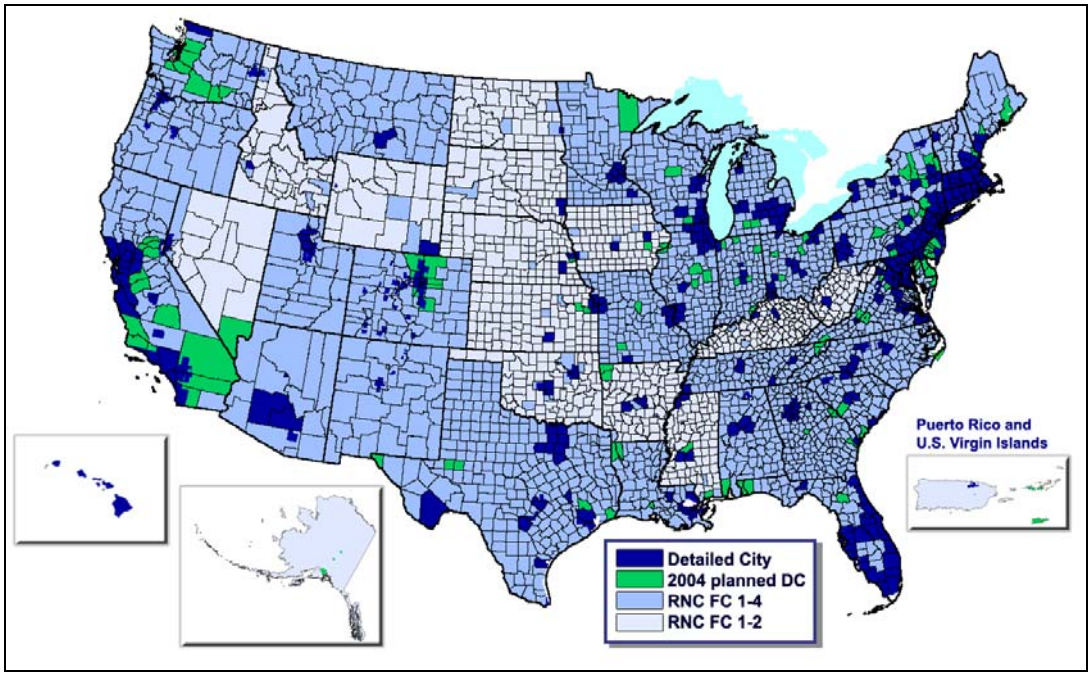

Figure B-38: Detailed city and inter-town extent (1st Quarter 2004)

Figure B-39: "Nighttime Lights of the USA" from NOAA

Latitude and longitude locations in the database are digitized with a precision of 0.00001 degree of latitude or longitude, which roughly corresponds to 1 m resolution (~1.113 m in latitude, or longitude at the equator; ~0.964 m in longitude at 30° latitude, ~0.787 m in longitude at 45° latitude).

Database geometry (detailed city and inter-town) is intended to represent the center of the roadbed. In some situations, including all freeways, each carriageway of a road is digitized separately. Other roads have a single road centerline representing both directions of travel.

Database locations also contain a "Z-level" (relative height) component when two or more features exist at the same latitude/longitude with vertical separation. There is no representation of actual elevation (altitude), grade (change in elevation longitudinally along a road), or superelevation (change in elevation laterally across a road).

Each geometric position is maintained as a "node" with a unique combination of latitude, longitude, and Z-level. A node can be defined as an "intersection node", which is used to define the end of one or more linear "links." A node can also be a "shape point," which serves to describe the shape along a link. A shape point never belongs to more than one link. If two or more links cross but do not intersect (vertical separation), the crossing point is defined as an intersection node or shape point in each of the crossing links, at different Z-levels.

The NAVTEQ databases have many additional data elements essential to applications such as route guidance, destination selection, and cartography that are not of particular interest to safety-related systems. These elements include feature names, addresses, points of interest, administrative areas, postal codes, land use polygons, and others. These are outside the scope of the EDMap project.

B.5.1.2 Curvature

Curved roads are represented as a series of piecewise-linear sub-segments, with "shape points" defining the ends of each sub-segment (see Figure B-40). The shape points (and intersection nodes separating links) are specified to be no less than 2 m apart. On DGPS field-collected roads, shape points are added or adjusted such that no portion of a road center deviates from a computed spline representation by more than 1 m (the "relative accuracy" requirement). These adjustments are intended to ensure in-spec relative accuracy, but do not attempt to provide mathematically "fair" changes to curvature over the length of a roadway. In these diagrams, intersection nodes are squares; shape points are circles.

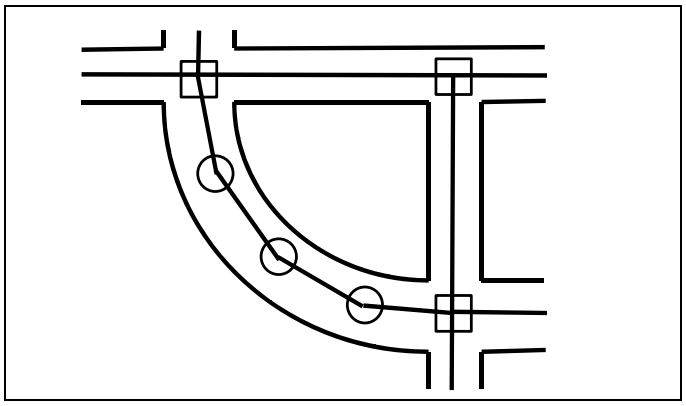

Figure B-40: Curves as piecewise-linear segments

Curvature is not a current data element. Because of the 0.00001° granularity of shape point positioning, deviations of a significant fraction of a meter between shape point locations and the computed spline representation are unavoidable. This also adversely affects the calculation of curvature. In Figure B-41, the database curvature at the two shape points on the left would be zero.

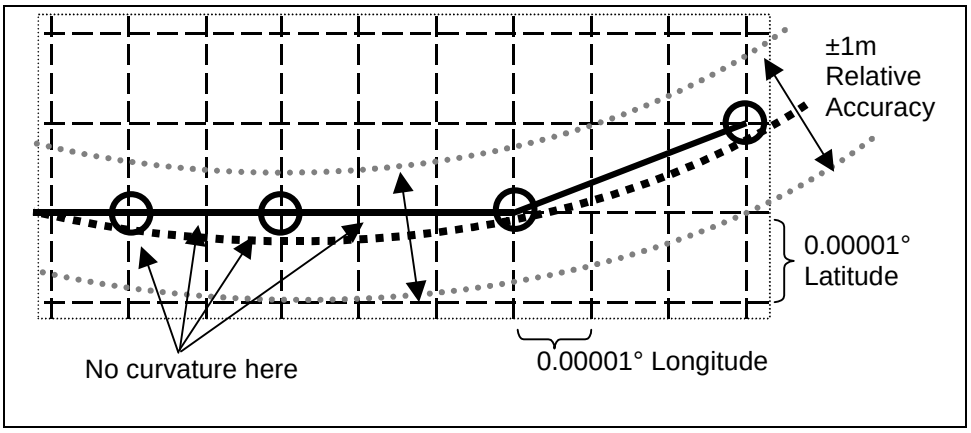

Figure B-41: Effects of 0.00001° granularity

B.5.1.3 Database Generalization

In all NAVTEQ databases, the database geometry is intended to correspond to the centerline of the roadway or carriageway. The centerline is intended to represent the mid-way point between the edges of the roadway, not including outside shoulders. (For bi-directional roads, the "roadway" can include areas between the directions of travel such as medians, inside shoulders, center turn lanes, HOV lanes, bus-only lanes, etc.) The road centerline may or may not correspond to a lane's centerline (see Figure B-42).

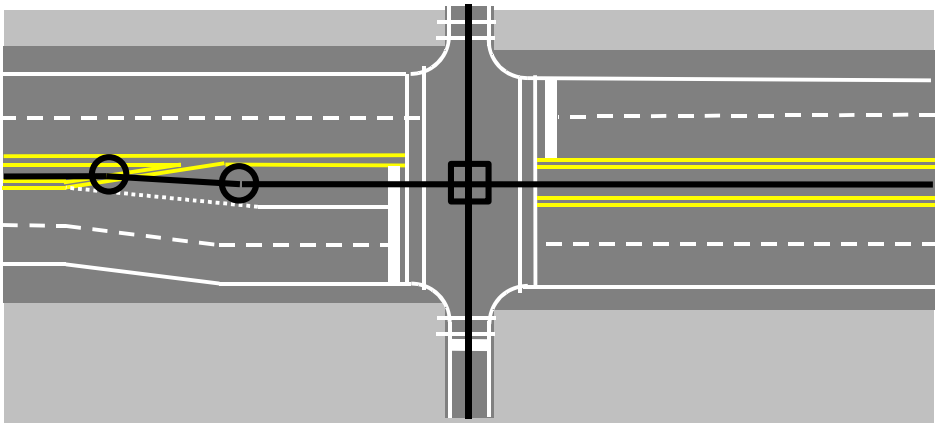

Figure B-42: Road centerline versus lane centerline

In order to support efficient route calculation and guidance, NAVTEQ has a number of "generalization" rules used when digitizing short links and other situations dealing with short distances. While these are of unquestioned benefit to existing navigation-based applications, these generalizations were expected to (and did) present challenges when EDMap applications used road-level map objects. Lane-level modeling in the mid-term and long-term EDMap databases helped solve these limitations.

Some of these generalizations are:

- "Turn lanes" (particularly right turn lanes) that are disjoint from the main road are digitized as a separate link only if the separation is at least 25 m long. Shorter turn lanes are not digitized as separate links (see Figure B-43).

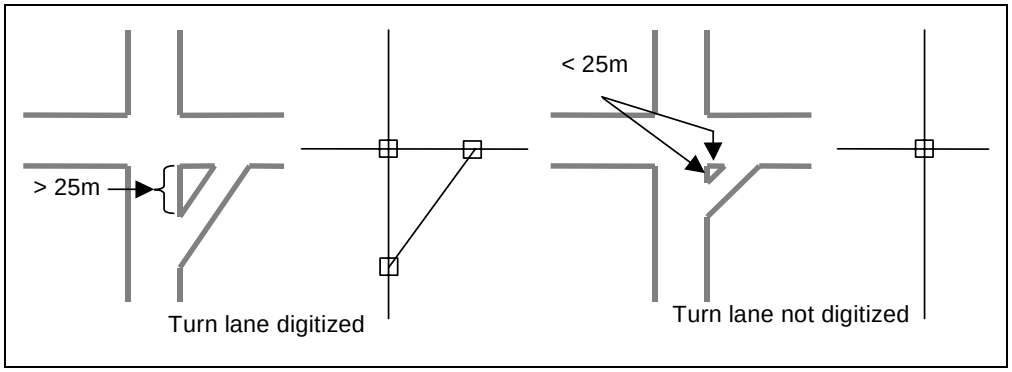

Figure B-43: Turn lane generalization

- Cul-de-sacs larger than 25 m in diameter are digitized as such; smaller cul-de-sacs are not represented (the road appears as a normal "dead end"), as shown in Figure B-44. Similarly, roundabouts larger than 25 m in diameter are digitized as such; smaller roundabouts appear as ordinary intersections.

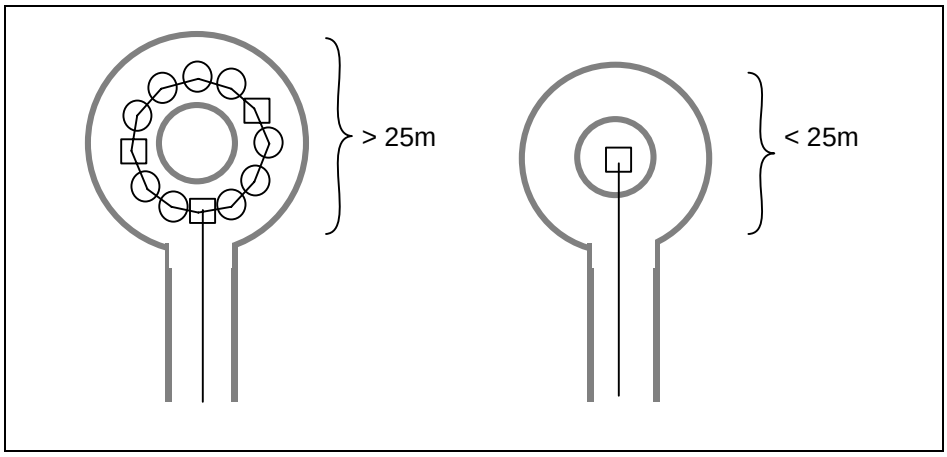

Figure B-44: Cul-de-sac generalization

- The centerline of the road merging in or out is limited to 75 m of overlap with the main roadbed, as shown in Figure B-45.

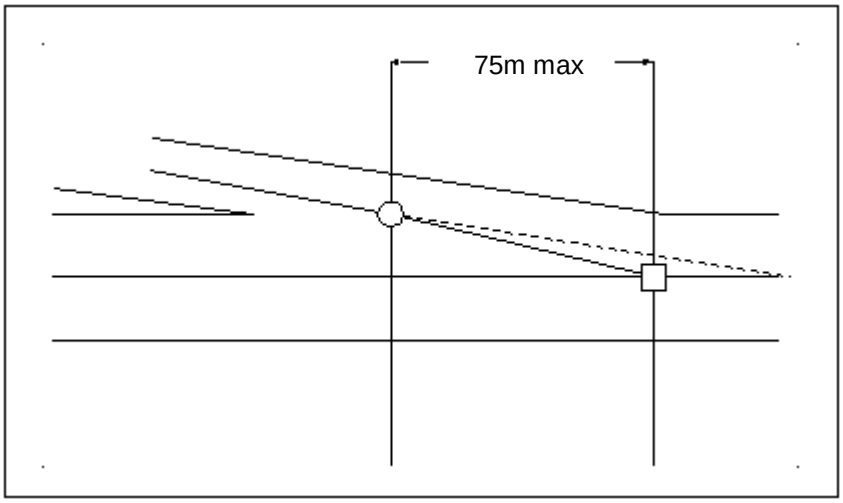

Figure B-45: Merges generalized to < 75 m

- Some centerlines at intersections will differ from the physical center of the roadbed, when appropriate, to better support route guidance and route calculation, such as when roads merge or intersect at a slight angle (see Figure B-45 and Figure B-46).

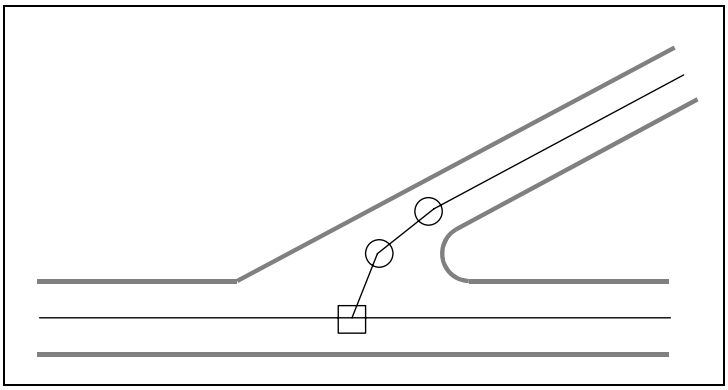

Figure B-46: Generalization of slightly angled intersections

- Roads that are offset on either side of an intersection are handled in two different ways, depending on the magnitude of the offset. If the offset is less than 5 m, the road centerlines are adjusted near the intersection so as to join the roads. Larger offsets are not adjusted and result in a short segment on the intersecting road (see Figure B-47).

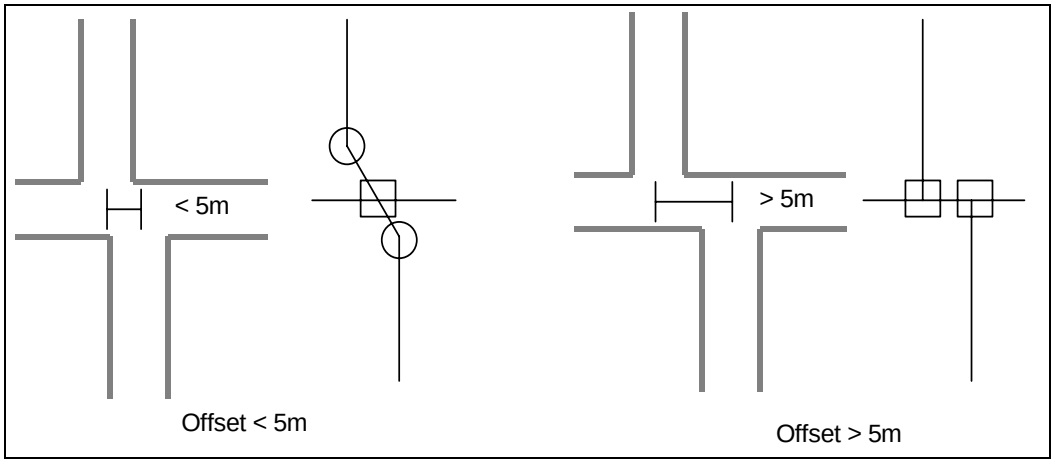

Figure B-47: Offset intersections

B.5.1.4 Data Elements (Pertinent to EDMap)

Some EDMap applications have specified needs for data attributes that are currently supported, or partially supported, in the NAVTEQ Detailed City databases or on DGPS field-collected roads.

B.5.1.4.1 Number of Lanes

All NAVTEQ databases include a "Lane Category" applicable to the roadway: 1 lane, 2 or 3 lanes, or 4 or more lanes.

Only DGPS field-collected roads include a discrete "Number of Lanes" attribute, reflecting the actual number of travel lanes present (main driving path for automobiles). Bi-directional DGPS field-collected roads have a separate number of lanes value for each direction of travel. Positional accuracy of number of lanes is specified as within 20 m.

B.5.1.4.2 Ramps

All NAVTEQ databases include a yes/no indication when a roadway is considered to be a ramp (defined as connecting roads that do not intersect at grade). This is applied to the entire length of the segment.

B.5.1.4.3 Road Class

There is no specific NAVTEQ data element called "Road Class," but rather a set of discrete attributes that can be used to classify a road. These attributes include:

- Functional Class: A number used to establish a hierarchical logical network for route calculation, ranging from Functional Class 1 for the highest-mobility roads to Functional Class 5 for the most local roads.
- Speed Category (all specification levels); also Speed Limit (only on DGPS field-collected roads): Speed Category and Speed Limit are discussed further below.
- Controlled Access (yes/no).
- Lane Category (all specification levels); also Number of Lanes (only on DGPS field-collected roads).
- Frontage Road (yes/no).
- Point-of-Interest Access Road (yes/no).
- Turn Lane and Similar "Maneuver" Roads: Turn lanes that are disjoint from the roadway for over 25 m are digitized separately from the roads they connect, as discussed earlier in Section B.5.1.2.
- Vehicular Access Types (yes/no for autos, buses, trucks, pedestrians, emergency vehicles, and others).
- Tollway (yes/no).
- Private Road (yes/no).
- Other than Number of Lanes, which has a 20 m accuracy specification, these attributes are applied to whole road segments, generally from intersection to intersection.

B.5.1.4.4 Speed Category and Speed Limit

Speed indications have always been present in NAVTEQ databases for the purpose of supporting efficient route determination. A typical criterion for route optimization in navigation systems is "time required"; route calculation algorithms thus need knowledge of the general speed characteristics of alternative roads. In this context, it is beneficial to know which roads are faster than others, but minor differences in speed limits have not been of concern to route-calculation applications.

All NAVTEQ databases have a "Speed Category" with eight discrete speed ranges.

DGPS field-collected roads also have a numeric speed limit, expressed in miles (or kilometers) per hour. These correspond to legal speed limits from posted signs or road markings, or default legal speed limits, when appropriate.

The DGPS field-collected positional accuracy specification for speed limit is 20 m, though there are some specific exceptions. When a speed limit sign is visible from the start of a road (after an intersection), the speed limit is applied to the beginning of the

road, even if it is more than 20 m from the sign. Speed limits for ramps are applied starting at the beginning of the ramp, even if the sign is more than 20 m before the start of the ramp. If different lanes have different speed limits or different directions on a bi-directional road, the lower speed limit is applied to the whole road (though in DGPS field-collected roads, the road is designated as having "Lane-Dependent" speed; see below).

In addition, DGPS field-collected roads support the following attributes, applied to a longitudinal section of roadway with 20-meter accuracy:

- Advisory speeds, when posted for curves, ramps, intersections, narrow bridges, etc. The advisory speed, as posted, is provided.
- Dependent speeds. These are speed restrictions that depend on school, rain, snow, time-dependent, lane-dependent, or approximate seasonal time. The type of dependency is provided, as is the speed limit (for other than the lane-dependent type).
- Traffic Calming Devices (speed bumps, dips, or chicanes that require reducing vehicle speed). These are marked by a 20 m segment (10 m on each side of the location of the device). These do not normally have a specific speed limit associated with them.
- Variable Speed Signs are provided within 20 m of the sign location.

B.5.1.4.5 Traffic Restrictions

All NAVTEQ databases provide the following information regarding traffic restrictions:

- Vehicular Access Types (yes/no for autos, buses, trucks, pedestrians, emergency vehicles, and others.) for each roadway.
- Direction of Travel on each roadway.
- Restricted Driving Maneuvers across two or more road segments. These are applied to legal, logical, or physical turn restrictions that are not implied by Direction of Travel.
- Gates or other movable barriers that restrict access to roadways.
- Any of the above restriction types can be specified with time-dependent and/or day-dependent rules. Examples include "Buses Only 7-9 A.M. Monday-Friday;" "No Left Turn 4-6 P.M.;" "One-way Northbound Sundays 7-10 A.M." Vehicular Access Types can also be combined with other restrictions (e.g., "One-way for Autos, Two-way for Buses, 7 A.M.-6 P.M. Monday-Friday").
- The EDMap test databases, as delivered, did not attempt to reflect restricted driving maneuvers, as the applications being supported were not navigation applications. Road “preview” thus included roads that were physically enterable, regardless of restrictions.

B.5.1.4.6 Bridges

All NAVTEQ databases provide a yes/no attribute for "Bridge." This attribute is applied to bridges of 200 m or more in length.

B.5.1.4.7 Tunnels

All NAVTEQ databases provide a yes/no attribute for "Tunnel." This attribute is applied to tunnels of 200 m or more in length.

B.5.1.4.8 Railroads

Many railroads are represented in the database. In the United States, the main lines of all above-ground railways are included (with the exception of local commuter railways, "light rail" networks, and cable car lines). These are primarily intended for cartographic display purposes, so the database does not attempt to indicate the actual number of tracks present or the vehicle stop locations for railroad crossings.

B.5.1.4.9 Other Conditional Attributes

Each roadway is coded as having a direction of travel and a set of vehicle access types. But these database attributes can also be applied to a roadway on a conditional basis, when the attribute varies at certain dates or times. Some examples include:

- Conditional Direction of Travel: e.g., a road that is one-way in one direction at certain days/times but the other direction (or two-way) at other days/times.
- Conditional Access Characteristics: e.g., a road that is accessible by cars at certain days/times but not other days/times. This can be applied to any vehicle type supported in the database.

The database provides flexibility in the way that the validity periods for conditional attributes are specified. There are several alternate methods for specifying dates, to meet international needs, but the most significant methods for EDMap are:

- Day of week (e.g., "Every Monday, Wednesday, and Friday")
- Day of week of month (e.g., "1st Tuesday of every month")
- Day of month (e.g., "5th day of every month")

These can be accompanied by a time range which further qualifies the condition, e.g., "10:00 A.M. to 4:00 P.M."

Furthermore, conditional coding also enables direction of travel to be dependent on vehicle type regardless of time/day. For example, a road may be accessible to all vehicle types, but is one-way for all vehicles except buses. This may have, but does not require, a time/day qualifier.

Road-to-road restrictions, such as turn restrictions and gates, can also be applied to all vehicle types, or a subset of vehicle types. These can also be applied on a time-dependent and date-dependent basis as well as full-time. For example:

- "No Left Turn" (all vehicles, all times).
- "No Left Turn, Monday-Friday 4:00-6:00 P.M" (all vehicles, certain times).
- "No Left Turn, except for buses" (certain vehicles, all times).
- "No Left Turn, Monday-Friday 4:00-6:00 P.M., except for buses" (certain vehicles, certain times).
- Conditional attributes as described here were not present in the EDMap test databases.

B.5.2 Near-term Database

The near-term database is intended to support near-term EDMap applications: Curve Speed Assistant (Warning), Stop Sign Assistant (Warning), and Speed Limit Assistant (Advisory).

B.5.2.1 Near-term Position Accuracy

In the near-term EDMap databases, the most stringent requirements for positional accuracy are absolute accuracy of ±5 m, relative accuracy of ±1 m, and heading to within 2 degrees. All the near-term applications' requirements for position accuracy are met by the current DGPS field-collected specification, where it is applied. (There are several new data attributes that must be defined and collected; see sections below.)

B.5.2.2 Near-term Curvature

The near-term applications require that curvature has at most a 10% curvature error, and curves must be "fair."

Curvature was not a previously supported NAVTEQ data attribute; some customers compute curvature based on the supplied data points. To support the near-term database requirements, the databases were enhanced to provide curvature parameters to facilitate derivation of curvature.

B.5.2.3 Other Near-term Mapplets

B.5.2.3.1 Improvements to Existing Data Elements

One of the mapplets required by near-term EDMap applications, Speed Limit, is similar to the Speed Limit in the existing NAVTEQ DGPS field collection process. The only difference is the positional accuracy specification (the point at which Speed Limits change or advisories begin); the EDMap applications require ±5 m, while the current DGPS field collection specification is ±20 m.

The NAVTEQ DGPS field collection process has some special exceptions to the positional accuracy rules, such as extending the extent of a speed zone to the start of a road segment when the speed limit sign is visible at an intersection but more than 20 m from the intersection. These exceptions are appropriate to the EDMap applications as well.

B.5.2.3.2 New Data Elements

Most of the mapplets required by near-term EDMap applications were not part of any previous NAVTEQ database specification. These include road condition, road grade, road surface type, stopping location, stop sign locations, superelevation, and yield sign locations.

The underlying data model was amended to support each of these new attributes, and the data was collected. The addition and collection of these data attributes with the given requirements were largely compatible with the fundamental software and database architecture already used and supported by NAVTEQ.

B.5.3 Mid-term Database

The mid-term database supports mid-term EDMap applications: Curve Speed Assistant (Control), Forward Collision Warning, Lane Following Assistant (Warning), Stop Sign Assistant (Control), and Traffic Signal Assistant (Warning).

B.5.3.1 Mid-term Position Accuracy

In the mid-term and long-term databases, position data refers to lane-level (not road-level) geometry. Lane-level modeling was a key requirement for all these applications, and required significant changes to the data model, digitizing rules, validation rules, and tools.

Probe vehicle data, which is not expected to be available on a commercial scale in the near-term timeframe, may become a key source for mid-term databases in the commercial timeframe. NAVTEQ generated a large amount of probe data in the test map areas, but the data ultimately was not suitable for creation of lane-level maps.

In the mid-term EDMap databases, the most stringent accuracy requirements for positional accuracy are an absolute accuracy requirement of 0.3 m (for the Lane Following Assistant and Stop Sign Assistant), then 0.5 m (for Forward Collision Warning). This requires higher-precision and higher-accuracy data points than previously supported. The existing unit size of 0.00001° was too large and was replaced with a finer precision (0.0000001°). The Curve Speed Assistant's required positional accuracy (3 m) is the only mid-term application that could conceivably be met with the 0.00001° data model; however, its curvature requirements (discussed below) precluded that possibility.

B.5.3.2 Mid-term Curvature Requirements

The Curve Speed Assistant expects "fair" curves, with less than 5% curvature error. Forward Collision Warning, while not dictating a specific curvature requirement, needs to have curvature as an accessible attribute.

B.5.3.3 Other Mid-term Mapplets

B.5.3.3.1 Improvements to Existing Data Elements

Some of the mapplets required by mid-term EDMap applications were similar to data elements in the existing NAVTEQ database specifications. These include lane direction, number of lanes, ramps, and road class.

B.5.3.3.2 Extension of Near-term Data Elements

All of the mapplets required by near-term EDMap applications were also required by the mid-term applications. The requirements for road grade, stop sign location, and yield sign location were the same for near-term and mid-term. For the remaining near-term mapplets, the requirement was more stringent for the mid-term databases.

Superelevation was applied on a per-road basis (not per-lane), as in the near-term databases. However, the mid-term specifications were more stringent; rather than a qualitative value (banked properly, not banked, banked improperly), the mid-term Curve Speed Assistant application required a quantitative superelevation measurement with 3% increments.

B.5.3.3.3 New Data Elements

The remaining mapplets required by mid-term EDMap applications were not part of any previous NAVTEQ database specification, nor were they implemented for near-term applications. These include intersection geometry, intersection location, lane marking types, lane width, railroad crossing information, roadside barriers, shoulder type, shoulder width, stationary roadside objects, stationary overhead structures, and traffic signal locations.

The underlying data model was amended to support each of these new attributes. Unlike the new near-term data elements, the addition and collection of most of these data attributes with the given requirements were not compatible with the fundamental software and database architecture currently used and supported by NAVTEQ; new techniques were necessary.

B.5.4 Long-term Database

The long-term database is intended to support long-term EDMap applications: Forward Collision Avoidance (Control), Intersection Collision Avoidance (Control), Lane Following Assistant (Control), and Lateral and Longitudinal Control.

For the most part, the map database requirements that have been determined for the long-term applications are similar to those for the mid-term applications. The differences can be summarized as follows:

- Positional accuracy improves from 0.3 m to 0.2 m.
- Lane Width accuracy improves from 0.3 m to 0.2 m.
- Superelevation accuracy improves to 2% accuracy in 2% steps (from 3% in mid-term).
- Intersection Lane Geometry is required to 0.3 m absolute accuracy (this refers to the lane-to-lane vehicle paths within an intersection).
- Road Surface Type is required in 5 m sub-segments, with 1 m accuracy, at all locations. In mid-term, this requirement exists within 200 feet (61 m) of a stop sign, but 10 m sub-segments and 5 m accuracy elsewhere.

While these requirements are only marginally different from the mid-term requirements, the long-term timeframe should present opportunities for better and more cost-effective data acquisition.

In the long-term timeframe, there is higher probability that a nationwide two centimeter positioning solution may be available, which would make the target accuracies much more achievable with mobile mapping and probe vehicle approaches.

Remote sensing sources will be higher quality and with broader coverage. IFSAR-based and Lidar-based imagery may be more affordable and more generally available. Satellite imagery, currently of too coarse a resolution to be useful for building lane-level EDMap databases, may become viable.

Probe vehicle data will be more plentiful and with richer content. In the mid-term timeframe, probe data had been hoped to provide basic two-dimensional geometry at a lane level, optimistically with three-dimensional components (pitch, roll), all taken from DGPS sensors. In the long-term timeframe, it is possible that probe data will be based on INS-equipped vehicles and augmented by vision systems that can recognize traffic signals, signs, and lane markings (both to report on the markings themselves and to compensate for off-center lane traces). Other vehicle sensor data (turn signals, radar reflections) conceivably may also be part of the probe data stream.

B.6 Demonstration Test Sites

The EDMap database comprises two test sites defined in the Southeast Michigan and the Northern California regions. The main motivation behind the definition of the test site locations is their proximity to OEM facilities (Ford, General Motors, and Toyota Technical Center are based in southeast Michigan, and DaimlerChrysler Research and Technology is based in Palo Alto). In addition, these two sites offer very diverse environments, especially terrain that strongly influences the nature of the road geometry.

B.6.1 Requirements

The objectives of the EDMap project impose the following requirements on the definition of the test sites:

- They must allow for extensive testing of the OEM-developed safety applications in a variety of situations (challenging and otherwise) encountered in everyday driving.
- They must facilitate NAVTEQ's ability to gain experience in map data collection methods that can be scaled to enable the development of enhanced maps for the entire country.
- They must be confined to areas where GPS differential corrections are available.

To meaningfully establish the potential of large-scale deployment of the safety applications and the enhanced maps, the defined test sites should be large in area and in road mileage. In addition, they must comprise roads with an assortment of features, namely:

- Combinations of freeways, ramps, and local streets
- Urban/rural roads
- Paved/unpaved roads
- Curves ranging from sharp to straight, and curve transitions from straight and to straight
- Speed limits and speed limit changes
- Number of lanes and lane widths
- Lane marker colors (white and yellow), type (dashed and solid), and condition (ranging from fresh paint to absent)
- Intersections, T-junctions, and traffic signs and signals
- Stop sign configurations (1-, 2-, 3- and 4-way) (with/without obstructed views)
- Traffic signal configurations (with/without obstructed views)

Apart from the aforementioned situations encountered in normal everyday driving, the OEM-developed, sensor-rich vehicles are expected to experience a variety of challenging circumstances. Roads that introduce such conditions must be included within the test site area. Examples of such conditions are:

- Hilly terrain (to provide winding roads with different levels of road grade)
- Variety of road grades and superelevation
- Multilevel highways

- Roadway objects (e.g., bridge abutments, overpasses, and overhead signs)
- Roadside objects (e.g., guard rails, median walls)
- Tunnels and urban canyons
- Tree cover

The specifics of the test sites were finalized using OEM insights on application development, experience of the NAVTEQ staff, and visual inspection of road maps and topographic maps of the areas under consideration.

B.6.2 Elements of the Test Site

To study the feasibility of scalable map data collection methods, a sufficiently large test area with a variety of desired road features for all road classes ranging from residential roads to freeways must be defined. Rather than defining the entire test area in a single contiguous stretch, it is broken into smaller areas of road concentration in the proximity of the OEM facilities (named tiles) and connecting freeway and non-freeway routes. The EDMap database comprises the following basic elements:

- **Tiles:** A tile comprises all the roads within a boundary. It includes the roads defined by NAVTEQ functional classes 1 to 5 (for definitions, see Appendix 2.6: NAVTEQ Functional Classes).
- **Tiles with principal roads:** This element consists of arterial roads defined by NAVTEQ functional classes 1 to 4. In other words, it includes all the roads contained in the tile boundaries excluding the NAVTEQ functional class 5 roads, which are typically low volume residential roads. This is a special case of a tile (defined above) that will be used in the Michigan test site. These special tiles were included to capture country roads and winding roads.
- **Swaths:** A swath comprises all the arterial roads defined by the NAVTEQ functional classes 1 to 4. The swath was defined to include interesting situations that do not occur within the tiles, and to form non-freeway routes to connect the tiles.
- **Routes:** Routes are broadly classified into freeway systems and non-freeway routes. The freeway system is defined as the freeway, including its ramps and service drives.

B.6.3 Southeast Michigan Test Site

The southeast Michigan road-level test site is shown in Figure B-48. This site has four tiles localized at each of the base station locations to maintain proximity with the CAMP and OEM facilities. In addition, a tile in the downtown Detroit area and two relatively large tiles with principal roads in the proximity of CAMP and Ann Arbor have been defined to capture special features not available in the other tiles. The Southfield Freeway (M-39), M-14, M-10, I-696, I-275, and I-96 serve as the main connectors between the various tiles, and the two swaths along I-696 and M-39 allow additional non-freeway connectors between a few tiles. Apart from the main connectors, several other freeway (depicted in blue color) and non-freeway (depicted in green color) routes have been developed to facilitate travel to and from tiles to enable exercising the safety applications and the map data collection methods in diverse situations.

The delivered content of the southeast Michigan lane-level test site is shown in Figure B-49. This was modified significantly from the road-level test site (Figure B-48) to meet schedule and budgetary constraints as more experience was gained in the map collection and editing methods. However, care was taken to ensure that these modifications did not compromise the overall goals of meaningful testing of safety applications and the estimation of the effort that would be required to develop such maps beyond the regions specified in this test site.

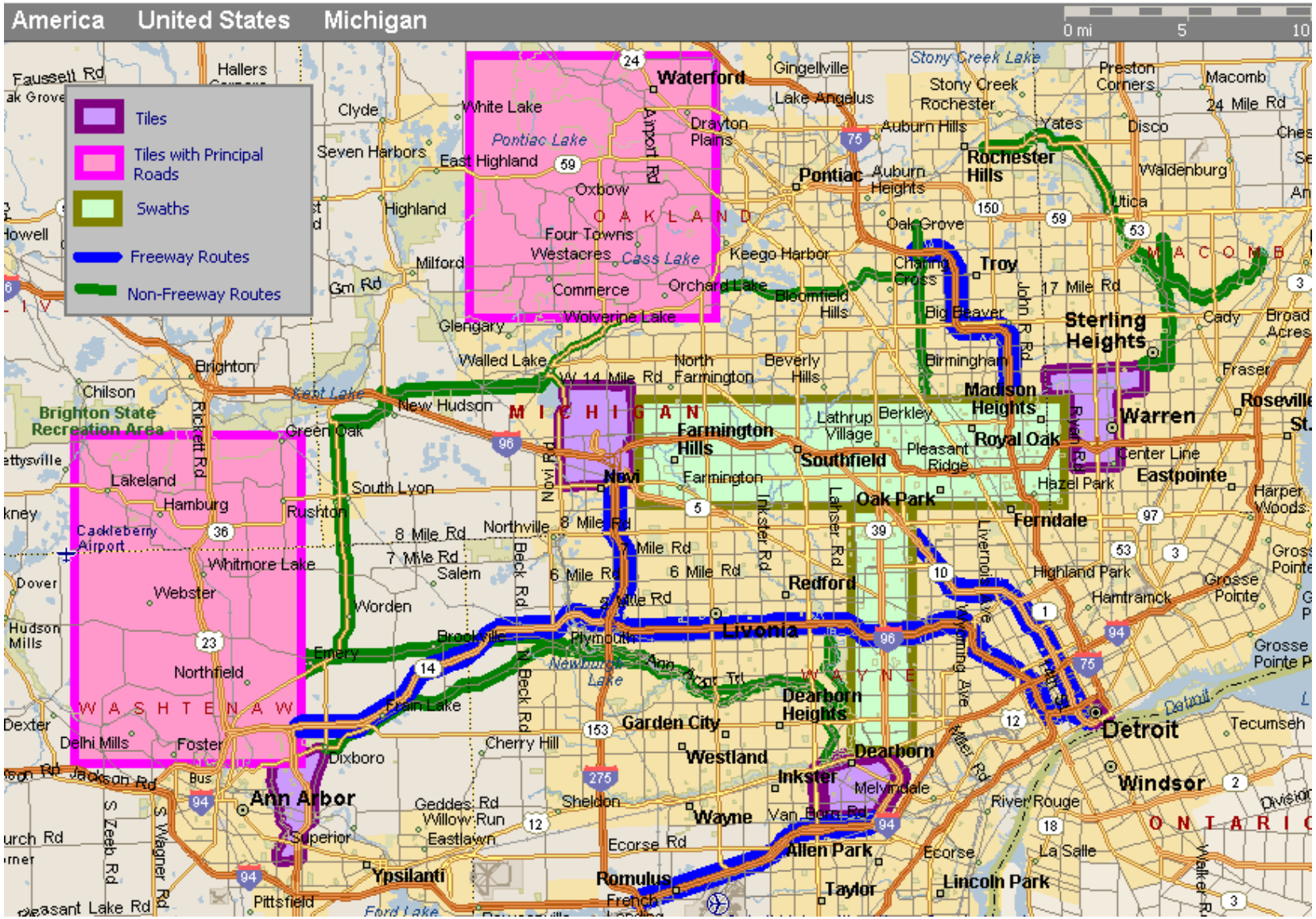

Figure B-48: Southeast Michigan road-level test site

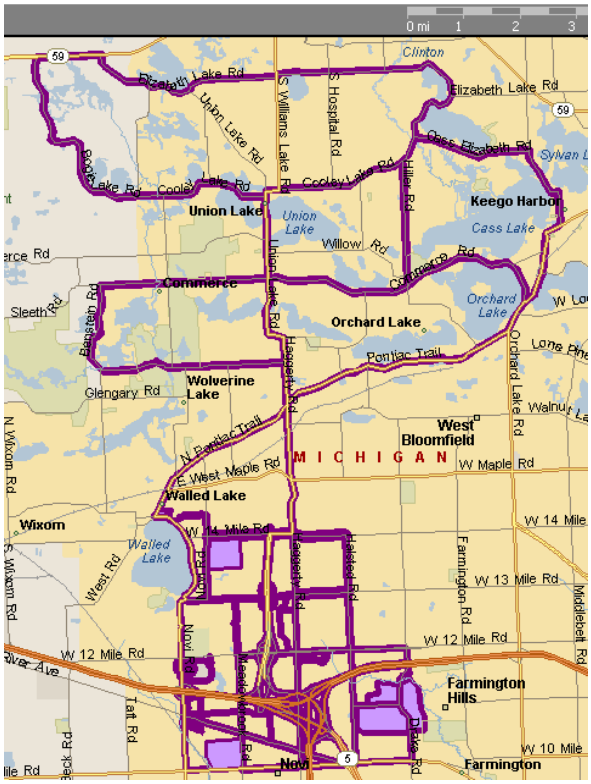

Figure B-49: Southeast Michigan lane-level test site

B.6.4 North California Test Site

The North California road-level (Figure B-50) and lane-level test sites (Figure B-51) have several smaller tiles (marked by lavender-colored areas) located close to the DaimlerChrysler Research and Technology Center in Palo Alto. This region is different from the Southeast Michigan test site in that the area in the vicinity of the DaimlerChrysler facility is rich with examples for almost every application, thereby obviating the need for swaths. In addition to these tiles, a set of routes defined by freeways and non-freeway road sections has been developed to include a variety of normal as well as challenging situations encountered in driving. This site includes most of the features required by all of the applications and has a relatively large number of miles of winding and hilly roads (not present in the Michigan test site) offered by its terrain.

The main routes in the road-level and lane-level test sites include sections of the I-280 and US-101 freeways and their associated ramps (depicted using blue color), and other local roads (depicted in purple color) in the Palo Alto area. The road-level test site (Figure B-50) includes additional non-freeway routes in the form of Skyline Boulevard (CA-35), Page Mill Rd., Alpine Rd., and Sand Hill Rd. that are located on a winding and hilly terrain, and are characterized by significant curvature and grade changes. Skyline Boulevard passes through a forest and is lined by tall trees on either side in close proximity to the road, and offers challenges to the vehicle positioning system.

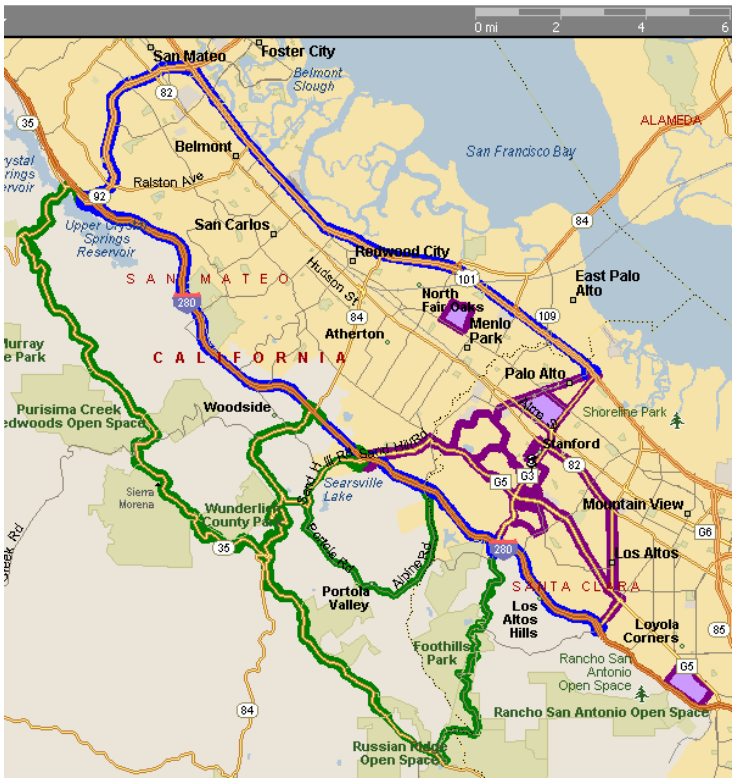

Figure B-50: California road-level test site

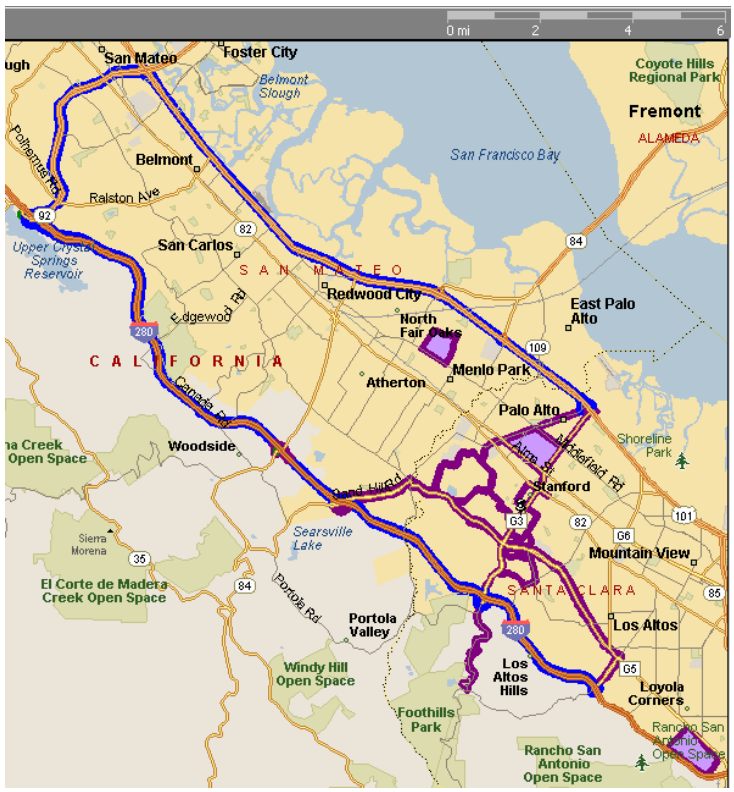

Figure B-51: California lane-level test site

Appendix C: Task 4 - Data Collection and Mapping

C.1 Mobile Mapping

Mobile mapping is one of the primary methods of data collection for EDMap databases. Limitations in other methods to collect all the relevant attributes makes it necessary to drive the roads to ensure that all the required attributes are collected. These include location of speed limits, traffic lights, travel restrictions, lane border type, etc. Hence, mobile mapping is an important method to understand when considering the feasibility and scalability of collecting and building EDMap quality databases

The following sections discuss the different subsystems considered for mobile mapping data collection, their characteristics, and their ability in use in a scalable deployment. This Appendix also discusses the tools developed to process the data collected from these subsystems.

C.1.1 Definition of Terms

DMI	Distance Measurement Indicator
GAMS	GPS Azimuth Measurement System (Applanix System)
GPS	Global Positioning Systems
IFSAR	InterFerometric Synthetic Aperture Radar
IMU	Inertial Measurement Unit
INS	Inertial navigation system
LIDAR	LIght Detection And Ranging
PPS	Pulse Per Second (an output from GPS receivers that indicates the rollover of a whole second on the GPS clock)
RT	Real-time
RTK	Real Time Kinematic
WAAS	Wide Area Augmentation System

C.1.2 Positioning Technology – Overview

C.1.2.1 GPS Systems

Positional accuracy is a fundamental component in a spatial database. The choice of positioning device and technology determines the quality of the database product. Ever since Selective Availability (SA) was turned off by the US Department of Defense, the positional accuracy of a standard low cost GPS receiver has improved. Advances in GPS device technology and reduction in prices offers a variety of choices for the positioning device. As part of the EDMap project, a select set of GPS receivers and correction services for experimentation was chosen. These devices were selected based on availability of products, their cost, and their ease of use in a mobile mapping environment.

The following table shows current lower and upper accuracy limits of GPS technologies in the kinematic and real-time operation.

Table C-1: Synopsis of Modern GPS Technologies Capability

Method	Data type	Distance (kms)	DGPS Service	Receiver Cost	Accuracy (m)	Vulnerability
Absolute or Point Positioning	Code	NA	NA	All	5 -10	Low
Relative or Differential Positioning	Code	0 - 100	WAAS/ DGPS	Medium/Low	0.5 - 5	High
	Code/Phase	< 20	OTF	High	0.05 - 0.5	High
	Code/Phase	< 10	RTK	High	< 0.05	Highest

The WAAS differential correction service is available throughout North America and is free of cost. There are also private differential correction service providers that transmit code-based differential correction service. The choice of correction service depends on the type of receiver used. Both WAAS and the subscription-based differential service result in approximately 1 to 2 m of absolute positioning accuracy. Such positioning accuracy is suitable for creating road-level database. Code/phase differential correction service offers very high position accuracy and is used for creating lane-level database. This is transmitted by a number of correction service provider vendors. Irrespective of the quality of the GPS receiver, positioning from a standalone GPS receiver is vulnerable to tree coverage, bridges, tunnels, and other multi-path conditions in urban canyons. The following figures show a sample data where GPS data quality is good and where it is at its worst.

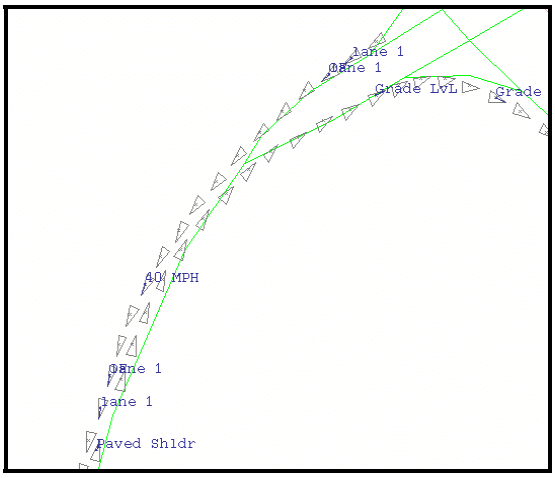

Figure C-1: Typical DGPS coverage

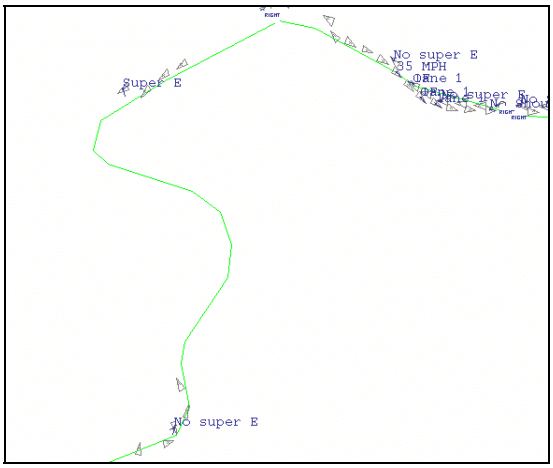

Figure C-2: Example of poor GPS coverage area

C.1.2.2 GPS / INS systems

Although GPS measurements can be sampled at higher than 1 Hz to get closely spaced points of trajectory, a number of other factors influence GPS reception that can cause data gaps and deterioration in accuracy. Some of those effects are due to the satellite constellation, the visible number of satellites, the type of GPS receiver used, observation types, data-gaps due to cycle slips, signal blockages, and the algorithms used for getting the positions (RT, post-processing, etc.). An example of poor GPS reception is shown in Figure C-3. As evident from this figure, the discontinuities in positioning impedes both database creation and application use. Because GPS cannot provide complete continuity, its integrity and accuracy cannot be taken for granted.

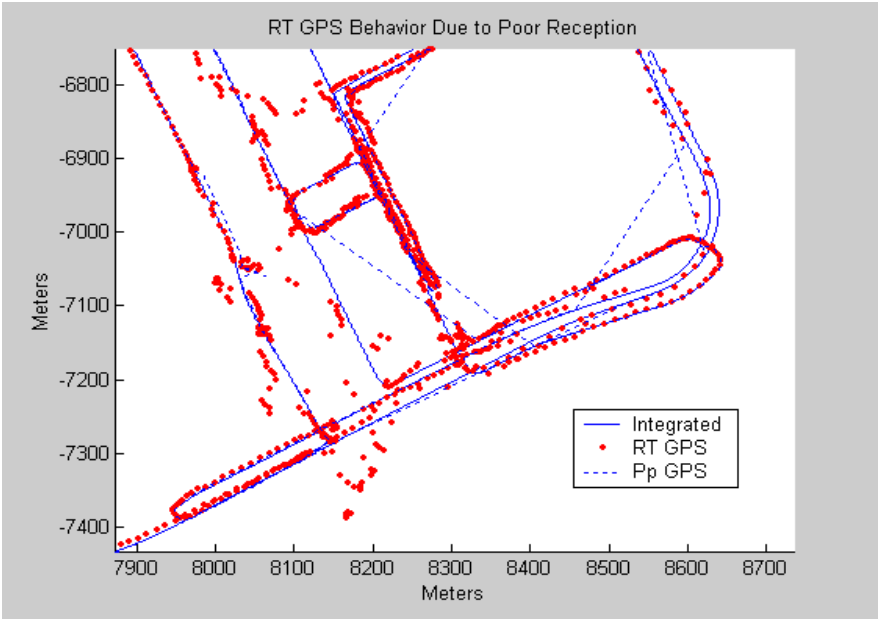

Figure C-3: An example of poor GPS reception (RT – real time, Pp – Post-processed)

To overcome these weaknesses, GPS is typically augmented with IMU sensors. Although this adds increased cost and system complexities, this integration of GPS and IMU data provides the required positioning continuity. For capturing road geometry, kinematic (D)GPS with or without INS system on board a vehicle is now a standard and widely used method.

Similar to GPS system, there is a wide range of choices in using IMU sensors of different precision and configuration. These sensors can be 2-D sensors or 3-D sensors. A simple gyro with an odometer falls in the low-end spectrum of IMUs, while the expensive Litton 100G units fall under the high-end units. It is also possible to do in-house custom development of a GPS-INS system to meet specific requirements. While this approach would be desirable in some cases, due to the expertise, maintenance, and deployment issues, it was decided to identify vendors with GPS/INS systems that meet program requirements. The need for different type of system configurations led to experimentation with a few commercially available systems of different quality.

The overall accuracy of the integrated system primarily relies on GPS accuracy and the type of the integration. Also, the accuracy varies based on the type of processing used to fuse GPS and INS data. The fusion can be done in real-time or in post processing. Real-time fusion requires continuous reception of correction information from a base station, while post processing is performed in the lab after collecting raw data. There are two types of post processing techniques - loosely coupled integration and tightly coupled integration. Theoretically, tightly coupled integration provides a higher degree of accuracy as it offers the possibility to identify and isolate gross errors and ambiguities.

C.1.2.3 Vision Systems

Vision systems are a useful aid for verifying data collected from positioning systems. Images collected during mobile mapping can be used for automatic extraction of geometry and attributes, and validating the information collected during driving. Vision systems are also an essential requirement for collecting lane level attributes. Advances in image processing and camera technology have enabled automatic lane detection and automatic sign recognition to be used in data collection systems. The use of this technology and the lessons learned in using these for data collection are discussed in later sections of this report.

C.1.3 Positioning Systems

This Appendix discusses the subsystems experimented in building EDMap's mobile mapping data collection system and describes how the systems outlined above are combined for the EDMap mapping system. This Appendix also discusses experience gained in using base stations, DGPS receivers (Satloc and Omnistar), IMUs (iMAR and PerformTech), and High-accuracy GPS receivers (Applanix and Honeywell).

C.1.3.1 Base Station

Base stations are stationary, high accuracy GPS receivers. Reference data collected from base stations is used for real-time corrections and/or post-processing. NAVTEQ's base station consists of an OEM 4 bases NovAtel receiver. Initially, the base stations were used only for the post processing of data and RTK capabilities were added later. A GSM cell phone was used to deliver the base station measurements to remote receivers. The base station setup described below is for the Chicago area work that NAVTEQ did when developing the required mobile mapping systems.

In order to achieve high accuracy positioning, it is required to have base stations within a distance of 20 miles. This calls for large number of base station installations throughout the nation. This is one of the important issues to be considered for scalability. The need for wireless connection

from the base station or ability to transfer base station data on a daily basis for post processing, pose challenges to collecting high accuracy geometry using mobile mapping. These necessitate the need for infrastructural support from the Government for high accuracy differential corrections.

C.1.3.2 Differential GPS Receivers

Two types of differential GPS receivers were used in our experiments in testing their accuracy for road-level database creation. One of them was from Satloc and the other was from Omnistar. Both these receivers accept cod-differential corrections and deliver similar position accuracy. They differ only in the type of correction service used. Both of these devices are compact and low power devices. These units require a 12-volt source for power and provide NMEA output. The units utilize similar antennas that magnetically mount to the roof of the vehicle. Both of these systems have support software for configuration and diagnostics.

The SATLOC receiver utilizes the WAAS differential corrections. A satellite broadcasts this correction over the entire United States. The NMEA output port can be configured to send the messages at either 4800 or 9600 baud.

The Omnistar receiver requires a subscription for differential service in order to improve accuracy. Contacting the subscription agency with the receiver serial number does activation of the service. The service then sends an authorization over the satellite channel to your receiver and enables the differential operation. Then the unit begins to download the ephemeris data. It takes up to a maximum of 30 minutes to get this data received by the Omnistar receiver. During the time the unit must be in clear view of the southern sky.

The Omnistar software View3200 has better functionality over the SATLOC SLXMON tool. Omnistar also supports selection of specific NMEA messages to control the amount of data transmitted. Omnistar also supports a wide range baud rates compared to Satloc.

C.1.3.3 INS Systems

This section discusses the results of experiments on two different types of INS systems. The INS systems that work with external DGPS receivers and deliver position information in real-time were chosen for our experiments. These were used only for creating road-level databases. In addition to system specifications and performance, they also differed considerably in price.

INS #1

This INS system consists of the following components:

- A system unit that contains the inertial unit and the computing system for data fusion with speed pulse, IMU, and (D)GPS.
- An external differential GPS unit, such as the OmniSTAR
- A speed pulse sensor that mounts on the inside of a wheel

The unit must be mounted securely to ensure that the INS sensors work properly. The unit must also have conditioned power. The system output can be configured to send out NMEA messages that have fused positions with DGPS and IMU. The data rate can be anywhere from 1 Hz to 10 Hz. The system also supports recording raw data and post processing this data later.

INS #2

The commercial version of this system uses an internal GPS receiver (Garmin) and an inertial sensor. The system is designed to accept the vehicle speed pulse and delivers an INS solution at 1 Hz rate. For our application, this system was customized to work with an external DGPS receiver and the interface messages were customized to suit integration with our data collection system.

The inertial sensor consists of an acceleration sensor and two vibration gyros (for yaw and pitch). The accuracies of these gyros are specified as less than 3 degrees. The system outputs the fused position as NMEA message at 1 Hz rate.

C.1.4 High Accuracy Position Systems

This section discusses our experiments with two high-accuracy positioning systems. These systems deliver submeter-positioning accuracy and are used for creating lane level databases. The high cost of these units is expected to reduce over time and increased volume.

C.1.4.1 Applanix

Description

Applanix POS LV420 is a state of the art, high-end positioning system from the industry leader, Applanix Inc. Applanix POS LV 420 consists of three fiber optic gyroscopes and three MEMS accelerometers configured in three orthogonal directions and parallel to each other, two GPS systems - primary (L1/L2) and secondary (L1 only), - and a Distance Measuring Instrument (DMI). Its firmware supports RTK-solution and real-time INS solution. It is a powerful system for its quality and reliability. Table C-2 (www.applanix.com) lists its capability for accuracy (in meters) under different GPS outage conditions.

Table C-2 : Applanix accuracy – GPS outage conditions

0 sec.			15 sec.			30 sec.			60 sec.			120 sec		
IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DPGS	IARTK	PP	DGPS
0.035	0.02	1.0	0.07	0.05	1.13	0.13	0.07	1.25	0.20	0.12	1.5	0.30	0.27	1.63

IARTK	Inertially-Aided RTK (for short distance, say < 10 kms)
PP	Post-processed
DGPS	Real-time Code DGPS

This unit is used as a primary system to collect high quality data and also to verify results from other positioning systems of lower quality. We have collected data under different conditions and evaluated this system to confirm its stated quality and understand its behavior under challenging conditions. Some of our experiments and results are explained under the data quality analysis section.

The system consists of the following components:

- A 2U rack mountable main processing unit with 2 internal GPS receivers
- An inertial unit that must be rigidly mounted
- A wheel mounted distance measurement instrument (DMI)
- Two GPS antennas to be roof mounted and separated by about 1.5 meters

To use the unit in RTK mode, one must also have a base station located within a short vicinity of survey location, and real-time data transmission system. If RTK is not feasible, it is possible to generate high accuracy measurements using post-processing. Real-time GPS solution and tightly coupled integrated solutions are available in all cases.

Operational Difficulties

While the Applanix system has largely been reliable, it does have some difficulties in operation.

It is estimated that the up time of this device to be 90 percent. Some down time has resulted from the following problem areas:

- DMI is fragile and poorly located, it has broken several times
- Upgrading the unit to new receivers and software was time consuming.

The DMI is a fragile unit. It is mounted off the driver side rear wheel. The mounting utilizes an aluminum plate and standoff bolts. The sensor itself is an electro-optical sensor that has 1024 pulses per revolution of the wheel. During the past year, three different type of traffic accidents resulted in physical damages to DMI.

Scalability

The Applanix system is not scalable for deployment in the field. In addition to its high costs, the external DMI is a big overhead in deployment and maintenance. The system also requires technical expertise for use and maintenance of this system. The system is a high end, complex system that is difficult for day-to-day operational use by field staff. The system can be used to bench mark other systems and can also be used to map areas where other systems fail.

C.1.5 Lane Keeping Systems

Lane keeping systems recognizes the lane markers and generates warning messages to the vehicle computer whenever the vehicle crosses the lane markers. These system uses a camera to detect the lane marker and computes lane parameters in real-time. These parameters include lane width and lane marker types. Some of these systems are also capable of recognizing current and adjacent lane parameters. A lane keeping system (LKS) and enhanced it with GPS input for time synchronization was used. The combination of GPS time stamp and lane attributes was used to create accurate lane-level geometry. Lane attributes-derived LKS system helped in correcting errors due to driver drift in deriving lane geometry.

The system also records video images captured from its camera. The frame rate at which the images are recorded can be controlled with a set of configuration parameters to optimize the number of images recorded.

C.1.6 Road Sign Recognition System

Road Sign Recognition System (RSR) is a vision system that automatically detects, recognizes, and localizes road signs. RSR includes a multi-spectral video camera and IR illuminator. The IR illuminator is used to detect potential road signs. The camera and the illuminator are mounted on the vehicle roof and are connected to an industrial rack-mount PC located inside the vehicle. A digital VTR records the video on digital videotape.

After the data collection, the tapes are played back with the VDR software in order to capture the video sequences of the detected road signs. The video files are linked to the GPS log file to get position of the traffic signs.

All video sequences are then analyzed by the recognition software (RSR). This software identifies the detected road signs from a user-defined database. It eliminates all false targets during this process. Under ideal conditions, the recognition rate is expected to be higher than 90%.

C.1.7 Additional Sensors/Input Devices

C.1.7.1 Barometer

Handheld barometer units used to measure atmospheric pressure can also be used to measure altitude. One such barometer with an RS232C interface was used in our experiments. The unit measures pressure to an accuracy of 0.0005 in Hg and outputs altitude in meters or feet.

C.1.7.2 Mobile Plotting

Mobile plotting is an established technique in NAVTEQ for capturing database attributes during mobile mapping. This is an add-on to the data collection software and enables registering the attributes at specific locations. For example, the field staff will be able to capture the location of a speed limit by press of a button as they are driving along the road. The position information (lat/long) and the speed limit attribute will be recorded in a file. Each attribute is coded to a unique number and will be interpreted by the data edit tool accordingly.

C.2 Probe Data

Probe data in very simple terms is the concept of using data from vehicles as the vehicles drive around in order to build maps and map information. Those vehicles will have to be enabled with appropriate equipment that will record and deliver necessary information. The map builder will require methods to receive the information and methods to process the raw vehicle information and transform the information into useful map information.

A discussion of terminology follows for clarity in this section. Probe data is gathered from probe vehicles. The probe vehicles are equipped with appropriate hardware that enables them to collect information such as location, speed, bearing, and more. This collected information is referred to as the "probe data" from the vehicles. Typically, the term “probe vehicle” refers to a vehicle that is intended for use in a large collection of vehicles to build up probe data over time. Building the probe data over time, in theory, yields information useable for map building that may otherwise be difficult to collect.

For example, hundreds of vehicles traversing a road segment would yield the shape of the road, the speed, and more. The notion of many vehicles helps separate probe vehicles from other forms of collection such as mobile mapping. Mobile mapping relies on vehicles specifically equipped to map roads. Generally, the mobile mapping technique differs from the probe vehicle technique of building map data in three key areas:

- Mobile mapping uses higher accuracy equipment, which typically costs more.
- Mobile mapping targets minimal driving to collect data whereas probe concepts rely on many passes of road segments.
- Mobile mapping typically employs drivers whose purpose is to map roads whereas probe data relies on drivers passively collecting data useful to build maps.

The probe data evaluation studies the technical feasibility and the potential of using probe data to enhance the EDMap database. The database enhancements may come in the form of additional attributes that can be gathered (or gathered more efficiently) using probe data over other map building methods. Additionally, the database enhancements might come in the form of more efficient data collection methods, faster map building, or higher quality map building.

The term probe data is used to describe data collected from numerous “probe devices". The probe devices are also referred to as "probe boxes", devices inside of a vehicle for purposes of probe collection.

Other devices such as a cell phone, a device not intended for probe collection, could be used for probe data collection. The various types of devices are discussed in the section on probe hardware.

"Probe data collection" is any means of gathering any road network-related attribute by causing mobile users to passively reveal their location and/or velocity to a central processing resource.

Many aspects of the probe analysis project will focus on both road-level and lane-level geometry and attributing. However, road- level analysis generally occurs first and then the analysis extends into lane-level analysis.

This section deals with the hardware and processing that occurs specifically for probe data. Some aspects of this project deal with both probe data and non-probe data:

- Curve fitting (fitting a road segment through a set of raw data)
- Curvature algorithms (maintaining smoothness)
- Curve fitting metrics (measuring a fitted data set)

The topics that address more than just probe data are dealt with in the section on curve fitting, The terms "geometry" and "attribute" are sometimes used in the process of using probe data to build maps. Probe data can be used to derive the shape of roads, i.e., the geometry, and can also be used to derive information about the roads, i.e., the attributes for the road.

The following image should give a quick understanding of probe data. The image shows a high level view on the EDMap test area with probe data overlayed onto the map (left portion of image). Two images at differing levels of zoom are also shown (outlined in red border and green border on right).

Figure C-4: Probe data on map of EDMap test area

C.2.1 Overview

A diagram representing how probe data fits into the EDMap database is shown below. The general approach to using the probe data for building portions of the database has been to have the probe data-derived map information appear identical to other derived map information. The probe data project uses processing that creates map information that seamlessly integrates into the EDMap database and appears identical to mobile mapping data. Of course, accuracy may vary when different methods are used to build map information, as discussed later. The goal is to determine in which circumstances probe data collection is the most reliable or easiest map

information method, and whether certain attributes of the EDMap database could best be built from other methods.

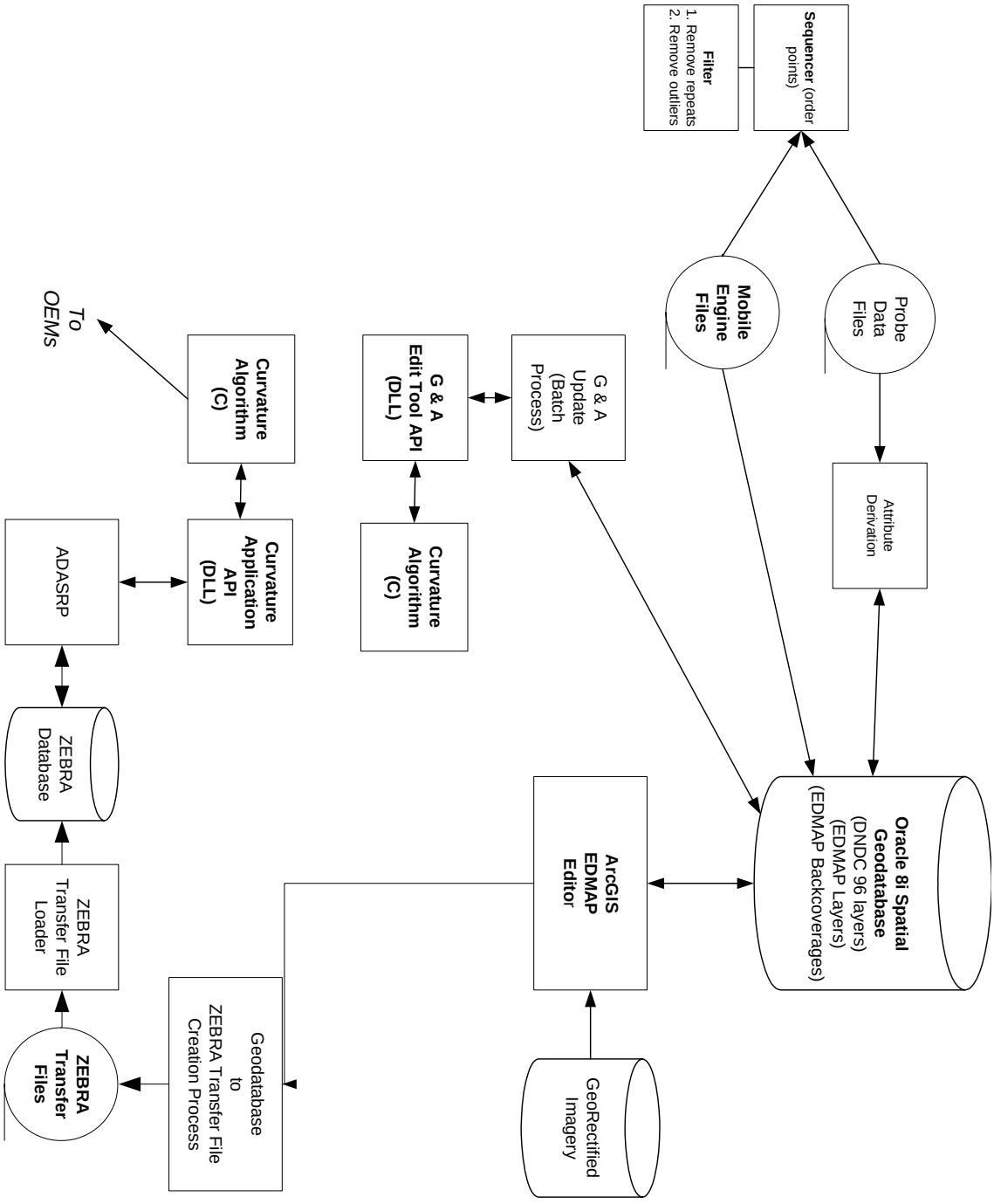

Figure C-5: EDMap database – probe data

C.2.2 Input Data

One of the work packages used gathers knowledge on the topics related to the input side of probe data. The input side of probe data includes the types of hardware, types of drivers, and the set of driving rules used to collect the data.

C.2.2.1 Various Hardware

A variety of hardware exists for gathering probe data. There are two general categories for probe collection hardware: active units and passive units.

Hardware intended for use with collecting data for probe usage is called an "active unit", e.g., commercial tracking boxes. Hardware intended for a separate primary purpose, but which can be used to collect probe data is called a "passive unit", e.g., cell phone. In other words, a cell phone would be in a vehicle for the purpose of providing communication, but collecting location information from the phone could be a means to collect probe data. No passive units were investigated in the EDMap probe analysis project.

The hardware used to collect the probe data plays a role in the analysis of the data. The accuracy of the equipment, e.g., 15 m, the frequency of data. e.g., 1 data point per second, and the amount of noise in the data are all examples of characteristics that affect the probe analysis.

For this project, a set of hardware devices has been identified for use or possible use in the collection of probe data.

Unit 1

The first unit has internal memory storage. The EDMap probe project recorded a data point once every second. National Marine Electronics Association (NMEA) 0183-formatted sentences were gathered.

The unit records the driving data on-board in memory. Thus, it must be removed from the vehicles for data downloading. The data downloading occurs daily and then the device is reset for use the next day. Downloading 8 hours of driving data requires approximately 10 minutes. Daily checking of data reduced the potential of wasted effort due to broken or non-functioning units.

Device Performance

- Receiver architecture 12 parallel channels, tracking and using up to 12 satellites
- Acquisition time 18 sec. typical (warm start)
- Position accuracy: 15 m
- Update rate: 1 sec. continuous
- Dynamics: Up to 50 m/s^2 (logging sustained)
- Power Supply: RS-232 5V, with reverse protection
- Power Consumption 105mA @ 5V
- Baud Rate: 4800bps
- Signal: 8N1

GPS Interface Capability

- Output protocol: NMEA 0183
- Standard output sentences GGA (GPS Position and Time)
- ZDA (Time and Date)
- VTG (Course and Speed over ground)
- GSV (Satellite Details)
- GLL (Latitude & Longitude)
- RMC (Position, Time, Speed and Course)
- GSA (Receiver Status and DOPs)
- Logger Interval RMC (01 sec.)

Unit 2

The second GPS unit has a built-in modem as well as a compact flash card memory slot for downloading data. The compact flash card records up to 6 months of driving data.

The units are not currently used in the real-time delivery mode due to constraints that include: wireless cost and bandwidth. However, the probe project is using the capability of this unit to use the compact flash card. In our implementation, about three days' worth of driving data is recorded to the compact flash card before downloading. Again, the three days' time frame is based on not wanting to lose too much data if things go wrong rather than a limitation of the hardware. The hardware is capable of recording six months' worth of driving data onto a compact flash card.

This unit has the easiest method to download the data as the unit writes to the compact flash card in DOS format. So the compact flash card needs only to be inserted into a card reader, and the file copied/pasted in order to use it.

Unit 3

The third unit is ideal for "plug and play" applications. Its power consumption is <1.5 W. The data protocol used for this project is the NMEA version.

This unit is not stand-alone (as are the other devices used in the probe project) in that it requires a connection to a laptop in order to store the collected data.

Performance Specifications

- General; L1 frequency, C/A code (SPS), 8-channel continuous tracking receiver
- Update rate: 1Hz NMEA
- Accuracy position: 25 m CEP (50%) without S/A
- Acquisition (typical) Cold start: <130 seconds (90%)
- Warm start: <45 seconds (90%)
- Hot start: <20 seconds (90%)

- Cold start requires no initialization. Warm start implies last position; time and almanac are saved by back-up power. Hot start implies ephemeris also saved.
- Reacquisition after signal loss: <2 seconds (90%)

C.2.2.2 Methods to Deliver Data

Probe data can be collected from a number of different devices. But, the probe data needs to get back to a main server for processing at some point. Each of the devices used in the probe project employ a varied technique to store and deliver the data. The following is a short discussion on the varying methods of delivering data.

Wireless

Some units were capable of delivering the probe data wirelessly to a main server once per second. Some experiments were done to determine if less frequent delivery impacted results enough to offset wireless costs.

Since the data can be plucked out of the air while being delivered wirelessly, measures need to be taken to encrypt or otherwise protect the data from eavesdroppers.

To deliver the data wirelessly, though, requires that the unit is in a coverage area. The concept is similar to one's mobile phone – there are times where one is out of coverage. In the case of dropouts, the unit stores the data on the compact flash and can deliver the data once coverage is regained. In the case where the data storage is not available, data loss occurs.

Compact Flash Card

Compact flash cards are readily available in stores everywhere, e.g., digital cameras. A compact flash card is relatively small, but it is larger than the MMC discussed below.

The compact flash cards are very easy to use as they behave like a hard drive when inserted into most computers. One simply collects the data, removes the compact flash from the probe unit, inserts the compact flash into a computer, and treats the data like a file.

Devices using compact flash cards do not have the coverage problems of wireless delivery units. Data is always being recorded on the card. However, the compact flash card must be removed by hand and the data downloaded periodically. The compact flash card must be retrieved and transported to a destination with capability to read the card. In some cases, this could be local, but in other cases, the plan might be to insert a new compact flash card while the filled card is shipped to a main office for processing. This retrieval of cards can be intrusive and prevents the probe units that use these devices from being completely transparent.

Multimedia Card (MMC)

The multimedia card is used mainly for the reason of size (about the size of a postage stamp), but also for slot compatibility with the Secure Digital (SD) card. The SD cards have the advantage of one more level of security for protection of data stored on the card. Security is a fundamental design component of the SD card.

Devices using SD cards do not have the coverage problems of wireless delivery units. Data is always being recorded on the SD card. However, the SD card must be removed by hand and the data downloaded periodically. The SD card must be retrieved and delivered to a destination with capability to read the card. In some cases, this could be

local, but in other cases, the plan might be to insert a new SD card while the filled card is shipped to a main office for processing. This retrieval of cards can be intrusive and prevents the probe units that use these devices from being completely transparent.

Onboard Technology

Other units simply store data onboard the device in persistent memory. At the end of the day, one plugs the unit into a desktop to download the data. There are no cards to insert or remove and thus, less chance of breakage or error. There is also no requirement for cellular coverage. The unit must be moved manually from the vehicle to an area where it can be plugged into a laptop. This may be onsite near the car, but it may also require shipping back to a remote or centralized processing site.

C.2.2.3 Types of Drivers

Different types of drivers have an effect on the attributes and on the methods used to determine attributes. If the probe vehicle fleet was comprised of emergency vehicles, the drivers may not always follow the rules of the road, which could lead to more complex attribute analysis since the data may not characterize "everyday" drivers. A fleet of bus drivers may "stop and go" as well as "hug" the curb; these characteristics would have to be taken into account when extracting road information from the data collected from this type of driver.

Temporary Drivers

In order to simulate the probe data collection from many probe vehicles, drivers were hired to drive a fleet of vehicles around the EDMap test area. An interesting issue was discovered during the test raising the question as to whether they represent the typical driver. The first thing the temporary driver wants to do is follow the rules of the road exactly so as to not get a ticket while driving for someone else; they have been hired to drive so they will be on their best driving behavior. But this does not model reality where, for example, some of the cars will speed, some will move at the speed limit, and others will be move slower than the speed limit.

Fleet Drivers

The analysis of the probe data derived from fleet vehicles should take certain factors into consideration. Fleet drivers have a primary job to do which is most probably not to collect probe data. Driving habits may include fleets that stop often or stop at "non-normal" stopping locations, e.g. a bus fleet or delivery company fleet. Fleets of police vehicles may routinely follow rules of the road that are different from those followed by regular drivers, e.g., police vehicle speed may not represent typical driver speed.

One set of fleet vehicles data was used for analysis even though the drivers were not part of the EDMap project.

C.2.2.4 Driver Rules

One of the goals of the research was to obtain an understanding of the effect that driving rules has on the data. Additionally, another goal was to study driver methods to determine attributes using at least two different sets of driving rules. A driver might be driving "as is", i.e., the driver is an "everyday" driver and is not doing anything special for our use in probe data. Alternatively, the driver might be driving for NAVTEQ and, as such, following a prescribed route with driving rules, e.g., drive each lane at least once, when gathering probe data.

Background

Upon hiring, temporary probe drivers were presented with a short discussion of the concept of probe data. That discussion follows:

"In the not-too-distant future, cars and other vehicles on the roadway will be able to participate in the upkeep of digital road maps, and provide useful information about how traffic is flowing.

Digital road maps are already in use today in applications such as in-car navigation systems such as the Hertz NeverLost, and internet travel applications such as MapQuest or Yahoo! Maps. Today's applications help the driver find a safe, legal and efficient route. Future digital maps and applications will enable improved route selection based on live traffic conditions, cruise controls that adapt to road curves and surrounding traffic, headlights that "aim" around curves, and a whole new generation of safety systems in cars.

Part of the challenge of developing and maintaining these digital maps is to know, as quickly as possible, when roads and traffic patterns change. That's where Probe Vehicles come in.

A 'probe vehicle' is an ordinary vehicle that has been equipped with some special data-gathering equipment, including a Global Positioning Satellite (GPS) receiver, and digital memory. The GPS equipment is capable of determining an exact location on the globe, to within a few feet. This is compared against the known locations of roadways in the digital map.

While this is similar to the data gathering already used in map making, probe vehicle data is characterized by having a large number of passes, with high frequency, with minimal or no driver interaction. Eventually, it is hoped that probe technology will be present on a significant number of vehicles on the road every day.

By careful analysis of the GPS locations traversed by a large number of probe vehicles, we expect to:

- *Be able to refine and improve the road positions in the digital maps, including mapping the individual lanes and intersection traffic patterns*
- *Detect the presence of traffic controls such as traffic signals and stop signs*
- *Determine traffic congestion patterns, in order to provide faster and safer routes.*

This project, called 'Enhanced Digital Maps' or 'EDMap', is research toward developing the next-generation digital maps to enable new safety-oriented applications. Test maps are being created in Michigan and California, in order to develop and test the methods for making advanced digital maps, and the applications that use them.

In selected areas, the probe cars should drive on every street (including side streets, subdivision roads, etc.). In other areas, the focus should be on arterial streets only, as provided."

It was emphasized that drivers should attempt to model reality by driving around the EDMap area in a manner typical of how they normally drive, e.g., they should turn where they normally turn; stop how they normally stop.

Driving Strategy

A goal of probe test-driving is to emulate the behavior of a large number of vehicles driving on the same sections of road. A relatively small number of test cars emulated larger volumes of traffic by having these cars focus on specific test areas.

The drivers were told to follow a set of guidelines:

- Safety first. Observe all traffic laws. Take a break after no more than 2 to 3 hours of driving, and do not exceed 8 hours of test-driving in a day.
- Make an effort to use different lanes when you return to a road driven previously. For example, drive primarily in the right lane (of two) in the morning, but drive primarily in the left lane when you return to the same road in the afternoon.
- Try to vary the routes you take within the test areas. It is valuable to capture not only the specific roads, but also the turning maneuvers at the various intersections, and travel in both directions on two-way roads.
- It is OK to change lanes as needed, such as to pass slower traffic or parked cars.
- It is also OK to go into driveways, parking lots, etc., as you would normally.
- In some cases, it will be necessary to go beyond the boundary of the test area (such as when you're on a freeway). Return to the test area as soon as practical.

The goal of the test-driving was to obtain “real” data that represented what probe data would look like if collected from many actual vehicles. To that end, the request was to have vehicles depart the roadway into parking lots and gas stations or not make complete stops at stop signs, for example. This would allow analysis of those real-life cases, rather than gathering data from “perfect” drivers who drove exactly the speed limit and stopped completely at every stop sign. This would have led to more consistent, but less realistic, data.

C.2.2.5 Driving Areas

The following is a discussion on the EDMap driving areas. There were two major areas, Michigan and California. In each area, there are tiles, swaths, and routes. Each of those topics is discussed below. A more detailed description of the test areas can be found in the Task 2 & 3 reports.

Michigan Test Area

Tiles in Michigan: Every Street Driven

For these five areas in Michigan, test probe cars should drive on every road, including the freeways, ramps, frontage roads, and side streets. Each of the five tile areas in the Michigan test area is discussed below.

- **Ann Arbor Tile:** The Ann Arbor tile is located in proximity of the Toyota Technical Center. Its north, south, west, and east borders are defined by the Plymouth/Ford Road, Packard/Cross Road, Huron Parkway, and North Dixboro Road, respectively.

- **CAMP Tile:** The CAMP tile is defined around the Crash Avoidance Metrics Partnership (CAMP) facilities in Farmington Hills. It is bounded by 14 Mile Road on its north, Halsted Road on its east, 10 Mile Road on its south, and Novi Road on its west.
- **Dearborn Tile:** The Dearborn tile is located around the Ford Motor Company facilities in Dearborn, Michigan. It is defined by Michigan Avenue on the north, Southfield Freeway on the east, Van Born Road on the south, and Cornell Street on the west.
- **Detroit Tile:** The Detroit Tile (Figure 6.7) is located in the heart of downtown Detroit. East Montclam Road, St. Antoine Street, Atwater Street, and 3rd Street define the tile's boundary.
- **Warren Tile:** The Warren tile encloses the General Motors Technical Center located in Warren, Michigan. It is T-shaped and defined by 14 Mile Road and 10 Mile Rd on its north and south sides. South of 13 Mile Rd, the east and west boundaries are Van Dyke Rd (M-53) and Ryan Road; north of 13 Mile Rd, the east and west boundaries are Hoover Road and Dequindre Rd.

Principal Road Areas in Michigan

In these areas, probe vehicles are required only to drive the arterial roads.

- **Principal Road Tile, North of Ann Arbor:** This is a semi-rural area north of Ann Arbor.
- **Principal Road Tile, North of CAMP:** This is a semi-rural area north of Farmington Hills.
- **Swath around I-96:** The I-696 swath is a connector element between several components of the southeast Michigan test site. 13 Mile Road on the north, Ryan Road on the east, 9 Mile Road on the south and Halsted Road on the west define the boundaries of this swath.
- **Swath around M-39:** The M-39 swath connects the Dearborn tile and I-696. The swath is bounded by 9 Mile Road on the north, Greenfield Road on the east, Michigan Avenue on the south and Evergreen Road/Avenue on the west.

Freeway and Non-Freeway Routes

There are also specific routes to be included in the probe data collection, involving certain freeways and other (non-freeway) roads. For this collection, only the specified roads need to be driven.

California Test Area

Palo Alto Tile: Every Road Driven

For this area in Palo Alto, California, test probe cars should drive on every road, including side streets. The tile is located around the DaimlerChrysler facility in Palo Alto, California. It is defined by the area enclosed by the following roads: Alma Street on the northeast side, Sand Hill Road on the northwest side, section of the Junipero Serra Freeway (I-280) on the southwest side and by the Foothill Expressway and San Antoine Road to connect back to Alma Street.

Circular Route

This is a circular test site has been developed around the San Francisco Bay to include the Bay Bridge (I-80) and the Dumbarton Bridge (CA-84) and connecting main roads on the east and west side of the bay including I-880 and I-280. It also includes sections of US-101 and other more local roads in the San Leandro area. Only the specified roads need to be driven. This starts and ends at the Palo Alto tile, and should be driven in both directions.

Foothills Roads

On the west side of the bay, Skyline Boulevard (CA-35), Page Mill Road, Alpine Road and Sand Hill Road have been specifically included to provide significantly winding roads placed on hilly terrain.

Road Scenarios

A variety of specialized road scenarios was specified for use in testing the probe analysis results. Examples of road scenarios are clover leafs, roads with stop signs, etc. The road scenarios are driven many times in order to allow for analysis on the special road scenario in combination with the number of passes of data.

The objective of this information will be to gain an understanding of road scenarios versus probe results, e.g., accuracy, number of passes required for attribute determination, etc.

The current use of the road scenario data has been to ensure good curve fitting using the probe data. Probe data tends to be noisy compared to mobile mapped data so the process of curve fitting proves to be more difficult. The road test scenarios are some worst-case scenarios that allow us to test the curve fitting.

C.2.2.6 Schedule

There are two concepts related to this topic, the actual schedule of collecting the probe data and the effect of the schedule on the probe data.

Below is a table listing the probe vehicle usage by month. One can see that probe data was collected for over 6 months. Part of the breadth of the collection schedule was to allow for variation in weather (winter weather probe data may be different than non-winter probe data), events (construction in a particular month), and more.

Additionally, the time of day, week, month, and year all have an effect on the probe analysis. Time of day analysis allows one to determine attributes related to time of day (e.g., turn restrictions at a certain portion of the day or speed averages in rush hour). Moreover, as the time period increases season to season analysis can be done (e.g., the effect of a snow covered road on probe analysis versus a clear summer road) or temperature analysis (e.g., the effect of probe equipment such as a barometer on probe analysis when evaluating data recorded in a cold climate versus hot or humid climate.)

The probe car usage by month also allowed for estimating data storage and miles of data collection.

As an example, see Table C-3, the Mar-03 column, for explanation. In Detroit, five drivers will be employed, each at 100%. Three drivers will be employed in the Palo Alto area at 100%, 75%, and 75%. Additionally, a car in Chicago is being used 10% of the month to collect certain test data, i.e., some of the test areas can be collected in Chicago to quickly validate curve fitting methods.

So nine drivers at 100% each would yield 900%. However, since not all nine drivers are 100% in this case, the total is 760%. At 20 days per month, this is 152 days (912 hours assuming 6 hours per day) of driving in Mar-03.

Finally, assuming 21 miles of driving per hour, we would expect 19,152 miles of driving. At approximately 69K of data per hour, this would lead to 64 MB of data for the month.

Note the estimate is approximately 111,000 miles of probe data to be collected across the EDMap test areas through the end of March 2003.

Table C-3: Probe car usage by month

Probe Car Usage By Month

	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Jan-03	Feb-03	Mar-03	Total
10 EDMap Cars										
Detroit										
Driver 1	25	25	100	100	100	100	100	100	100	
Driver 2	25	25	100	100	100	100	100	100	100	
Driver 3			100	100	100	100	100	100	100	
Driver 4			100	100	100	100	100	100	100	
Driver 5			100	100	100	100	100	100	100	
Driver 6										
Palo Alto										
Driver 7				100	100	100	100	100	100	
Driver 8									75	
Driver 9									75	
Driver 10										
Field Cars										
Field 1		10	10	10	10	10	10	10	10	
Field 2										
Field 3										
Field 4										
Field 5										
Total	50	60	510	610	610	610	610	610	760	
Days	10	12	102	122	122	122	122	122	152	886
Hours	60	72	612	732	732	732	732	732	912	5316
Miles (IT)	1260	1512	12852	15372	15372	15372	15372	15372	19152	111636
Miles (DT)	480	576	4896	5856	5856	5856	5856	5856	7296	42528
Storage	4,194,304	5,033,165	42,781,901	51,170,509	51,170,509	51,170,509	51,170,509	51,170,509	63,753,421	371,615,334

Hours/Day	6
IT Miles/Hr	21
DT Miles/Hr	8
Bytes / Hr	69905.067

32 MB / 20 days = 1.6 MB / day = 69905 bytes/hr

C.2.2.7 Using Vehicle ID

There are two possibilities when using probe data regarding identifiers:

- An ID exists that links individual data points to a particular vehicle. In other words, a vehicle could be tracked from start of trip to end of trip. That identifier is called a "mobile ID".
- An ID does not exist.

Of course, the reason for the two possibilities is primarily due to privacy considerations. There is a chance that people providing probe data will not want identifiers linked to the data. Therefore, it was assumed that no mobile IDs existed in the data. If mobile IDs do exist, then certain aspects of the analysis will actually become easier. It was decided to choose the more difficult problem and provide a solution robust enough to support either scenario.

Also, remember that it is not simply the link to a particular vehicle that is the problem, rather it is the path of a vehicle from a particular point that may be a problem with regard to privacy. In other words, seeing a vehicle leave a certain home day after day that goes to a certain office building day after day would allow the determination of "home" and "office". Combine that knowledge with an address and name list (e.g., telemarketing list) and a rather robust database of information about a person begins to be built.

Other methods do exist that attempt to provide a balance between the two possibilities of ID and no ID. For example, the ID randomly changes and the probe box randomly collects data. One day the probe box delays collection for 1 minute before collecting, another day it delays 10 minutes.

C.2.3 Probe Data Derived Geometry: Measures and Metrics

Topics discussed in other parts of this document all demonstrate the ability to use probe data to determine road segments. However, it is now necessary to measure and compare the quality of the probe derived information to alternative methods of building that information.

The geometry built from probe data has certain accuracy. This accuracy needs to be measured. Different hardware suites will lead to different levels of accuracy within the collected probe data. This section examines the effect of varying levels of input accuracy on the output level of accuracy. For example, determine the accuracy in a database created from probe data using a 15 m accurate GPS unit as the input source.

The effect of density of data can also be measured. One of the goals of the probe project was to research the effect on varying amounts of data, e.g., the attributes and accuracy of those attributes when using 5 passes of vehicle tracks versus the attributes and accuracy of those attributes when using 20 or more passes of vehicles tracks.

C.2.3.1 Grouping the Data

The probe data sets obtained from the different drivers for the different tiles were classified into groups for the purpose of analysis. The groups were set up to determine the impact of a particular parameter on the accuracy of data. The parameters included drivers, devices, seasons and tiles.

Drive-based Analysis

A separate dataset was maintained for each driver. Each dataset's name contained the driver's identification and the tile information. Based on this information all the datasets were put in five different folders, one each tile.

Device-based Analysis

All the datasets were again divided into five different folders representing five tiles based on the device.

In both of the above cases, the datasets were grouped by number of runs to analyze the impact of more number of data points on accuracy.

C.2.3.2 Method for Processing

The probe processing software was used to fit a spline representing the road centerline using the data points in each of these datasets. This software calculated the metrics related to the accuracy of the spline fitted.

C.2.3.3 Analysis

The metrics obtained from the running the probe software did not vary much based on driver or device although the number of datasets impacted the metrics.

C.2.3.4 Distance Analysis

In this analysis, the splines were calibrated for every segment present both in the probe and mobile mapped data. The data obtained from Mobile Mapping (MM) was given as input to the Probe software to calibrate the splines representing roads. As the MM data is very accurate (within 10 cm), the splines obtained using this data were considered to be the ground truth (GT). In other words, the splines derived from ground truth data were assumed to represent the actual centerline of the road segment.

Assuming the length of each spline to be 1 unit, 10 points were chosen on each of the spline starting at 0 (beginning point of the spline) such that they were 0.1 unit of distance apart and spanning the entire length of the spline. The distance between these points corresponding to each spline was calculated. The results were analyzed by calculating the average of the 10 distances per segment. The following tables show the distribution of average distances among segments for the range between 0 and 50 m on data obtained from 2 devices.

This analysis allowed comparison of a variety of information to what was considered ground truth. For example, as the number of datasets increased, it could be determined if the resulting data was getting better in accuracy. To do this, the resulting data was compared to the ground truth baseline data.

Table C-4: Average distance of splines obtained from 2 devices

Average distance of splines obtained from 2 devices								
Tile	No. of datasets used	Percentage of segments in distance ranges from 5 to 50 meters						No. of segments
		<5m	<10m	<15m	<20m	<25m	<50m	
AA	1	10	15	25	30	40	60	20
	3	24	52	67	75	81	92	467
Camp	3	33	65	78	86	90	93	620
	6	39	70	82	89	92	97	925
Warren	3	25	54	74	83	88	97	512
	7	21	53	73	82	87	98	559
Dearborn	2	23	62	79	88	93	98	723
	6	19	58	76	87	90	97	843
Detroit	2	35	70	82	87	91	96	255
	6	37	69	81	89	91	97	291
AA	1	23	53	72	83	91	98	160
	2	20	54	71	79	86	98	232
Dearborn	1	24	67	81	89	92	97	496
	2	23	65	79	89	91	98	575
Detroit	1	39	70	88	94	96	99	241
	3	36	66	83	90	92	97	292

Table C-5: Average distance of splines obtained from all devices and drivers

Tile	No. of datasets used	Percentage of segments in distance ranges from 5 to 50 meters						No. of segments
		<5m	<10m	<15m	<20m	<25m	<50m	
Warren	33	8	31	55	73	83	97	570

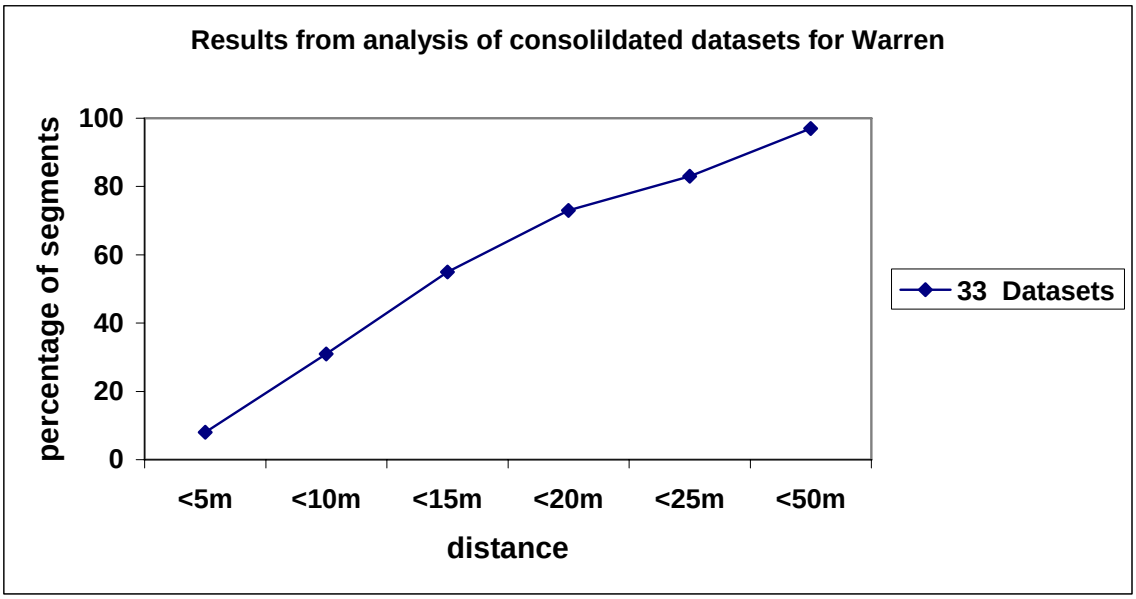

Figure C-6: Warren results

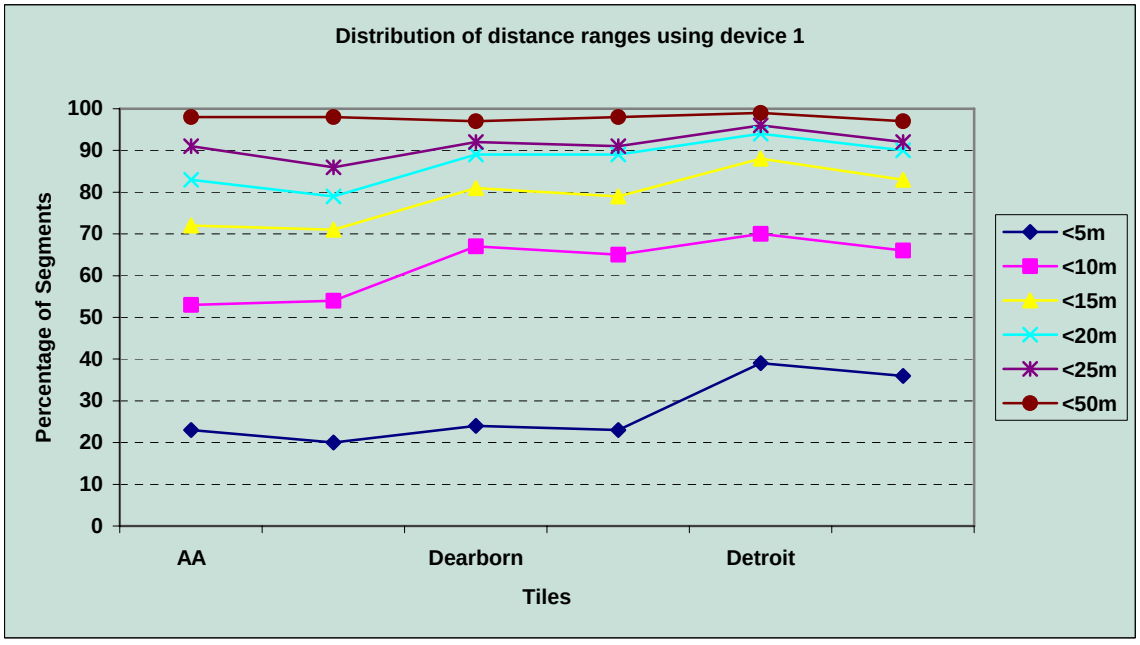

Figure C-7: Distribution of distances – device 1

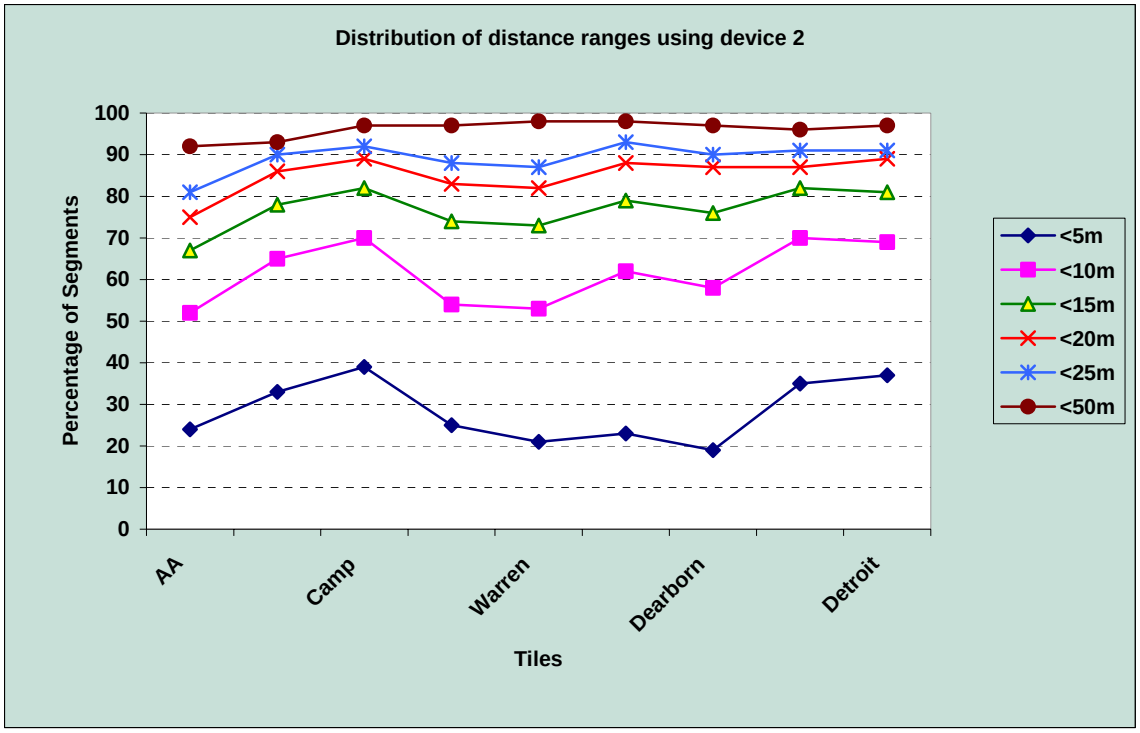

Figure C-8: Distribution of distances – device 2

The graphs in the figures above show that more than 90% of segments mapped using probe data is within 25 m of the GT using either device. More importantly, it shows that even for a small number of vehicle traces, the data was within 10 m of ground truth more than 50% of the time.

In the five figures below, the graphs show the weighted percentage of segments falling within each 5-meter range. One of the inferences made from the earlier analyses for spline fit was that in the case of splines calibrated using higher number of datasets, the spline tends to be more towards the center of the road. The weighted graphs below from the distance analysis corroborate this inference as higher percentage of road segments seem to get closer to the GT as the datasets increase.

The weighted percentage was calculated as the ratio of the segments per case to the total segments in both the cases.

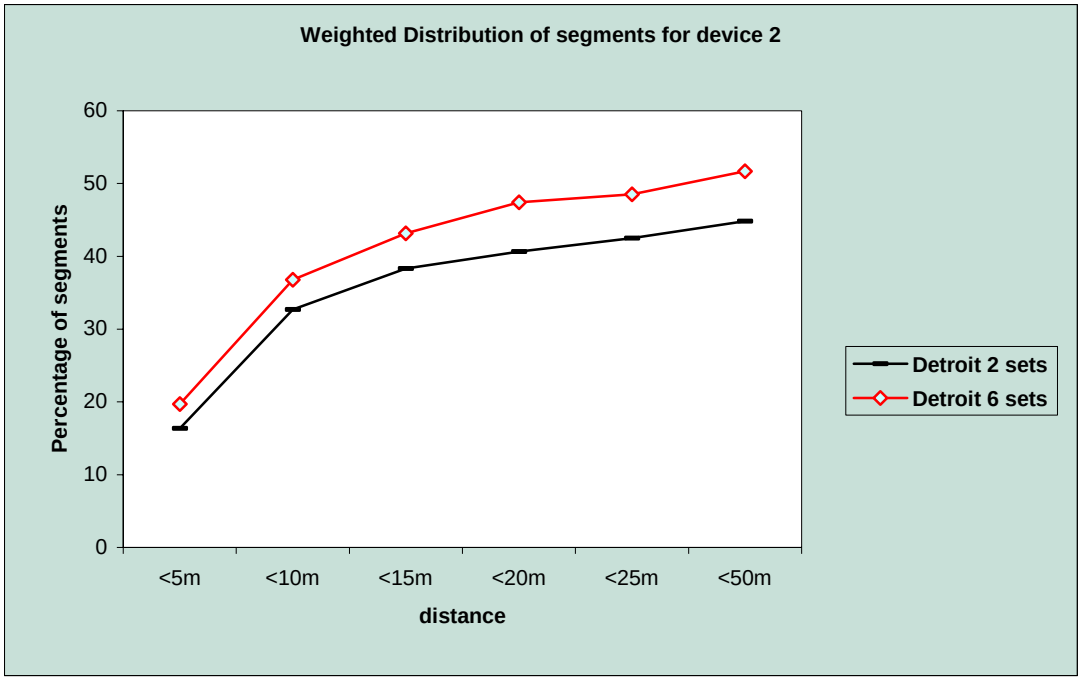

Figure C-9: Weighted distribution - Detroit

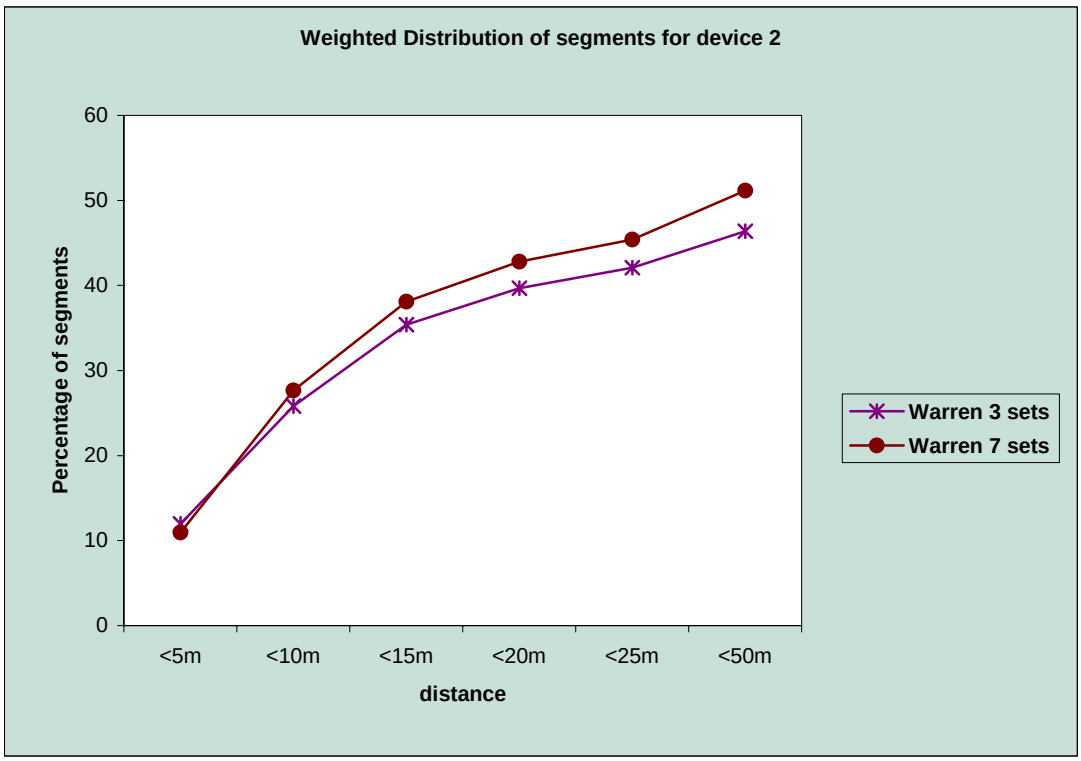

Figure C-10: Weighted distribution - Warren

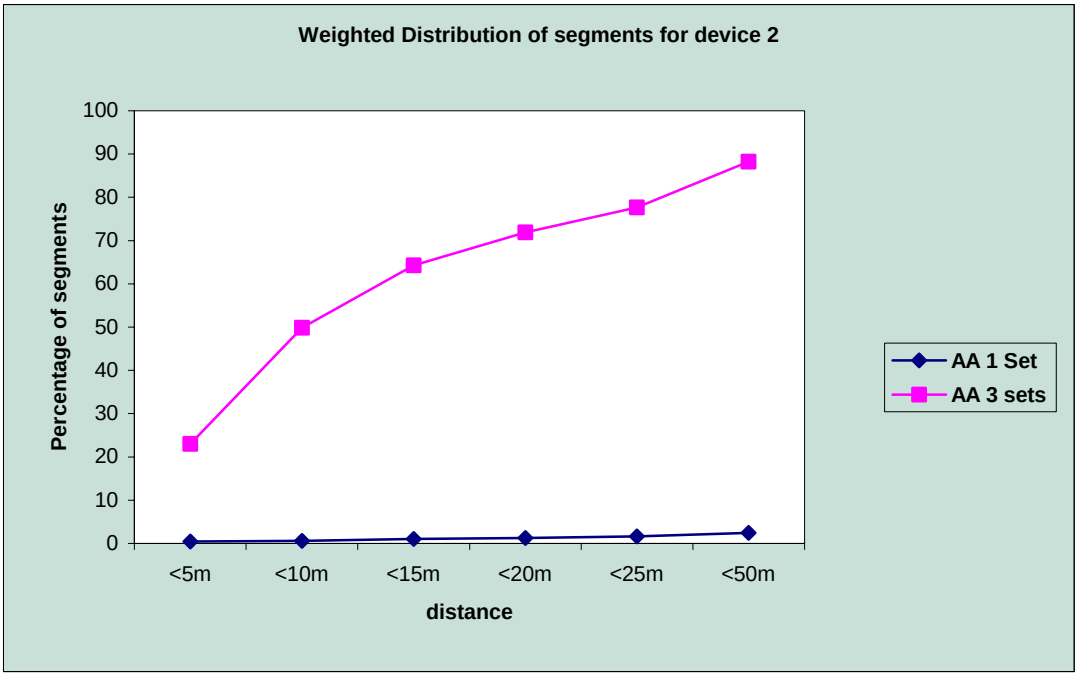

Figure C-11: Weighted distribution - AA

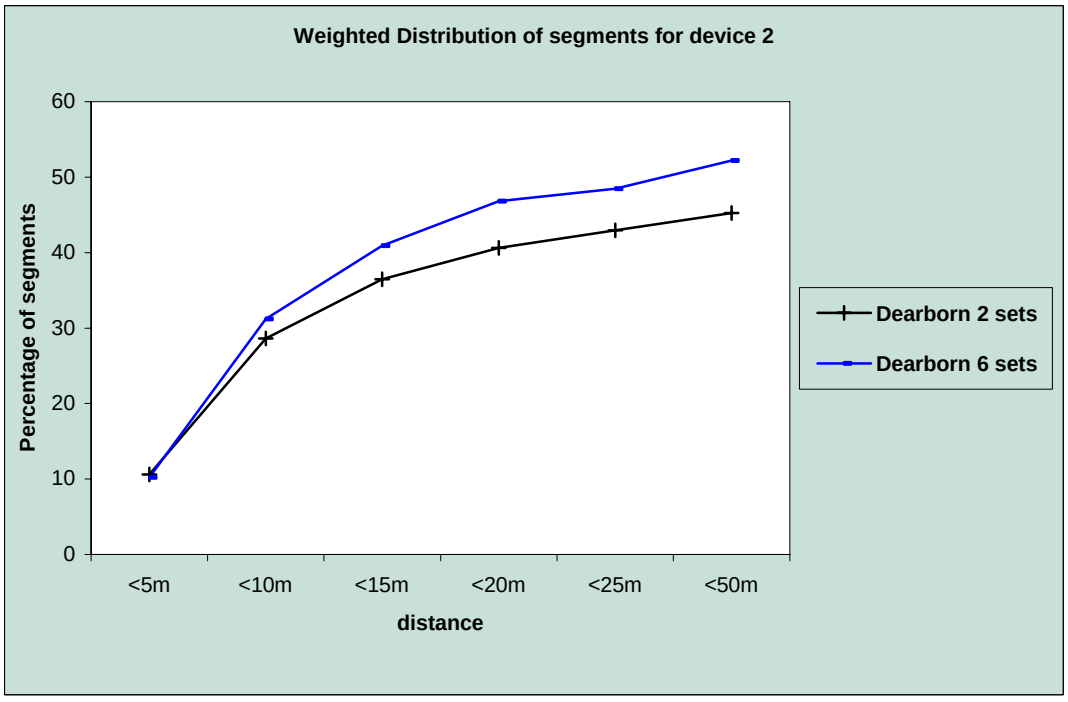

Figure C-12: Weighted distribution - Dearborn

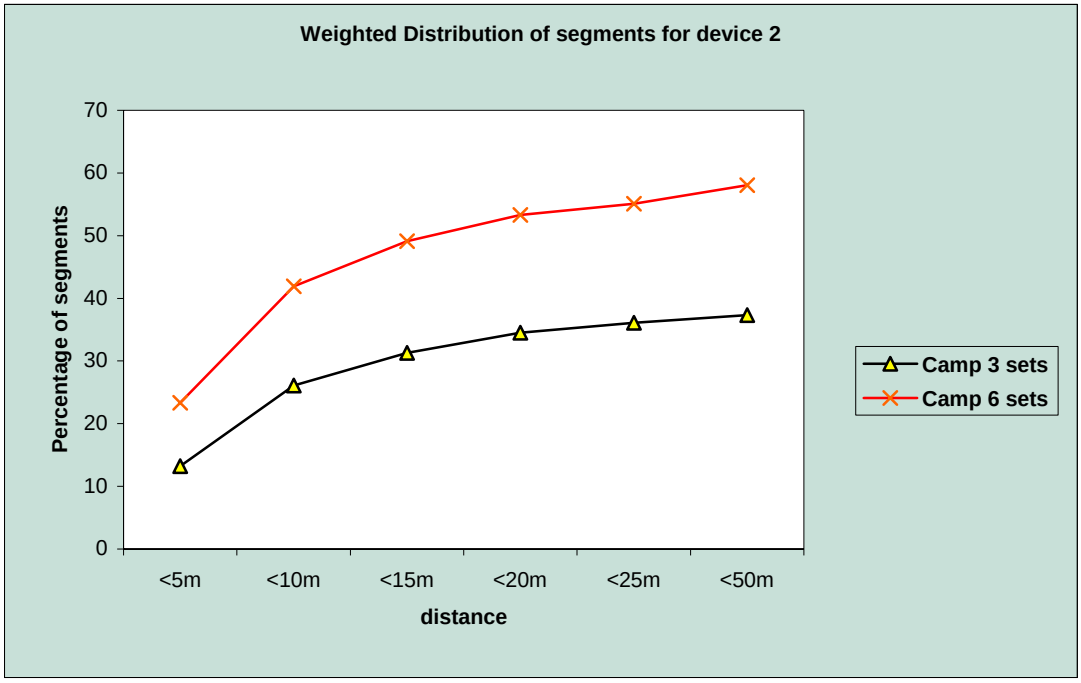

Figure C-13: Weighted distribution - Camp

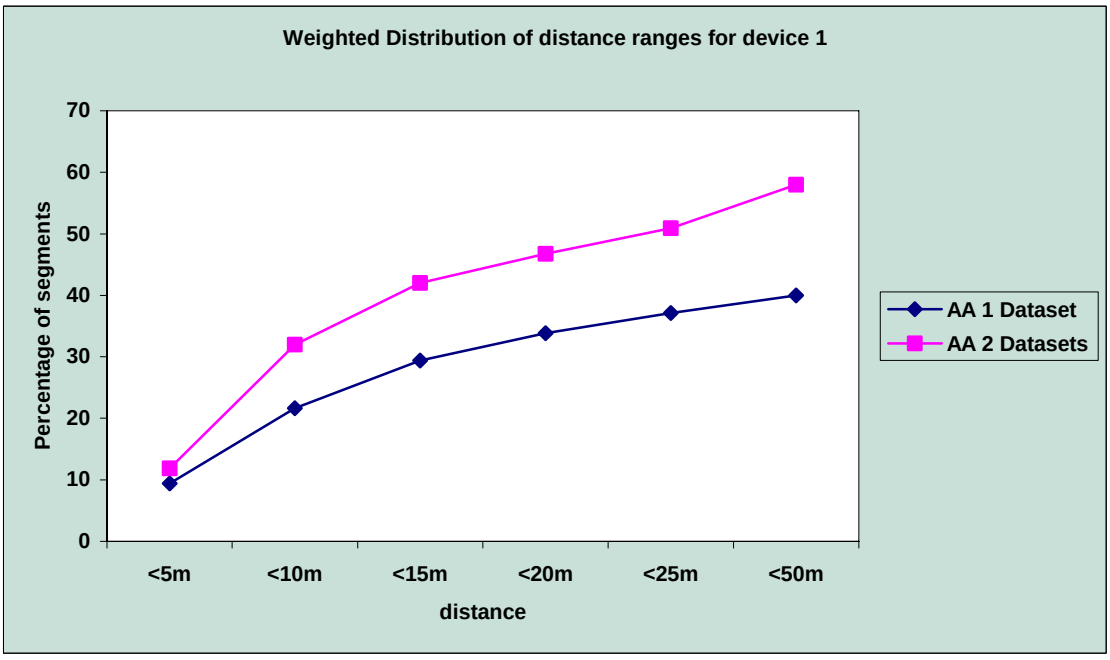

Figure C-14: Weighted distribution - AA

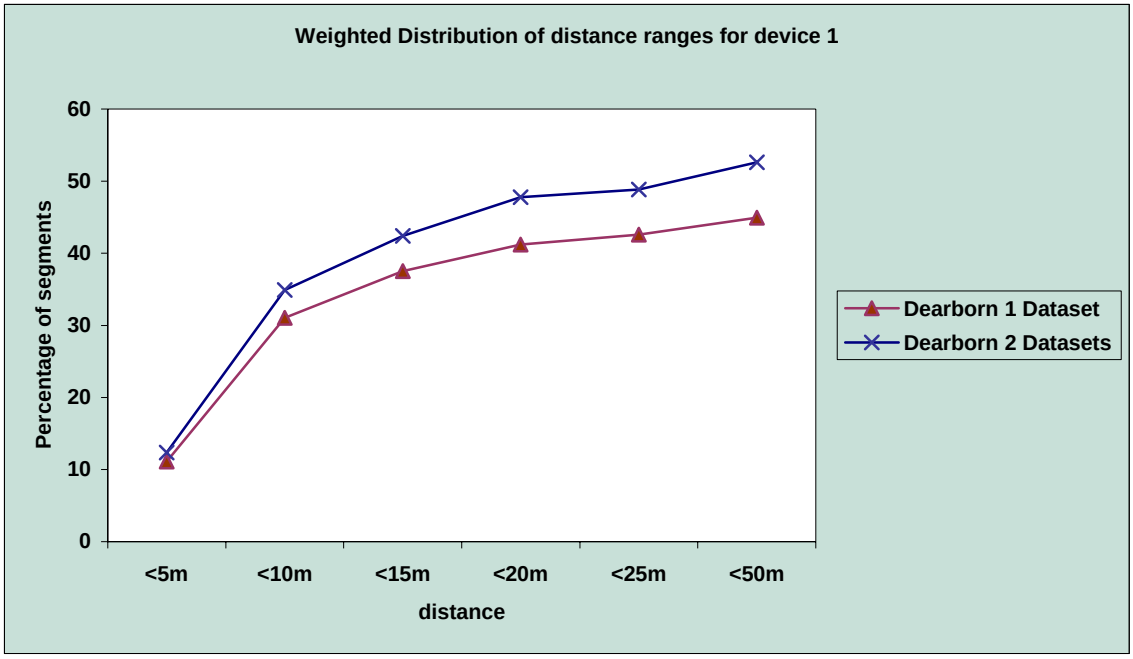

Figure C-15: Weighted distribution - Dearborn

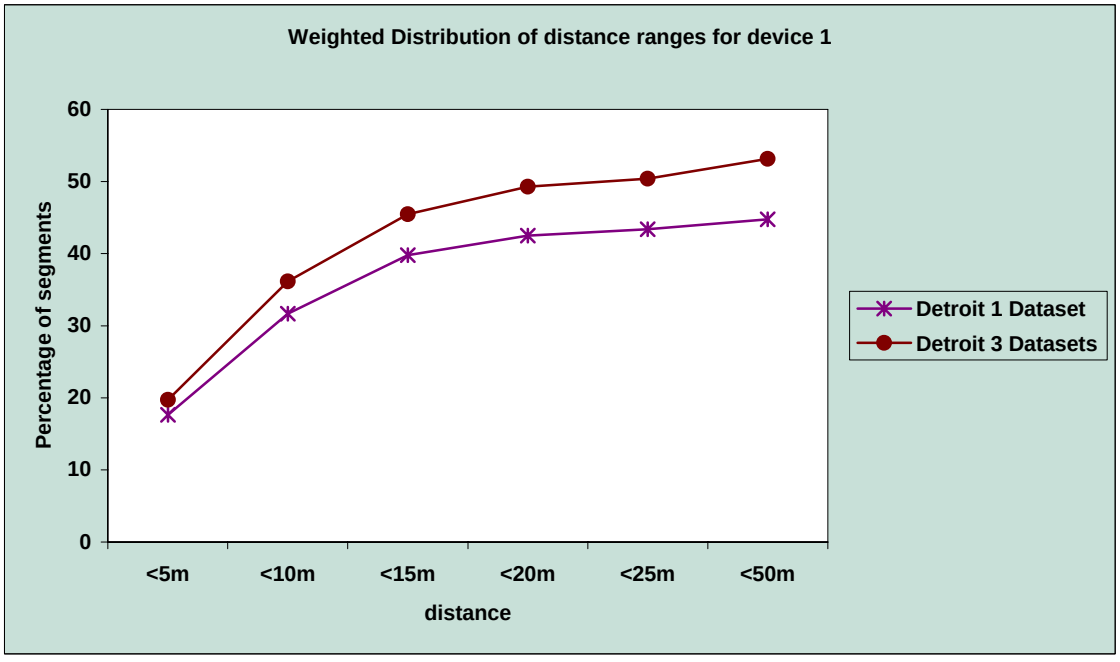

Figure C-16: Weighted distribution - Detroit

C.2.4 Probe Data Uses

During the probe data project, a number of theories were chosen to be tested on the uses for probe data with regard to map databases. Some of those theories included:

- **Recognizing and updating existing links (centerline data)**
  Using probe data, roads that are currently in map databases should be able to be validated. As vehicles travel along roads, probe data will allow for the verification of the existing shape of the road in the database. Moreover, other attributes like speed or turning restrictions could also be validated as probe data is gathered.
- **Recognizing and changing existing links (centerline data)**
  One step beyond validating the existing link information is to actually recognize when the data should be changed. For example, thresholds could be created that signal that when probe data indicates that a road in the existing database is in an incorrect location, it could be shifted to the correct location.
- **Recognizing new links (centerline data)**
  Using probe data, new roads that are not currently in map databases should be able to be recognized. This will allow more efficient updating of map databases by allowing map developers to quickly recognize new roads.
- **Improving absolute road accuracy (centerline)**
  Probe data gathered over time will lead to more accurate road positioning. Statistically, the probe data gathered over time will lead to accurate road positioning information that could be used to update current map databases.
- **Improving road shape representation (centerline)**
  Probe data gathered could also lead to improved road shape representation, i.e., the shape of the road could easily be derived from evaluating numerous vehicle tracks of data along the road.
- **Mean (average) driving pattern (driver habits)**
  One of the interesting issues that arises when using probe data is this: probe drivers indicate where drivers drive not where the road is necessarily positioned. For example, drivers traveling on a highway ramp rarely drive down the center of the lines painted on the ramp. Probe data easily shows this phenomenon.
- **Verifying existing attributes**
  Probe data gathered over time could be used to validate existing attributes on the roads as indicated in the map database. For example, turn restrictions during certain times of the day could be validated by evaluating probe data gathered over time for that road.
- **What new attributes can be found**
  Probe data may also be able to add new attributes that are not collected today for map databases, e.g., stop light timing. Probe data could indicate that a given road signal is red for a certain number of seconds and green for a certain number of seconds. This information could be derived from the probe data in the intersection. Some cars stop, while others go, and then the trend switches as lights change.
- **Determining lane level attributes for each direction of travel**
  Using probe data, lane-level attributes for each lane could be determined. For example, lane one may be a right turn only lane; lane two may be a left turn only lane. Using the probe data for those lanes, those attributes could be determined.

C.2.4.1 Developing Methods to Automate the Database Building Process Using Probe Data

During the probe project, areas where probe data could lead to automated database building were researched. For example, stop sign derivation is something navigable map developers must do manually if it were added to the database. Using probe data could lead to automated derivation and insertion of stop sign information. Moreover, many of the current map creation processes include human interaction for digitization or validation of road information. Probe data could automate many of those procedures.

During the process, metrics could be used to ensure the process is meeting configurable thresholds. So, for example, the spline fitting may occur numerous times until a spline fit that meets all metrics is achieved. If one of the metrics cannot be automatically achieved, the goal is to flag those exception segments where a human could then interact with the editing tool to correct the situation.

Extracting lane information from probe data is a challenging problem since the high noise level of the probe GPS sensors causes the collected data from each lane to overlap. If the spread in the probe data had been less than the lane width, it would be possible to classify the lane to which each data point belongs. Having classified the data into such lane data groups, a curve fitting technique to determine the geometry for each lane could be developed for each lane data group. However, since the spread in the data from the low accuracy probe GPS sensors exceeds the lane widths, the data cannot easily be classified into the individual lanes, which renders a direct curve-fitting approach infeasible.

C.2.4.2 Processing: Deriving Attributes from Probe Data

This work package researches the topics associated with deriving attributes from probe data. The attributes associated with a road are items such as stop sign locations, speed limits, stop light locations, and more.

The tasks related to probe data have been broken out into two major areas: deriving geometry and deriving attributes. The task of deriving geometry from the probe data is discussed in Section C.2.3 Probe Data Derived Geometry: Measures and Metrics.

C.2.4.3 Evaluation Methods for Deriving Attributes from Raw Data

There are a number of attributes that could be determined from probe data. Some of those attributes are listed below along with a discussion of work in using probe data to determine the attributes. Many of the attributes can be determined at the road-level and/or lane-level. Initial work in this area, though, is currently focused on road-level determination. For example, stop locations on a road, rather than lane by lane, were attempted to be found.. In the future, further work could determine the stopping point for each lane of a road.

Stop Location/Stop Point

The following image is a display of stop locations determined by the probe analysis software on map display software.

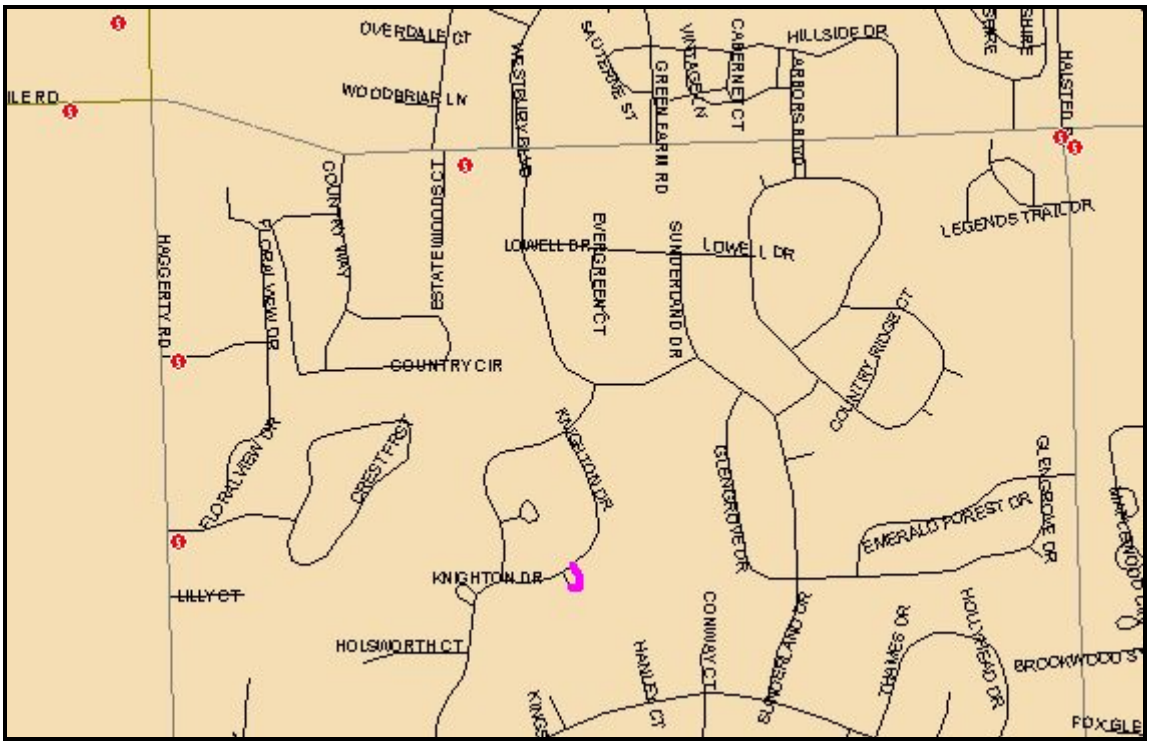

Figure C-17: Stop locations derived from probe data

Stop Line

The stop line is the location of the white stripe (in the U.S.) on the ground where the front of a vehicle is required to stop at a stop sign or stop light.

Stop Light

A stop light attribute is a location given near the node of a road near an intersection that has a stoplight. Probe data may be able to yield the stopping times for each of the various signals. For example, probe data can enable the calculation of the length of time that the signal remains green and red.

Stop Sign

A stop sign attribute is a location given near the node of a road near an intersection that has a stop sign.

The location of stop sign could be determined as discussed in the section above “Stop location/stop point”.

C.2.4.4 Speed Limits and Mean (Average) Speeds

Overview

During the data collection phase for the Probe Data project, the low resolution (error range of 15 m-25 m) GPS system is used to trace the geometry and attribute information of the tracked vehicle. The ability to use the collected attribute information to extrapolate

other relevant properties of the roads and traffic characteristics would allow a more well-defined and detailed understanding of future capabilities for building the next-generation navigable maps.

In short, it would be desirable to determine if probe data can lead to a derivation of the speed limit on a road as well as average speeds (per time of day) on a road.

Initial Analysis Considerations

The purpose was to explore these variables and flesh out any details including the need to collect additional data, discuss issues and potential side effects, and take the first steps towards deriving a speed limit algorithm.

High Level Design for Speed Limit Analysis

Phase 1

Objective

The initial objective includes defining the initial framework of requirements and assessing the current knowledge base. This includes better understanding of what data currently is captured or needs to be captured, and the technology and tooling in place to perform the analysis and to develop the initial prototype.

Requirements

Req. #1: Understand the current knowledge base and technology

Req. #2: Perform the initial phase of analysis by exploring the concepts, variables, and issues related to analyzing speed limits.

Req. #3: Process raw data files to extract ‘Segment ID’ and speed data.

Req. #4: Plot speed vs. time graph using data for a typical scenario.

Req. #5: Calculate mean speeds based on raw data which link information.

Conclusion

There are patterns in speed ranges and these distinct macroscopic segments can be grouped into several categories. It appears that there is some consistency in the data distribution for the speeds. There are logical speed demarcations that appear with regular consistency. In the higher speed segments, the range appears to be tighter and thus has a smaller standard deviation. However, in the lower speed areas, there are larger variances possibly due to stop-and-go behavior from the existing traffic noise. This conforms to some of the preliminary assumptions about lower speed segments. It will be necessary to pursue a more thorough investigative analysis using more information to better understand these relationships.

Phase 2

Objectives

The objective in this phase is to refine the speed limit algorithm by further developing upon the initial phase. The calculations from the prototype will be compared against attributes independently field collected. In addition, the mean speeds will be calculated for each segment and the relationships between mean speeds of various segments will be compared to independently collected data.

Requirements

Req. #1: Calculate low and high speeds, sample count, and mean speeds for each segment.

Req. #2: Independently collected data

Req. #3: Compute the speed limit algorithm value for each link segment.

Conclusion

Several key statistical metrics were calculated such as mean speed, low speed, high speed, and the number of points used in the data sample. In addition key road metrics were separately collected; this includes the Rank, Lane Category, Speed Category, and Speed Limit attributes.

From the prototype, it is evident that the speed limit algorithm values that were calculated for each physical link do not fall within the specified parameters of the Speed Category definitions based on independently collected data. In most cases where the mean speed falls outside this range it is most likely due to the initial acceleration and deceleration of the boundaries of the segment, since each link is defined at its limits by a street marker such as a stop sign or the presence of a street light. In almost all cases where this occurs, the mean speed misses the range on the lower side because of the stop and go characteristics at the boundaries of the street segments. Specifically, only 46.9% of the segments met category ranges, which does not provide good confidence that using the current algorithm, without any optimizations would not provide realistic guidance about the posted speed limit.

Realizing that some significant improvements can be made to optimize the speed limit algorithm to eliminate the presence of noise in the data sample due to “stop and go” traffic from street lights, stop signs, and other unnaturally occurring factors, there is considerable confidence that a higher level of Speed Category range compliance can be achieved through further analysis and prototyping considering these factors.

Although some of the preliminary assumptions about determining traffic speeds have been validated at a macroscopic level, there is significant room for improvement for many more optimizations. We will not be able to consider evaluating speed limits for individual roads until this macroscopic objective is reached.

C.3 Remote Sensing

Table C-6: Comparison of remote sensing technologies

Technology	Date Available	Usefulness	Geometry Accuracy	Attribute Accuracy	Database Accuracy	Cost	Reliability	Comments	Suitability for EDMap
Aerial									
Conventional Moderate Accuracy	Now	Creation, correction and change detection	3-5 m / 7 m	Detectable attributes within 3-5 m	5-12 m	Low	High	Conventional method used by NT for several years	Near-term
High Accuracy	Now	Creation, correction and change detection	1m / 2.5 m	Detectable attributes within 1-3 m	2-3 m	Medium	High	Only major US urban areas will be available	Near-, mid-term
Satellite									
1 m – 0.6 m accuracy	Now in limited areas or by special tasking	Creation, correction and change detection	4m / N/A	Detectable attributes within 4-6 m	4-10 m	Medium to High depending on currency	High. Quality of images dependent of weather.	Limited coverage and vendors.	Due to cost, availability, not scalable in mid-term
IFSAR									
Lower accuracy	Now	Creation, correction and change detection	4 m / 3 m	Image detail not as clear as aerial	5 m	Medium	Major roads and large features can be distinguished. Smaller roads, ramps, and small features can be hard to detect. Not dependent on weather and atmospheric conditions.	Requires significant additional training to interpret data	Does not provide suitable digitizing accuracy consistently across coverages. Other attributes not feasible
Higher accuracy	Limited areas now. Not widely available for ~ 3 yrs.	Creation, correction and change detection	1.25 m / 3 m	Image detail not as clear as aerial	Slightly better than 5 m for high level roads	Estimates are high	Image somewhat more clear, but still not significantly better for small features	Requires significant additional training to interpret data	Better, but still does not consistently yield accurately digitized geometry
LIDAR									
	Now	DEMs for grade information	0.15 m vertical	N/A	Can provide elevation and grade data. Grade probably accurate to within 1%	Very expensive	Not dependent on weather and atmospheric conditions.	May be viable only if available from free or low cost sources like USGS	Cost prohibitive not widely available. Not commercially feasible

C.4 Edit Tool

C.4.1 Overview

The EDMap edit tool was developed around ArcGIS. The data repository was stored in an Oracle 8i spatial database. The spatial features of Oracle were used for storing the position information. The database creation was done in a personal geo-database. Personal geo-databases are Access databases that are compatible with ArcGIS. Use of personal geo-databases simplified the process of database creation and compilation at remote locations. The rest of this section describes the architecture of this edit tool, the data flow and the pros and cons of this approach.

C.4.2 Architecture

Figure C-18 illustrates different components in the Data Edit tool. ArcGIS as the front-end tool provided the main user interface for the user to visualize and create the database. This tool could be used with either Oracle database or with Access database. Data could be converted between Access and Oracle using standard ArcGIS utilities to maintain consistency between them.

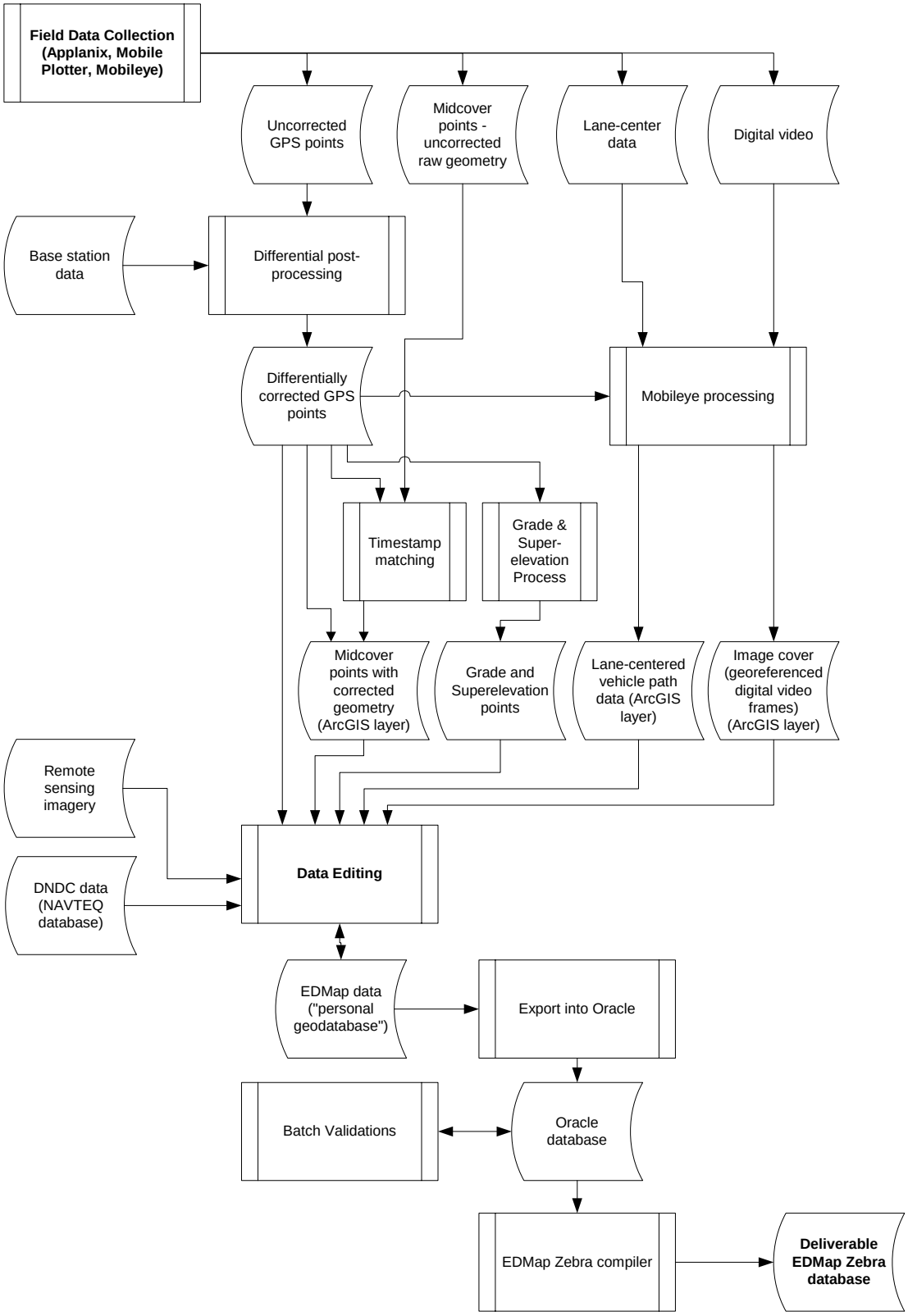

Figure C-18: Data edit tool components

As a first step, the mobile mapping data files were gathered and processed using a set of post processing software (pre-processing from Edit-tool point of view). This included post processing GPS data: concatenating and merging other sources of data (lane data, barometer data, mobile plot data, grade sources, etc). The details of the data merging process are explained in the Data Collection section of this report. The processed data files were then converted into different data layers (also called back covers). This enabled creation of EDMap database. The user in creating the EDMap database using the ArcGIS tool applied a set of standard operating procedures and prior knowledge on creation of road network databases. A number of plug-in modules were used in the process of database creation. These included parametric representation of the geometry and photogrammetry. Once the database was created and visually verified by the user to meet the data requirements, the database was ready for next stage of processing. This included converting the personal geo-database into Oracle and running batch validations. Once the database was completely processed and error-free, the data was exported to a set of ASCII transfer files used for the final database compilation.

The compiler identified errors in the editing process that did not conform to the data integrity requirements and could not be detected with other validations. The editor used the error reports from the compiler to rectify these errors. This was iteratively used until the data compilation was successful.

C.4.3 Data Layers

ArcGIS operates on data layers. The data layers contain information of a specific category. These data layers can be of different data types, namely points, lines, images, or text. These data layers are called back covers or frontcovers. Back covers are read-only data layers. These layers were used as reference for creating data in frontcovers. Any information that is to be modified was moved from backcover to frontcover.

EDMap edit tool used a number of back covers as reference data and created the EDMap geometry and attributes in frontcovers.

Back covers were created for road geometry represented by GPS points, Mobile Plot information, Lane attributes, Barometer data, DEM data and images captured during data collection. Frontcovers include ZElink, ZEsublink, ZEpoint, ZEintersection, etc.

This section describes the back covers, its contents and how they were used in the edit tool.

C.4.3.1 DNDC Layer

This layer contained geometry information from the current NAVTEQ database, including shape points, nodes and polylines representing. The links and link attributes in this layer were used as the starting point for making improvements to geometry and adding EDMap attributes. Before making a test database, it was required to create this layer from the existing database.

C.4.3.2 Vehicle Path Layer

This layer contained the actual vehicle drive path. No data filtering was done for this layer. This implies that if the vehicle was moving slow due to traffic conditions the points are denser, and if there were loss of GPS, then there were no points (in a GPS-only system). The drive path may be a sequence of GPS points or GPS/INS points. The GPS/INS points could be derived from post processing or real-time correction. Latitude, longitude, elevation, standard deviation, solution status are some of the attributes that are associated with each position information in this layer. Elevation data from GPS and Barometer (if available) were also stored in this layer.

C.4.3.3 Centerline Layer

This layer was applicable only for the mid-term database. The centerline path reflected the calculated lane centerline position. The centerline path was calculated by combining the physical vehicle location (given by the INS position) adjusted by the lane information from lane data. The lane information data included the position of the left and right lane marker with respect to the camera mounted in the data collection van. The details of computing this centerline are discussed in the data collection part of the report.

It is to be noted that the information in this layer did not have a continuous set of points, as there were no lane parameters in areas where the lane markings are of bad quality or not present.

Elevation data from GPS and barometer (if available) were also stored in this layer. This information is redundant with respect to the vehicle path layer.

C.4.3.4 Mobile Plot Layer

Mobile plot events were stored in this layer. This layer contained the position information (lat/long) of the mobile plot location, attribute type and value. Each mobile plot attribute could be displayed as different icons using ArcGIS built-in support. This was a very useful feature for the user while creating the sublink or sublane attributes. This layer was used for both near-term and mid-term databases.

C.4.3.5 Lane Layer

This layer contained left- and right-lane marker types and current lane width. The information collected by the lane keeping system was geo-referenced and created as the lane layer. This layer was used in combination with Vehicle Path layer and Centerline layer to derive lane geometry. Due to errors in the lane keeping system and the absence of lane markers, information from this layer was not consistent throughout the roads. This was especially true in low speed roads and at exit/entrance ramps.

C.4.3.6 Image Layer

This layer contained the name of the image file that was captured at this location. Images were captured at different frame intervals based on a combination of configuration parameters and vehicle speed. This layer maintained the relationship with the position data and the video frame at this location. This layer was used for quality assurance purposes (to resolve ambiguity on road geometry, attributes) and for deriving attributes using photogrammetry.

C.4.4 Link Level Database

C.4.4.1 Links

NAVTEQ uses its proprietary tools for creating the navigation-quality database. These tools are the result of 15 years of development effort and they ensure integrity of the database and support ease of use during database creation. This tool, called WinGWS, supports database creation from mobile mapping sources. However, this tool does not support additional attributes that are needed for EDMap.

Hence, in order to maximize the use of existing tools and focus on EDMap specific attributes, link creation for EDMap was done as a multi-stage process using WinGWS and ArcGIS based Edit tool.

1. Mobile mapping data (DGPS based position information) was used in WinGWS and the links were created using the standard procedures used for creating NAVTEQ databases. This tool ensured that these links have standard navigable attributes and that the integrity of the database was maintained. This tool also takes into account the modifications required to adjust the link geometry due to driver errors (changing from lane 1 to lane 3 to avoid a stalled car).
2. Once the basic database with standard attributes was created, this database was imported to the ArcGIS environment. The ArcGIS edit tool also used the DGPS traces and mobile plots as reference. Each link was then selected and its shape modified as necessary to reflect ground truth. The shape of the geometry was modified by adding, moving or deleting shape points in order to reflect reality. Remote sensing imagery was often used to ensure the correctness of road shape.
3. Once the shape of the road was modified to reflect reality, a parametric representation is fit through the shape points in each link. This was done interactively and the results were displayed to the user. This helped the user to confirm that the parametric representation of the selected link reflected reality based on additional viewable evidence.

Once the links are created, the ZElink and ZEsublink attributes are added using custom tools created in ArcGIS.

C.4.4.2 Creating Links

A link for EDMap was different from the existing links in NAVTEQ database. Zebra is the database compiler used for creating the OEM-usable database product. A link created by the edit tool should be usable by the Zebra compiler. Hence, to denote this relationship between EDMap and Zebra, and to differentiate from current NAVTEQ links, EDMap links are called ZElinks (Zebra-EDMap Link).

A ZElink is defined as an entity that represents a road between intersections. A ZElink may consist of a number of current NAVTEQ database links (hereafter called, Links). A separate link exists whenever there are significant attribute changes along the road. For example, a change to a speed limit between intersections causes a link to be split in the current NAVTEQ database. So multiple links which are connected using bivalent nodes (due to attribute changes), could be combined to form a single ZElink.

As a first step, a link in DNDC is first converted into a ZElink.. The ZElink inherited relevant attributes from the DNDC link.. Once a ZElink was created, it could be modified to represent EDMap type geometry and attributes using the Edit tool.

C.4.4.3 Creating Link Geometry

In order to generate a parametric representation for the links, a parametric curve was fitted, using as input the shape points. Use of parametric curvature was necessary to enable smooth representation of the geometry.

During the first phase of development, an automated batch process did the conversion of shape points to parametric representation. This was implemented in order to generate smooth curvatures at link intersections. The algorithm used connectivity between links and generated a smooth transition between them. This also helped increase productivity, as the user need not have to traverse each lane to adjust the geometry.

However, the results from this batch process highlighted the need for interactive creation of links. Whenever the number of existing shape points are sparsely placed, the resulting representation did not represent ground-truth reality. This was verified by visual inspection. One such example is shown below. This could be avoided if the geometry were created interactively.

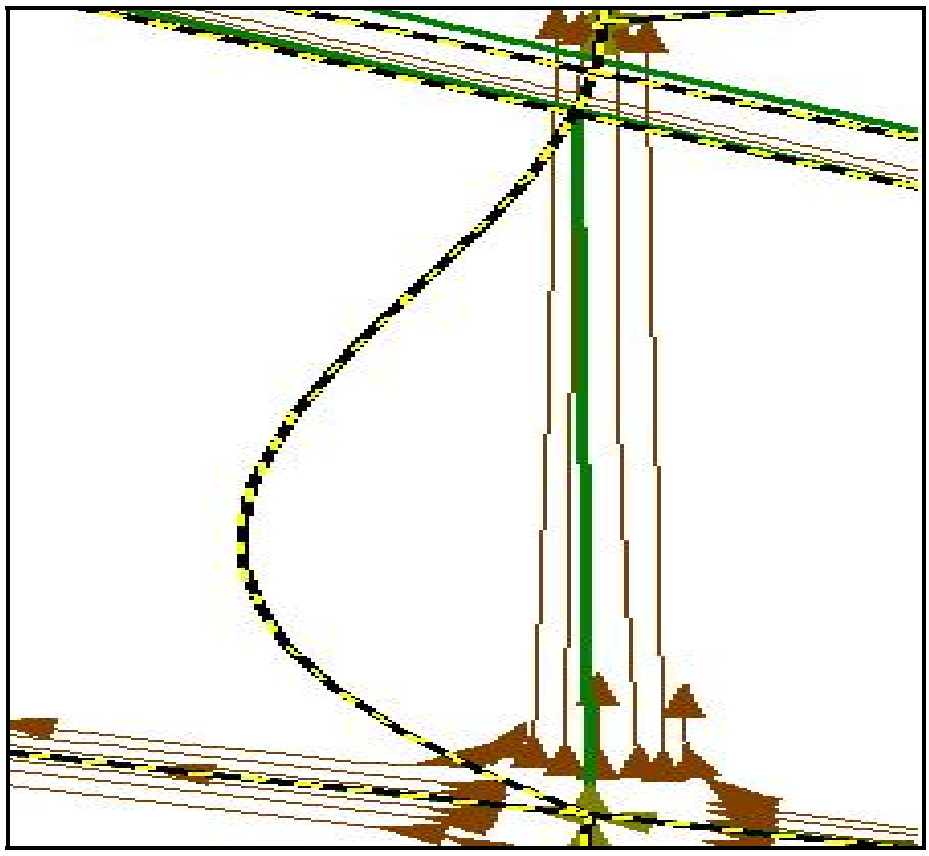

Figure C-19: Conversion of shape points to geometric representation

Hence during the second phase of development, we implemented features to create parametric curves interactively in the ArcGIS edit tool. Once the shapes were in conformance with real world geometry, the batch program was run to achieve a better fit at intersections. This results in the best parametric representation for all links.

The differences in creating links interactively versus in batch mode are given below.

Table C-7: Link creation – interactive vs. batch mode

Interactive Process	Batch Process
Pros: Editor can visually check and correct the generated geometry for the ZElink and resubmit for corrections. **Cons:** Time and labor consuming process. Invalid data can be introduced due to user error or application process.	**Pros:** Large volume of data is processed within a short period. Smooth geometry, based on the positions of the link ends and shape points. **Cons:** No control over the shape of the geometry creation.

C.4.4.4 Sublink

A number of EDMap attributes for the near term database are represented as sublink attributes. Sublinks were used whenever an attribute pertained to part of, but not all of, the length of the ZElink. Sublink attributes have a starting and ending longitudinal position along a link. Each sublink also has a sublink type and a set of values. The values for a sublink vary based on the sublink type. For example, a sublink for Speed Limit will have the ”Speed Limit” as its value, while a sublink for grade will have the ”Grade bin” and the actual grade (in percentage) as the values. The details of sublink types and values for each sublink were designed and implemented as part of our schema design for the edit tool.

Some of the valid sublink types were: speed limit, advisory speed limit, road grade, superelevation, number of lanes, road condition, pavement status, road surface type, etc.

C.4.4.5 Creating Sublinks

Information for creating a sublink was typically taken from the Mobile Plot data. ArcGIS back covers were created for mobile plot attributes and these attributes were then displayed at their recorded location. The built-in feature of ArcGIS to display different mobile plot attributes using different symbology helped the user in creating sublinks with minimal complexity. This was especially useful in areas where a number of mobile plot attributes are captured at the same location (e.g., change in road surface type, speed limit, and number of lanes happening very close to each other). Figure C-20 illustrates a set of typical sublinks and their representation.

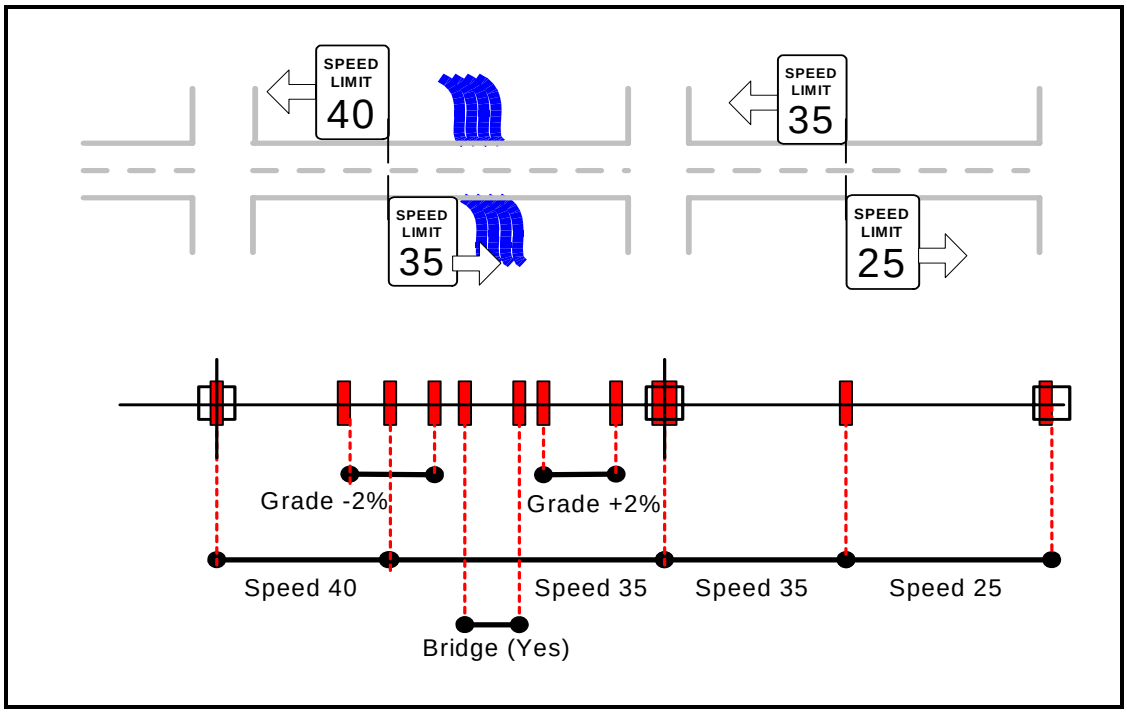

Figure C-20: Typical sublink representation

A sublink was applied by selecting a ZElink, indicating the start/end points and providing the attribute value. In order to eliminate redundancy and for better representation, a number of optimization procedures were implemented while creating a sublink. For example, if the end point of a sublink was within 1 m of the link node, the sublink record was extended to the end of the link. In all cases, the start/end points selected are snapped to the link. This prevents data inconsistency and maintains data integrity.

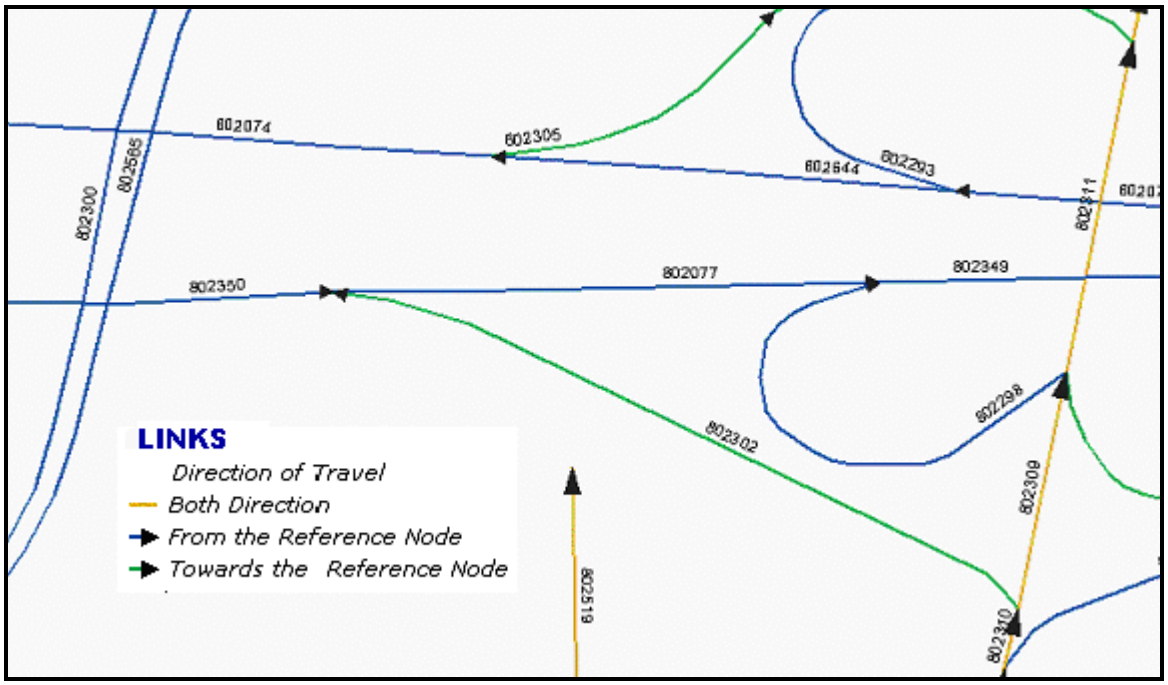

Figure C-21: Sample links

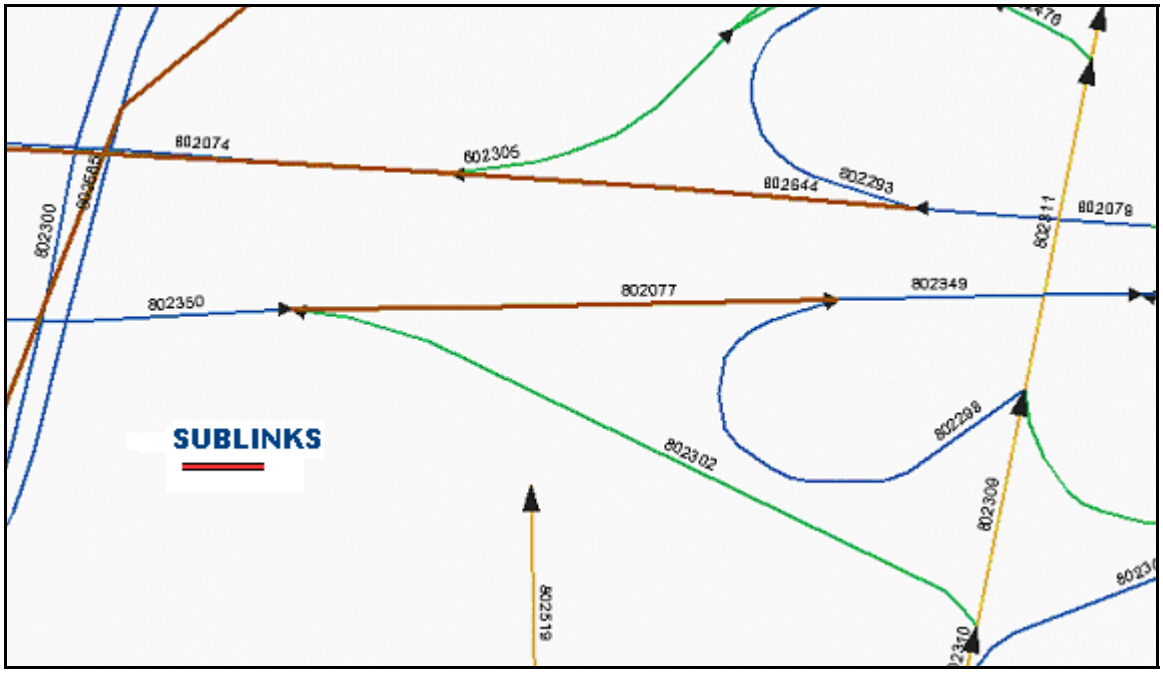

Figure C-22: Sample sublinks

C.4.4.6 Point Attributes

Certain attributes applied to specific points, rather than a longitudinal stretch of roadway, and were maintained as "point" attributes. Some of the point attributes in EDMap were: Stop Sign location, Stop Ahead Sign location, Yield Sign location, and Stopping Location.

The user created a point attribute through the point attribute function menu, which displayed each point type (and "point facing"orientation) as an option. This created a ZEpoint record for the type of point at the selected location. All Repaints were snapped to the link, and their distance along the link (in centimeters from Node 0) was also computed and stored in the schema.

C.4.5 Lane-level Database

In EDMap environment, each lane was associated with a link. A lane had its own shape and was terminated by lane nodes. A lane inherited relevant attributes from its parent link. In addition to link attributes, lanes also had a number of lane-specific attributes. Unlike links, lanes are not connected to each other. Lanes do not continue through intersections. This implies that lanes are physically isolated entities and only have logical relationship to the links. Figure C-23 illustrates typical lane level representation in EDMap database.

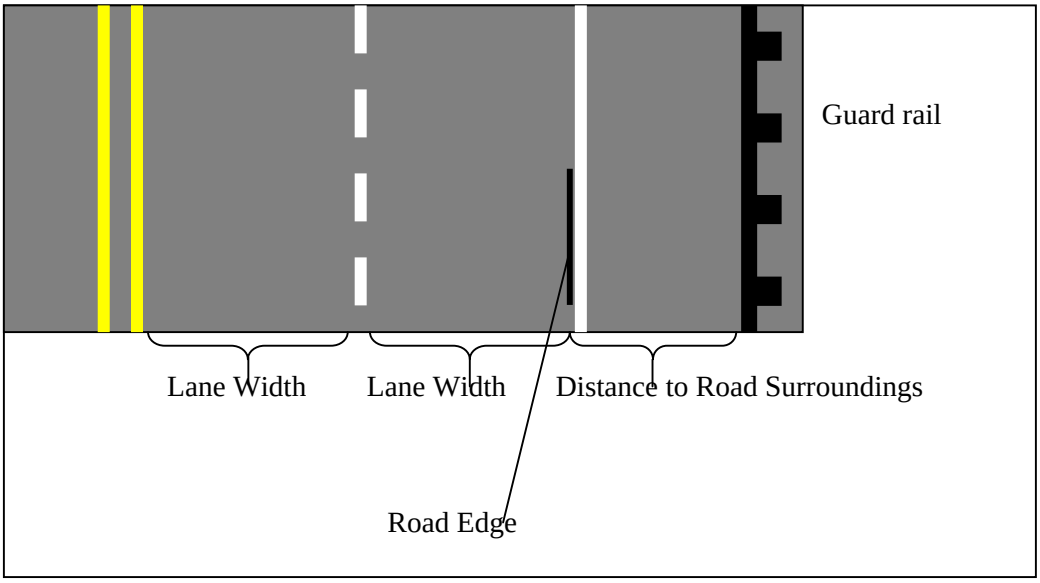

Figure C-23: EDMap database lane representation

Lane geometry represented the actual shape of the lane, as defined by lane markers and/or the road edge. Lanes could be created from a number of input sources, including mobile mapping, remote sensing imagery and probe data, provided the source accuracy was adequate to meet the increased accuracy requirements for lane geometry. In addition, it was learned that the use of remote sensing imagery was very useful when creating lanes. Figure C-24 and Figure C-25 illustrate mobile mapping data as collected by driving on different lanes. Use of the imagery in conjunction with mobile mapping data could reduce ambiguities.

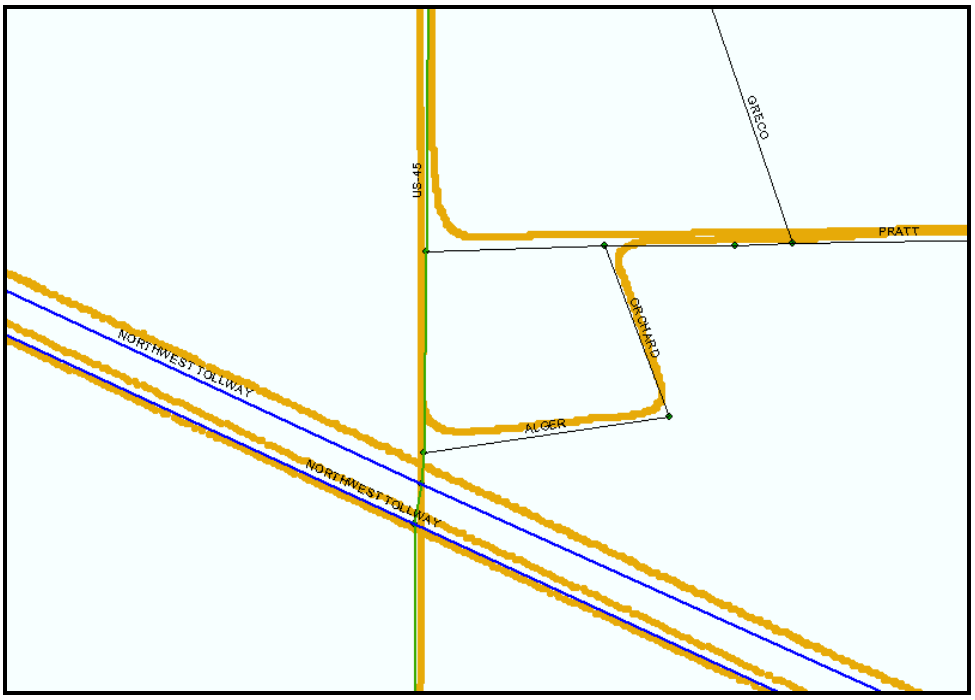

Figure C-24: GPS/INS traces with DNDC backcover

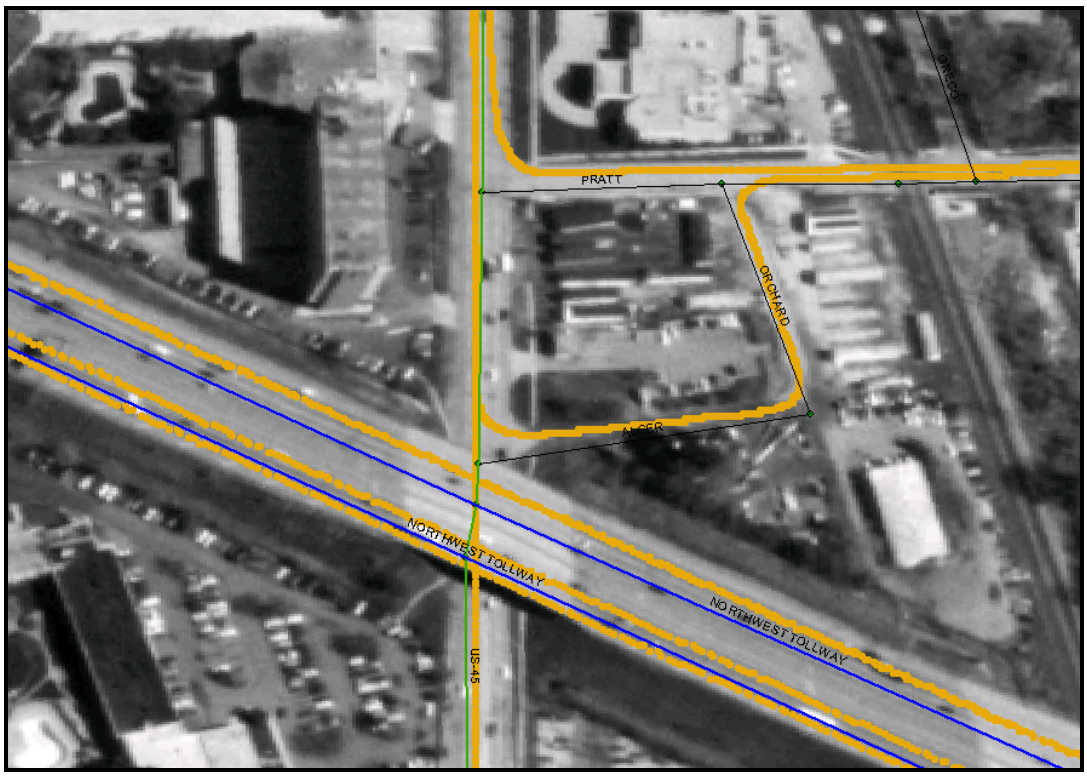

Figure C-25: GPS/INS traces with imagery

The edit tool needed to support creation of lanes from one or more of these data sources. This required a controlled data-editing environment, where data could be viewed and modified in an interactive way. The built-in feature of ArcGIS to view imagery as a background was fully utilized in creating mid-term databases. Software tools were added to create lane geometry interactively by fitting a parametric representation on the selected set of points. Enhancements were made to create lanes from one of the following three approaches.

- Using remote sensing imagery as reference, create lane geometry. Standard ArcGIS edit tools are used along with special algorithms for creating lane records.
- Using GPS positions collected using high-end position systems
- Using centerline layer created from the combination of GPS points and lane keeping systems

Software tools used for lane creation using these approaches are discussed in the following section.

C.4.5.1 Creating Lanes Using Remote Sensing Imagery

This the simplest form of creating lane geometry but requires high-resolution images for reference. In order to create a lane-level database with sub-meter accuracy, the user should be able to see the lanes and pick points manually. Without high quality images, it is difficult for the users to digitize lanes resulting in erroneous lane representation.

The imagery used should also be current (i.e., have current road data), because an old image may not have the current road changes, resulting in erroneous lane geometry. This method is also not suitable for complex lane geometry, like ramps, tunnels, Lane junctions etc., as the user will not be able to see the details of roads and lanes under these conditions.

The process of lane creation starts with selecting the desired ZElink. A list of points representing the lane (called vertices) will then be selected, using the imagery as the reference. At the end of selecting these points, the edit tool will generate a lane geometry going through these points. The edit tool also allows the user to interactively modify the digitized lane, by adding or deleting vertices, until the parametric representation reflects the true lane geometry. The user will also be able to view the control points that form the lane geometry. The control points are part of the read-only layer and are automatically generated by the geometry creation routine. The control points are stored as the parametric representation of the desired lane. This interactive process ensures that the lane geometry reflects the road geometry as desired by the user.

Advantages

- Imagery enables inclusion of small lane elements, such as turn lanes, which are not likely to be driven directly during mobile mapping.
- Use of imagery offers a quick start to adding geometry, as opposed to the time consuming process of mobile mapping data collection
- This can be used as one of the ways to derive the base geometry, which can be improved with mobile mapping data.
- Availability of low cost imagery can be used for deriving attributes that cannot be gathered from mobile mapping without video images (for example, location of guard rails, shoulders, etc)

Disadvantages

- This approach introduces subjective errors due to editor's discretion of the position and shape of the roads.
- This approach also requires very high quality imagery, which is expensive and is not always available for all areas of interest.
- This approach cannot be used for creating geometry in all sections of the road due to overlay of roads (bridges, tunnels, ramps).
- This approach is not suitable for deriving a number of road attributes (road surface, lane marker, lane width, etc)
- Subtle variances in editor-placed vertices are likely to introduce subtle perturbations in curvature and heading.

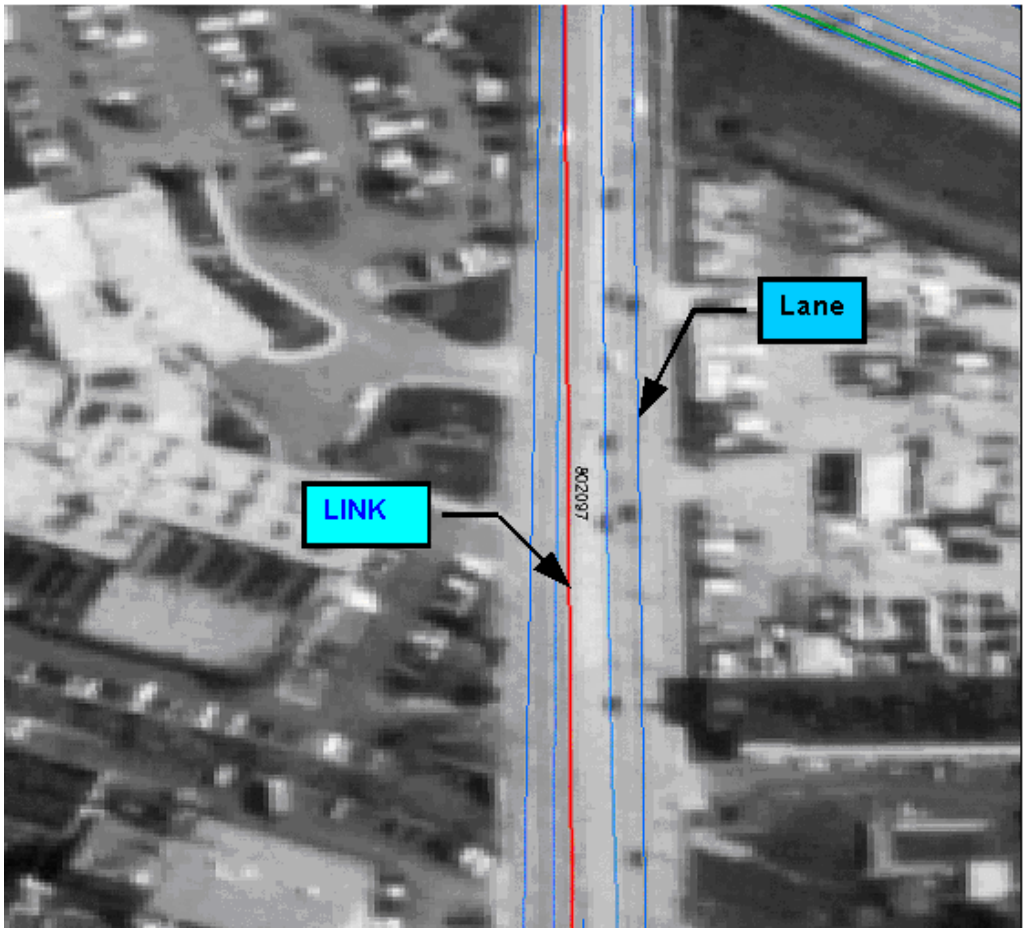

Figure C-26: Lane digitizing using remote sensing image

C.4.5.2 Creating Lanes from GPS/INS Points

This method used the vehicle path captured from GPS/INS system and generated lane geometry using custom ArcGIS tools. After selecting the ZElink, the starting and ending GPS/INS points that are part of this lane were selected. The edit tool used GPS/INS timestamps to sequence the GPS/INS points and fit a parametric representation through these GPS/INS points. This approach also supported addition/deletion of vertex points to ensure that the database representation reflected the actual lane geometry. In view of the ambiguities in selecting starting and ending GPS/INS points, this method was always used with the existing link level database and remote sensing imagery as references. The following figure illustrates the ambiguities involved in selecting starting and ending GPS/INS points in the absence of imagery.

The use of GPS/INS timestamps for sequencing the points introduces additional process overhead in selecting the points from the same drive, as it is likely to have GPS/INS points from multiple passes of the same lane/road may be overlapping with each other.

Figure C-27: Lanes from GPS points

Figure C-28: Lane control points

Advantages

- Since GPS/INS points were available continuously in all roads, using high accuracy GPS/INS points provided a reliable input source for geometry creation.
- Use of GPS/INS points with imagery helped resolve ambiguities due to driving and the ageing in the imagery.

Disadvantages

- Use of GPS/INS points introduced large amounts of data. This was especially true when the data was collected at 10 Hz or more. Data recorded while the vehicle is stationary or at slow speeds were redundant and could have potential distortion effect in geometry.
- The large volume of data also had an effect on performance of the edit tool. Display refresh takes much longer than low-density data points. When this was used along with remote sensing imagery and lane centerline points, it had significant performance impacts on the process of database creation.

C.4.5.3 Creating Lanes from Lane Centerline points

Lane creation using lane centerline was, from an edit tool perspective, the same as that of creating lanes from GPS/INS points. The edit tool treated these two set of input points in a similar way. However, it is to be noted that in many cases, lane centerline points were not available throughout the length of a link. In addition, the errors in lane tracking system and centerline generation algorithm were also reflected in the lane geometry creating using lane centerline points.

Like GPS/INS points, the lane centerline cannot be used reliably in areas where there are lane changes (during driving and lane transitions).

Figure C-29 illustrates the typical variations in lane centerline data.

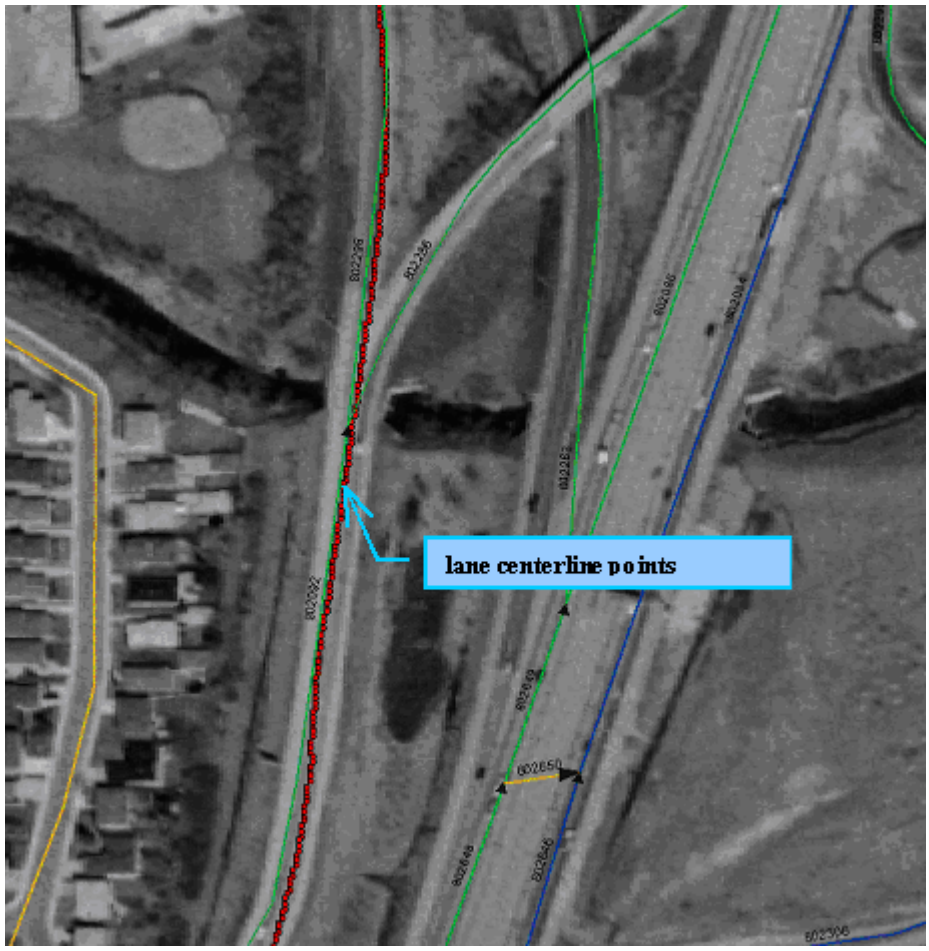

Figure C-29: Lane centerline data

Advantages

- This method helps created true lane centerline as accurately as possible.
- Since lane centerline points were created in a post processed approach by combining GPS/INS points with lane tracking system parameters, it was possible to refine this approach to eliminate system errors.

Disadvantages

- Lane tracking system did not always have continuous set of information.
- Errors in lane tracking system may result in skewed lane centerlines.
- Lane changes and entrance/exit ramps may results in erroneous lane centerline.

C.4.5.4 Additional Features for Lane Geometry Creation

In an effort to simplify the efforts needed to create lane geometry, a number of additional tools were created in the edit tool. These were incorporated based on the user feedback in creating mid term databases. These tools are briefly described below.

Shifting Lanes

This feature supported new lane geometry to be created from the existing lane geometry. The new geometry could be created either by shifting the existing lane geometry to a specified location or by the shifting it by a specific distance.

This feature was an effective way of creating lane geometry for multiple lanes. Typically, the outer lanes in a multilane road (say 3 lanes) were driven. Using the lane shift command created the geometry for the middle lane. The lane offset for the shifted lane was specified either from the available lane width data or from the imagery information.

Shifting the current shape points a perpendicular offset of n meters from its original geometry derived the shape points for the new lane. This not only affected the new lane's position, but also its shape and curvature. Thus, if a new lane was created for a ramp using this method, the new lane's length and curvature were modified to take into account the shift in position. The algorithms behind this implementation are discussed in different sections of this report.

Recreating Lanes

This feature is a powerful tool for making corrections to the existing lane. Whenever vertex points were added or deleted, the curve parameters for the lane could be re-calculated, keeping non-curve-related attributes for the lane intact.

There were some situations where a lane's geometry needed to be re-created, such as when a centerline point data became available for a lane originally created manually from remote sensing imagery. A tool was developed to allow the editor to define new lane geometry from the better source, and then merge all the attributes, relationships, etc., from the original lane onto the newly created lane.

C.4.6 Traffic Signals

A traffic signal is a multi-colored light governing traffic flow. Traffic signals differ from other road attributes because the EDMap applications need the positions of each signal face, both laterally and longitudinally. The number of signal faces does not necessarily correspond to the number of lanes. A traffic signal is identified by its position and also from which direction and to which maneuvers(s) it is relevant. Each traffic signal is associated with one or more lanes.

At data collection time, the operator indicates (via a "mobile plotting"-type entry) that a traffic signal is present. This information will appear as an icon on the map display, which will indicate that a traffic signal is to be added at this intersection.

Mobile plotting alone is not an option to derive locations of traffic signals. This implies that traffic signals can be added only if images are recorded. A very high quality of imagery is needed in order to create traffic signal locations using remote sensing imagery, and other traffic signal attributes cannot be determined from the imagery. While it may be possible to derive intersection maneuvers from probe data, the precise positioning of traffic signals requires imagery.

The precise entry of the traffic signal positions was done using the photogrammetry tool. Positions could be triangulated from two image frames directly in the photogrammetry tool A sequence of two images was brought up for display at the intersection, and a pair of corresponding clicks in each image created the traffic signal.

Alternatively, the editor could place a traffic signal by reconciling artifacts in the Photogrammetry tool image against other evidence. For example, if the imagery indicated that a signal was located directly over a lane center and directly over a crosswalk, the editor could place the signal based on the lane center (as indicated by centerline points) and the crosswalk (as seen in remote sensing imagery).

Regardless of which method was used to place a traffic signal, the editor then indicated the signal's attributes, including an indication as to whether the signal is a "left turn signal."

If any road that participates in an intersection has a traffic signal, it is expected that all other roads participating in the same intersection also should have a traffic signal. Legal exceptions are possible; for example, intersections with separately digitized right-turn lanes may or may not have traffic signals for the turn lanes. Each road segment that has one or more traffic signals will need to have an associated stopping location.

Once a traffic signal was created and positioned, it was associated with other signals sharing identical characteristics to form a traffic signal "cluster." The cluster was then associated with the particular intersection maneuver(s) governed by that set of signals.

Some of the logical validations for traffic signals include:

- If at least one traffic signal cluster exists for an intersection, then each lane maneuver for the intersection must be controlled by at least one traffic signal cluster
- A single traffic signal cluster only controls maneuvers originating from a single link. If it controls maneuvers originating from multiple links, generate a warning message.
- Every traffic signal cluster must control at least one maneuver. Every traffic signal must be part of at least one traffic signal cluster.
- Multiple traffic signals cannot have the same lat/long in the intersection.

C.4.7 Photogrammetry

Photogrammetry was one of the most valuable add-in for the edit tool. This tool allowed the editor to create attributes accurately based on video images recorded during mobile mapping. This tool is also the only option to create some of the EDMap database attributes such as shoulder width.

Video images were recorded as part of mobile mapping. These were recorded as individual image frames. Each frame was stored as a separate image file. The frame rate for these images was controlled by a set of configuration parameters. As part of the merge process, these images were assigned to a location.

The backcover creation module generated an image layer and stores the name of the image file for each location. Camera configuration parameters were also stored in the database repository.

The cross-reference information with location and image file was used by the edit tool to display these images at a specific GPS location. The display of images let the editor play back the mobile mapping drive to clarify ambiguities during database creation. Two frames from consecutive locations were displayed to help the user understand the driving scenario. Figure C-30 illustrates the typical display of two frames in an edit tool environment.

Figure C-30: Two frame edit tool display

Since these images are geo-referenced, it was possible to locate the position of the objects in these images. This tool could also be used to measure the width of a lane.

C.5 Maintainability

C.5.1 Overview

Like any map, the EDMap map database is a representation of ground truth in the real world at a particular time. The map database thus loses accuracy any time an element of the real world changes (until the map is updated accordingly). Any reduction in accuracy can diminish the effectiveness of the EDMap applications. Thus, the map database must strive not only to be created with high quality, but also to be kept current with changes in reality.

A prerequisite to keeping the map databases current is the knowledge that a change in the real world has occurred (or will occur). Various methods and strategies for detecting or predicting change are discussed in Section C.5.2.

The impact of data change or inaccuracy are analyzed for each EDMap attribute in Section C.5.3. This section appropriately focuses on the types of change that have the most serious consequences to applications.

Any updates to the digital map will need to be available to the EDMap applications, potentially very quickly. Section C.5.4 discusses alternative methods to deliver map updates.

The digital map's response to real-world changes depends to a large extent on the underlying nature of the changes. These can be classified into three distinct categories:

- "Permanent" change is a deliberate change to the roadway or related infrastructure, with lasting effects. (The term "permanent" should not be interpreted as "eternal", but rather "indefinitely long".) The most obvious example is a new road, or a major reconstruction project that changes the characteristics of the road. But any lasting change to any aspect of the road that is reflected in the database is also a permanent change, e.g., a change to speed limits, a new road surface, addition of stop signs, changes to traffic signals, etc.
- "Acute" change refers to short-term situations that may have a serious effect on traffic flow and traffic safety for a brief period of time. An example would be a small construction project that closes or shifts some traffic lanes for the duration of the project. Crashes or other traffic incidents that disrupt traffic or affect safety could also be considered to be a type of acute change.

  The extent to which map databases can or should be concerned with acute change is not clear. Certainly, even a system with very quick response time will not be capable of reflecting an incident instantly. However, these just-occurred incidents may be the most important ones for vehicle safety systems analysis.
- "Evolutionary" change refers to changes that occur naturally, or because of activities other than intentional roadway infrastructure change. The EDMap database maintains an assessment of road surface quality; this quality may degrade over time. Road markings may erode or fade. Roadside clutter, such as mailboxes, sign posts, etc., may accumulate. Tectonic changes (relative motion of portions of the earth's crust) are detectable with the highest-accuracy positioning devices, including base stations. The WGS84 standard ellipsoid takes tectonics into account.

C.5.2 Methods of Detecting Change

Currently, NTC employs a variety of methods to detect real-world change. No single method is adequate for all types of change detection. Each method has particular strengths and costs. In addition to methods currently being used or being considered, some additional methods particularly suited to EDMap data are emerging.

C.5.2.1 Local Knowledge

"Local knowledge" takes advantage of the geographic diversity of the NTC field staff. As of February 2003, field personnel are based in 51 different field offices in the 48 contiguous states. Because of their presence in the area, field personnel are likely to be aware of changes that are taking place in their respective areas, from direct observation, local newspapers, TV/radio, etc. They may even be aware of changes that are forthcoming.

However, local knowledge has limitations. Clearly, this will be strongest in areas where the field personnel are present the most often, in the vicinity of their homes and offices. Other areas are less likely to benefit. Thus, information from local knowledge will not be ubiquitous.

C.5.2.2 Official Contacts

The field staff has generated relationships with local governments, highway departments, and other pertinent agencies, to enable acquisition of information about new and changed map elements. As with local knowledge, this method of obtaining information could potentially inform NTC about future changes, thereby improving the timeliness of the updates. Contact with these agencies can be systematic and is not limited to the areas where field staff live and work.

There is still a lack of consistency from place to place regarding the quality and value of information obtained from official contacts. Some areas employ database or GIS systems, and may make data available digitally. Other areas may have only minimal paper records.

The Government Accounting Standards Board (GASB) statement 34 establishes asset reporting requirements for local governments, including highway infrastructure elements. The implementation of this standard may make data regarding roads, bridges, traffic controls, and similar elements more available and more consistent between localities. GASB 34 reporting will become more prevalent in coming years, though the timing of adoption will vary.

C.5.2.3 Postal Reporting

NTC uses publicly available data from the United States Postal Service (USPS) to help determine when new streets are being created. USPS listings of street names and address ranges are crosschecked against the NTC map and new street names, or new address ranges (indicative of new construction) are detected. This is a cost-effective method that NTC already uses successfully. The coverage is nationwide. Timeliness is good, as USPS data is updated with new streets before homes or other buildings on that street can begin to receive mail.

Postal reporting has limitations. While a good indicator of new streets, it does not offer any indication of changes or problems on existing streets. Freeways are generally not included. And even when there is a clear indication that a new street is being created, the only data provided about the new street is its name, addresses, and ZIP code. Field staff will still need to collect the geometry and attributes for the new street.

C.5.2.4 Customer Feedback

NTC has established a method whereby its customers (and OEM customers) can provide feedback to NTC regarding changes needed in the map database. The company provides this system on its public Internet page. Data is then disseminated to the appropriate field office for research and update.

This is a purely reactive system. By the time a customer observes a change, the map database had already been released, published and distributed. Thus, a significant time lag is inherent. Changes are more likely to be caught in areas with a higher density of navigation system users. Only attributes that are evident to the end-user are likely to be reported. The quality and reliability of this feedback depends on the diligence of the customer. Invariably, the field staff will visit the site of the reported error to verify and recollect if needed.

C.5.2.5 Mobile Mapping

As with the initial map creation process, mobile mapping is the collection of data in the field with specialized equipment and techniques. A mobile mapping drive for update would typically be in response to a "research lead" - an indication from some source that a change has taken place. Postal reporting, customer feedback, and information from local knowledge or official contacts are all forms of research leads. It is also possible to detect previously undetected changes while mobile mapping, e.g., when en route to an area of new roads.

Mobile mapping has the capability to obtain virtually any map attribute, if the mobile mapping vehicle is appropriately equipped.

But mobile mapping is not a broad solution for change detection. The capacity to collect is necessarily limited by staff and equipment, and thus the re-visit frequency will be low. It is not cost-effective to simply periodically re-collect an area in the hope that changes will be detected, without benefit of research leads. Because the re-visit frequency is low, mobile mapping is not suitable for detecting acute problems.

C.5.2.6 Remote Sensing

Remote sensing sources, particularly aerial photography, are widely used as sources to assist in database creation. Compared to other techniques, remote sensing offers the opportunity to obtain data for a large area with a single source. Remote sensing sources can provide a number of relevant attributes, including road (and potentially lane) geometry. In theory, a comparison of new remote sensing data against existing maps (or previous remote sensing data) could be a means to detect change.

Historically, remote sensing techniques have not been used as sources for change detection, largely because of timeliness:

- Imagery is not re-captured very frequently, in part, due to costs but also because relatively few days per year provide optimal conditions for aerial photography.
- There is a significant time delay between the time an area is photographed to the time it is available for use. Imagery needs to be orthorectified before it can be used for map-making. Orthorectification compensates for distortion caused by viewing angles and altitude variation.

Use of radar (IFSAR) imagery rather than visible light enables collection on days that are not optimal for normal optical photography. However, IFSAR imagery has limitations when observing road networks. Road features are not nearly as conspicuous as with optical photography.

Imagery from satellites, rather than aircraft, would seem to address the problem of timely re-visitation. At present, however, satellite imagery is not continuously available and freshness and frequency of satellite imagery is comparable to aircraft-based sources. This is a technology to watch, however, as quality, availability, and cost should continue to improve.

Because of the timeliness aspect, remote sensing is unsuitable as a source for detecting acute (short-term) change. Aside from timeliness, the high cost of high-end remote sensing data make it less practical as a source to detect change.

C.5.2.7 Probe Vehicle Analysis

The use of data from probe vehicles is a very promising approach to change detection. With a sufficient "fleet" of probes on the road, re-visit rates can be very high and coverage very broad. With suitable communications from probes, timeliness can be very good, even to the point of enabling detection of acute change. Probes with basic GPS-based positioning equipment can reveal road geometry and, potentially, lane geometry. If and when additional sensors become incorporated into probe vehicles, relevance to additional attributes is possible.

At present, probe data analysis is a research topic. The data available for research is somewhat artificial (being based on highly-repetitive drives with a small fleet). Actual availability of real probe data is still in the future. A number of communications, data storage, and privacy issues need to be solved in order to enable ubiquitous sources of probe data. Probe vehicle techniques are not expected to be viable in the EDMap near-term time frame, but for the long-term it shows promise.

C.5.2.8 Traffic Reporting Systems

Real-time traffic reporting systems are starting to become integrated with digital maps and, to some extent, in-vehicle navigation. These are systems focused on highly timely reporting of changes in road and traffic conditions, including actual traversal speeds and points of obstruction. Thus, these systems have the potential to provide information about acute change.

For the foreseeable future, these systems will be limited to major roads (freeways and perhaps key arterial surface streets). A traffic reporting system could be expected to provide an indication that there is an acute problem, such as a crash or lane closure, but will not provide update lane-level geometry or other attributes. Like probe vehicle techniques, traffic-reporting systems are not expected to contribute to EDMap change detection in the near-term time frame.

C.5.2.9 Highway Infrastructure

Other potential real-time sources of information along the road network are fixed-position sensors installed in or near roads. These are capable of reporting acute incidents in the road very quickly.

In practice, these systems are somewhat fragmented, as they are maintained by various local and regional agencies. The most sophisticated sensors are concentrated on major roads and these sensors may be a primary data source for traffic reporting systems (described above). Data from sensors on more local roads, such as for traffic signal actuation, is used within the immediate system but is less likely to be centrally available.

C.5.3 Evaluation for Each EDMap Attribute

This section will review the various EDMap near- and mid-term attributes, and describe:

- The type(s) of change that are anticipated (permanent, acute, evolutionary)
- Causes and likelihood of change
- Methods to detect change

C.5.3.1 Near-term Attributes

Road Geometry: Centerlines, Curvature, and Number of Lanes

Permanent changes to road geometry are caused by new roads and major construction projects (road rebuilding). These changes are infrequent and generally well known in advance. Many established methods will indicate that a change is forthcoming. These include local knowledge, official contacts, postal reporting, customer feedback, mobile mapping, and even remote sensing.

Acute changes to road geometry are caused by small road-repair projects, crashes, and other road incidents (e.g., a stalled car, emergency services, etc.) that cause vehicles to deviate from normal road paths. These changes are likely to happen any time, and are therefore difficult to anticipate or predict. It is possible to know in advance about some roadwork projects via official contacts or local knowledge. Incidents, of course, cannot be predicted.

Traffic reporting systems and probe analysis can report any acute changes that affect road geometry, but these are not expected to be widely deployed in the near-term timeframe.

Long-term changes in the earth's surface (plate tectonics) could be considered to be an evolutionary change to road geometry. These changes are in the order of centimeters per year, and are thus not really a factor at the road-level, where centerline accuracy targets are 5 m.

Road Geometry: Road Grade, Superelevation

These aspects of road geometry are not really subject to acute or evolutionary change. The nature and causes of permanent change to road grade or superelevation are the same as other permanent changes to road geometry (new roads and major construction projects, with the same established methods to know that a change is forthcoming).

Road Surface Type

The type of material present on the road surface will change only as a result of road construction projects (major or minor). As a result, awareness of these changes is most readily obtained from local knowledge, official contacts, and (in the case of new roads) postal reporting. Mobile mapping and remote sensing may also detect new or repaired roads.

Occasionally, a road with one surface type may get repairs with another. The most typical example is an asphalt patch on a concrete road. Over time, these may change the predominant surface type of the road if a significant portion of the road has been patched.

Road Condition

The physical condition of the road surface is capable of changing unintentionally as well as intentionally. New roads, or road repair projects, cause a permanent change to a road’s condition. These changes are infrequent and predictable. Awareness of these changes is

thus obtainable from local knowledge, official contacts, postal reporting (for new roads), and to a lesser extent, mobile mapping or remote sensing.

Acute incidents do not affect road condition. An incident such as a spill can affect the surface of the road, but this is considered to be outside the scope of the digital map, as is the case with rain, ice, or snow on the road surface.

Road condition is an attribute that is subject to gradual, evolutionary change, as the road surface decays over time. These changes are likely, but not reliably, predictable. They can be detected by local knowledge or official contacts. Some road agencies obtain and record a "Pavement Condition Index" (PCI), a numerical index representing the pavement's functional condition, as a means to prioritize road repair projects. Not all agencies have, or share, this information.

In EDMap, road condition is a somewhat subjective attribute. Roads are rated as "smooth", "rippled" (laterally uneven) or "uneven". There is no quantified threshold separating these ratings, and thus it will be difficult to determine when a road's condition warrants re-rating.

Road Class

EDMap uses NTC's road classification ("functional class"), which is a ranking of roads in accordance with hierarchical traffic usage. Road classification is really only an issue for new roads, or highly significant improvements to existing roads. Therefore, changes to road class are unlikely, and any changes that occur are highly predictable.

Like any new roads project, changes can be predicted or detected through local knowledge, official contacts, postal reporting (for new roads), and to a lesser extent from mobile mapping or remote sensing.

Signs and Stopping Locations

Near-term databases record stop signs, stop ahead signs, yield signs and stopping locations (painted stop lines). These signs are subject to permanent change, caused by new roads or by other activities such as local initiatives intent on traffic calming.

Changes to these signs may be detected (or occasionally predicted) via local knowledge, official contacts, a mobile mapping revisit, and (for new roads) postal reporting.

Signs and stopping locations are not subject to acute or evolutionary change. The temporary absence of a sign (such as from collision damage) does not warrant its removal from the map database.

C.5.3.2 Mid-term Attributes

Some mid-term EDMap attributes are similar to near-term attributes and the same issues and approaches for change detection apply. Geometry, curvature, surface type, and condition are also applied to individual lanes in the mid-term map.

The time frame for mid-term maps should allow exploitation of the probe vehicle and traffic reporting sources, neither of which is expected to be feasible in the near-term time frame.

Lane Geometry: Lane Centerline and Lane Curvature

Lane centerlines and curvature have issues similar to those for near-term road centerlines and road curvature.

However, incidents that cause acute change will have a more profound impact on lane-level geometry than on road-level geometry. For example, a car stalled in a traffic lane may or may not cause the effective road centerline to vary, but it will certainly affect the blocked lane and perhaps its neighbors as well.

Probe vehicle data is expected to be a significant help to detect acute change. It can indicate the effective temporary lane centerline, and curvature can be determined from the centerline. This is of course dependent on the ability to get accurate lane-level positioning from probe data.

Lane Width

Like other permanent geometry changes, the width of a lane will be established or re-established when a road is built or reconstructed. These changes are infrequent and predictable, as is the case with other road construction situations.

Activity or incidents along the road are likely to cause an acute change in lane width. Small roadwork projects, lane striping, and utility work are examples of "activity". Some of this activity can be reported based on predictions by local knowledge or official contacts. The empirical effect on lane width may be detectable by probe vehicle data, if inferred from lane centerlines.

Lane Markings

Permanent changes to lane markings are similar to other permanent geometry changes (caused by new roads or major construction projects, predicted or detected by local knowledge or official contacts). The presence of new roads, and thus new lane markings, can be predicted or detected by postal reporting, customer feedback, mobile mapping, remote sensing, or probe vehicles.

Acute changes to lane markings, such as temporary re-striping for roadwork, or utility work, may be detectable indirectly from probe vehicle data or official sources. None of these sources, however, is expected to provide any details about the temporary markings (such as placement, configuration or color).

Lane markings are subject to evolutionary change only in the sense that they can become less visible over time, such as when lane paint erodes or flakes off. However, this would not change the underlying nature of the lane marking as maintained in the database (placement, configuration or color), and therefore there is no real impact of lane marking degradation on the map database.

Shoulders: Pavement Type, Width

Changes to shoulder pavement type (paved/unpaved) or width are unlikely to change except in the event of a new road or major construction project. The methods previously described to detect new roads or construction projects apply to shoulders as well.

However, the acquisition of updated information about the shoulder pavement type or width will need to be done similarly to how the data is collected initially; most likely with mobile mapping (including in-vehicle image capture), and sometimes augmented by remote sensing sources. Probe vehicles are not expected to traverse shoulders, and would not provide pavement type or width information regardless.

Shoulder pavement type and width is not subject to acute or evolutionary change. A paved surface would have to be horribly eroded for the width to change, or to be considered "unpaved”.

Intersection Location and Intersection Geometry

These mapplets refer to the point at which a lane enters an intersection, and maneuvers within the intersection respectively. For the most part, these will change only if there is a reconfiguration of the intersection itself, with the same issues and responses as for other mapplets affected by road construction.

It is also possible that the set of valid intersection maneuvers (input lane to output lane) can change, if a turn restriction is imposed or removed. Local knowledge, official contacts, customer feedback or mobile mapping can be used to predict or detect turn restriction changes. Turn restrictions are already maintained in current NTC digital maps.

Lane Direction

This mapplet refers to the direction of travel defined for a lane. This is highly unlikely to change on a permanent basis, with the exception of new roads. The same detection methods previously cited for new roads would thus apply here.

It is possible for lane direction to change temporarily in the event of roadwork, utility work, or incidents. This could be detected by probe vehicle data along with other acute changes to lane geometry.

Traffic Signals

Permanent changes to traffic signals can stem from several causes. The most obvious is new road construction, with signals added not only to the new road but also to existing intersecting roads. As with stop signs and yield signs, traffic signals may be introduced as a response to local initiatives intended to calm traffic or improve access to arterial roads. Changes to traffic signals are most likely in high-growth areas.

Local knowledge and highway agency contacts will be the primary sources for predicting change to traffic signals. Fortuitously timed mobile mapping can detect changes as they are being implemented, such as when signals are being installed. Probe vehicle analysis could be used to determine when traffic signals have been made operational. A dynamic evaluation of probe data at an intersection can reveal when intersections are controlled by signals or stop signs.

Mobile mapping with in-vehicle imagery is the only technique at hand that can be used to create traffic signal data per EDMap requirements. Probe data or other sources can indicate that a signal is in use, but will not provide the data necessary to add the traffic signal into the database.

Traffic signals are not really subject to acute or evolutionary change. Any signal malfunction will need to be detectable in the applications.

Overhead Structures

Overhead structures change rarely, and any changes would be considered permanent. Potential causes of new or changed overhead structures are road construction projects, the addition of new signage on freeways, or construction of overpasses for railroads or walkways. Information about these changes would be obtained from local knowledge, official contacts, and, for new roads postal reporting or probe vehicle data.

Once established, acute or evolutionary change to overhead structures will be rare. Structures that are abandoned, such as viaducts for vacated railroads, are likely to remain in place indefinitely. If an overhead structure were to be removed, local knowledge or official contacts would be the primary sources of information.

Roadside Barriers

Metal and non-metal barriers along the roadway are most likely to change with the new road construction or reconstruction. Information to predict or detect these changes will come from local knowledge, official contacts, or mobile mapping re-visitation.

Some barriers will be evident in remote sensing data—particularly, metal barriers with radar-based sources—but, as discussed earlier, these sources are not expected to have the timeliness to be a dependable source for change. Probe vehicle data and traffic reporting systems will not provide any indication of changes to roadside barriers.

Barriers are in the database to assist radar-based applications, and would not normally be displayed to a navigation user. Therefore, it is not expected that customers would provide information about changes to barriers as they might today report changes to roads or points of interest. It is conceivable that in the future, EDMap-equipped vehicles could accumulate data about "false positive" radar warnings, and provide that information as feedback back to the map maintenance process.

Stationary Roadside Objects

This mapplet refers to miscellaneous roadside clutter, such as signposts, light standards, mailboxes, and so on. This is assessed subjectively and applied to the database as a numerical rating (0-4).

In general, a Stationary Roadside Object score is not expected to change over time. As with Road Condition, there is no quantified threshold separating these ratings. The addition or deletion of individual objects should not affect a road's rating. Large-scale changes, of course, could warrant a re-assessment of a road's rating.

C.5.4 Delivery of Map Updates

Current production-level in-vehicle applications using map databases (navigation systems) invariably are on-board systems, i.e., a copy of the digital map is stored in the vehicle. The databases are updated on a quarterly or semi-annual basis, and as a result the map freshness is measured in terms of months. It is unlikely that this approach will be timely enough to suit the requirements of most safety applications.

An alternate technology being developed is the "off-board" system. Map data is stored in a central server, and communicated to the vehicle as needed. In these systems, map delivery would not impede freshness as with on-board systems. These systems would require a high communications bandwidth to handle the volume of data between the central server and the served vehicles.

A "hybrid" technology attempts to leverage the advantages of both on- and off-board systems. Map data is stored in the vehicle, and updated periodically as it is in on-board systems. But updates (deltas between the most-current map and the on-board map) are communicated from the central server. This provides the timeliness of off-board systems, but with lower demands on communications and bandwidth. The in-vehicle database would still need to be updated periodically, and the overall system has a higher complexity than either an on- or off-board system.

To reap the benefits of off-board or hybrid systems, maps will need to be updated and delivered in much closer to real-time than they are in today's maps for navigation. Prototype work to support frequent updates and real-time delivery of maps is proceeding, and preliminary products are becoming available. And of course, applications will have to be engineered to take advantage of real-time updates.

C.6 ADASRP

ADASRP stands for Advanced Driver Assistance Systems (ADAS) Research Platform. It is an application framework that provides ADAS research and development engineers with access to digital map data attributes about the roadway lying ahead of a moving vehicle. With ADASRP, the engineers can quickly do experiments with those attributes to see how they can be used and what effects they have in ADAS applications. ADASRP is a combination of hardware and software that runs in a Microsoft Windows NT or 2000 environment.

C.6.1 Architecture

A concept central to ADASRP is Electronic Horizon (EH). An Electronic Horizon is a tree of potential driving paths of the vehicle from the current vehicle position. The Electronic Horizon's construction process is based on the road network of the area surrounding the current vehicle position. It requires a valid vehicle position on a specific location of a specific link. The electronic horizon (EH) distance, which is configurable by the user, determines the extent of the electronic horizon. For example, if the EH distance is set to 200 meters, then all the links in front of the vehicle that are within 200 meters from the current vehicle position will be included in the electronic horizon.

The following diagram shows the architecture and components of the ADASRP base system. A brief description of each component of the ADASRP is provided.

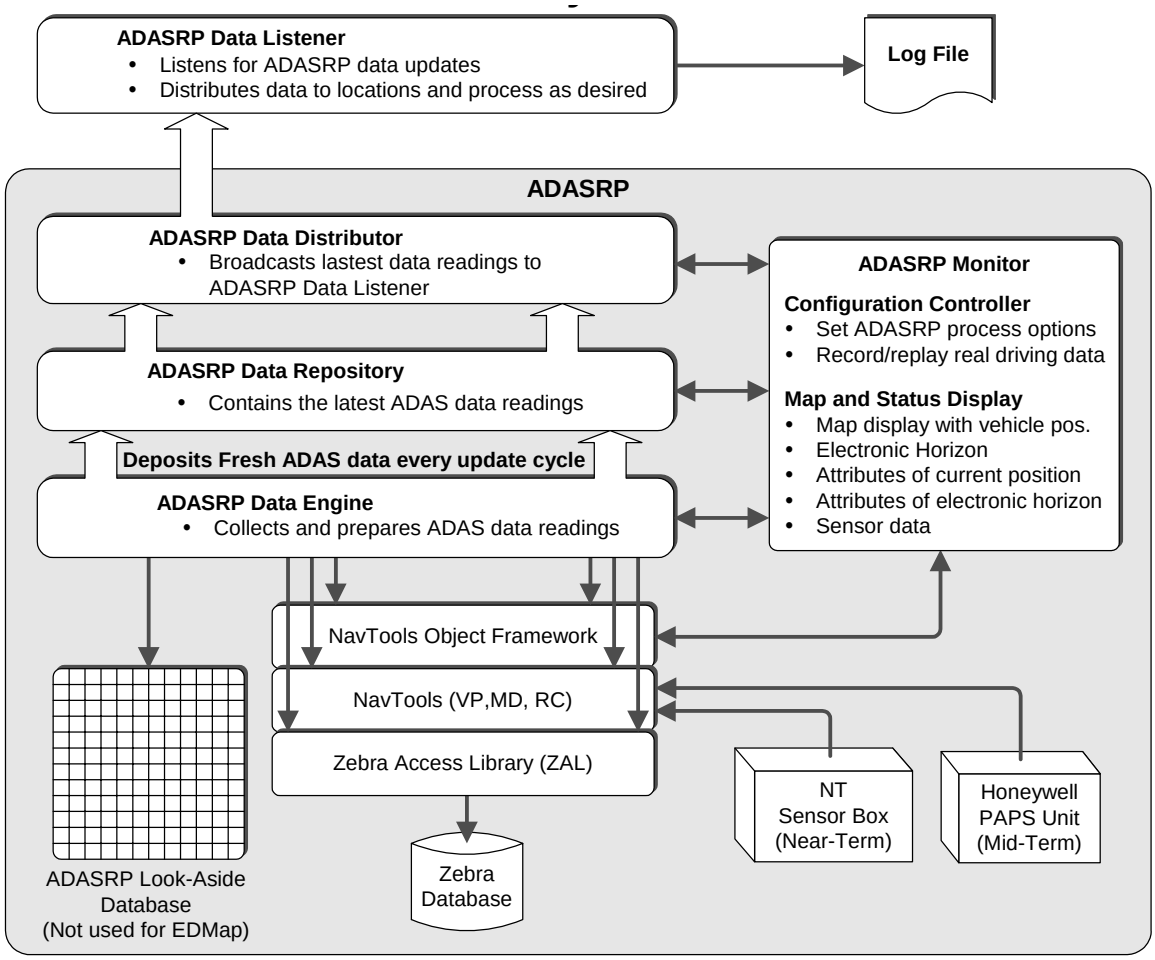

Figure C-31: ADASRP system overview

C.6.1.1 ADASRP Data Engine

The ADASRP Data Engine performs the ADASRP data readings at intervals determined by a user set parameter. At each cyclic execution, the ADASRP Data Engine determines which links fall inside the Electronic Horizon and then performs ADASRP data reading operations for each of those links.

C.6.1.2 ADASRP Data Repository

The ADASRP Data Repository holds the sets of ADASRP data readings created by the N most recent cyclic executions of the ADASRP Data Engine, where N is configurable by the user. The repository contains the attributes of links within the Electronic Horizon, the vehicle position, and the sensor readings.

C.6.1.3 ADASRP Data Distributor

The ADASRP Data Distributor broadcasts events upon the availability of new ADASRP data readings in the ADASRP Data Repository to all ADASRP Data Listener processes who have registered. Since the ADASRP Data Repository contains three different types of data (electronic horizon data, sensor readings data, and vehicle position data), three different types of events are broadcast to three different types of ADASRP Data Listeners.

C.6.1.4 ADASRP Data Listener

There are three different types of ADASRP Data Listeners, one for electronic horizon, one for sensor readings, and one for vehicle position. An ADASRP Data Listener is notified whenever new data readings the Data Listener is listening for are available in the ADASRP Data Repository. Once the Data Listener is notified, the data can be easily retrieved from the ADASRP Data Repository by a separate function call.

C.6.1.5 ADASRP Look-aside Database

The ADASRP Look-aside Database contains additional map data that is beyond the contents of the current standard map database. It is a quick way for ADAS engineers to add additional map attributes that are required by ADAS applications but are not available yet in the standard map database. Since the additional map attributes required by EDMap ADAS applications are compiled directly into the Zebra map database, the look-aside database is not used for EDMap.

C.6.1.6 ADASRP Monitor

The ADASRP Monitor is a sample application that provides a graphical user interface for ADASRP. It acts as a graphical front end for configuring and starting/stopping the ADASRP Engine as well as viewing the map data through the ADASRP Data Listeners. The ADASRP Monitor provides a map display environment that includes the display of current vehicle position, planned route, link attributes, and electronic horizon.

C.6.1.7 Zebra Database

The ADASRP utilizes the Zebra Database to support vehicle positioning, route calculation and map display, and to provide much of the data readings placed in the ADASRP Data Repository by the ADASRP Data Engine.

C.6.1.8 Zebra Access Library (ZAL)

Zebra Access Library contains a set of functions (APIs) to support access of map attributes in the Zebra Database.

C.6.1.9 NavTools (VP, MD, RC)

NavTools contain a suite of tools, built on top of Zebra Access Library, to support operations frequently used in vehicle navigation systems, including Geocoding (GC), Map Display (MD), Route Calculation (RC), Route Guidance (RG), and Vehicle Positioning (VP). ADASRP currently uses only Map Display, Route Calculation and Vehicle Positioning tools.

C.6.1.10 NavTools Object Framework

NavTools Object Framework (NTOF) is an object-oriented wrapper around Zebra and NavTools to simplify their use and facilitate rapid development of prototype applications in a Microsoft Windows NT / 2000 environment.

C.6.1.11 NT Sensor Box

NT Sensor Box contains positioning sensors, which are used by the Vehicle Positioning tool to determine the position of the vehicle on the road at the time of each ADASRP data reading. NT Sensor Box is used for EDMap near-term applications.

C.6.1.12 Honeywell PAPS Unit

Honeywell PAPS Unit is a high precision Prototype Automotive Positioning Sensor (PAPS), which is used by Vehicle Positioning tool to determine the position of the vehicle on the road at the time of each ADASRP data reading. Honeywell PAPS unit is used for EDMap mid-term applications that require higher positioning accuracy.

C.6.1.13 Advantages

Many car manufacturers have used ADASRP with their ADAS applications to utilize the additional road attributes to develop safety features for the next generation of cars. ADASRP generates the electronic horizon ahead of the vehicle that contains potential paths the vehicle may travel and the road attributes along those paths. The electronic horizon allows the ADAS applications to look ahead of the roadway and to take appropriate actions when necessary. For example, when a vehicle is approaching a curve road, the ADAS application can get the road curvatures ahead of the vehicle from the electronic horizon and determine the safe speed of going into the curve road without overturning the vehicle. If the vehicle speed at that moment is greater than the safe speed derived from the road curves, the ADAS application can either warn the driver or apply the brake to slow down the speed to safe level.

ADASRP was selected to deliver the EDMap attributes because its electronic horizon concept meets the needs of the EDMap ADAS applications. By adapting ADASRP to EDMap, we did not have to spend the time developing an entire database attribute delivery software suite.

Another advantage of using ADASRP for EDMap is its data listener concept that isolates the EDMap ADAS applications from the details of accessing map database. Typically, an ADAS application is running on a dedicated micro-controller connected to an in-vehicle data bus, while the ADASRP engine is running on a separate processor. The ADASRP data listener can be adapted to interface to the in-vehicle data bus, such as the CAN bus, and to communicate the ADASRP data readings to the ADAS application using the standard methods and protocols of the in-vehicle data bus. The following diagram shows the communications between ADASRP and ADAS applications through a customer-adapted ADASRP data listener and a customer in-vehicle data bus.

By adapting the data listener concept of ADASRP, the ADAS engineers can concentrate on developing their core safety applications utilizing the additional EDMap attributes while leaving the details of accessing map database to the ADASRP engine and the details of filtering and packaging the EDMap attributes to the ADASRP data listener. As long as the protocol and data format of the in-vehicle data bus is agreed upon, ADASRP and ADAS application can be developed independently and any changes or improvement on one side will not affect the other.

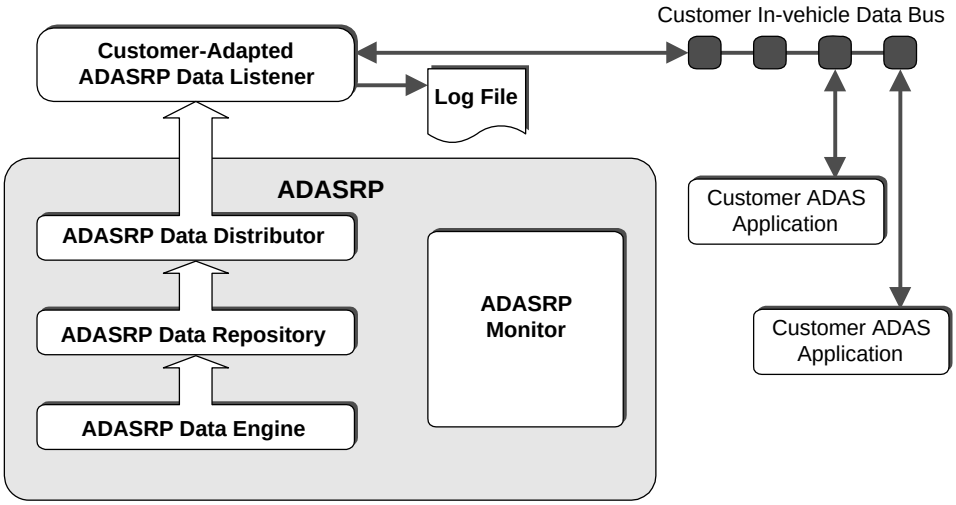

Figure C-32: ADASRP customer-adapted listener

C.6.1.14 Off-The-Shelf Features

In addition to the built-in concepts of electronic horizon and data listeners, ADASRP supports the following off-the-shelf features:

- The ADASRP Monitor, which is a graphical user interface for configuring and starting/stopping the ADASRP Engine. It also provides a map display environment that includes the display of road network, current vehicle position, planned route, link attributes, and electronic horizon.
- The Vehicle Positioning (VP) module that works with positioning sensors to determine the current vehicle position on the road network.
- The Route Calculation (RC) module that allows the user to calculate a route and simulate the route in the laboratory without actually driving the vehicle on the road.
- The recording and playback of DIL (device independent layer) files. A DIL file contains vehicle positions recorded during a live driving session on the road. It can be played back repetitively in the laboratory without going out on the road again. A DIL file can be stepped through in a playback mode.
- The recording and playback of raw files. A raw file contains complete data readings from the positioning sensors recorded during a live driving session on the road. It can be played back repeatedly in the laboratory without going out and driving the road again. When a raw file is played back, the data is fed into the VP tool very closely simulating the original drive.

C.6.1.15 EDMap Enhancements

As discussed in previous Zebra sections, the EDMap project decided to use a Zebra database to carry the new EDMap attributes (mapplets) because of its extendibility, higher precision, and sub-link attribute support. Since ADASRP was originally developed using SDAL (Shared Database Access Library) databases, it was necessary to port it from SDAL to Zebra.

In addition to the existing road attributes available in the standard Zebra database, a set of new road attributes was identified by EDMap as described in previous Zebra sections. Since these new

EDMap attributes are compiled into the Zebra database, there is no need to use the look-aside tables. ADASRP was enhanced to get the new EDMap attributes directly from the Zebra database, instead of from the look-aside tables.

ADASRP was also enhanced to support 7 digits accuracy (sub-meter) in Zebra databases as required by EDMap applications, instead of 5 digits accuracy (meter) in SDAL databases.

The SDAL database used a series of shape points to describe the road geometry. Zebra database was extended for EDMap to present the road geometry with non-uniform b-splines. As a result, ADASRP was enhanced to support the non-uniform b-splines, which are parametrically represented by a set of control points and knots.

Another significant enhancement of ADASRP is to support the lane-level data in Zebra database. Since SDAL database supports only link-level data, the original ADASRP was designed based on the link. Significant efforts were made to enhance ADASRP to not only support the link-level data but also the lane-level data.

The EDMap near-term applications require only link-level data while the EDMap mid-term applications require not only the link-level data but also the lane-level data. The electronic horizon of ADASRP was enhanced to carry both link-level and lane-level data to support both near-term and mid-term applications.

EDMap also selected the Controller Area Network (CAN) bus as the communication mechanism between the ADASRP and ADAS applications. To transfer the ADASRP electronic horizon to the ADAS applications through the CAN bus, two sets of CAN messages were defined, one for near-term applications and one for mid-term applications. Each set of CAN messages was designed to represent the EDMap attributes within the electronic horizon in a way meaningful to ADAS applications so that the electronic horizon can be reconstructed by the ADAS applications if necessary.

Two new data listeners were developed, one for near-term applications and the other for mid-term applications. The data listener retrieves all the EDMap attributes within the electronic horizon, packages them in the formats defined by the CAN messages, and transmits them over the CAN bus to the ADAS applications.

Two CAN bus interface modules that actually package and send the CAN messages to the CAN bus were developed, one for near-term attributes and the other for mid-term attributes. These CAN bus interface modules were used by the data listeners.

The CAN interface was enhanced to also be able to receive messages from the applications. This allows the applications to change the behavior of ADSARP dynamically. For example, ADASRP was enhanced to allow the ADAS applications to change the electronic horizon distance dynamically based on the vehicle speed or other in-vehicle data available.

C.6.1.16 Data Model Differences between Zebra LDM and CAN Messages

In the Zebra Logical Data Model (LDM), all the road attributes are grouped around links. Link data contains all the attributes that are associated with the link, including the link curves that consist of control points and knots. From the link data, one can retrieve the link extension data, which is created specifically for EDMap to carry the EDMap attributes. From the link data, one can retrieve the lane data of all lanes within the link. The lane data contains all the attributes that are associated with the lane, including the lane curves that consist of control points and knots.

ADASRP generates the electronic horizon that consists of all the links ahead of the vehicle within the EH distance. The electronic horizon contains all the link and lane data needed by the ADAS

applications. However, it is impractical to send the whole electronic horizon in the Zebra LDM format to the ADAS applications because:

- The Zebra LDM contains too much data and much of this data is not actually needed or used by ADAS applications.
- The CAN bus has only limited bandwidth and it is impossible to send the whole electronic horizon in Zebra LDM format to CAN bus at the expected update rate.
- The ADAS engineers would need to understand the details of Zebra LDM in order to retrieve the EDMap attributes from it.
- ADAS applications would need to spend valuable CPU time on retrieving and processing EDMap attributes from Zebra LDM while performing time critical safety functions.

To reduce the burden of the CAN bus and to make it easier for ADAS engineers to use the EDMap attributes, a set of CAN messages are defined to carry only the needed EDMap attributes over the CAN bus to the ADAS applications. The CAN messages are designed to come to the ADAS applications in a way that is most meaningful and useful to the ADAS applications. Each CAN message carries a specific EDMap attribute and it contains parameters such as the applicable path and the distance from vehicle. After receiving all the CAN messages for an electronic horizon, the ADAS applications can basically reconstruct the road network with all the EDMap attributes ahead of the vehicle and will have a good picture about what EDMap attributes are there and where they are with respect to the vehicle.

Appendix D: Task 6 - OEM Test Vehicle Setups

D.1 DaimlerChrysler Vehicle Architecture

Figure D-1 illustrates the vehicle architecture used by DaimlerChrysler.

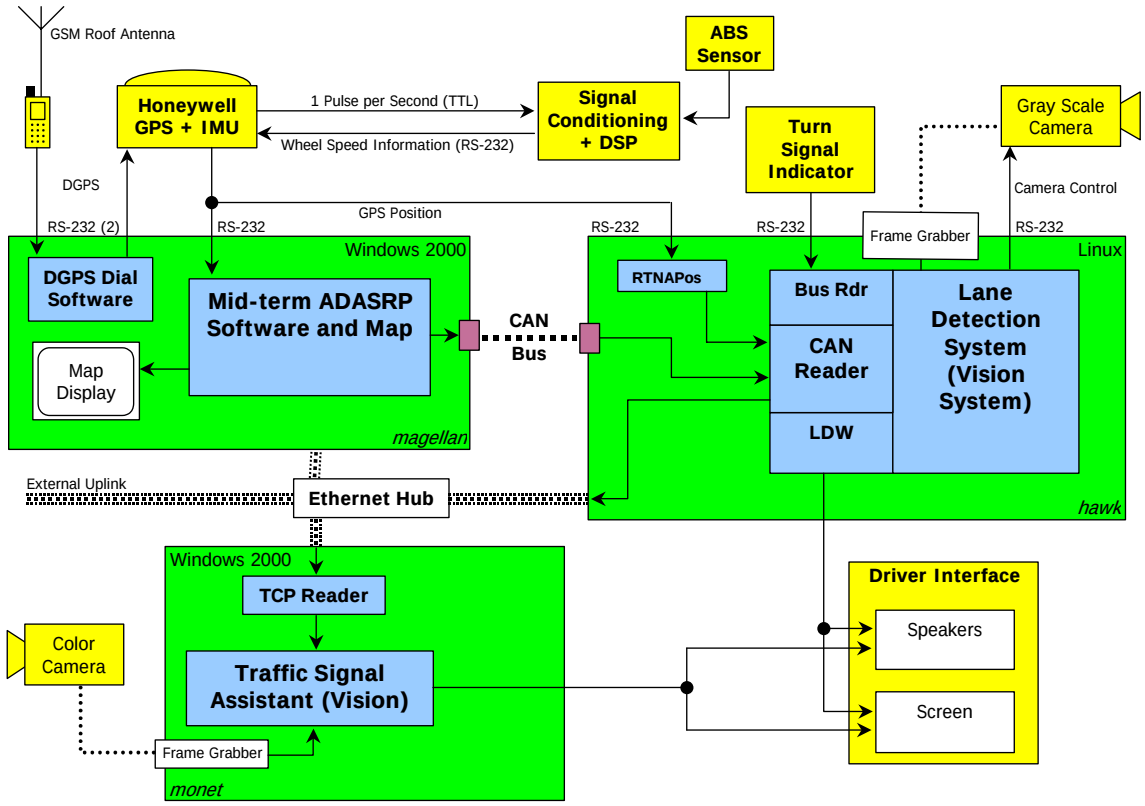

Figure D-1: DaimlerChrysler demonstration vehicle system architecture

The ADASRP platform is a rack-mounted, Windows 2000 based system designated "magellan" that resides in the trunk of the vehicle. This system performs the following function specific to the DaimlerChrysler applications:

Function	Description
Map display	The ADASRP platform outputs map information to a display screen.

D.1.1 Lane Detection System

The Lane Detection System is a rack-mounted Linux based system designated "hawk" that resides in the trunk of the vehicle. This system employs a gray-scale single camera system mounted near the rear-view mirror of the vehicle to determine the boundaries of the travel lane. It performs the following function:

Function	Description
Communication with ADASRP	The system receives electronic horizon information in the form of CAN messages from the ADASRP platform and the CAN Reader reconstructs the electronic horizon, combines it with the most current GPS position and redistributes the relevant data over an Ethernet connection to the demonstrator application (LDW and TSA).
Input from vehicle sensors	The system receives information from vehicle (turn signal indication) via a serial bus interface to properly execute the application.
Input from GPS receiver	The system receives GPS data directly from the Honeywell PAPS unit. The rtnapos component is an internal library used to parse messages from the Honeywell PAPS position data. The data is forwarded to the CAN Reader to be combined with the latest electronic horizon delivered by the map.
Application control software host & execution	The application control software resides in "hawk" memory. The LDW component merges the inputs from vehicle sensors, the Honeywell PAPS unit, the vision based lane detection system and the electronic horizon to determine if an audio warning is necessary.
Output to driver interface	The Lane Detection System sends a signal to the Driver Interface when it determines that the vehicle is about to inadvertently depart the lane.

D.1.2 Traffic Signal Assistant

The Traffic Signal Assistant (TSA) is a rack mounted Windows2000 based system designated "monet" that also resides in the trunk of the vehicle. This system employs a high-dynamic-range color camera mounted behind the windshield to obtain color images of the forward traffic scene. It performs the following functions:

Function	Description
Communication with ADASRP	The TSA receives electronic horizon information from the ADASRP platform via an Ethernet interface.
Input from GPS receiver	The TSA receives GPS data through an Ethernet connection. The data from the GPS unit is read, combined with other electronic horizon data and prepared on “hawk”.
Application control software host & execution	The application control software resides in "monet" memory. The TSA incorporates traffic signal locations received from the ADASRP platform in order to reduce the area of the images that needs to be searched for traffic signal indications.
Output to driver interface	The TSA sends a signal to the Driver Interface when it determines that the driver may not stop at a red traffic signal.

D.1.3 Driver Interface

The Driver Interface performs the following function:

Function	Description
Warnings	The Driver Interface generates audible warnings based on inputs from the Traffic Signal Assistant and Lane Detection Systems. The Traffic Signal Assistant provides visual advisories as well.

D.2 Ford Vehicle Architecture

Figure D-2 illustrates the Ford vehicle system architecture.

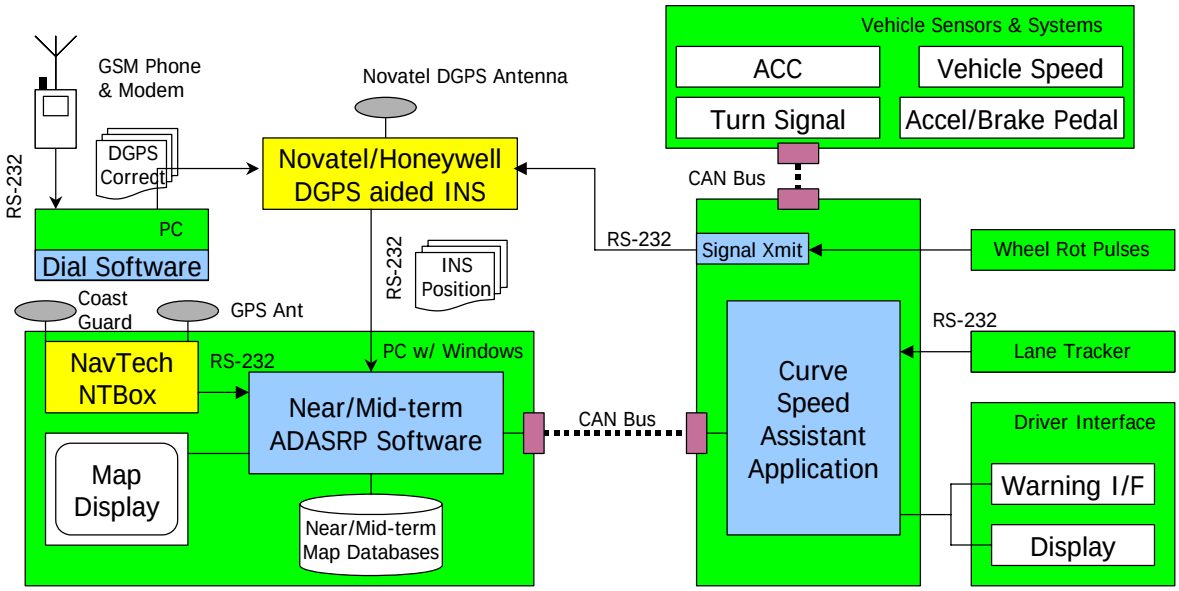

Figure D-2: Ford demonstration vehicle system architecture

The PC platform is a Windows 2000, 2.2GHz Pentium 4 based machine that resides in the trunk of the vehicle. This computer performs the following functions specific to Ford application implementation:

Function	Description
Map display	ADASRP outputs map information to a display screen.
Dial Software	GSM cell phone modem connection and differential corrections transfer.

D.2.1 Curve Speed Assistant

The Curve Speed Assistant Application runs on a dSPACE Autobox. The Autobox also manages several interface data streams both in send and receive.

Function	Description
CSA Application	Mathworks Simulink/Stateflow representation of CSA application runs in the Autobox.
CAN Bus Interface	In addition to the CAN bus for ADASRP, the Autobox also interfaces with vehicle sensors and systems.
RS-232 Interface	The Autobox handles interfaces for Honeywell output data and wheel speed messages, and Lane Tracker.

D.2.2 Vehicle Sensors and Systems

The Vehicle Sensors and Systems is a collection of existing onboard sensor output and system interfaces. The data is used by the CSA application and are available via CAN bus on the Jaguar XKR demo vehicle.

Function	Description
Vehicle Speed	Wheel speed derived and filtered vehicle speed.
Accel/Brake Pedal	Throttle pedal position, brake pedal position, and brake pressure.
ACC	Interface to Adaptive Cruise Control system: settings, current values, and throttle and brake actuator control access.
Turn Signal	Activation status of left and right turn signals for route change determination.
Wiper Status	Windshield wiper status for assessing curve speed.
Traction Control	Data indicating activation of traction control system for assessing curve speed.

D.2.3 Lane Tracker

The Lane Tracker is a stock Assistware SafeTrac system with an RS-232 interface to the dSPACE Autobox.

Function	Description
Lane Tracker	Track driver lane keeping behavior into, during, and out of curves.

D.2.4 Driver Interface

The Driver Interface provides CSA warning information to the driver and allows driver to make preference settings.

Function	Description
Warning Interface	Selector switches allowing driver to set CSA warning behavior.
Display	Haptic seat to provide warning to driver.

D.3 General Motors Vehicle Architecture

Figure D-3 illustrates the GM vehicle system architecture.

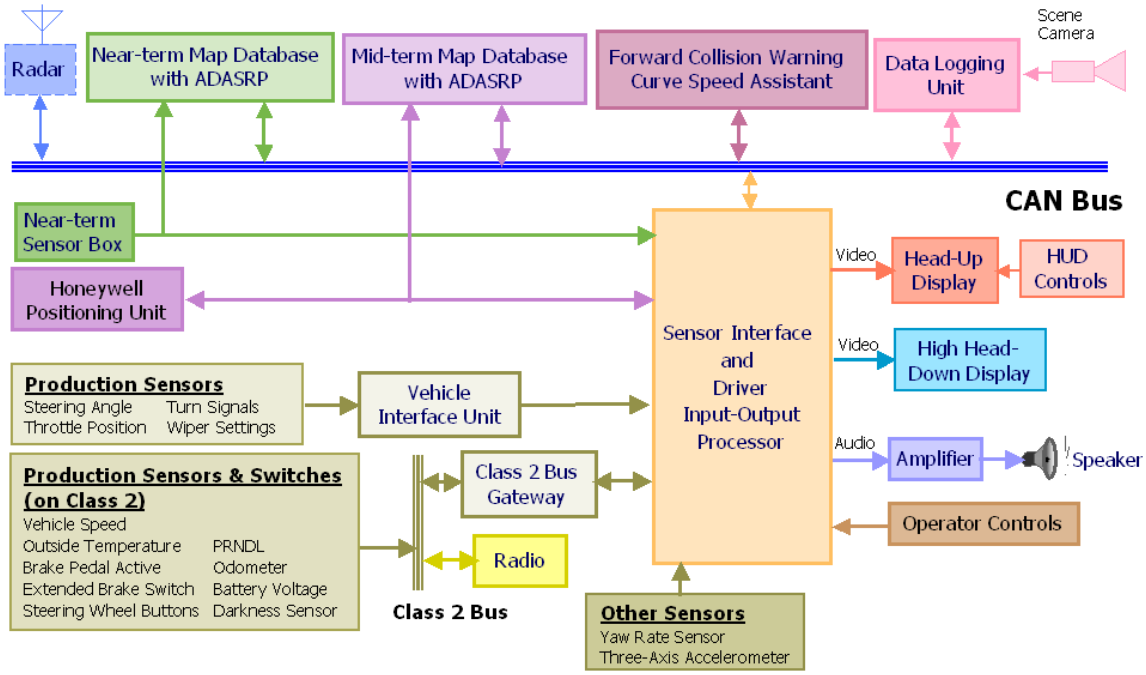

Figure D-3: General Motors demonstration vehicle system architecture

The GM test vehicle operates both the near-term (CSA) and mid-term (FCW) applications concurrently, and therefore exercises the near- and mid-term sensors and maps at all times. As shown in the block diagram of this vehicle, a number of sensors and processors are used to accomplish the task at hand. The main connector of the system is a CAN bus used for communicating data between the different processors and the sensors. It operates at 500 Kb rate and uses 11-bit identification for messages. The operating details of the various sensors and processors are described below.

D.3.1 Non-production Sensors and Input-Output Devices

D.3.1.1 Forward Collision Warning Sensor

The Forward Collision Warning Sensor is a 77 GHz millimeter wave radar manufactured by Delphi and is mounted in front of the vehicle behind the grille. It is directly interfaced to the CAN bus and performs the following function:

Function	Description
Transmits information regarding all the targets appearing in its field of view.	The radar sensor communicates (at a rate of 10 Hz) the overall radar system status and information related to each target in the form of range, range rate, acceleration, azimuth angle, motion status (stationary or movable), bridge, target class and status (primary target, coasting, invalid, etc.) onto the CAN bus for use by the FCW algorithms.

D.3.1.2 External Sensors

The test vehicle is equipped with two external non-production sensors, namely a KVH fiber optic gyro and a Crossbow three-axis, high-stability accelerometer.

Function	Description
Yaw rate measurements	The KVH fiber optic gyro is used for making vehicle yaw rate measurements.
Acceleration measurements	The three-axis Crossbow accelerometer is used for making measurements of the lateral, longitudinal and vertical accelerations.

D.3.1.3 Heads-Up Display

A non-production Heads-Up Display (HUD) is installed in place of the production HUD in the test vehicle. The HUD is a driver-centric, reconfigurable display developed by Delphi-Delco capable of presenting a 320 x 240 image in full color. It renders an image projected several meters in front of the driver and in close proximity to the forward visual scene. It performs the following functions:

Function	Description
Display safety messages to the driver	The HUD displays appropriate graphics, icons and textual messages as commanded by the application via the sensor and driver I/O processor.
Control intensity and position of HUD images via switches	Production based up/down control switches are used to control the HUD intensity and adjust the eyebox (image) position based on the driver's height. These switches are easily accessible and are located on the instrument panel close to the steering wheel.

D.3.1.4 High Heads-Down Display

A High Heads-Down Display has been installed at the center of the instrument panel, on top of the radio. It is a 5" reconfigurable color liquid crystal display that performs the following function:

Function	Description
Display safety messages for demonstration purposes	The safety messages displayed on the HUD are visible only to the driver. This LCD has been installed for demonstration purposes only and displays exactly the same information projected on the HUD. This allows the passengers to see the information that is being communicated to the driver.

D.3.2 Sensor Interface and Driver Input-Output Processor

The Sensor Interface and Driver Input-Output Processor is a PC/104-based computer running under the VenturCom operating system. It serves as the main interface between the vehicle, the driver, and the application systems. It performs the following four functions:

1. Receives input from various production and non-production sensors (described above) in various formats e.g., digital, analog or serial.

Function	Description
Interface with the in-vehicle production sensors and devices via Class 2 bus interface	All the sensor information that is required by the CSA and the FCW applications that is available on the vehicle Class 2 bus is monitored and captured, and input serially using a RS232 format to the sensor interface and driver I/O processor using the Class 2 Bus Gateway. Examples of parameters communicated by the dedicated Class 2 bus are current vehicle state (vehicle speed, brake pressure, etc.) and environmental conditions (outside temperature, lighting level).
Direct sensor interface	Sensor or device parameters that are not available on the Class 2 bus are directly interfaced to the processor either through discrete digital inputs (e.g., turn signals) or an analog to digital converter (e.g., steering wheel angle, throttle position sensor).
Interface to non-production sensors	The yaw rate sensor (manufactured by KVH) and the 3-axis accelerometers (manufactured by Crossbow) are connected to this processor serially using the RS232 format.
Interface with the vision processor	The vision processor communicates the host vehicle state to the sensor interface and driver I/O processor using the serial interface.
Interface with NT-box	The NT-box is serially connected to the sensor interface and driver I/O processor using the RS232 format.
Interface with the Honeywell PAPS unit	Four serial ports on this processor are dedicated to the mid-term Honeywell positioning unit and perform the following functions: Receive differential corrections from the cell modem Output above-mentioned differential corrections to the PAPS unit Communicate the wheel speed information to the PAPS unit Receive the vehicle positioning data from the PAPS unit.

2. Converts sensor data into appropriate engineering units and transmit the resulting data on the CAN bus for use by other processors and functions

Function	Description
Output sensor data to other processors	Convert the sensor values obtained in step 1 (above) into appropriate engineering units and place them onto the CAN bus for use by other processors and functions

3. Obtains driver preferences.

Function	Description
Interface with driver controls	Receive driver preferences via up/down type control buttons located on the steering wheel. Examples of driver preferences obtained via operator controls are deceleration rate, lateral acceleration on a curve, headway setting, etc.

4. Outputs safety messages to the driver.

Function	Description
Output visual advisories and warnings via HUD	Using the HUD, visual advisories and warnings are communicated to the driver using graphics, icons and textual messages under warning conditions. The type of warning conveyed is based on the estimated warning level by the CSA and the FCW applications.
Output visual advisories and warnings via Head-Down Display	The information that is displayed on the HUD is duplicated on the High Head Down Display. This is a redundant display device and is primarily used for demonstration purposes.
Output audible advisories and warnings via speakers	The Sensor Interface and Input-Output Processor generates audible advisories and warnings via a speaker to get the driver's attention under warning conditions.

D.3.3 ADASRP Host PCs

The current design of the ADASRP allows the use of either the near-term or the mid-term maps, but not both simultaneously. Since the CSA and FCW are designed for concurrent operation, two identical ADASRP host PCs for the near-term and the mid-term applications are included in the test vehicle. The near-term and the mid-term ADASRP each run on a small P4 PC that is based on an Intel P4 2GHz processor and functions under the Windows 2000 operating system. Its speed (2 GHz), small size (7.79" x 6.34" x 2.44"), and light weight (2.8 lbs) makes it a suitable component of an in-vehicle system.

The near-term ADASRP performs the following functions specific to the CSA application:

Function	Description
Provide all map-based information required by the CSA application	Uses vehicle position information from the NT-box to extract a specified length (in meters) of preview definition of the primary upcoming road in terms of control points of the spline-based representation of the road, speed limits, grade, superelevation, surface type, surface conditions, number of lanes and confidence. Also uses information from the near-term map database related to alternate paths that the host vehicle could take as it encounters forks or intersections and places it on the CAN bus for use by the CSA algorithms.
Map Display	The ADASRP computer outputs map information in terms of an electronic horizon and current vehicle position to a display screen.

The mid-term ADASRP performs the following functions specific to the FCW application:

Function	Description
Provide all map-based information required by the FCW application	Uses vehicle position information from the Honeywell PAPS unit to extract a specified length (in meters) of lane-level preview of the upcoming host vehicle path in terms of geometry (control points of the spline-based representation of the lane) along with the confidence and look-ahead range, alternate upcoming host vehicle paths (as forks or intersections are encountered by the host vehicle) with limited look-ahead ranges, lane width, upcoming intersection(s) information (location, geometry, etc.), shoulder information (width, type, etc.), road level information namely – number of lanes, overhead stationary roadway structures, stationary roadside objects and barriers, road condition, surface type, grade, superelevation and class from the mid-term map database and place it on the CAN bus for use by the FCW algorithms.
Map Display	The ADASRP computer outputs map information in terms of an electronic horizon and current vehicle position to a display screen.

The application software for curve speed assistant and forward collision warning resides in a single PC/104-based computer. This processor runs under the VenturCom operating environment and performs the following functions:

Function	Description
Curve Speed Assistant application	This application receives the required near-term mapplets over the CAN bus, via the near-term ADASRP. It also receives the sensor data, host vehicle state, and driver preferences over the CAN bus via the sensor interface and driver I/O processor. This application evaluates the current vehicle speed with respect to the upcoming road geometry to determine if the vehicle is approaching a curve at a speed higher than the upcoming curve's estimated negotiable speed, and if needed generates an appropriate warning level.
Forward Collision Warning application	This application receives that data from the radar via the CAN bus, which contains the target tracks and additional pertinent information related to detected targets. It receives sensor data, driver preferences, host vehicle state and all the required mid-term mapplet data, via the sensor interface and driver I/O processor, and the mid-term ADASRP processor respectively, over the CAN bus. Based on the radar targets and the predicted upcoming lane geometry it identifies the most threatening targets. The threat assessment algorithm is applied to this target based on the kinematics of the vehicle (monitored by the sensor interface processor) and the target (determined by the radar track information), and a threat level, if any, is defined. Apart from categorizing radar targets as threatening or not, this function reduces the number of false alarms by eliminating irrelevant radar targets using other mapplet information regarding roadside objects/barriers and roadway stationary objects.

The Data Logging Unit comprises a Matrox 4 Sight II PC/104 video server and a Dell Latitude laptop that host the GM R&D developed data logging software and performs the following functions:

Function	Description
Log video and CAN bus data	The Data Logging Unit is used to perform in-vehicle and on-bench data acquisition. It uses the video server to log the digital video sequences from the forward-looking scene camera (located behind the rear-view mirror), and uses the laptop to log all (or a user selected subset) of the vehicle CAN messages and generates a composite data set that has the video data time-aligned with the radar and other sensor data.
Data Visualization	Apart from the data logger, the laptop hosts the data visualization software that is used to perform the real-time playback, and visualization, verification and analysis of the logged data.

Not shown in the vehicle architecture diagram, is an engineering terminal that is a liquid crystal display and a keyboard mounted in the back seat directly behind the front passenger. A single display and keyboard support multiple computers in the vehicle via an electronic switch box that is installed in the opening between the trunk and the passenger compartment. Pushing the selector switch on this box connects the terminal to the computers in a round-robin fashion.

D.4 Toyota Vehicle Architecture

Figure D-4 illustrates the Toyota vehicle system architecture.

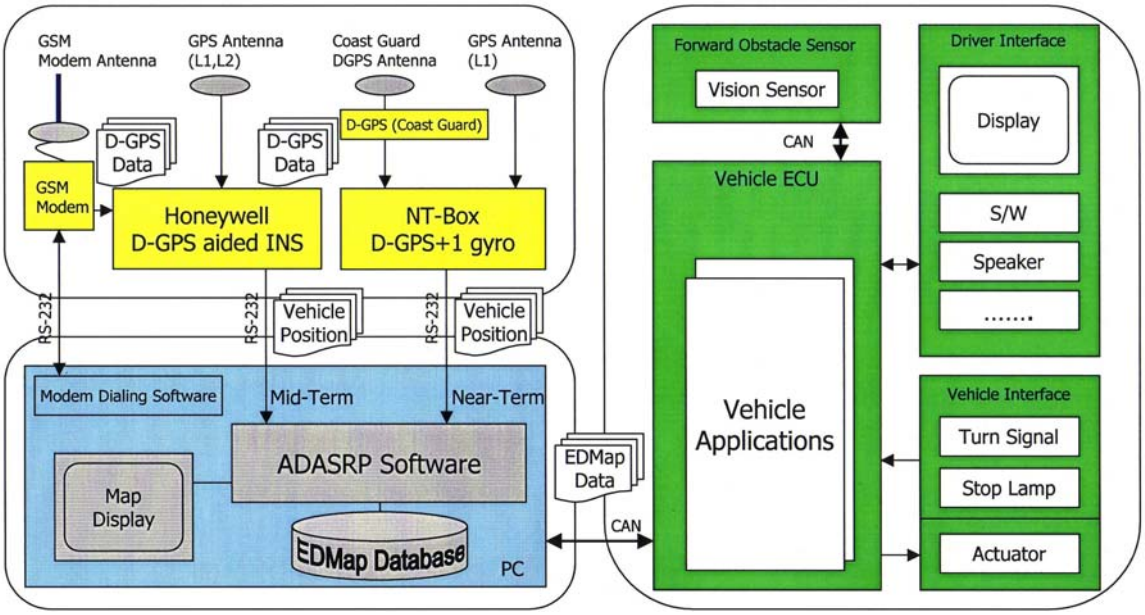

Figure D-4: Toyota demonstration vehicle system architecture

The ADASRP platform is a custom-built, rack mounted, 2.4 GHz Intel Pentium 4, Windows 2000 based computer that performs the following function specific to the Toyota applications:

Function	Description
Map display	The ADASRP platform outputs map information to a display screen.

D.4.1 Forward Obstacle Sensor

The Forward Obstacle Sensor is a prototype mono-camera vision system developed by MobilEye Vision Technologies and performs the following function:

Function	Description
Communication with Vehicle ECU	The Forward Obstacle Sensor communicates object distance and relative speed information in the form of CAN message to the Vehicle ECU.

D.4.2 Vehicle ECU

The Vehicle ECU is a dSPACE MicroAutobox that performs the following functions:

Function	Description
Communication with ADASRP platform	The Vehicle ECU receives CAN message data from the ADASRP platform and extracts information regarding distance between vehicle and mapplet, road grade, etc. from them in order to properly execute the application.
Forward object detection	The Vehicle ECU receives CAN message data from the Forward Obstacle Sensor and extracts object distance and relative speed information in order to compare against information from the ADASRP platform and adjust the timing for advisories, warnings and brake control as necessary.
Inputs from vehicle	The Vehicle ECU receives inputs from the turn signal and brake lamps to properly execute the applications.
Application control software host and execution	The application control software resides in Vehicle ECU memory. The Vehicle ECU executes the application control software to generate advisories and warnings for the near- and mid-term applications and to generate signals for controlling the brake actuator for the mid-term application.
Driver interface I/O	The Vehicle ECU communicates information to the driver interface in order to generate advisories and warnings. The vehicle ECU also receives input from the driver interface in the form of parameter settings that are then stored in Vehicle ECU memory.
Brake actuator control	The Vehicle ECU communicates brake control signals to the vehicle interface.

D.4.3 Drive Interface

The Driver Interface is a Panasonic Toughbook model 34 laptop computer and performs the following functions:

Function	Description
Communication with vehicle ECU	The Driver Interface allows the user to change the system's operating parameters and to view system performance data by inputting information and commands through a keyboard and touch screen.
Advisories and warnings	The Driver Interface generates visual and audible advisories and warnings based on input from the vehicle ECU. Visual advisories and warnings are displayed on the Driver Interface display screen while audible advisories and warnings are issued via a speaker built into the Driver Interface.
System operating parameters and performance data display	The Driver Interface displays system operating parameters and performance data on the Driver Interface display screen.

D.5 Near-Term ADASRP CAN Message Definitions

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed?	Range/Values	Resolution	Units	Notes
0x100	ADASRP/Map Status #1	Sequence Count	0,1	16			1		2 byte number that increments every new chunk of data
		GPS Week	2,3	16		0 to 65535	1	week	GPS Week of position data
		GPS Time in Week	4,5,6,7	32		0 to 604799999	1	s	GPS Time of position data that is used
0x101	ADASRP/Map Status #2	VP Base Longitude	0,1,2,3	32	yes	$+/-180 * 10^7$	1	DMD	Position from VP. Bit 3/7 is the sign bit: 0=Pos, 1=Neg.
		VP Base Latitude	4,5,6,7	32	yes	$+/-90 * 10^7$	1	DMD	Position from VP. Bit 7/7 is the sign bit: 0=Pos, 1=Neg.
0x102	ADASRP/Map Status #3	GPS Base Elevation	0,1	16	yes	+/-4915	0.15	m	Elevation from GPS. Bit 1/7 is the sign bit: 0=Pos, 1=Neg.
		Data Latency	2,3	16		0 to 65535	1	ms	Latency for ADASRP to deliver data
		Total Paths	4/0-3	4		0 to 8	1		Total number of paths reported
		Distance From Entry	5,6,7	24		0 to 16777215	1	cm	Vehicle's distance from current link's entry node
0x103	ADASRP/Map Status #4 (No. of Instances)	Stop sign locations	0/0-3	4		0 to 15	1		Total number of stop sign locations reported
		Stopping locations	0/4-7	4		0 to 15	1		Total number of stopping locations reported
		Stop Ahead sign locations	1/0-3	4		0 to 15	1		Total number of stop ahead sign locations reported
		Yield sign locations	1/4-7	4		0 to 15	1		Total number of yield sign locations reported
		Number of Lanes	2/0-3	4		0 to 15	1		Total number of number of lanes reported
		Road Conditions	2/4-7	4		0 to 15	1		Total number of road conditions reported
		Road Surface types	3/0-3	4		0 to 15	1		Total number of road surface types reported
		Road Grades	3/4-7	4		0 to 15	1		Total number of road grades reported
		Road Classes	4/0-3	4		0 to 15	1		Total number of road classes reported
		Superelevations	4/4-7	4		0 to 15	1		Total number of superelevations reported
		Speed Limits	5/0-3	4		0 to 15	1		Total number of speed limits reported
		Lane Direction	5/4-7	4		0 to 15	1		Total number of lane directions reported
		Data Compatibilities	6/0-3	4		0 to 15	1		Total number of data compatibilities reported
		Data Qualities	6/4-7	4		0 to 15	1		Total number of data qualities reported
		Splines	7	8		0 to 255	1		Total number of splines sections to follow (each "section" contains a Spline Header message followed by a number of Control Point messages)
0x104	ADASRP/Map Status #5	VP Candidate Probability	0	8		0 to 100	1	%	VP Candidate Probability = (Probability of the best candidate / Sum of probabilities of all candidates) * 100%.

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed?	Range/Values	Resolution	Units	Notes
0x105	ADASRP/Map Status#6	ADASRP Version Major	0/0-3	4		0 to 9	1		ADASRP Version Number: Major
		ADASRP Version Medium	0/4-7	4		0 to 9	1		ADASRP Version Number: Medium
		ADASRP Version Minor	1	8		0 to 99	1		ADASRP Version Number: Minor
		Database Version Number 1	2	8		0 to 255	1		Term. 0=Near-Term, 1=Mid-Term
		Database Version Number 2	3	8		0 to 255	1		Region. 0=Rosemont, 1=Palo Alto, 2=Detroit
		Database Version Number 3	4	8		0 to 255	1		Flavor. 0=V1, 1=With USGS Grade, 2=With ISTAR Grade, 3=Ann Arbor, 4=Warren, 5=Dearborn
		Database Version Number 4	5	8		0 to 255	1		Sequential Release Number
0x110	Stop Sign Location	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stop sign location might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	5,6	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stop sign location might apply to multiple paths
0x111	Stopping Location	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stopping location might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	5,6	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stopping location might apply to multiple paths
0x112	Yield Sign Location	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one yield sign location might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	5,6	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one yield sign location might apply to multiple paths

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed?	Range/Values	Resolution	Units	Notes
0x113	Stop Ahead Sign Location	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stop ahead sign location might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	5,6	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stop ahead sign location might apply to multiple paths
0x114	Road Condition	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	0/4-5	2		0 to 2	1		0=smooth, 1=rippled, 2=uneven
		Distance from host	1,2	16		0 to 65535	1	cm	0=current road condition
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road condition might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	4/4-5	2		0 to 3	1		0=smooth, 1=rippled, 2=uneven, 3=unknown
		Distance from host	5,6	16		0 to 65535	1	cm	0=current road condition
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road condition might apply to multiple paths
0x115	Road Surface Type	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	0/4-6	3		0 to 5	1		0=rigid/concrete, 1=flexible/asphalt, 2=metal grating, 3=mixed, 4=block, 5=invalid
		Distance from host	1,2	16		0 to 65535	1	cm	0=current road surface type
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road surface type might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	4/4-6	3		0 to 3	1		0=rigid/concrete, 1=flexible/asphalt, 2=metal grating, 3=mixed, 4=block, 5=invalid
		Distance from host	5,6	16		0 to 65535	1	cm	0=current road surface type
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road surface type might apply to multiple paths
0x116	Road Grade	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	0=current road grade
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road grade might apply to multiple paths
		Value	4/0-5	6	yes	-16 to 16	1		Signed grade percentage from -16 to 16 in increments of 2%. Bit 4/5 is the sign bit: 0=Pos, 1=Neg.

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed?	Range/Values	Resolution	Units	Notes
0x117	Superelevation	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	0/4-5	2		0 to 2	1		0=none, 1=pos [prevents lateral movement], 2=neg [adds to lateral movement]
		Distance from host	1,2	16		0 to 65535	1	cm	0=current superelevation
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one superelevation might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	4/4-5	2		0 to 2	1		0=none, 1=pos [prevents lateral movement], 2=neg [adds to lateral movement]
		Distance from host	5,6	16		0 to 65535	1	cm	0=current superelevation
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one superelevation might apply to multiple paths
0x118	Number of Lanes	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	0/4-6	3		0 to 7	1		Number of automobile traffic lanes along the driving direction. 0 when link is one-way in opposite direction.
		Distance from host	1,2	16		0 to 65535	1	cm	0=current lane count
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one number of lanes might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	4/4-6	3		0 to 7	1		Number of automobile traffic lanes along the driving direction. 0 when link is one-way in opposite direction.
		Distance from host	5,6	16		0 to 65535	1	cm	0 when link is one-way in opposite direction.
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one number of lanes might apply to multiple paths
0x119	Lane Direction	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	0/4	1		0 to 1	1		0=one way, 1=two way
		Distance from host	1,2	16		0 to 65535	1	cm	0=current lane direction
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one lane direction might apply to multiple paths
		Instance #	4/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value	4/4	1		0 to 1	1		0=one way, 1=two way
		Distance from host	5,6	16		0 to 65535	1	cm	0=current lane direction
		Applicable Path	7	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one lane direction might apply to multiple paths

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed?	Range/Values	Resolution	Units	Notes
0x11A	Speed Limit	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Value Type	0/4-5	2		0 to 2	1		0=speed limit, 1=advisory speed, 2=lower speed ahead (dependency on school zone or hospital zone etc..)
		Distance from host	1,2	16		0 to 65535	1	cm	0=current speed limit
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one speed limit might apply to multiple paths
		Value	4	8		0 to 255	1	kph	speed limit along the driving direction
0x11B	Road Class	Instance #	0/0-3	4		0 to 15	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	0=road class of current position
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road class might apply to multiple paths
		Road Class Flags	4	8		0 to 7 (bit flags)	1		bit0=ramp, bit1=controlled access, bit2=toll road bit3=multiply digitized, bit4=frontage road, bit5=turn lane, bit6=tunnel, bit7=unpaved
		Functional Class	5/0-2	3		1 to 5	1		1=primary high volume, maximum speed artery, … 5=side street
0x11C	Spline Header	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances which are specified in the Map Status #4 message (byte 7. See above)
		Number of Control Points	1	8		0 to 255	1		Specifies how many control point messages will follow for this spline section
		Number of Knots	2	8		0 to 255	1		Specifies how many knot messages will follow for this spline section
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one spline section might apply to multiple paths
		Arc length of Spline	4,5,6,7	32		0 to 10E9	1	cm	This allows for a spline length of 10000 km
0x11D	Control Points	Point #	0	8		0 to 255	1		The sequence number of this control point (specifies the ordering of the control points with a given spline)
		Latitude delta	1,2,3	24	yes	-8388607 to 8388607	1	DMD	Degree change in latitude from value reported in Map Status #2 message. Bit 3/7 is the sign bit: 0=Pos, 1=Neg.
		Longitude delta	4,5,6	24	yes	-8388607 to 8388607	1	DMD	Degree change in longitude from value reported in Map Status #2 message. Bit 6/7 is the sign bit: 0=Pos, 1=Neg.
		Instance #	7	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances which are specified in the Map Status #4 message (byte 7. See above)
0x11E	Knots	Value	0,1,2,3	32		0 to 4294967295	1		Original knot value multiplied by 1000000. Application needs to divide this value by 1000000 to get the original knot value.
		Instance #	4	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to number of instances which are specified in the Map Status #4 message (byte 7. See above).
		Knot #	5	8		0 to 255	1		The sequence number of this knot (specifies the ordering of the knots with a given spline)

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed?	Range/Values	Resolution	Units	Notes
0x11F	Data Compatibility	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance From Host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one data compatibility might apply to multiple paths
		Value	4/0	1		0 to 1	1		0=NearTerm Data, 1= Non-NearTerm Data. This message is sent only if the Value is 1 (i.e., when a link within the electronic horizon is not near-term compatible). A link is near-term compatible if it contains EDMap near-term attributes, including the link geometry.
0x120	Data Quality	Instance #	0	8		0 to 255	1		Instance number corresponds to the instance number reported in the spline header message
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one quality might apply to multiple paths
		Value	4	8		0 to 100	1		Data quality is assigned to each link. It is not defined and populated in the database yet. Its value range of 0 to 100 is set arbitrarily here and may be changed in the future.
0x150	EH Distance	New EH Distance	0,1/0-1	10		0 to 655	1	m	Set a new Electronic Horizon Distance

D.6 Near-term ADASRP CAN Message Definitions

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x200	ADASRP/Map Status #1	Sequence Count	0,1	16		0 to 65535	1		2 byte number that increments every new chunk of data
		GPS Week	2,3	16		0 to 65535	1	week	GPS Week of position data
		GPS Time in Week	4,5,6,7	32		0 to 604799999	1	ms	GPS Time in Week of position data that is used
0x201	ADASRP/Map Status #2	VP Base Longitude	0,1,2,3	32	yes	$+/-180 * 10^7$	1	DMD	Position from VP. Bit 3/7 is the sign bit: 0=Pos, 1=Neg.
		VP Base Latitude	4,5,6,7	32	yes	$+/-90 * 10^7$	1	DMD	Position from VP. Bit 7/7 is the sign bit: 0=Pos, 1=Neg.
0x202	ADASRP/Map Status #3	GPS Base Elevation	0,1	16	yes	+/-4915	0.15	m	Elevation from GPS. Bit 1/7 is the sign bit: 0=Pos, 1=Neg. Application needs to multiply this value by 0.15 to obtain the Elevation in meters.
		Data Latency	2,3	16		0 to 65535	1	ms	Latency for ADASRP to deliver data
		Total Paths	4/0-3	4		0 to 8	1		Total number of paths reported
		Distance From Lane Start	5,6,7	24		0 to 16777215	1	cm	Vehicle's distance from the start of current lane
0x203	ADASRP/Map Status #4	VP Heading	0,1	16	yes	+/-180 * 100	1	MD	VP Heading. Bit 1/7 is the sign bit: 0=Pos,1=Neg. MD = MiniDegree; 1 Degree = 100 MiniDegree
		Distance from Lane Centerline	2,3	16	yes	+/-1023	1	cm	Distance from lane centerline. 3/7 is the sign bit: 0=Pos, 1=Neg. Positive indicates vehicle is to the right of lane centerline. Negative indicates vehicle is to the left of lane centerline.
		VP Candidate Probability	4	8		0 to 100	1	%	VP candidate probability. This probability is returned directly from the VP tool, which indicates how confidence VP is about picking this candidate as the vehicle position. 100% means total confidence.
		VP Status	5/0-2	3		0 to 3	1		0=Off Road,1=On Road, 2=Within Intersection, 3=Lane Transition
		Honeywell PAPS INS Status	5/3-5	3		0 to 6	1		0=INS Inactive, 1=INS Aligning, 2=INS Solution Bad, 3=INS Solution Good, 4=Reserved for future use, 5=Reserved for future use, 6=Bad INS/GPS Agreement
0x204	ADASRP/Map Status #5	ADASRP Version Major	0/0-3	4		0 to 9	1		ADASRP Version Number: Major
		ADASRP Version Medium	0/4-7	4		0 to 9	1		ADASRP Version Number: Medium
		ADASRP Version Minor	1	8		0 to 99	1		ADASRP Version Number: Minor
		Database Version Number 1	2	8		0 to 255	1		Term. 0=Near-Term, 1=Mid-Term
		Database Version Number 2	3	8		0 to 255	1		Region. 0=Rosemont, 1=Palo Alto, 2=Detroit
		Database Version Number 3	4	8		0 to 255	1		Flavor. 0=V1, 1=With USGS Grade, 2=With ISTAR Grade, 3=Ann Arbor, 4=Warren, 5=Dearborn
		Database Version Number 4	5	8		0 to 255	1		Sequential Release Number

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x205	ADASRP/Map Status#6 Number of Instances	Midterm Stop Sign Locations	0	8		0 to 255	1		Total number of stop sign locations reported
		Midterm Stopping Locations	1	8		0 to 255	1		Total number of stopping locations reported
		Midterm Stop Ahead Sign Locations	2	8		0 to 255	1		Total number of stop ahead sign locations reported
		Midterm Yield sign locations	3	8		0 to 255	1		Total number of yield sign locations reported
		Midterm Number of Lanes	4	8		0 to 255	1		Total number of number of lanes reported
		Midterm Road Conditions	5	8		0 to 255	1		Total number of road conditions reported
		Midterm Road Surface Types	6	8		0 to 255	1		Total number of road surface types reported
		Midterm Road Grades	7	8		0 to 255	1		Total number of road grades reported
0x206	ADASRP/Map Status#7 Number of Instances	Midterm Road Classes	0	8		0 to 255	1		Total number of road classes reported
		Midterm Superelevations	1	8		0 to 255	1		Total number of superelevations reported
		Midterm Speed Limits	2	8		0 to 255	1		Total number of speed limits reported
		Midterm Lane Directions	3	8		0 to 255	1		Total number of lane directions reported
		Midterm Splines	4	8		0 to 255	1		Total number of splines sections to follow (each "section" contains a Spline Header message followed by a number of Control Points and knots messages)
		Midterm Data Qualities	5	8		0 to 255	1		Total number of data qualities reported
		Midterm Lane Widths	6	8		0 to 255	1		Total number of lane widths reported
		Midterm Left Adjacencies	7	8		0 to 255	1		Total number of left lane adjacencies reported

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x207	ADASRP/Map Status #8 (Number of Instances)	Midterm Right Adjacencies	0	8		0 to 255	1		Total number of right lane adjacencies reported
		Midterm Lane Markings Types	1	8		0 to 255	1		Total number of lane markings types reported
		Midterm Traffic Signal Locations	2	8		0 to 255	1		Total number of traffic signal locations reported (each "section" contains a traffic signal location header followed by a traffic signal location message)
		Midterm Intersection Locations	3	8		0 to 255	1		Total number of intersection locations reported (each "section" contains a intersection location header followed by a number of intersection location messages)
		Midterm Overhead Structures	4	8		0 to 255	1		Total number of overhead structures reported
		Midterm Roadside Objects	5	8		0 to 255	1		Total number of roadside objects reported
		Midterm Roadside Barriers	6	8		0 to 255	1		Total number of roadside barriers reported
		Midterm Data Compatibilities	7	8		0 to 255	1		Total number of data compatibilities reported
0x208	ADASRP/Map Status #9 (Number of Instances)	Midterm Lane Types	0	8		0 to 255	1		Total number of lane types reported
0x210	Midterm Stop Sign Location	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stop sign location might apply to multiple paths
0x211	Midterm Stopping Location	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stopping location might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
0x212	Midterm Yield Sign Location	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one yield sign location might apply to multiple paths

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x213	Midterm Stop Ahead Sign Location	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stop ahead sign location might apply to multiple paths
0x214	Midterm Road Condition	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current road condition
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road condition might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Value	4/5-6	2		0 to 3	1		0=smooth, 1=rippled, 2=uneven, 3=unknown
0x215	Midterm Road Surface Type	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current road surface type
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road surface type might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Value	4/5-7	3		0 to 5	1		0=rigid/concrete, 1=flexible/asphalt, 2=metal grating, 3=mixed, 4=block, 5=invalid
0x216	Midterm Road Grade	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current road grade
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road grade might apply to multiple paths
		Value	4/0-5	6	yes	-31 to 31	1	%	Signed grade percentage from -31 to 31 in increments of 1%. Bit 4/5 is the sign bit: 0=Pos, 1=Neg.
0x217	Midterm Superelevation	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current superelevation
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one superelevation might apply to multiple paths
		Value	4/0-5	6	yes	-30 to 30	1	%	Signed percentage from -30 to 30 in increments of 1%. Bit 4/5 is the sign bit: 0=Pos, 1=Neg.

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x218	Midterm Number of Lanes	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current number of lanes
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one number of lanes might apply to multiple paths
		Value	4/0-4	5		0 to 16	1		Number of automobile traffic lanes along the driving direction. 0 when link is one-way in opposite direction.
0x219	Midterm Lane Direction	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current lane direction
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one lane direction might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Value	4/5	1		0 to 1	1		0=one way, 1=two way
0x21A	Midterm Speed Limit	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current speed limit
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one speed limit might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane. If lane number is -0 ("10000" in binary), this speed is applied to all lanes.
		Value Type	4/5-6	2		0 to 2	1		0=speed limit, 1=advisory speed, 2=lower speed ahead (dependency on school zone or hospital zone etc..)
		Value	5	8		0 to 255	1	kph	Speed limit along the driving direction.
0x21B	Midterm Road Class	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current road class
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one road class might apply to multiple paths
		Road Class Flags	4,5/0	9		0 to 8 (bit flags)	1		bit 4/0=ramp, bit 4/1=controlled access, bit 4/2=toll road bit 4/3=multiply digitized, bit 4/4=frontage road, bit 4/5=turn lane, bit 4/6=tunnel, bit 4/7=unpaved, bit 5/0=poi access
		Functional Class	5/1-3	3		1 to 5	1		1=primary high volume, maximum speed artery, … 5=side street

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x21C	Midterm Spline Header	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to number of instances.
		Number of Control Points	1	8		0 to 255	1		Specifies how many control point messages will follow for this spline section. If number of control points is 0, this spline header represents an intersection maneuver and the "Arc length of Spline" represents the straight line length of the maneuver.
		Number of Knots	2	8		0 to 255	1		Specifies how many knot messages will follow for this spline section. If number of control points is 0, number of knots will be 0 as well.
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one spline header might apply to multiple paths
		Entry Lane Number	4/0-4	5	yes	-15 to 15	1		Entry Lane number or which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane. If number of control points is 0, indicates the lane number of the lane going into the intersection maneuver. If number of control points is not 0, indicates the lane number of the spline.
		Exit Lane Number	4/5-7, 5/0-1	5	yes	-15 to 15	1		Exit Lane number for which the message applies.Bit 5/1 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane. If number of control points is 0, indicates the lane number of the lane going out of the intersection maneuver. If number of control points is 0, indicates the lane number of the spline.
		Arc length of Spline	5/2-7,6,7	22		0 to 4194303	1	cm	This allows for a spline length of 41 km. If number of control points is 0, indicates the straight line length of the intersection maneuver. If number of control points is not 0, indicates the arc length of the spline.
0x21D	Midterm Control Points	Point #	0	8		0 to 255	1		The sequence number of this control point (specifies the ordering of the control points with a given spline)
		Latitude delta	1,2,3	24	yes	-8388607 to 8388607	1	DMD	Degree change in latitude from VP Base Latitude reported in Map Status #2 message. Bit 3/7 is the sign bit: 0=Pos, 1=Neg.
		Longitude delta	4,5,6	24	yes	-8388607 to 8388607	1	DMD	Degree change in longitude from VP Base Longitude reported in Map Status #2 message. Bit 6/7 is the sign bit: 0=Pos, 1=Neg.
		Instance #	7	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to number of instances.
0x21E	Midterm Knots	Value	0,1,2,3	32		0 to 4294967295	1		Original knot value multiplied by 1000000. Application needs to divide this value by 1000000 to get the original knot value.
		Instance #	4	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to number of instances.
		Knot #	5	8		0 to 255	1		The sequence number of this knot (specifies the ordering of the knots with a given spline)

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x21F	Midterm Data Quality	Instance #	0	8		0 to 255	1		Instance number corresponds to the instance number reported in the midterm spline header message
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one quality might apply to multiple paths
		Value	4	8		0 to 100	1		Data quality is assigned to each link. It is not defined and populated in the database yet. Its value range of 0 to 100 is set arbitrarily here and may be changed in the future.
0x220	Midterm Lane Width	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current lane width
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one lane width might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Value	4/5-7,5/0-6	10		0 to 1023	1	cm	Lane width

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x221	Midterm Left Adjacency	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances. Left adjacency message is sent for the current vehicle lane or the most likely lane only.
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current left adjacency
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one left adjacency might apply to multiple paths
		Adjacency Type	4/0-3	4		0 to 11	1		0=Enterable Lane, 1=Non-Enterable Lane, 2=Transition Start (Lane forming), 3=Transition Start (Lane ending), 4=Shoulder, 5=Other drivable surface, 6=Non drivable surface, 7=Where adjacent lane is part of another link, 8=Opposing direction Lane, 9=Transition End (Lane forming), 10=Transition End (Lane ending), 11=Single Point Crossing Legality
		Lane Type	4/4-7	4		0 to 12	1		If Adjacency Type = 0, 1, 2, 3, 8, 9, 10 or 11: 0=through lane, 1=left turn only lane, 2=right turn only lane, 3=suicide lane, 4=left shoulder sometimes, 5=right shoulder sometimes, 6=merge lane, 7=ramp lane, 8=through or left turn lane, 9=through or right turn lane, 10=left exit lane, 11=right exit lane, 12=N/A
		Shoulder Type	5/0-1	2		0 to 2	1		If Adjacency Type = 4 or 5: 0=paved, 1=unpaved, 2=N/A
		Width	5/2-7,6/0-3	10		0 to 1023	1	cm	If Adjacency Type = 0, 1, 2, 3, 8, 9, 10 or 11, then Lane width. If Adjacency Type = 4, then shoulder width. If Adjacency Type = 5, then other drivable surface width. If Adjacency Type = 6 or 7, then not applicable.
		Number of Lanes	6/4-7	4		0 to 15	1		number of lanes on the left.

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x222	Midterm Right Adjacency	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances. Right adjacency message is sent for the current vehicle lane or the most likely lane only.
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location. 0=current right adjacency
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one right adjacency might apply to multiple paths
		Adjacency Type	4/0-3	4		0 to 11	1		0=Enterable Lane, 1=Non-Enterable Lane, 2=Transition Start (Lane forming), 3=Transition Start (Lane ending), 4=Shoulder, 5=Other drivable surface, 6=Non drivable surface, 7=Where adjacent lane is part of another link, 8=Opposing direction Lane, 9=Transition End (Lane forming), 10=Transition End (Lane ending), 11=Single Point Crossing Legality
		Lane Type	4/4-7	4		0 to 12	1		If Adjacency Type = 0, 1, 2, 3, 8, 9, 10 or 11: 0=through lane, 1=left turn only lane, 2=right turn only lane, 3=suicide lane, 4=left shoulder sometimes, 5=right shoulder sometimes, 6=merge lane, 7=ramp lane, 8=through or left turn lane, 9=through or right turn lane, 10=left exit lane, 11=right exit lane, 12=N/A
		Shoulder Type	5/0-1	2		0 to 2	1		If Adjacency Type = 4 or 5: 0=paved, 1=unpaved, 2=N/A
		Width	5/2-7,6/0-3	10		0 to 1023	1	cm	If Adjacency Type = 0, 1, 2, 3, 8, 9, 10 or 11, then Lane width. If Adjacency Type = 4, then shoulder width. If Adjacency Type = 5, then other drivable surface width. If Adjacency Type = 6 or 7, then not applicable.
		Number of Lanes	6/4-7	4		0 to 15	1		Number of lanes on the right.
0x223	Midterm Lane Markings Type	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one lane markings type might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Side	5/0-1	2		0 to 3	1		0=N/A, 1=Right, 2=Left, 3=Both Sides
		Closest Stripe Type	5/2-4	3		0 to 4	1		0=None, 1=Solid, 2=Dashed, 3=Dotted,4=Erratic
		Second Stripe Type	5/5-7	3		0 to 4	1		0=None, 1=Solid, 2=Dashed, 3=Dotted,4=Erratic
		Closest Stripe Color	6/0-1	2		0 to 2	1		0=No Color, 1=White, 2=Yellow
		Second Stripe Color	6/2-3	2		0 to 2	1		0=No Color, 1=White, 2=Yellow
		Medium	6/4-5	2		0 to 2	1		0=No Medium 1=Paint, 2=Botz dots
		Reflectors	6/6	1		0 to 1	1		0=No, 1=Yes

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x224	Midterm Traffic Signal Location Header	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances. Instance number in traffic signal location header has a one-to-one relationship with the instance number in traffic signal location.
		Applicable Path	1	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one Traffic signal location might apply to multiple paths
		Lane Number	2/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Left Turn Signal	2/5	1		0 to 1	1		0=No, 1=Yes
		Three Lens Signal	2/6	1		0 to 1	1		0=No, 1=Yes
		Control Flag	2/7	1		0 to 1	1		0=No, 1=Yes. If set then this indicates that the traffic signal controls the lane indicated in lane number.
0x225	Midterm Traffic Signal Location	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances. Instance number in traffic signal location has a one-to-one relationship with the instance number in traffic signal location header.
		Latitude delta	1,2,3	24	yes	-8388607 to 8388607	1	DMD	Degree change in latitude from VP Base Latitude reported in Map Status #2 message. Bit 3/7 is the sign bit: 0=Pos, 1=Neg.
		Longitude delta	4,5,6	24	yes	-8388607 to 8388607	1	DMD	Degree change in longitude from VP Base Longitude reported in Map Status #2 message. Bit 6/7 is the sign bit: 0=Pos, 1=Neg.
0x226	Midterm Intersection Location	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one Intersection location might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Type	4/5-6	2		0 to 2	1		Intersection type. 0=Standard; 1=Roundabout; 2=Railroad Crossing
0x227	Midterm Overhead Stationary Roadway Structures	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one overhead roadway structure object might apply to multiple paths
		Height	4/0-7,5/0-1	10		0 to 1023	1	cm	Height of the overhead structure if posted. 0 if unposted.
		Length	5/2-7,6,7	22		0 to 4194303	1	cm	Longitudinal length of the overhead structure. 0 if the overhead structure is shallow (such as sign structures and walkways).

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x228	Midterm Stationary Roadside Objects	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stationary roadside object might apply to multiple paths
		Lateral Distance	4,5	16		0 or 200 to 400	1	cm	0=N/A; 200 to 400 = Lateral distance of the closest objects when Object Density = 0.
		Object Density	6/0-2	3		0 to 4	1		"0" - Closest object is >2m from roadway (distance provided), "1" - Sparsely placed objects within 2m of roadway, "2" - Low density of objects within 2m of roadway, "3" - Significant density of objects within 2m of roadway, "4" - Very dense placement of objects within 2m of roadway
		Side	6/3-4	2		0 to 3	1		0=N/A, 1=Right, 2=Left, 3=Both Sides
0x229	Midterm Stationary Roadside Barriers	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance from host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one stationary roadside barrier might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Side	4/5-6	2		0 to 3	1		0=N/A, 1=Right, 2=Left, 3=Both Sides
		Type	5/0-1	2		0 to 2	1		0=No Barrier, 1=Metal, 2=Non Metal
0x22A	Midterm Data Compatibility	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance From Host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one data compatibility might apply to multiple paths
		Value	4/0	1		0 to 1	1		0=MidTerm Data; 1=Non-MidTerm Data. This message is sent only if the Value is 1 (i.e., when a link within the electronic horizon is not mid-term compatible). A link is mid-term compatible if it contains EDMap mid-term attributes, including lane-level data and lane geometry.

CAN ID	Mapplets	Information	Byte/Bits	Req'd Bits	Signed ?	Range/Values	Resolution	Units	Notes
0x22B	Midterm Lane Type	Instance #	0	8		0 to 255	1		Instance number being reported in this message. Instance number must always be less than or equal to Number of Instances
		Distance From Host	1,2	16		0 to 65535	1	cm	This mapplet's distance from current vehicle location
		Applicable Path	3	8		0 to 7 (bit flags)	1		bit0=Path0, bit1=Path1,… There should be as many bits as paths, one lane type might apply to multiple paths
		Lane Number	4/0-4	5	yes	-15 to 15	1		Lane number for which the message applies. Bit 4/4 is the sign bit: 0=Pos, 1=Neg. Lane number 0 is the vehicle lane or most likely lane.
		Value	5/0-3	4		0 to 12	1		0=through lane, 1=left turn only lane, 2=right turn only lane, 3=suicide lane, 4=left shoulder sometimes, 5=right shoulder sometimes, 6=merge lane, 7=ramp lane, 8=through or left turn lane, 9=through or right turn lane, 10=left exit lane, 11=right exit lane, 12=N/A
0x250	Midterm EH Distance	New EH Distance	0,1/0-1	10		0 to 655	1	m	Set a new Electronic Horizon Distance

Appendix E: Quality Assessment Report

E.1 Introduction

E.1.1 EDMap Overview

The Enhanced Digital Map (EDMap) Project is a three-year effort launched in April 2001 to develop a range of digital map database enhancements that enable or improve the performance of driver assistance systems currently under development or consideration by U. S. automakers.

The project began with identification of safety related applications, from near-term to long-term, that would benefit from or be enabled by map database improvements. The map database requirements for each application were then determined using feedback from the map database supplier with regard to data collection feasibility and database maintainability. Using the application requirements, the map database supplier constructed map databases for specified test areas in the Palo Alto area in California and the Detroit area in Michigan. The participating automakers each evaluated and demonstrated implementations of selected driver assistance systems in the Palo Alto test area in November 2003 and the Detroit test area in March 2004. The project result is to be an assessment that will provide direction to the map suppliers, in terms of the enhancements needed for future driver assistance systems, and provide a roadmap to the USDOT in terms of safety focused systems that are enabled by enhanced map databases.

The objectives of the EDMap project are to: develop specifications for enhanced map databases to improve driver safety assistance systems, develop prototype tools and processes to produce these databases, and assess the commercial feasibility of creating these advanced map databases.

Applications having significant safety potential were selected for:

- Near-term (2004-2006)
  - Speed Limit Advisor
  - Curve Speed Warning
  - Stop Sign Warning
- Mid-term (2007-2011)
  - Curve Speed Control
  - Stop Sign Control
  - Forward Collision Warning
  - Lane Following Warning
  - Traffic Signal Warning

Near-term applications can be supported by databases with information at the road level of granularity, the granularity of navigation level databases today. For example, navigation and near-term databases represent geometry as the centerline of the road in the case of a two-lane road and the centerline of each side of the road in the case of a multi-lane divided highway. The attribution for near-term databases remains at the road level, similar to navigation-level databases today, but provide more detail. For example, navigation databases store speed ranges and a range for the number of lanes to determine traversal time estimates. Near-term databases store actual speed limits and the exact number of lanes, still as road attributes. Stop sign attributes are not in today's navigation-level database but have been added for near-term database requirements.

However, mid-term applications, such as Lane Following Warning and Forward Collision Warning, require a database with increased accuracy and information at a lane level of granularity. For example, mid-term applications require information about the centerline and width of each lane so that position in the lane can be determined. Mid-term databases require lane centerline representation with the precision and accuracy at the decimeter level. Storing lane information requires collecting not only road type attributes about each lane, but additional attributes as well, such as lane striping and shoulder information that were not required at the road level.

E.1.2 Explanation of the Four Databases

To demonstrate the capability of future EDMap databases, four test databases were created in the selected test areas (see figures Figure E-1 and Figure E-2):

- Near-term Michigan
- Near-term California
- Mid-term Michigan
- Mid-term California

The test databases consist of the following elements: tiles, swaths, and routes. A tile is a complete rectangular region containing all roads in that region. A swath is a connector corridor between tiles consisting of the connector road and its immediate surrounding road geometry. The swaths provide connectivity between test regions within each of the test areas. Routes, selected sets of connected roads (freeways and non-freeways), demonstrate certain road or terrain types and road scenarios, such as clover leafs, roads with stop signs, etc.

The database coverage is the same for the near-term and mid-term databases in each of the test areas. Near-term database requirements are a superset of currently planned map database enhancements and specify road-level geometry and attributes. Mid-term database requirements specify lane level instead of road-level geometry and attributes and have tighter accuracy requirements than the near-term databases.

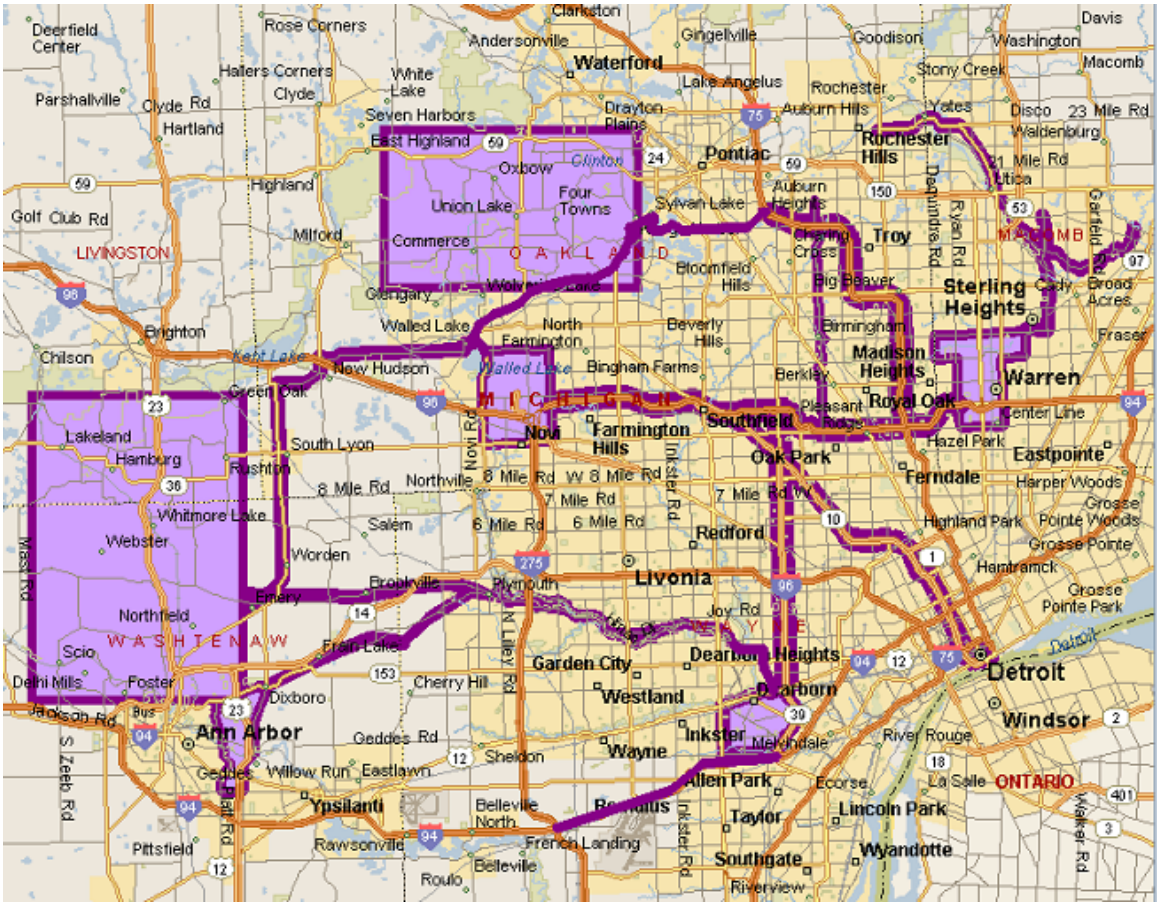

Figure E-1: Detroit test areas and routes

Figure E-2: Palo Alto test areas and routes

E.1.3 Structure of the Report

This quality assessment report is structured in the following manner:

- **Introduction** (Section 1)
- **Unit Testing** (Section 2): describes equipment unit testing (i.e., the process of understanding the performance of the equipment used to collect EDMap data).
- **Geometric Quality Methodology** (Section 3): provides an overview of the methodology used to determine the geometric accuracy of the EDMap databases.
- **Attribute Assessment Methodology** (Section 4): describes attribute assessment as the task of understanding the quality of the road features recorded in the databases.
- **Sampling Methodology** (Section 5): introduces the sampling methodology used to evaluate the accuracy and precision of the four EDMap databases.
- **Collection Methodology** (Section 6): describes the collection methodology for obtaining the source of reference data (ground truth data) used in the quality assessment work.

- **Validation of 35** (Section 7): describes the process used to verify the sampling methodology used.
- **Summary of Results** (Section 8): describes results from the analysis for geometry and attributes for the near-term and mid-term databases. The results for Michigan and California databases are discussed in this section.

E.2 Unit Testing

Unit testing is the process of understanding how the equipment used to collect EDMap data performs. In particular, unit testing aims to assess whether or not each unit meets the manufacturer accuracy specification for typical collection conditions.

The three units listed below were used to produce the near-term and mid-term databases.

Unit	Purpose	Database
Satloc SLX 300g	Positional (DGPS)	Near-term
PerformTech	Positional (INS)	Near-term
Applanix	Positional (GPS/INS)	Mid-term and parts of near-term which could not be collected by Satloc

Table E-1: Collection units used to construct the EDMap databases

E.2.1 Satloc SLX 300g

The SLX-300 receiver is designed for multiple applications including air, ground, marine and GIS. It is a GPS receiver with built-in WAAS or L-band differential and 300 kHz Beacon differential. It can provide differentially corrected positions at up to 5 Hz, (Satloc, 2001).

The Satloc manufacturer's stated positional accuracy of 1 meter 66% of the time (assuming a good view of the sky and minimal multipath) appears to be fair from the results of this experiment.

Under less-than-optimal conditions, the Satloc positional accuracy is approximately 2m +/- 0.14m at the 95% confidence interval. The heading accuracy appears to degrade with signal interference, with errors from true heading increasing by up to three times.

E.2.2 Applanix POS/LV 420

The POS LV 420 uses strap down inertial navigation, Kalman filtering, GPS, GPS azimuth measurement, and a Distance Measurement Indicator (DMI), to provide position and orientation data that has a high bandwidth, excellent short-term accuracy and minimum long-term errors. The system provides dynamically accurate, high-rate measurements of the full kinematic state of the host vehicle.

E.2.3 PerformTech INS

The PerformTech INS performs within manufacturers stated accuracy threshold for 4.5 complete turns of the host vehicle, under test conditions.

Clearly, the PerformTech INS unit provides unsatisfactory accuracy for trace over large distances. The output trace appears to exceed the five meter EDMap near-term geometric absolute accuracy requirement over a distance of 405 m, if the car were traveling in a straight line. Changes in direction will adversely affect this metric. However, for short-term GPS outages, the unit performs adequately.

E.3 Geometric Quality Methodology

This section provides an overview of the methodology used to determine the geometric accuracy of the EDMap databases.

E.3.1 Absolute and Relative Accuracy

Figure E-3 illustrates the difference between absolute accuracy and relative accuracy.

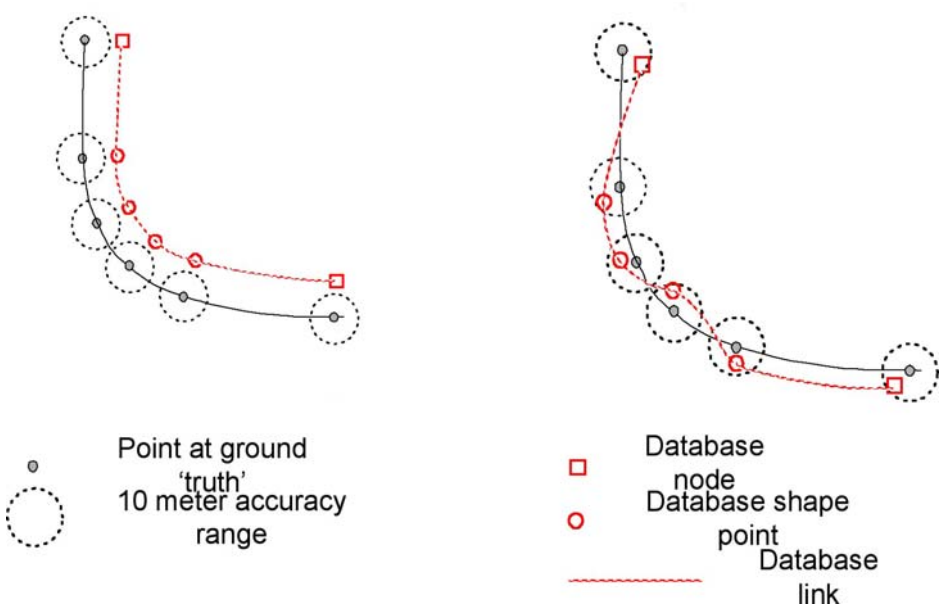

Figure E-3: (Left) the absolute accuracy is outside of the 10 m range, but the relative accuracy is correct. (Right) the absolute accuracy is within the 10 m range, but the relative accuracy is not correct.

Absolute accuracy is the spatial deviation (perpendicular distances) between the two geometries (i.e. database geometry and the ground truth geometry). Relative accuracy is calculated by first aligning the two geometries, and then computing the spatial deviation between the two geometries.

A QA Geotool was designed for the quality assessment of geo databases for the EdMap project. The main task of the tool was to give a quantitative analysis of the two spline representations of the road or lane segments. The results computed by the tool were used as a measure of relative accuracy. The following subsection describes the algorithm used by this tool.

E.3.2 High-Level Explanation of the QA TOOL Algorithm

Suppose there are two geometries—Ground Truth geometry (GT) and Original geometry (ORIG). The tool performs affine transformation to the ORIG geometry to bring it closer to the GT geometry.

1. Find the coordinates of the center of gravity of GT spline
2. Find the coordinates of the center of gravity of ORIG spline
3. Translate ORIG spline so that its center of gravity coincides the center of gravity of GT.

4. Rotate ORIG geometry with respect of the GT's center of gravity by the angle calculated as the mean angle difference of the two geometries (see next section for the detailed calculation of the rotation angle).
5. Scale ORIG to GT (see next section for the details of the scaling factors calculation)
6. The tool determines how close the two geometries are lined up after the transformation by determining maximum deviation along the spline length.

Quantitative characteristics of the difference between two geometries include:

- Translation distances
- Rotation alignment angles
- Scaling factors, and
- Maximum deviation.

E.4 Attribute Assessment Methodology

The attribute assessment methodology is the task of understanding the quality of the road features recorded in the databases. Attributes are the features of the road that are collected specifically for EDMap. Examples of attributes are: speed, number of lanes, surface type, and lane width for the near-term and lane width and overhead structures for the mid-term.

The attribute assessment consists of a four-way analysis of errors. Where appropriate, each attribute is assessed for the type of error.

E.4.1 Errors of Omission

An omission error occurs when an EDMap-collected attribute is present in reality but is missing from the EDMap database. As Figure E-4 shows, in reality there are two stop-ahead signs on the road; however, the most westerly sign has been missed. An error of omission is more severe than an error of classification.

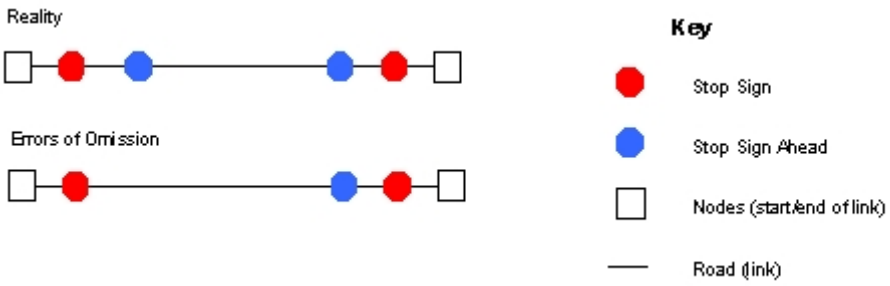

Figure E-4: Omission error

E.4.2 Errors of Commission

A commission error occurs when the EDMap database contains an attribute that is not found in reality. In the example in Figure E-5, an extra stop sign has been added incorrectly.

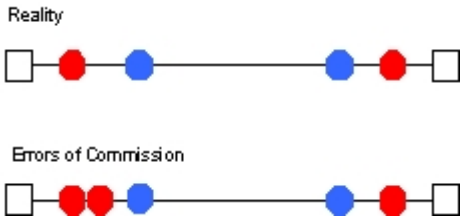

Figure E-5: Commission error

E.4.3 Errors in Classification

An error in classification occurs when an attribute has been correctly included and located; however, the type of attribute (its specific information) is wrong. For example, a point attribute of a stop-ahead sign is found in reality however, it has been incorrectly coded as a stop sign. This is illustrated in Figure E-6.

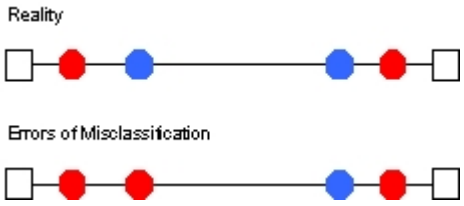

Figure E-6: Classification error

E.4.4 Positional Errors

A positional error occurs when an attribute is positioned in the wrong location. Figure E-7 illustrates an example of an attribute that is positioned in the wrong location along the road.

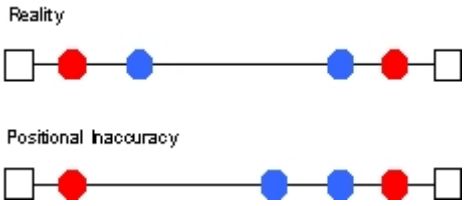

Figure E-7: Positional error

The positional accuracy will be calculated using the road distance between the ground truth and the original attribute. This is illustrated for both straight and curved geometry in Figure E-8 below. The orange sections of road indicate the distance measure that will provide the measure of positional error in the attribute assessment.

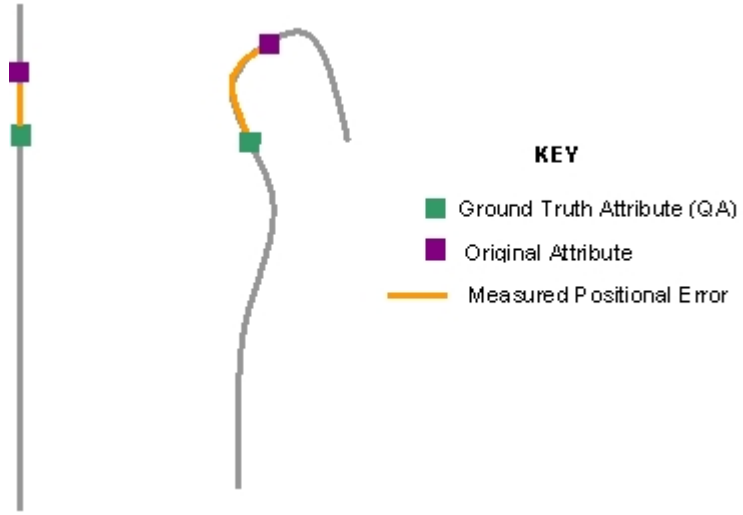

Figure E-8: Positional error measure for straight and curved road geometry

The attribute error analysis process is summarized in the following three steps:

1. **Determine number of matches and non-matches.** The number of correctly identified EDMap attributes is identified, as well as the number of non-matches or errors.
2. **Determine error type.** The criteria used to determine whether an original attribute is matched to one in reality (the QA collected data) are based on the specifications written for each attribute. For example, stop signs as a near-term attribute are to be within 1m of the true stop sign location. A match would constitute an original EDMap stop sign falling within 1 meter of the QA assessment's "ground truth".
3. **Determine degree of error.** The degree of error (the metric of positional error) is also reported. For example, for stop signs, the proportion of stop signs that are with 1m, 2m, 5m, 10m etc. of reality is reported.

E.5 Sampling Methodology

E.5.1 Overview

This section describes the sampling methodology used to evaluate the accuracy and precision of the four EDMap databases.

The goal of the QA assessment is to evaluate the accuracy and precision of the four EDMap databases. A source of comparable, yet superior data is required in order to produce suitable metrics. To obtain the superior data, roads were re-driven, and a separate QA "ground truth" database was created for each of the four EDMap databases. Comparisons were then performed between the post-collected EDMap databases and the QA databases at the original database level.

Re-collection of 100% of the databases was not feasible due to the time, cost and practicality constraints of such a large-scale collection. Thus, a more refined sampling approach was justified.

The first step in the sampling process was to determine the sampling unit. The sampling unit chosen for the QA assessment is known as a *Road Section* for the near-term databases and a ZElane for the mid-term databases. A road section is defined as a section of road, at least 250m (unless the road terminates) from one intersection to another, or ramp to ramp on a highway. This unit of measurement overcomes the problem of short and inappropriate ZElinks. A ZElane is defined as a lane of a ZElink. ZElinks are geometric entities in the EDMap databases And are defined as a stretch of road from intersection-to-intersection. Occasionally, a road from one intersection to another is broken into two or more parts. Defining a road section to be at least 250m ensures that an adequate number of road characteristics are recorded for the attribute assessment.

A sampling design should be chosen to ensure that the individual samples collected are both representative and unbiased observations of the population. "Representative" means the fair reflection of the population in question. An "unbiased sample" requires the random selection of a sample, whereby each entity has an equal opportunity of being selected.

Generally, roads possess a variety of characteristics. Distinctions occur in terms of the curvature, number of lanes, speed, and other features, many of which are recorded in the EDMap databases. A *stratified* sampling approach is preferable for the complex and diverse nature of a road database.

A stratified sampling involves dividing the population into at least two subgroups each of which possesses different population characteristics. A sample is captured from each group. When data has diverse characteristics, it is important to include that diversity within the sample. Stratified sampling ensures that a sample is a fair representation of the database, so long as the subgroups are correctly defined.

Initial analysis has shown that many of the EDMap attributes cluster according to road type. For example, stop signs are most commonly found on residential roads, but are not found on highways.

To ensure that resources (time and manpower) were used efficiently, a routing technique was determined to be the most appropriate way to recollect road geometry and attributes. This involved driving continuous road sections so that no data became redundant. The idea behind routing is to maximize attribute collection during the sample drive.

An optimal sampling size of 35 was chosen in order to minimize data collection cost and time while at the same time ensuring that the sample size yielded statistically significant results. A sample size of 35 has been proven to yield a reasonable level of uncertainty; it makes the first digit of the proportion reliable and has been accepted as the EDMap QA assessment sample size. This number is regarded as the minimum sample needed that will yield statistically significant results. It reduces the standard error in the binomial distribution to +/- 2-3% at a 97% confidence interval. This sampling size dictated 35 sample routes to be driven for each subgroup, each of which contained at least 35 road sections.

To define the sample routes for the EDMap database test areas, it is necessary to understand the distribution of attributes and geometry over the population of the dataset, which may or may not match the geography of the dataset. This will allow like roads to be grouped with like roads to build up sample routes within the dataset. Due to the connective nature of roads, the sample routes must consist of at least 35 road sections composed of connecting ZElinks.

Two clustering techniques were used to determine the database stratification (grouping of roads). The California near-term and mid-term databases as well as the Michigan near-term database were first analyzed with a FANNY (Fuzzy Analysis Clustering) clustering method with statistics drawn from the dataset to determine exactly what the clusters were referencing followed by a refinement step of the clusters as necessary using the statistics and local knowledge. For the near-term Michigan database, a CLARA (Clustering Large Applications) clustering method was used to define strata, because the database was too big to apply a FANNY clustering method.

These clustering techniques yielded clusters that appeared to be roughly split down the following Functional Class (FC) classifications: FC1 and FC2 are highways, FC3 and FC4 are connector roads, and FC5 represents residential roads. Using the results of the clustering techniques and local knowledge, the final clustering stratification for the databases is shown in Table E-2:

Near-term Michigan	Near-term California	Mid-term Michigan	Mid-term California
FC1-2	FC2	FC1-2	FC2
FC3-4 urban	FC3 & 4	FC3-4	FC3-4
FC3-4 rural	FC 5, and	FC5	FC5
FC5	Steeply graded roads		

Table E-2: Near-term and mid-term clustering stratification results

Unlike the Michigan near-term dataset, the other datasets appear to not differentiate between urban and rural areas. Local knowledge of the California area suggests that there were significant areas of elevation that are not recorded in the California near-term dataset. This cluster was, therefore, added to the California near-term stratification.

E.6 Collection Methodology

This section describes the collection methodology for obtaining the source of reference data (ground truth data) used in the quality assessment work.

The QA data must at least equal the accuracy of the original EDMap data. Ideally, more accurate reference data is sought. Confidence in data being of a higher accuracy can be gained only if collection methods superior to the original are used.

E.6.1 Near-term Collection Equipment

Creating a superior near-term sample of data is a relatively straightforward process, as many mid-term tools can be used to gain a superior source of reference data for both geometry and attributes. Two passes with the mid-term high accuracy tools were used for near-term QA ground truth data. Table E-3 compares the data collection equipment and number of passes used to collect the original near-term databases to the QA ground truth databases.

Original EDMap Geometry	QA Geometry (Ground Truth)
Satloc GPS PerformTech GPS/IMU Single pass of roads	Applanix Integrated GPS / INS / DMI system 2 passes of each route

Table E-3: Near-term geometry collection equipment

The Mobile Plot tool was used in the field to record road attributes such as number of lanes, speed changes and the location of stop signs. The original near-term set-up was integrated with the Mobile Plot tool to the Satloc system to provide location for the recorded attributes.

The near-term attributes for the QA assessment were recorded using a slightly different set-up of equipment from the original. The positional accuracy of the attribute was determined by the specific GPS used. The Mobile Plot tool was integrated with the higher-accuracy Applanix system, so the positioning of the attributes is more accurate in terms of the attribute's actual location than was possible in the original database. Collecting the data twice and averaging the results further increased confidence in the position of each recorded attribute.

Original EDMap Attributes	QA Attributes (Ground Truth)
Mobile Plot connected to Satloc system Single pass of roads	Mobile Plot connected to Applanix system Collection of Mobileye imagery 2 passes of each route

Table E-4: Near-term attribute collection equipment

E.6.2 Mid-term Collection Equipment

The assessment of the mid-term data was more challenging, because the equipment used for the original collection was the best available at the time. This meant that the only option for superiority was to use the same equipment and the theory of repeatability.

Original EDMap Geometry	QA Geometry (Ground Truth)
Applanix Integrated GPS / INS / DMI system	Applanix Integrated GPS / INS / DMI system
Single pass of roads	3 passes of roads

Table E-5: Mid-term geometry collection equipment

The concept of multiple passes was perceived as the best and more practical option to collect ground truth data for the mid-term databases. Three collection passes were averaged and used for representing reality (ground truth).

Original EDMap Attributes	QA Attributes (Ground Truth)
Mobile Plot connected to Applanix system	Mobile Plot connected to Applanix system
Single pass of roads	Collection of Mobileye imagery
	3 passes of each route

Table E-6: Mid-term attribute collection equipment

Following the success of the near-term attribute collection, the mid-term attributes (with the exception of lane width, grade, and super elevation) were recorded using the Mobile Plot tool. The combination of tools for near-term attribute assessment surpassed the original attribute collection; therefore it was deemed acceptable to repeat the near-term collection processes for the midterm attributes.

As with the near-term assessment, attribute positioning is derived from the Applanix system. The multiple passes increase the potential of a more accurately placed attribute based on the theory that the field analyst will remember the location of an approaching attribute.

The attribute of lane width was collected in the same manner as the original EDMap collection. To gain a more precise measurement for lane width, the average of three traverses was used to derive the final lane width value.

E.6.3 Mid-term Sampling Unit

Due to the complex nature of the lane-level mid-term databases, the sampling unit had to be adjusted for the mid-term assessment. A ‘Road Section’ was not appropriate for the lane level data of the mid-term databases. To ensure that the sample population was large enough without introducing bias, the decision was made to use the ZElane as the sampling unit for the mid-term assessment.

E.7 Validation of 35

E.7.1 Introduction

The goal of this section of work is to verify 35 as the minimum sample size required in order to produce statistically significant and reliable results for the analysis of the four EDMap databases.

A sample size of 35 is regarded as the minimum sample needed. It reduces the standard error in the binomial distribution to +/- 2-3% at a 97% confidence interval. The EDMap road databases provide a complex population of study, with no two individuals the same. Therefore, it was crucial to test the theory of 35 as a minimum sample size for the specific purpose of sampling roads.

E.7.2 Methodology

The experiment involved collecting different samples of 35 from a single subgroup and comparing the collected data to the original EDMap data. If '35' is appropriate, the *differences* in the standard error should be minimal. Larger disparities would mean that the sample size needs to be reconsidered.

Sampling is a method used in statistics to alleviate the problem of re-collecting an entire population of data. Often, it is impractical or even impossible to collect all relevant data. An accepted practice is to sample a proportion of the population. There are numerous ways this can be achieved depending on the type of data and ultimate purpose. A stratification sampling method was selected for the QA assessment, whereby the databases were divided into subgroups that are internally homogeneous and externally heterogeneous.

The stratification of the databases ensures that like roads are grouped together. Dividing the database into subpopulations would lead to the expectation that accuracy levels may vary according to road type. With this in mind, it is crucial to perform the validation at a subgroup level. The FC5 subgroup was chosen for the validation exercise, primarily because of the overwhelming abundance of point attributes. Approximately 90% of stop signs and stopping locations fall on FC5 roads. Data from the validation exercise will be used in the sampling; therefore, using this subgroup will increase the proportion of attributes used in the attribute analysis. Moreover, the average number of links per road section is considerably lower for the FC5 subgroup.

Using the sample size of 35, the results show a very small difference in the standard error of the sampled routes, indicating that this sample size is sufficient for the EDMap databases to yield statistically significant results.

E.8 Summary of Results

These sections discuss the results from the quality analysis using the stratified sampling. EDMap-like databases were created for the sampled areas and were compared with EDMap databases delivered to the OEMs. The results of these comparisons for the near-term databases are discussed in this section; the mid-term databases are discussed in Section E.8.2. Each database was analyzed for geometry and attributes. These sections, however, give an overall summary of these results. The results for each of the individual attributes were compiled to arrive at these charts and tables.

E.8.1 Near term databases

E.8.1.1 Geometry

The reference database and the EDMap database geometry were compared using a process of scaling, rotation, and sampling to compute the relative accuracy for each ZElink in the reference database. Figure E-9 shows the maximum deviation values within a certain range (1m, 2m, and 4m respectively) for the Michigan, California, and combined Michigan-California databases.

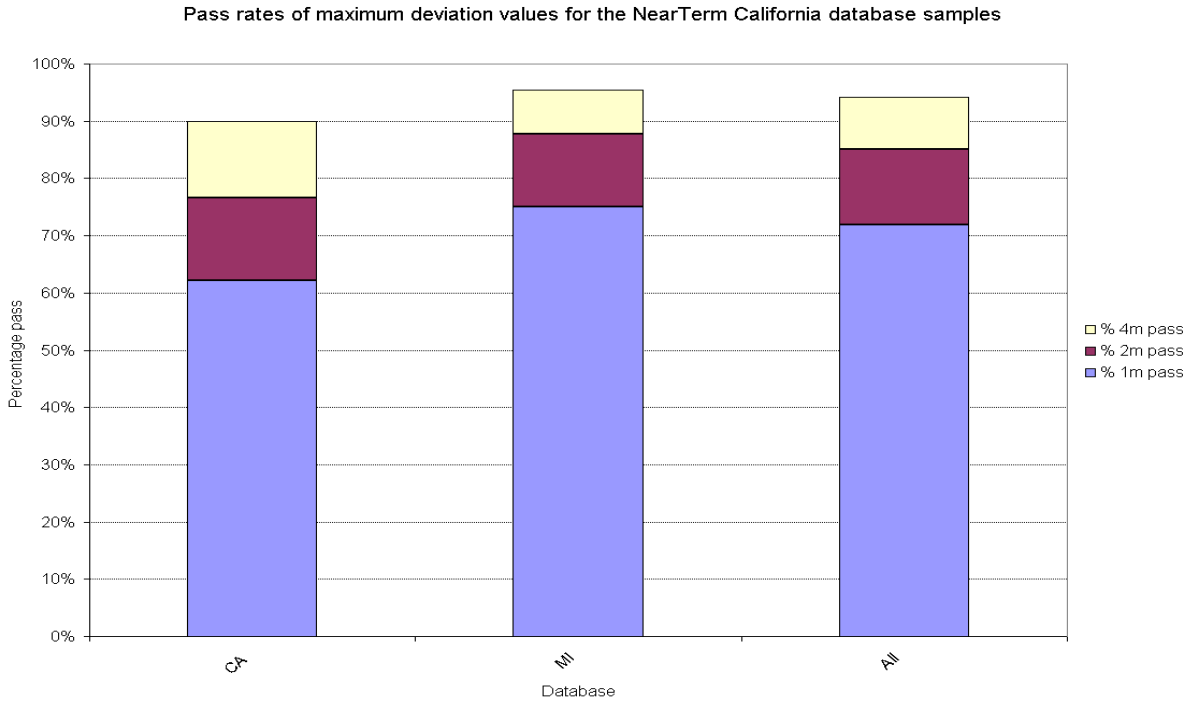

Figure E-9: Percentage of database within maximum deviation ranges for the databases. 'California' relates to the values for the entire California database, 'Michigan' to Michigan. 'All' relates to values for the project as a whole.

It can be seen from Figure E-9 that the near-term Michigan database features significantly more accurate geometry when compared to the near-term California database. It can be seen that the relative accuracy of the geometry within the original EDMap specification of 1 meter maximum deviation was 77% for the near-term Michigan database and 60% for the near-term California

database. When this ‘pass’ rate is raised to 4 m, the percentage of population meeting this maximum deviation threshold rises to 95% for near-term Michigan and 90% for near-term California.

The relatively poor performance of the near-term California database is likely to have been influenced by the bad results of the ‘Steeper’ road sample. This sample featured the highest mean maximum deviation values and the highest observed maximum deviation. Indeed, visual comparison of the geometry of this route against the ground-truth and Applanix trace from which the ground-truth was derived confirms obvious discrepancies in the digitizing of this area. The GPS signal along this route is noted as being particularly poor, with aerial photogrammetry failing to detect much of the road due to overhanging vegetation. Clearly, near-term geometry production methodologies are unsuitable for production of highly accurate road geometry under such conditions.

Based on further analysis of the sample clusters, it was found that by ignoring the steeper roads, the FC3 and 4 (‘connector’) roads are seen to have the lowest maximum deviation. These roads are generally non-sinuous, which implies that the potential for high maximum deviation values is reduced. FC2 (‘highway’) roads are seen to have similar mean average maximum deviation values, but a slightly larger spread. In the database, these links are, on average, the longest and can feature significant sinuosity over their length. Therefore, the results for these road types are quite comparable.

FC5 results are seen to closely match the average for the database. This is a result of the Steeper Road sample pulling down the average rather than an indication of a large FC5 sample, which would then allow them to dominate the overall database results.

Figure E-10 represents the normalized population distribution for the databases (Michigan, California, combined) by maximum deviation value. The area under the curve represents the population of the dataset, so that the curves might be looked at as high-resolution histograms. The crest of the curve represents the mean average value of the dataset. The more ‘peaky’ the graph, the less spread the distribution of maximum deviation values over the sample and, hence, the smaller the standard deviation of the dataset. In other words, tall curves that are more biased towards zero maximum deviation (the left of the graph) are the best. Short, flat graphs that are biased towards higher maximum deviation values (the right of the graph) are the worst.

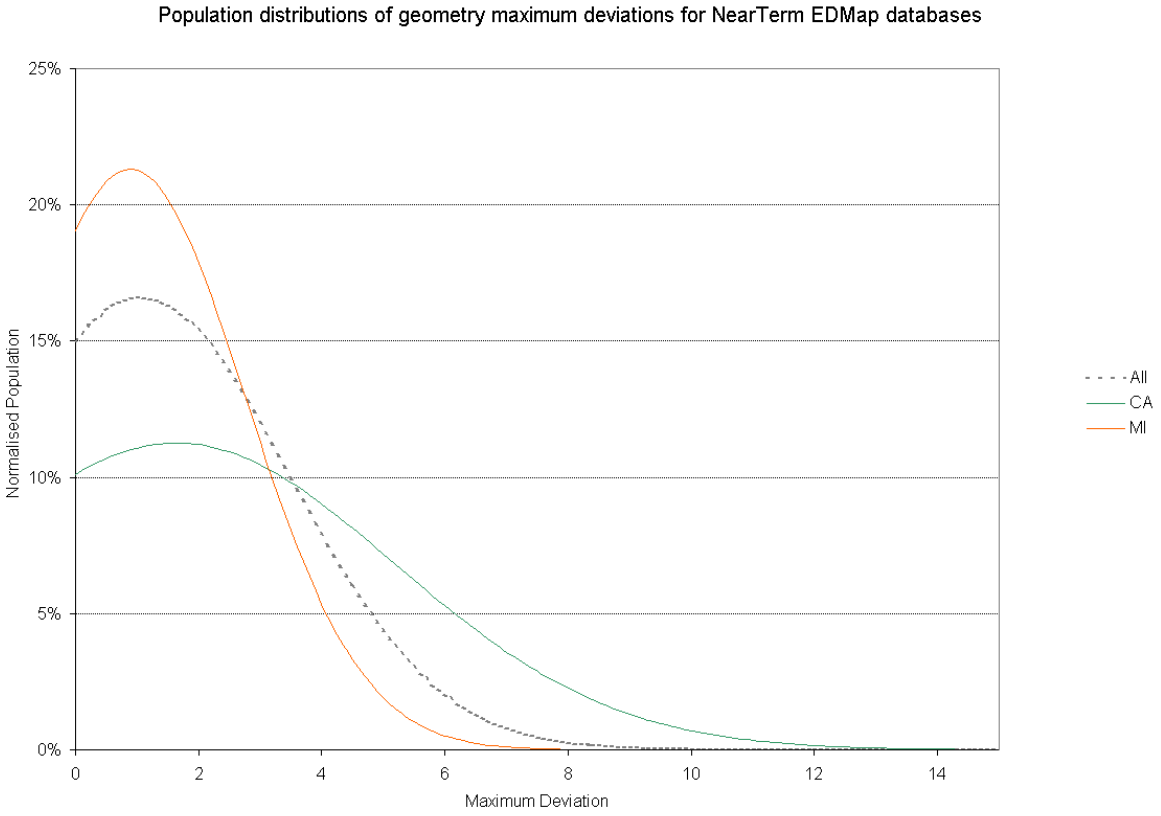

Figure E-10: Population distributions of geometry maximum deviations for Near-term EDMap databases. '' relates to the maximum deviations from all samples taken from the California databases, '' to all samples from the Michigan. 'All' relates to both databases.

The maximum deviation results for near-term Michigan are nearly identical to those for near-term California for FC1 and 2 roads. Near-term Michigan FC3 and 4 urban roads follow a similar population spread as their near-term California counterparts, but feature a population mean of 0.4 m less. FC3 and 4 urban roads are seen to feature the best average maximum deviation values for the EDMap project with an average maximum deviation of 0.69m +/- 0.17m at the 95% confidence interval.

Near-term Michigan FC5 roads score much better than near-term California FC 5 roads, featuring an average maximum deviation and standard deviation that is over half as small. This average is helped by the lack of large outliers in this dataset meaning that the population curve is particularly 'peaky'. These roads also just meet the specification with an average of 1m +/- 0.14m at the 95% confidence interval.

Overall the Michigan Near-term database is seen to feature geometry that is closer to ground-truth than the California Near-term database, and on average is within EDMap specification, at 0.97m maximum deviation -/+ 0.12m at the 95% confidence interval.

On average, the EDMap databases are outside of the specification of 1 meter relative accuracy by 0.19m +/- 0.12m at the 95% confidence interval.

E.8.1.2 Attributes

This section presents the results generated for the quality assessment of the near-term attributes. The EDMap databases that were used for the demonstration of OEM applications to the DOT were used for this analysis. Even though most of the errors identified in the demo area were rectified by NAVTEQ, because the samples used for quality analysis are randomly distributed over all of EDMap database, the quality analysis results are NOT influenced by the specific fixes made for the demo area.

One of the attribute analyses involved assessing the correctness of each sampled ZElink based on the value assigned to each of the populated database fields. The analysis examined the percentage of matches for each selected attribute. The deviation from reality is identified as an error. Figure E-11 shows the results of the ZElink attribute matching errors for the near-term Michigan and near-term California databases.

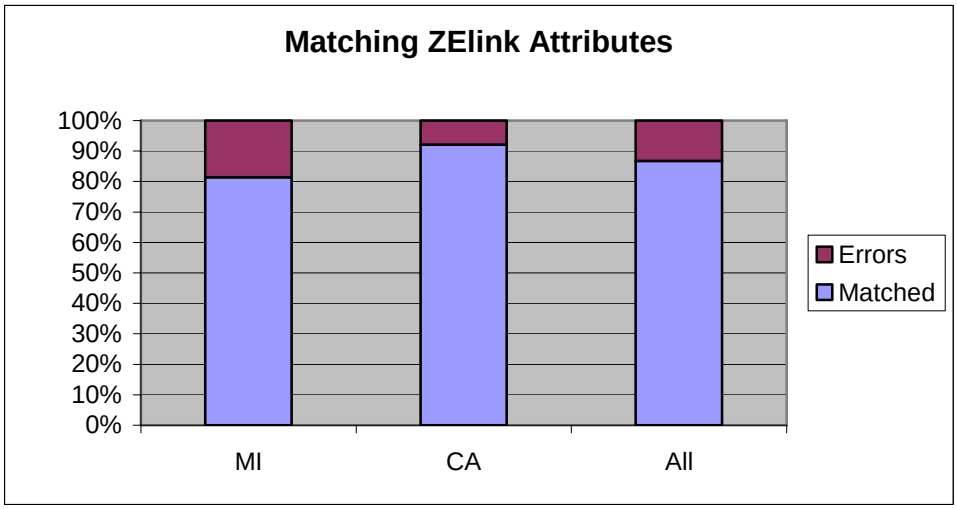

Figure E-11: ZElink Attribute: Pass/Fail by Subgroup

For the entire Michigan database, 81.4% of the ZElink attributes were correctly coded (based on lanes, speed, road condition, and road surface type). The FC5 roads were the more accurate, with approximately 86% correctly classified.

Overall, the near-term California database performed well in terms of ZElink attributes. 91% of ZElinks attribute were correct in terms of lanes, speed, road condition, and road surface type. However, the subgroup “Steeper roads” was significantly lower than the average for all four categories. FC5 roads were found to be 99% correct in terms of the overall ZElink attributes. These types of road tend to be similar in terms of attributes, and therefore little change is experienced. The ZElink attributes of FC2 roads in near-term California database were consistently and accurately recorded (90%), while the same subgroup in the Michigan database had a matching rate of only 76%.

Another approach to attribute analysis was to classify the types of ZEpoint errors. All ZEpoints in the sample database were evaluated to for Omission, Commission and Classification errors. Figure E-12 illustrates the results of this analysis.

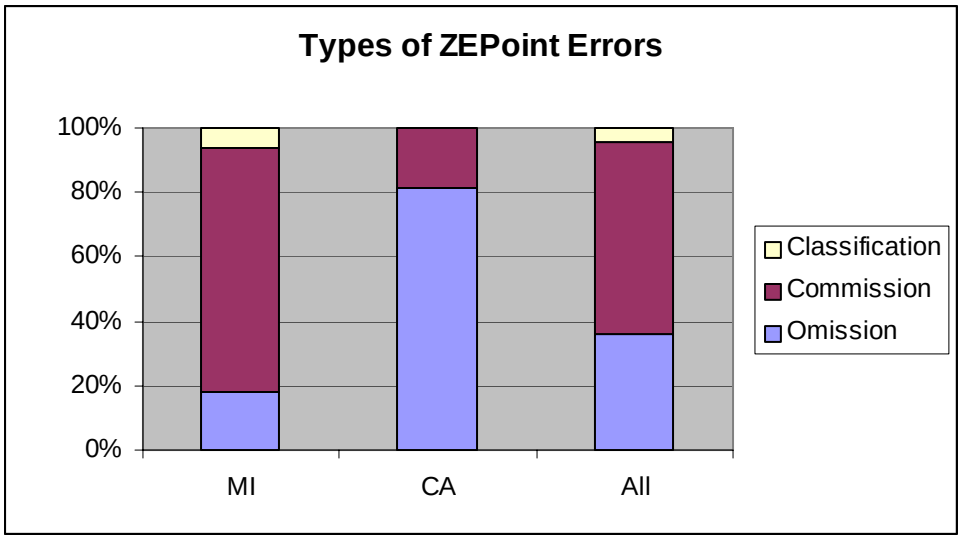

Figure E-12: Types of ZEpoint errors

It was surprising to note that in the Michigan database the majority of errors were errors of commission. This is where an extra or duplicate attribute is found, which in reality is not there. In contrast, the California database suffered more errors of omission (81%). The Michigan database omission errors represented 18% of all the errors.

Figure E-12 also shows that the overwhelming majority of errors that were found in the original EDMap California database were errors of omission. This includes a number of missing stop signs, stopping locations and stop-ahead signs. None of these were mistakenly named as a different ZEpoint attribute, as there were no errors of classification found. Approximately 20% of the errors found were extra or duplicate ZEpoint attributes.

Another type of attribute analysis was to assess the positional accuracy of each of these attributes. This was done for each near-term attribute in the Michigan and California databases. Figure E-13 illustrates the positional accuracy plot for some of the near-term attributes (stop signs) in the Michigan database. It was found that dense tree coverage in FC5 areas results in positional inaccuracies in near-term database (DGPS only systems) and this in turn results in positional errors for stop signs. It can also be observed that a greater number of Stop ahead signs and Yield signs have higher positional accuracy errors, which reflects the way these attributes are collected using mobile mapping (these attributes are collected while driving whereas stop signs and stopping location are collected when the vehicle is at a complete stop.

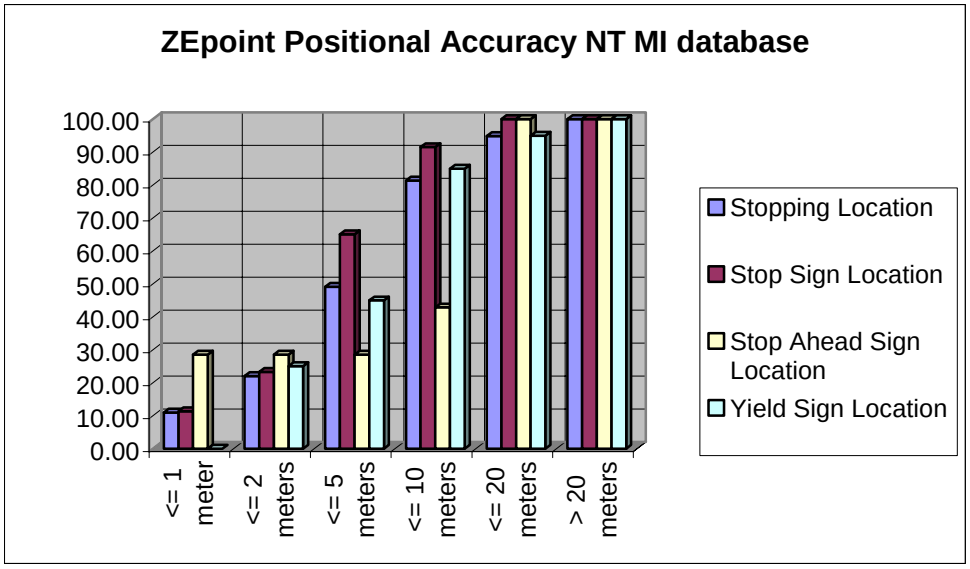

Figure E-13: Stop signs, positional accuracy

E.8.2 Mid-term Database results

E.8.2.1 Geometry

The algorithms and tools used for near-term geometry analysis were modified to suit lane geometry analysis. Figure E-14 illustrates the relative differences in accuracy between the EDMap database and the Quality database. The accuracies of the EDMap database were improved in many areas after this analysis was performed, especially for the demo area to meet the application needs.

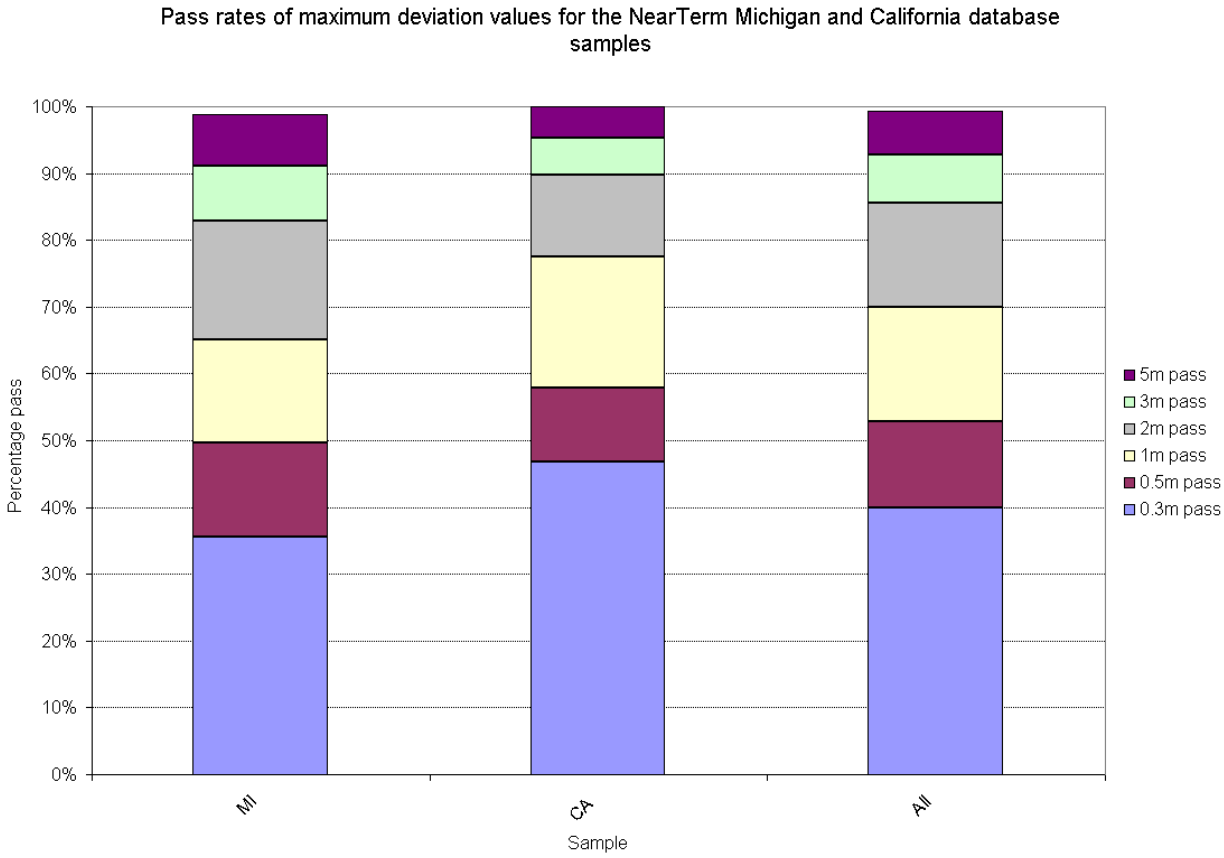

Figure E-14: Percentage of database within maximum deviation ranges for the samples from the Michigan and California Mid-term databases

'All' relates to values for the project as a whole (Michigan and California databases combined).

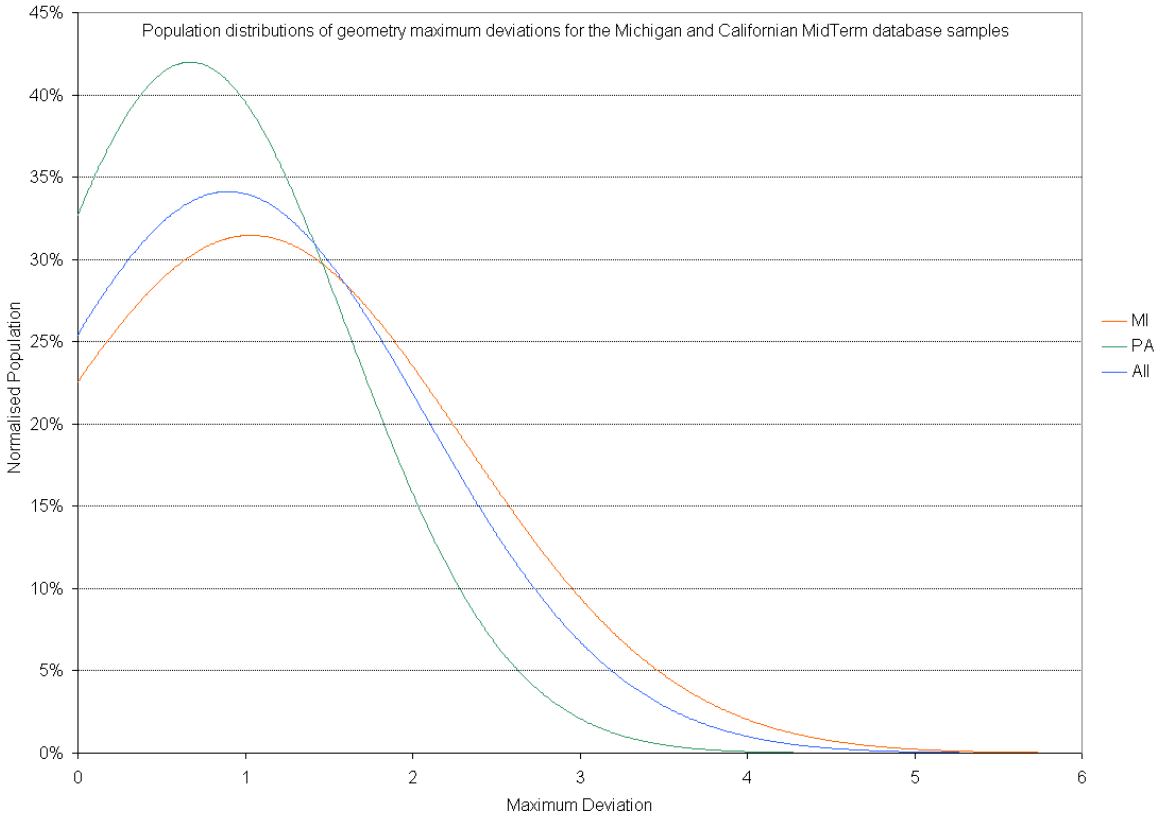

Figure E-15: Population distributions of geometry maximum deviations for the Michigan and California Mid-term databases.

'All' relates to values for the project as a whole (Michigan and California databases combined).

The average results in these plots are inherently biased as a consequence of the characteristics of in the range of the maximum deviation measure (i.e., it can't be less than zero but is not constrained for positive values). It was suggested that the median value might be a more appropriate measure of the database quality. For both database samples combined, the median value is seen to be 0.80m.

The smaller standard deviation values for the Near-term results are the direct result of the larger sample size.

In general, more than 88% of the geometry in both databases is seen to experience maximum deviation values of less than an average lane width (taken to be 3.5m). Approximately 73% of this is likely to experience maximum deviations of less than half a lane width and 52% less than a quarter lane width, based on the samples presented here.

Since the lanes were created using the high position GPS traces or from the lane center-line traces, the relative accuracy of the mid-term database was expected to be better than that of the near-term database. During the geometry analysis, it was felt that the process of scaling and rotation also magnified the errors that may be experienced by the application. This was observed in several links and lanes where the curvature of the geometry was the same between the test and reference links (lanes), but the relative accuracy metric was quite large. It was also observed that long lanes (in highways) results in poor relative accuracy, due to the process of rotation and scaling employed in our relative accuracy calculation methods. Further refinements to the

algorithm that computes the relative accuracy metric and use of a more controlled process for aligning reference and test geometry is expected to yield better and more realistic results.

E.8.2.2 Attributes:

Attribute analysis similar to what was done for the near-term database was also performed for the mid-term database. However, the mid-term attribute analysis was performed only on the California database. Figure E-16 illustrates the percentage of ZElink attributes in the test database that matched the reference database. The additional mid-term attributes that are not part of the near term database were primarily present in FC3-4 roads; this is evident with the larger errors in Figure E-16.

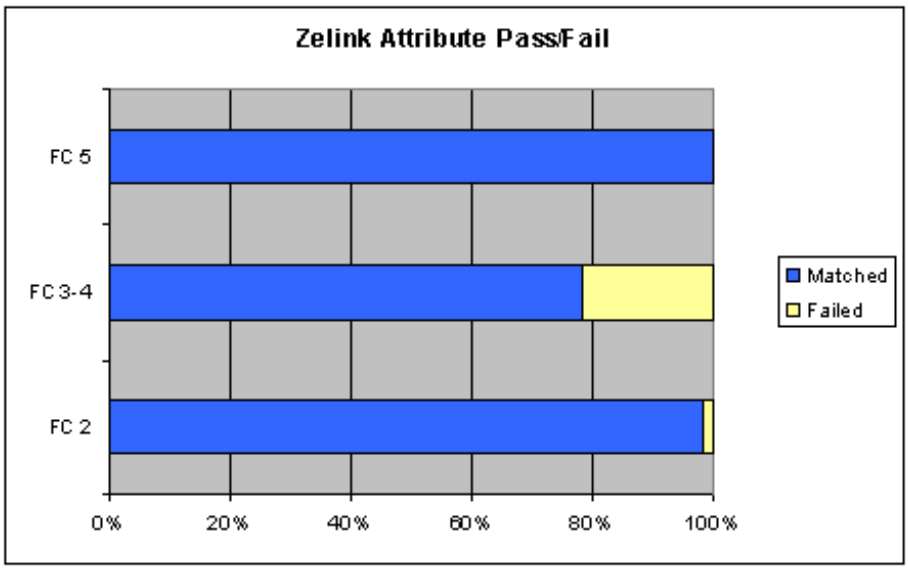

Figure E-16: ZElink attribute: pass/fail by subgroup

Lane width was chosen as one of the attributes to be analyzed for its correctness. The analysis examines lane width in terms of error categories for each road functional class (FC).

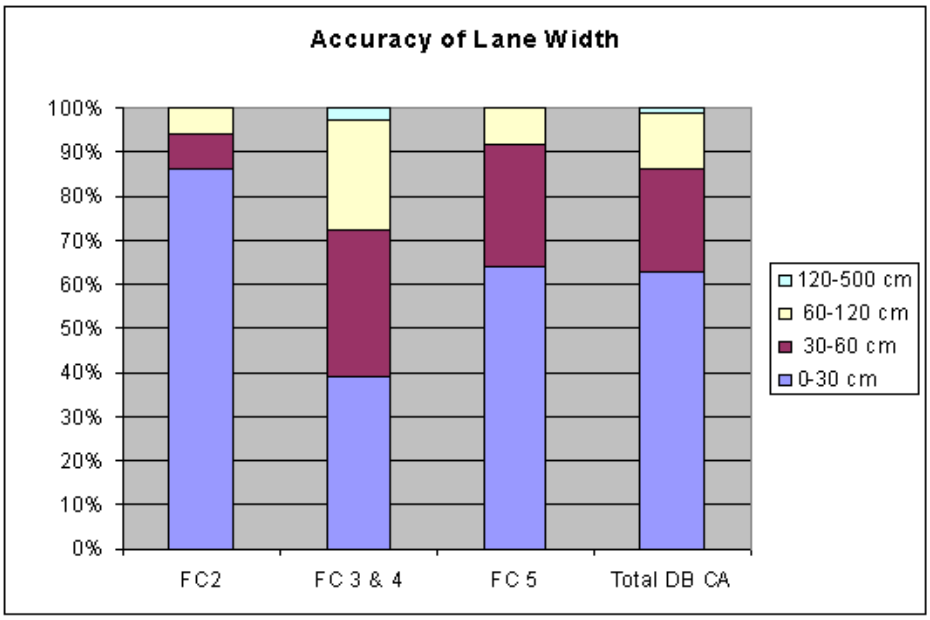

Figure E-17: Lane width deviation from QA database

Figure E-17 shows that in excess of 60% of all roads are accurate to within 30 cm. FC 3 4, and 5 show higher deviations due to the generally poor lane paint stripe quality for those road categories. It was also observed that the creation of the lane width attribute has evolved over time.. Lane width attribute for Quality databases were created using photogrammetry while different areas in EDMap databases were created using different approaches. The random samples captured errors during the early stages of lane width attribute, as well. The samples that had lane width along the demo routes were found to be within 30cm.

One of the challenges of quality analysis has always been in following identical procedures to create the quality database and the test database. Variations due to different data editors (personnel) and continually changing editing environment (software changes) to improve the database quality has made it challenging to assess the database using the same set of tools and processes. It will be appropriate to carry out further quality analysis after the databases are delivered, and the software tools are fully matured.

Appendix F: Curve Speed Assistant Evaluation

F.1 Tools

To validate the advisory feature of the Curve Speed Assistant (CSA) application, a tool was developed to utilize yaw-rate and vehicle speed to generate an estimate for road shape and road curvature using the following equation:

$$k = \frac{\dot{\phi}}{v},$$

where k is the road curvature and is the inverse of curve radius, v is the vehicle speed, and $\dot{\phi}$ is the change in heading, or yaw-rate, of the vehicle. The equation was derived from the basic equation for arc length, d, from angle, ϕ, and circle radius, R:

$$d = \phi R = \frac{\phi}{k}$$

To understand the impact of yaw-rate and vehicle speed errors on the curvature estimate, the derivatives of curvature reveals its sensitivity to these measurements:

$$dk = \frac{1}{v} d\dot{\phi} - \frac{\dot{\phi}}{v^2} dv$$

Assuming $d\dot{\phi}$ and dv represent the measurement error at a point around $(\dot{\phi}, v)$, the percent error in k is determined by dividing this equation with the original equation used for the yaw-derived curvature estimate:

$$k_{error\%} = 100\%\left(\frac{d\dot{\phi}}{\dot{\phi}} - \frac{dv}{v}\right)$$

The percent error equation roughly indicates the accuracy of this method for estimating curvature. With an ideal speed sensor, a 0.4 degrees per second error in the yaw-rate sensor for 5 degrees per second curve results in an 8% difference in the curvature estimate. Likewise, a 0.5 m/s error at speeds of 20 m/s, 45 mph, with an ideal yaw-rate sensor will yield a 2.5% error in the curvature estimate. To improve the estimate of the road curvature, a finite impulse response, low-pass filter was implemented to reduce the effects of transient noise in the measurements. Although the effect of sensor errors is variable at differing speeds and yaw-rates, it is anticipated this method results in curvature estimates with less than 10% error.

F.2 Mapping Challenges

F.2.1 Curvature Performance Evaluation – California Route 17

California Route 17 is a four-lane divided highway that goes south to Santa Cruz. The road was not included on the EDMap demo routes as it was too far to reach during the Palo Alto demos. Figure 2-2 (Section 2.1.2) shows the section of Route 17 that goes from Los Gatos in the valley to the mountain ridge before descending toward the ocean. The roadside Jersey barriers are marked in almost all of the curves with evidence of being sideswiped by vehicles, making this area a prime place for CSA.

The route was evaluated four times, and the plots below are representative of the curvature values reported by ADASRP. This is near-term mapping to be used by the warning feature. As described earlier, the yaw rate curvature was used to evaluate the accuracy of the database along this section of Route 17. The approach taken uses the yaw rate curvature as truth, and then statistically compares the curvature coming out of ADASRP (kMap in Figure F-1 and Figure F-2) with a filtered version of curvature from inside the CSA algorithm. The filtered curvature (kMapFilt in Figure F-1 and Figure F-2) filters over a preview distance ahead of the vehicle. It is the filtered curvature that is used to calculate the curve speed.

Figure F-1 shows the results of curvature accuracy for 14 curves (seven going south up the mountain, and the same seven complementary curves, i.e., Curve6=Curve9, coming right back down to the start). The plot shows the yaw-based curvature compared to each of the two map-derived curvature values, and includes the 1-sigma values to show the range of variation. Figure F-1 shows that the raw kMap curvatures are noisy, but that the filtering can remove most of the variation. Curve 5 and its complement Curve 10 continue to have large variation even after filtering.

Figure F-2 shows the curves from Figure F-1 represented by % error from the yaw-derived curvature with respect to mean and 1-sigma values. Here, it is a different story. Figure F-2 shows the actual error in curvature, and the range of error in percentage is typically less than 20% for the filtered curvature. The raw map values are worse, and while filtering does help, the noise level is quite significant.

These plots are shown as an example of the kind of curvature values that can be expected from the spline fit map data. CSA performance on Route 17 was not reliable at low lateral acceleration limit values, but performed satisfactorily at higher lateral acceleration values. What this means is that the variation in curvature accuracy does not create detection errors, but rather, creates errors in predicted curve speed that are more obvious at lower lateral acceleration thresholds. For example, at 0.4 lateral Gs, an over-speed threshold is less likely to be perceived as incorrect by the driver, but lower Gs are more perceptible, and missing the curve speed is interpreted as a false alarm or missed alarm.

A mitigating factor occurs based on the basic equation to calculate the curve speed. In its most basic form:

$$V_{curve} = \sqrt{\frac{a_{lat}}{k}}$$

which is less sensitive to errors in curvature, k, due to the square root function.

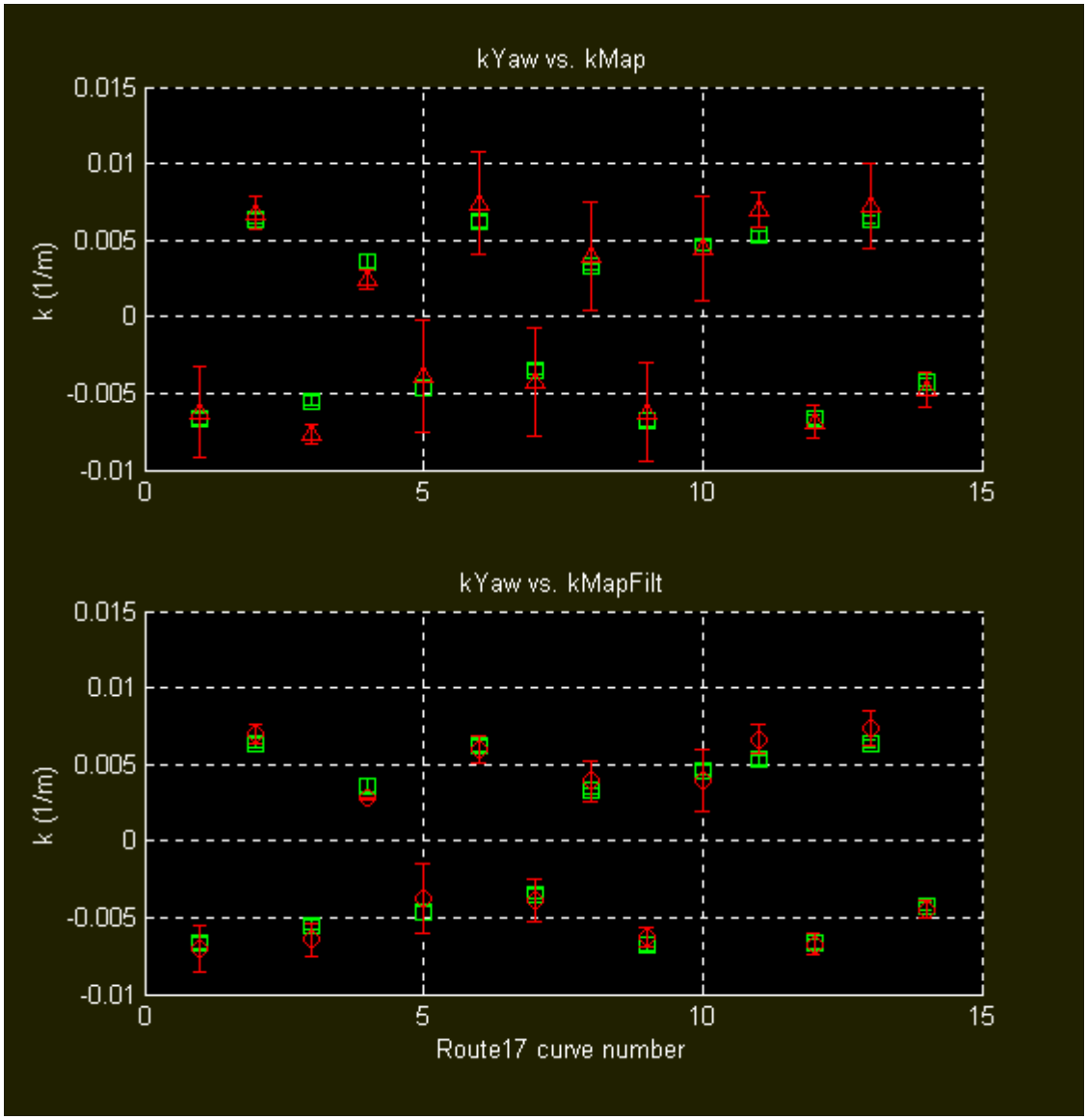

Figure F-1: Error bar plot along California Route 17 (14 curves)

Green squares are yaw-derived curvature values and red circles are map or filtered map-extracted curvatures; 1-sigma variation is plotted as error bars.

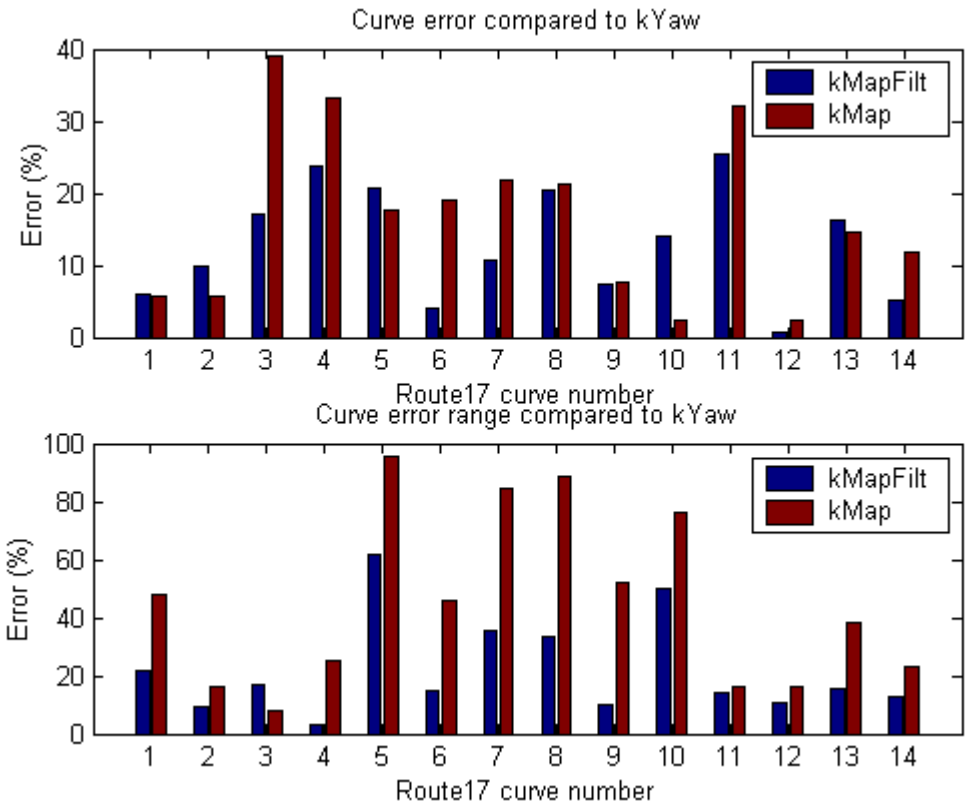

Figure F-2: The curves are represented by % error from the yaw-derived curvature with respect to mean and 1-sigma values

F.2.2 Curvature Behavior at Intersections

As currently defined in EDMap, splines are not fit through intersections as a general rule. The rule is adopted from the basic map link structure where road segments either begin or end at intersections of three or more connections. The resulting road segment spline fits indicate the curvature of the link ends connecting the intersection. This approach typically has no effect on CSA as there is typically some kind of traffic control device, e.g., stop sign or traffic signal, at the intersection. Moreover, an intersection can be viewed as not meeting the function scope of a curve for CSA.

A road section in Palo Alto showed that there can be a negative effect of the current curve representation at intersections. Figure F-3 shows a section of Page Mill Rd. south of I-280, as it winds through the hills.

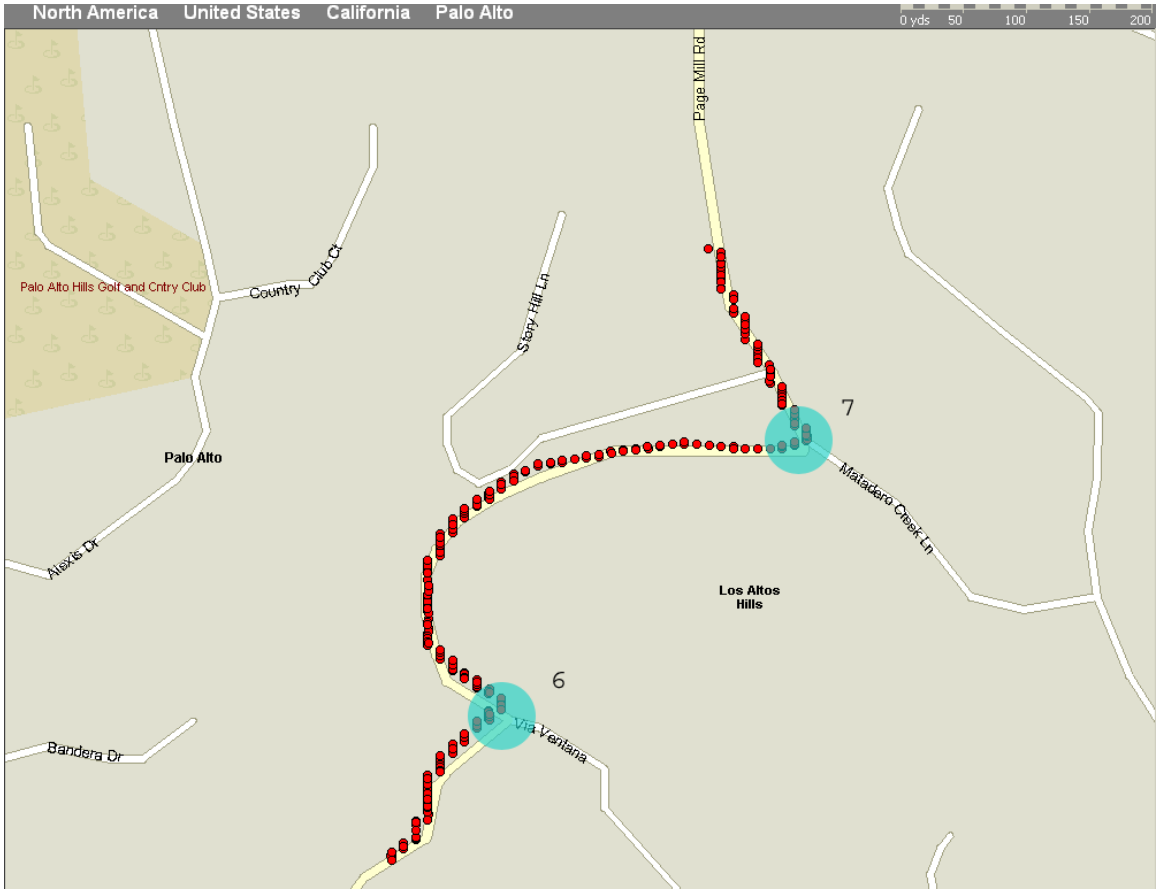

Figure F-3: Invisible curves

The two intersections shown in blue circles are numbered 6 and 7. In both cases, the intersections are three-way, but normal driving on Page Mill Rd. does not require stopping. Both are driven as curves. Figure F-4 shows the curvature values for links 5, 6, and 7. Links 5 and 6 meet at essentially an intersection of zero curvature. Intersection 7 does show some curvature, but it does not approach the effective curvature of 0.1 1/m (10 m).

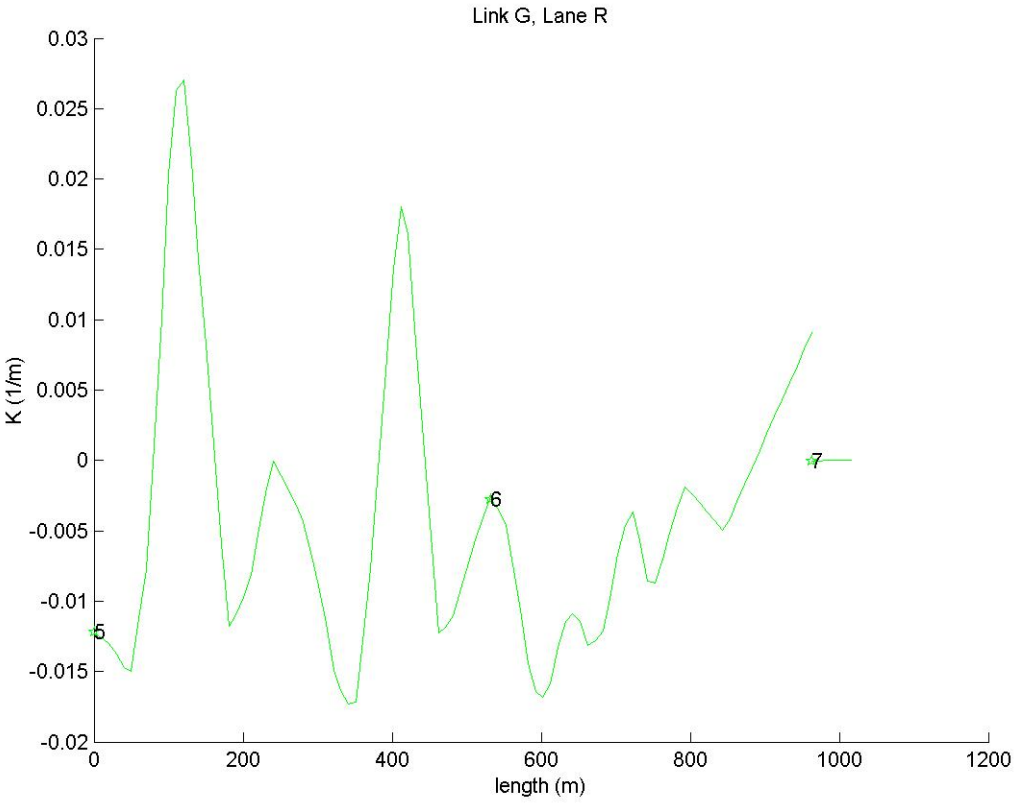

Figure F-4: Curvature plot for Page Mill Rd. intersections 5, 6, and 7

The invisible curve does not pose a false warning problem as the curve is not detected in the first place. Once in the curve, a warning could be provided, but the late timing would provide little opportunity to slow the vehicle. Heading of the road segments could be calculated, and it could be determined that the preview path comprises two road links with connection angles that are near 90 degrees. This may be useful, but was untested. The CSA algorithms did not attempt to warn on intersection turns. One could consider fitting a curve through both segments to capture the invisible curve, but map database intersection structure would be violated and would need to be modified. Through-node curve modifications were not evaluated.

F.3 Road Exposure Calculation

Here is the calculation performed to determine the 2% 25mph CSA exposure based on [Najm, Schimek, and Smith 2001]. Using Table 7, *Distribution of Posted Speed Limits in Target Off-Roadway Pre-Crash Scenarios on Non-Freeways for Light Vehicles*, 11.6% (25mph) and 2.7%, (<20mph) out of 133,000 crashes occurred where the primary factor was "lost control in a curve" out of 761,000 run-off-road crashes in non-freeway scenarios. In addition, from Table 6, there were 132,000 freeway crashes. The 25mph and less exposure (out of the whole Target Off-Roadway population) was calculated from:

$$25\ mph\ Exposure = 100\left[\frac{(0.116+0.027)(133000)}{(761000+132000)}\right] = 2\%$$

In a narrower view, the road exposure for only "lost control in a curve" crashes would be:

$$25\ mph\ Exposure\ CSA\ only = 100\left[\frac{(0.116+0.027)(133000)}{(133000+7000)}\right] = 14\%$$

where 7000 "lost control in a curve" crashes happen on freeways.

Appendix G: Forward Collision Warning Evaluation

G.1 FCW Demonstration and Evaluation Routes

The Forward Collision Warning (FCW) application was demonstrated and evaluated over a broad range of scenarios on selected routes in Palo Alto, California and southeast Michigan (Figure G-1). These routes have been described in Section 2.3.1. Table G-1 provides the lengths of the various sections of the demonstration and evaluation routes, and associates the names of the evaluation files (used in the remainder of this Appendix) with specific sections of the California and Michigan routes.

Table G-1: Description of evaluation/demonstration routes

Route	Length (miles)	Evaluation Files	Comments
CA non-freeway route	5	L0121_00 and L0121_02	Green-colored trace in Figure G-1a
CA freeway route	11.5	L0121_01	Blue-colored trace in Figure G-1a
MI freeway route	10.5	L0302_00	Blue-colored trace in Figure G-1b
MI non-freeway route	7	L0305_01	Red-colored trace in Figure G-1b
MI non-freeway route	4	L0305_03	Green-colored trace in Figure G-1b

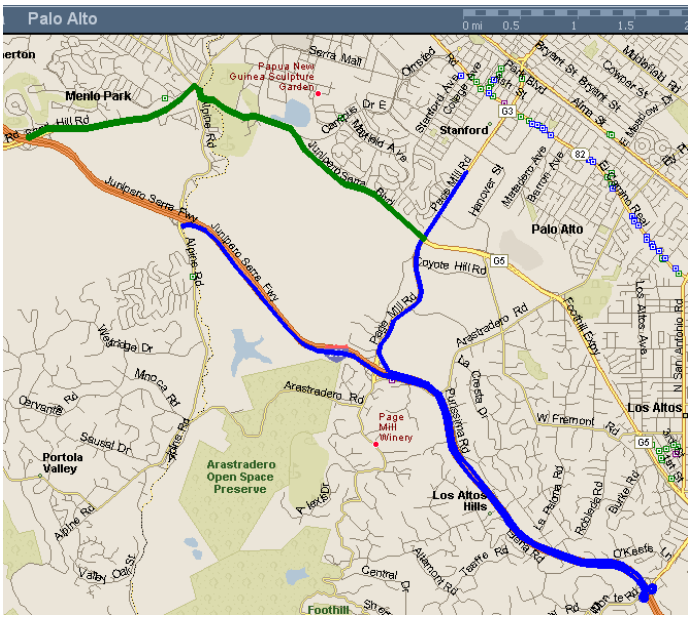

Figure a

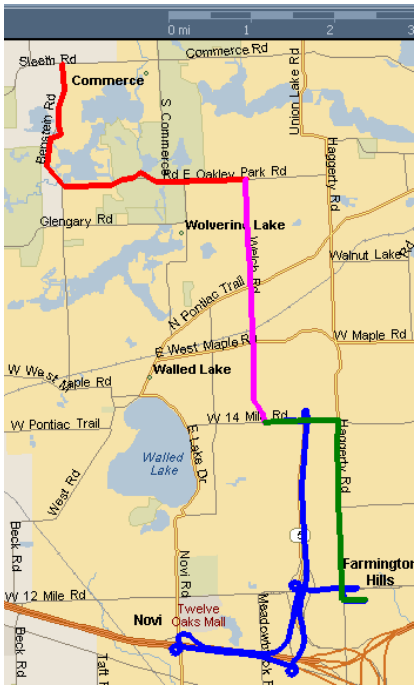

Figure b

Figure G-1: California (left) and Michigan (right) FCW demonstration and evaluation routes

G.2 Tools

G.2.1 Post-processed Ground Truth

To evaluate the performance of the predicted host path, a ground truth method to determine the actual path driven by the vehicle has been developed. It uses the vehicle speed and yaw rate to trace the actual vehicle path traversed by the vehicle. Yaw rate is converted to a local tangent plane coordinate system by integrating yaw rate into a heading angle and incrementally computing the new position based on speed and heading. It was determined that the error sources in the measured yaw rate could be ignored by limiting the yaw rate integration to a short interval of 6 seconds, with vehicle speeds greater than 25 mph.

G.2.2 Data Logger

The data logger (a video and CAN data logging tool) is used to perform in-vehicle data logging. This tool uses a video server to log the digital video sequences from the forward-looking scene camera (located behind the rear-view mirror), and uses the laptop to log all (or user-selected subset) of the vehicle CAN messages. The data logger collects compressed digital sequences, time-aligned with radar and other vehicle sensor data, and thus has the capability of recreating the driving experience on the bench setup.

G.2.3 Visualization Tool

A special visualization tool, nicknamed “vtool” (hosted on a laptop or desktop), performs off-line real-time playback, visualization, verification, and analysis of data logged using the EDMap vehicle. This tool uses the video logs and the raw CAN logs collected from logging sessions. The advantage of the vtool over the real-time displays is that the logged data can be replayed any number of times at any desired speed, including single step and backward.

Figure G-2a, Figure G-2b, Figure G-2c, and Figure G-2d show the graphical screens of interest from vtool that will be used to describe the results in the remainder of this report. Figure G-2a shows the radar targets using their target IDs overlaid on the logged video image, where targets displayed in red color are slowing targets while those displayed in blue are moving away from the host vehicle. Figure G-2c shows a graphical top-down view of the upcoming primary road-level geometry (red-colored lines) and Figure G-2d shows the primary lane-level geometry (green-colored lines) as computed by ADASRP, with superimposed radar targets. In the top-down view, red radar targets indicate slowing targets, green indicate speeding targets, and blue represent stationary targets. The size, in terms of the thickness of the target representation in the top-down view, provides a visual indication of the strength of the radar signal return from each of the radar targets.

In addition to the primary path geometry, Figure G-2c and Figure G-2d show the secondary paths for road-level and lane-level geometries in gray color, and the curvature along the primary and secondary paths using cyan and gray-colored lines, respectively. The dark blue-colored line plotted from the host vehicle represents the actual path driven by the host vehicle. This is derived by post processing data collected during the data logging sessions.

Figure G-2c and Figure G-2d, when observed in conjunction with the video/radar-overlaid screen (Figure G-2a), provide an immediate visual indication of algorithm performance in terms of in-path/out-of-path targets. Figure G-2b shows the results of EDMap-based target selection algorithm in terms of the closest in-path vehicle (CIPV), and the closest in-path stationary target (CIPS). It also shows the CIPV selected by the yaw rate-based target selection algorithm contained in the forward-looking radar and primarily used for adaptive cruise control applications. In addition, Figure G-2b depicts the ID of the radar target that is used by the threat assessment algorithm for further processing.

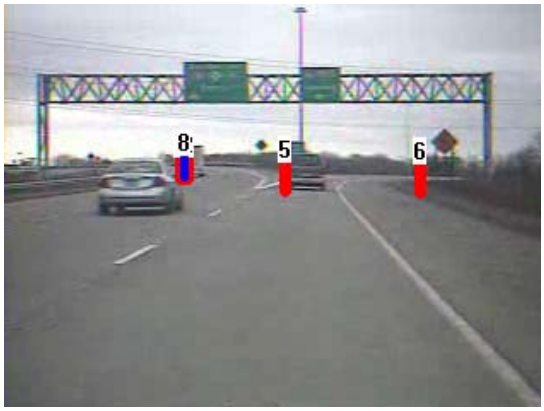

Figure a: Video and radar overlay display

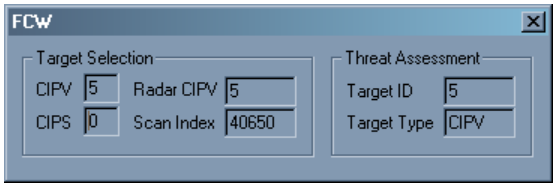

Figure b: Target selection results

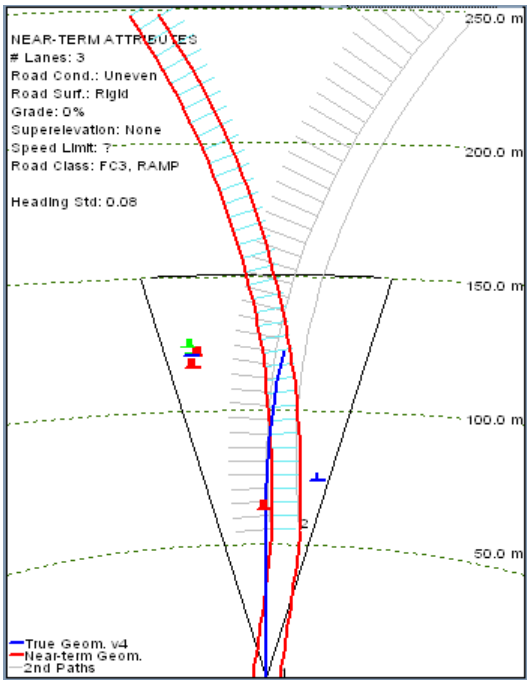

Figure c: Road-level preview

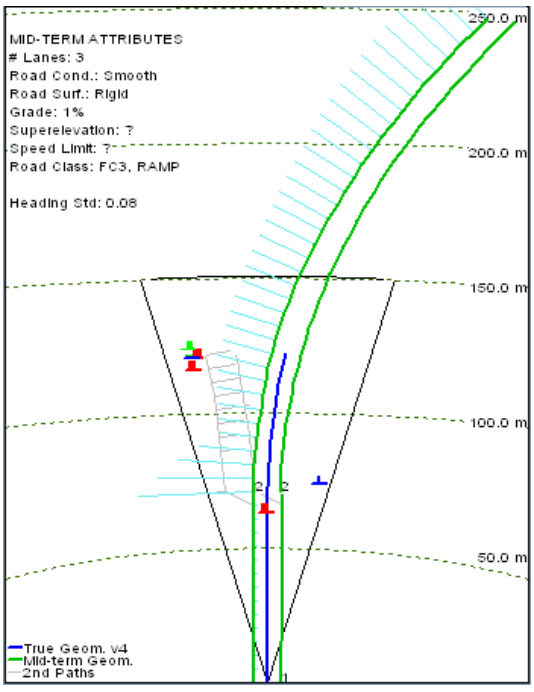

Figure d: Lane-level preview

Figure G-2: Upcoming road and lane preview with superimposed radar tracks

G.3 Application Evaluation

This section provides the results of the map-based FCW application evaluation with emphasis on the role of maps in the target selection module.

G.3.1 Evaluation Method

The results are presented by evaluating the map-based target selection against two other sources. The first comparison target selection algorithm is the yaw rate-based algorithm contained in the forward-looking radar (also known as radar-based target selection) and primarily used for adaptive cruise control applications. The other comparison is the same target selection algorithm used with the map-based data but using the GM-developed ground truth instead of the map.

Logged data from the files listed in Table G-1 were processed to derive files containing the information shown in Table G-2 for each instance where EDMap target selection, the radar's target selection, and ground truth differed. In addition, a count of the number of times that the three methods agreed was maintained.

Table G-2: Scoring record format

	Item	Description
Automatically Generated Information	Time (ms)	Log time
	CIPV	Closest In-Path Vehicle using EDMap path
	CIPS	Closest In-Path Stationary object using EDMap path
	Yaw-based CIPV	CIPV chosen by the yaw-based host path prediction method
	GT CIPV	CIPV chosen by ground truth algorithm
	LW CIPV	CIPV chosen using EDMap path and EDMap lane width
	GT LW CIPV	CIPV chosen using ground truth path and EDMap lane width
Manual Scoring	EDMap correct	1 if EDMap-based target selection is judged correct, 0 otherwise
	Radar correct	1 if yaw-based target selection is judged correct, 0 otherwise
	Ground truth correct	1 if ground truth-based target selection is judged correct, 0 otherwise

The records produced in this way were then validated by inspection of logged data using vtool and by analysis of target selection log files. For each record, the reason for the discrepancy was determined and a score of either a one or zero was assigned to the rows "EDMap correct", "Radar correct", and "Ground truth correct" according to whether the decision was judged to be correct or incorrect, respectively.

The main reasons that interfered with correct decisions or that caused disagreements between EDMap-based, yaw-based, and ground truth-based target selection are tabulated in Table 2-3.

Table G-3: Factors that interfere with correct target selection decisions or cause disagreement with radar

Factor	Comment
Inaccurate path geometry	While path geometry generally appears to be within the 0.5 m accuracy specified for mid-term geometry, even an error of 0.5 m can on occasion result in incorrect target classification.
Target turning/changing lanes	When a target is turning or changing lanes, it becomes a judgment issue to identify when the target enters or leaves the host path.
Host turning/changing lanes	When the host is turning or changing lanes, it becomes temporarily difficult to establish host heading and host path.
Range > look-ahead range	EDMap limits look-ahead range to 120 m. The yaw-based method sometimes classifies targets at greater ranges.
ADASRP selected wrong path	The ADASRP software must perform a path prediction function to determine the most probable host path. On occasion, this prediction is made incorrectly.
Multiple targets per vehicle	The radar frequently detects multiple targets on a single vehicle. When this occurs, EDMap target selection may declare one target CIPV while the yaw-based target selection declares another target on the same vehicle. This of course does not indicate any error on the part of EDMap target selection; it simply indicates that the two methods chose different targets on the same vehicle and those records had to be manually examined to confirm this occurrence.

G.3.2 Validation of the Ground Truth-based Evaluation

One factor that can interfere with the automatic evaluation of the target selection based on ground truth is host vehicle lane changes. Figure G-3 shows a top-down view of the predicted lane-level geometry prior to a host vehicle lane change. From this figure, it is clear that the EDMap-based geometry indicates target #6 is not an in-path target. However, since the ground truth method is privy to an upcoming lane change, the ground truth geometry will indicate that target #6 is in the path of the vehicle. This situation causes a discrepancy between the results obtained from target selection based on EDMap and ground truth. Therefore, during the evaluation process, the records corresponding to host vehicle lane changes were evaluated separately. As a note, the analysis assumes that the host vehicle cannot determine when the driver will change lanes and therefore the selection of any adjacent lane target is incorrect.

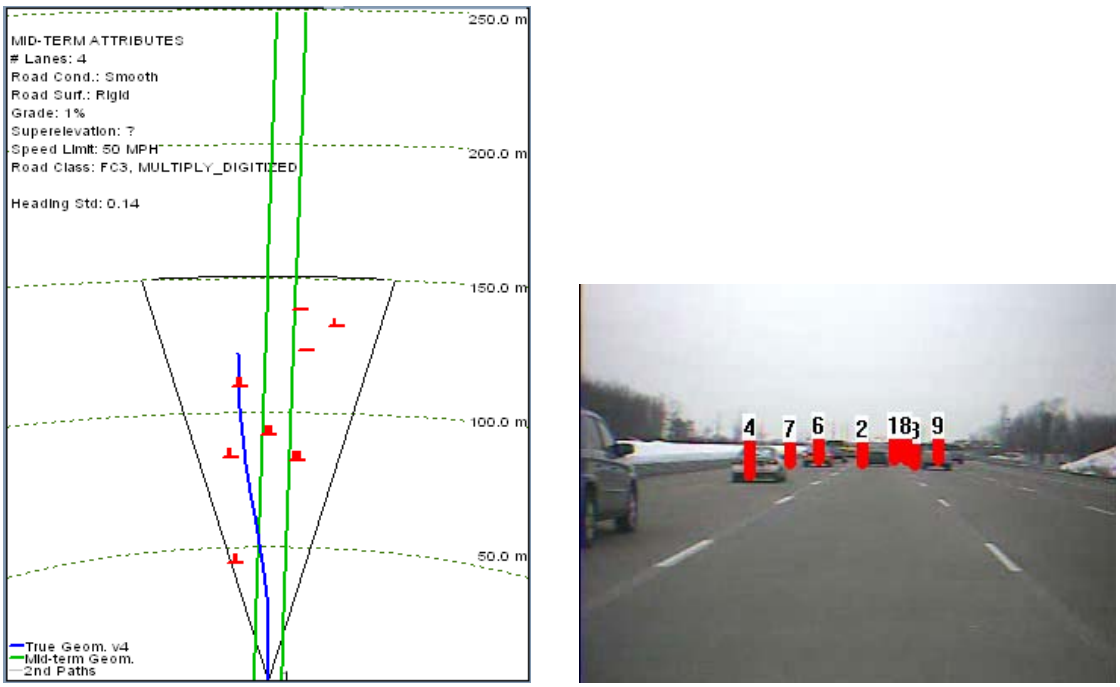

Figure G-3: Prior to lane change, driver intent is unknown (L0121_01 – 382454 msec)

To determine the impact of lane changes on ground truth accuracy, the scores judged correct during manual inspection are tabulated by log file name in Table G-4 and Table G-5, based on the number of host vehicle lane changes. During manual processing, it was recorded that file L0121_00 had very few lane changes and L0305_01 had no lane changes. In addition, numerous host lane changes were noted in files L0121_01, L0121_02, and L0305_03. The first rows of Table G-4 and Table G-5 (labeled "Correct Score") show the number of correct target identifications automatically generated by the ground truth algorithm, the second rows list the total number of records considered, and the third rows express the correct score as a percent of the total records.

Table G-4: Ground truth-based target selection accuracy for files with few host vehicle lane changes

	CA	**MI**	**Total**
	L0121_00	L0305_01	
Correct Score	677	272	949
Total Records	687	276	963
Percentage	98.54	98.55	98.5

As shown in Table G-4 , for the log files that had few (if any) host vehicle lane changes, a high level of accuracy (over 98%) has been obtained for the target selection performed using the ground truth as the host vehicle path descriptor.

Table G-5: Ground truth-based target selection accuracy for files with many host vehicle lane changes

	CA		MI		Total
	L0121_01	L0121_02	L0302_00	L0305_03	
Correct Score	377	137	1160	97	1771
Total Records	466	230	1216	128	2040
Percentage	80.9	59.6	95.4	75.8	86.8
Host Vehicle Lane Changes	59	82	20	13	174
Range to Target > 120 m	0	0	1	13	14
Adjusted Percentage	92.6	92.6	97.1	95.1	95.6

The ground truth-based path prediction did not yield the correct targets (as concluded by manual inspection) in the proximity of host vehicle lane changes, as seen from Table G-5. Here, the accuracy of the automatic evaluation based on ground truth dropped to 86%. However, the percentage improves to 96% when the records related to host vehicle lane changes, and where the "range to target was greater than 120 m" records, are deleted from the total records (EDMap limits look-ahead range to 120 m; the yaw-based and ground truth-based target selection methods can at times classify targets at greater ranges than 120 m.)

Based on the examination of records, when all six evaluation files are considered for which EDMap or radar target selection differed from ground truth, it was determined that for 91% (98.5% from Table G-4 and 86.8% from Table G-5) of the total instances, the target selection based on ground truth was able to automatically select the correct target and ignore the incorrect one. This percentage can be improved by employing an automatic lane change detection system.

The results obtained by visual inspection of the records lead to the conclusion that records in which EDMap target selection, yaw-based target selection, and ground truth agreed can safely be considered instances of all three being correct, because in such circumstances it is unlikely that the host vehicle is undergoing or has an upcoming lane change maneuver. This reduced the scoring problem to one of scoring those records in which there was a disagreement between targets selected by the ground truth method and either the yaw rate-based or EDMap-based methods.

G.3.3 Results

The overall results are divided into two groups: those for which the ground truth-based path prediction selects the correct in-path target automatically (Table G-6), and those for which it chooses an incorrect target (Table G-7). In these tables, the values are percentages of the total number of records in the file, where the vehicle speed was greater than 25 mph. The two columns labeled "EDMap" and "Radar" on the left side of each table contain the truth values that denote the correct/incorrect status of the corresponding row, with "1" indicating correct and "0" indicating incorrect. For example, the second row of each table represents results when EDMap-based target selection was judged incorrect and radar (yaw-based target selection) was judged correct. Table G-8 aggregates the results of Table G-6 and Table G-7 . The first row of Table G-8 is the sum of the table rows in Table G-6 and for which EDMap was correct, and the second is the sum of the table rows in Table G-6 and Table G-7 in which radar-housed, yaw-based method was correct.

Table G-6: Scores of EDMap-based versus radar-based target selection when automatic ground truth evaluation is valid

Scores		CA			MI			Total
EDMAP	**Radar**	L0121_00	L0121_01	L0121_02	L0302_00	L0305_01	L0305_03	
0	**0**	1.0	1.4	0.2	1.6	0.6	0.3	1.1
0	**1**	2.4	2.0	0.7	1.7	0.9	1.7	1.7
1	**0**	14.6	5.0	8.8	29.4	9.4	8.5	13.4
1	**1**	81.7	89.6	82.9	65.7	89.0	87.0	82.0
Total records with vehicle speed > 25 mph		2169	4340	1250	3495	2489	1195	14938

Table G-7: Scores of EDMap-based versus radar-based target selection when automatic ground truth evaluation is invalid

Scores		CA			MI			Total
EDMAP	**Radar**	L0121_00	L0121_01	L0121_02	L0302_00	L0305_01	L0305_03	
0	**0**	0.2	0.1	0.4	0.2	0.0	0.0	0.1
0	**1**	0.0	0.3	0.0	0.1	0.1	1.5	0.2
1	**0**	0.1	1.1	5.4	0.8	0.0	0.6	1.0
1	**1**	0.1	0.6	1.7	0.5	0.0	0.5	0.5
Total records with vehicle speed > 25 mph		2169	4340	1250	3495	2489	1195	14938

Table G-8: Cumulative scoring results

	CA				MI				Total
Cumulative Correct Scores	L0121_00	L0121_01	L0121_02	Total	L0302_00	L0305_01	L0305_03	Total	
EDMap	96.45	96.29	98.72	96.7	96.37	98.39	96.57	97.1	96.91
Radar	84.19	92.44	85.28	88.9	67.95	90.00	90.71	79.38	84.37

Table G-6, Table G-7, and Table G-8 show that:

- A fairly large sample size of approximately 15,000 records was evaluated at both the California and Michigan EDMap test sites to study the usefulness of EDMap for FCW applications.
- Table G-6 and Table G-7 confirm the conclusion that the ground truth-based target selection is a good predictor of the correct target selection choice. The highest percentages of correct decisions are correlated with correct decisions by ground truth.
- A breakdown of the total analysis revealed that:
  - In a majority of the instances (over 82%), the EDMap-based and the yaw-based target selection both agreed with each other and selected the correct target. It is reassuring to note that the EDMap-based target selection agreed overwhelmingly with the yaw rate-based target selection results because yaw-based target selection has traditionally proven to be a very accurate predictor of road geometry under conditions of constant curvature (straight and curved roads).
  - A significant value added by maps was observed in 15% of the total cases, where the EDMap-based target selection consistently selected the correct targets and the yaw-rate based target selection either selected an incorrect target or missed a target. This information is gathered from the third rows of Table G-6 and Table G-7. This observation is attributed to the fact that although the yaw rate-based road curvature prediction has proven to be an excellent source of local road shape through the vast majority of the driving experience, it is a very poor predictor in the presence of upcoming road curve transitions (curve entry and exit scenarios) during host vehicle lane changes, and it degrades significantly at low host vehicle speed.
  - Of the total records, very few instances (approximately 1.2%) of both EDMap-based and yaw rate-based target selection being incorrect were noted.
  - A detrimental effect of using maps for target selection was observed in a small percentage (approximately 2%, obtained from the second rows of Table G-6 and Table G-7) of the total records when the yaw-based method selected the correct target while EDMap-based target selection either selected an incorrect target or missed a target. These instances are attributed to the cases of inaccurate path geometry, and when the distance to the target was over 120 m. EDMap limits look ahead range to 120 m, while the yaw-based and the ground truth based target selection are at times able to classify targets at ranges greater than 120 m.
- In Table G-6 and Table G-7, the zeros in the first column correspond to instances when the EDMap-based target selection made an error (false detection or missed detection). A false detection (see Section 3.5.3.2 for detailed examples) is defined as an instance in which target selection designates a particular target as the CIPV when another target (including no target) is correct, while a missed detection (see Section 3.5.3.3 for detailed examples) is defined as an instance in which target selection does not pick a CIPV when one exists. Table G-9 presents a detailed breakdown of rows 1 and 2 of Table G-6 and Figure G-2, and tabulates the false and missed detections experienced by EDMap-based target selection for all the files collected on the FCW evaluation routes. Overall, the percentage of

missed detection is higher than the false detection and is attributed to the cases where the distance to the target is over 120 m and to inaccurate path geometry (note that inaccurate path geometry also influences false detection).

Table G-9: False and missed detections by EDMap-based target selection

Evaluation File	False Detection (% of all instances)	Missed Detection (% of all instances)	Total Records
L0121_00	1.15	2.44	2169
L0121_01	1.82	1.73	4340
L0121_02	1.2	0.08	1250
L0302_00	2.17	1.49	3495
L0305_01	0.0	1.61	2489
L0305_03	0.08	3.35	1195

- From the cumulative scores tabulated in Table G-8, it can be seen that EDMap-based target selection outperformed the yaw-based target selection by approximately 13% in all instances - a significant result.
- From Table G-6, Table G-7, and Table G-8 it can be seen that overall the EDMap target selection performed better on Michigan evaluation routes than in California by a slight margin.
- In file L0302_00, the sum of the fourth rows from Table G-6 and Table G-7 (logged on the Michigan freeway route) shows a 66% agreement between the EDMap-based and radar-based (yaw rate) target selection (16% below the average of 83%). However, these 16% of all instances in which the yaw-based target selection was unable to classify the targets correctly were captured by the EDMap-based target selection. This fact is evident from row three of Table G-6, where 30% of all instances (16% above the average of 14.4%) are captured correctly by EDMap-based and not by the yaw-based method.
- In Table G-6 and Table G-7, files L0121_00 and L0121_02 correspond to the same route driven twice by the same individual. The main difference between these two trips is the fact that during the first trip (L0121_00) the driver followed the lead vehicle at a close range (between 20 m and 50 m), and during the second trip (L0121_02) the lead vehicle was ahead of the host vehicle by 40 m to 110 m at most times. In spite of the differences between the lead vehicle ranges, fairly consistent results were obtained across trips when a route was driven twice by an individual (as shown in Table G-10).

Table G-10: Results of repeated trials

EDMAP	Radar	L0121_00	L0121_02
0	0	1.15	0.56
0	1	2.44	0.72
1	0	14.71	14.16
1	1	81.74	84.56

G.4 Mapplet Evaluation

This subsection presents the results of the evaluation of all the mapplets that were used in the implementation of the FCW application. The same files listed in Table G-1 and used for application evaluation in above Section of this Appendix have been used for the mapplet evaluation in this section. Here, the file L0121_02 has not been evaluated any further because it was a repeat run of the first file, namely L0121_00. Also, it should be noted that a large number of lane changes were recorded in file L0302_00 which tend to negatively influence results that were automatically generated.

G.4.1 Lane Geometry

The FCW application depends on the accuracy of the lane level geometry for a range of 120 m ahead of the host vehicle. The accuracy specified for the lane geometry is 0.5 m. This specification was derived from the overall FCW requirement of allowing a maximum error of half a lane width (at 120 m look ahead) required to correctly classify a radar target as in-path (or not) at the maximum look ahead range of 120 m. To assess the accuracy of the lane level geometry, the difference between the lane geometry furnished by the ADASRP and the GM developed ground truth (see Section 3.5.2.2 for details) has been computed.

To allow the ease of comprehension of the results, this difference between the geometry defined by the ground truth and that predicted by the ADASRP from the lane level maps has been computed and summarized at two discrete preview distances of 60 m and 120 m from the host vehicle. The 60 m preview represents the distance corresponding to a 3-second headway at speeds of 45 mph seen on most arterial roads encountered in suburban driving, and is relevant for the FCW application. The 120 m preview distance is selected because it is important to evaluate the accuracy of the lane geometry at the maximum range for which the FCW application is specified to operate.

Figure G-4 depicts the mean error and its standard deviation observed for all the evaluation trips at the 60 m and 120 m preview distances. As expected, the results obtained for a 60 m preview distance are better than those obtained for the 120 m preview distance. The mean error for the 60 m preview distance is less than 0.5 m for all evaluation files (except L0302_00, where it is 1.1 m mostly because of a large number of lane changes recorded in this file), with a standard deviation ranging from 1.6 m to 4.6 m. For the 120 m preview distance, the mean error is approximately 1 m for all files (except L0302_00, where it is 3.1 m) with a standard deviation ranging from 7.2 m to 12.3 m. The overall mean obtained by considering all the evaluation files is 0.25 m for the 60 m preview distance and 0.75 m for the 120 m preview distance.

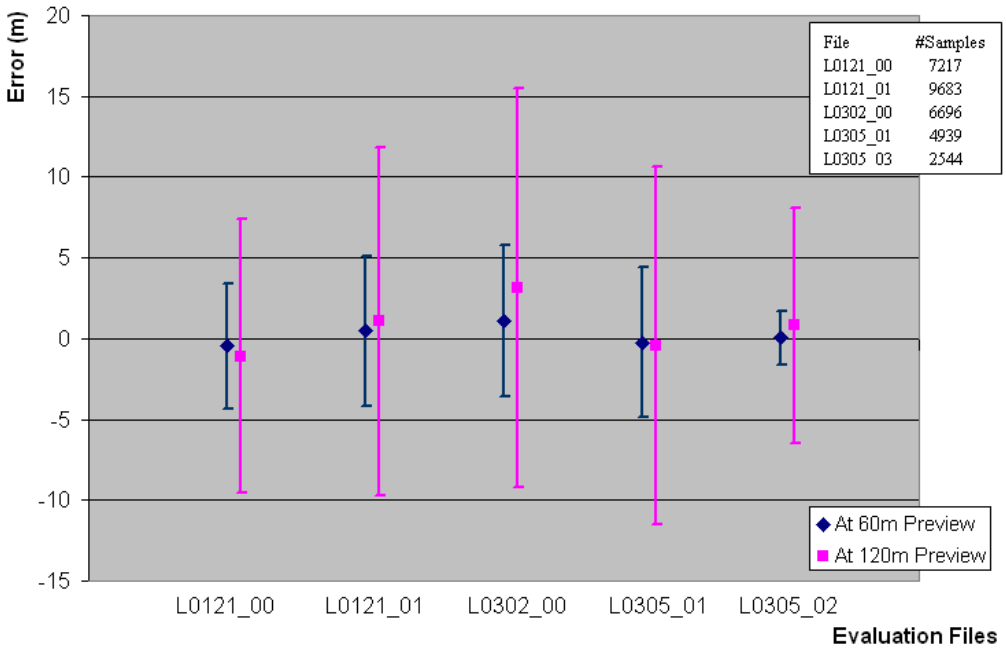

Figure G-4: mean error and its standard deviation for all evaluation trips

Figure G-4 shows that

- File L0305_02 exhibited the smallest errors as compared to the other evaluation files. This is because most of this file contains straight road segments, which are generally easier to map.
- File L0305_01 experienced larger standard deviations although the mean errors at both the 60 m and 120 m preview distance are low, because this route is located in the CAMP north tile and exhibits many curves which contribute to a greater deviation from the mean error value.
- Relatively higher values for mean error (and standard deviation) were observed at both the 60 m and 120 m preview distance with the L0302_00 file, because the host vehicle had undergone a large number of lane changes. As mentioned in section 3.5.4.2 the automated validation of the accuracy of lane geometry against the ground truth method is incorrect during host vehicle lane changes because of the discrepancies it introduces which tend to negatively impact the computation of errors in lane geometry.

Next, for each trip the error in lane geometry was separated into 3 different bins of the following sizes:

- Error <0.5 m, to capture the percentage of total instances when the lane geometry met the accuracy specification of 0.5 m.
- Error >1.75 m, to capture the percentage of total instances when the lane geometry had an error of over half a lane width (Assumption: a typical lane is 3.5 m wide).
- 0.5 m < Error < 1.75 m, to capture the percentage of total instances when the lane geometry had an error greater than 0.5 m but less than half a lane width.

For the different evaluation files, Figure G-5 and Figure G-6 depict the error distribution in the three bins for the 60 m and 120 m preview distance respectively.

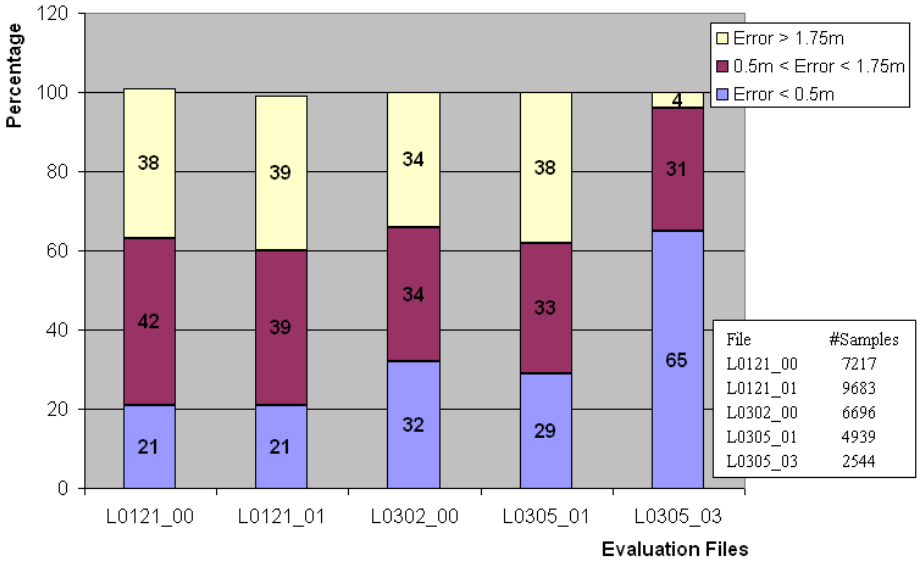

Figure G-5 Error distributions at 60 m preview distance

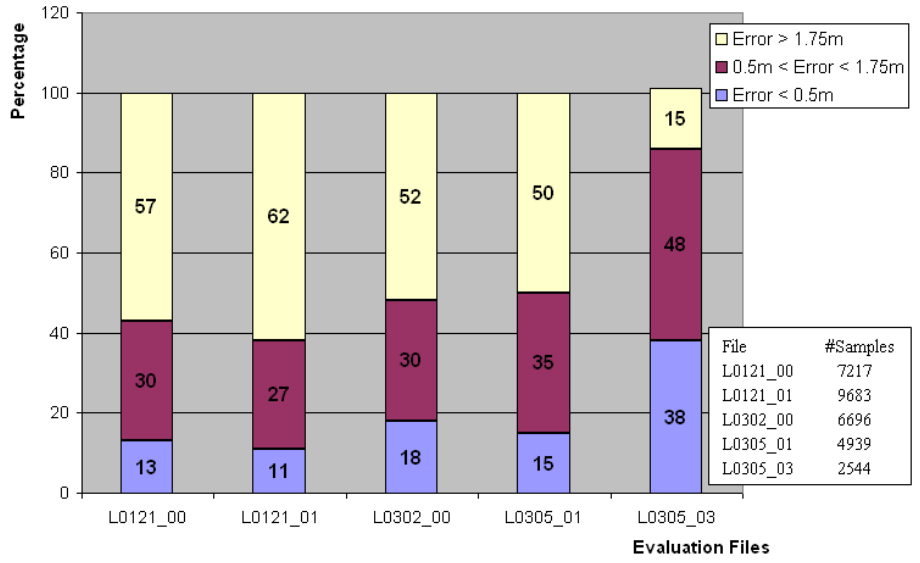

Figure G-6 Error distributions at 120 m preview distance

For the 60 m preview distance, Figure G-5 shows that over 20% of all instances in each file have an error of less than 0.5 m. In fact, the evaluation files logged in Michigan show an even better performance where approximately 30% of all instances lie within the specified accuracy of 0.5 m. Figure G-5 also shows that for a 60 m preview distance, over 60% of all instances exhibit an error of less than half a lane width. In particular, data for file L0305_03 in Figure G-5 (which predominantly comprises straight road sections) shows that 65% of total instances lie within 0.5 m and over 95% of all instances fall within half a lane width.

Comparison of Figure G-5 and Figure G-6 shows that the overall accuracy of lane geometry is reduced when the preview distance is increased from 60 m to 120 m. At the 120 m preview distance, the percentage of total instances that lie within a 0.5 m error range from 11% to 38% as compared to the 21% to 65% for the 60 m preview distance. Over 40% of all instances for each file record an error of less than half a lane width. Again, file L0305_03 is seen to be outperforming all other evaluation files with 85% of all its instances within half a lane width error.

Table G-11 shows the results of separating the total instances from all the evaluation files into the 3 different error bins. Overall, 28% of all instances are within 0.5 m accuracy specification for the 60 m preview distance while only 16% conform to the specification when the preview distance is increased to 120 m.

Table G-11: Error distribution for all evaluation files

Error bins	60 m Preview Distance	120 m Preview Distance
Error < 0.5 m	28	16
0.5 m < Error < 1.75 m	37	31
Error > 1.75 m	35	53

Although the overall accuracy of the lane geometry seems to deviate from the specification of 0.5 m for a significant portion of all instances (see Table G-11), it was found to work satisfactorily for the FCW application (see Application Evaluation Section) where EDMap chose the correct target over 95% of the time. One reason for the seemingly large errors can be attributed to the fact that, since the evaluation was performed, files logged during the demonstration drives by subjects that contain a significant number of lane changes yield large differences (and therefore error) between the EDMap predicted lane geometry and the ground truth. It is recommended that this mapplet at the originally specified accuracy be included in future lane-level map databases developed for the FCW application.

G.4.2 Lane Width

The implementation of the target selection module in the GM EDMap demonstration vehicle utilizes a fixed lane width of 3.5 m to decide if a target in its forward view is in-path or not. In general, making the lane too wide invites false alarms by including targets from adjacent lanes (or from the roadside) that do not necessarily pose a collision threat. In the current implementation, the chosen fixed lane width of 3.5 m has proved to be a generous, but not too generous, margin for the test vehicle to negotiate its lane and select the correct in-path targets.

Evaluation files logged during the Michigan tests were reanalyzed using the lane width information populated in the mid-term EDMap databases. Table G-12 details the effect of using EDMap lane width on the target selection performance. It was observed that the results of the target selection module were nearly the same (approximately 0.5% betterment in performance was observed) as those obtained using the fixed lane width of 3.5 m. A review of the EDMap lane widths used in the reanalysis revealed that nearly all the populated lane widths were larger than the 3.5 m originally used in the test vehicle. Thus, the target vehicles registered as in path using 3.5 m continued to be flagged as in path targets using the EDMap lane widths. No instances were found in which using the (generally larger) path widths furnished by EDMap degraded the target selection performance.

Table G-12: Effect of using EDMap lane width in target selection

Evaluation File	% Number of decisions corrected	% Number of erroneous decisions introduced	Total records
L0302_00	15.8	0.0	126
L0305_01	1.48	10.0	270
L0305_03	0.0	1.79	168

As seen from Table G-12 although the lane width information did correct some of the results generated by the EDMap-based target selection using fixed lane widths, it also introduced errors in other cases. It is concluded that the benefit of including the lane width in the mid-term database is marginal (if any) for the FCW application and it is therefore recommended that this mapplet be deleted from the original mapplet set specified for the FCW application.

Appendix H: Common Vehicle Components and Architecture

H.1 Introduction

H.1.1 Common Vehicle Components

All demonstration vehicles employ the same architecture in terms of map databases, generation and delivery methods of map information and reception of GPS data. Two main configurations, near-term and mid-term, have been established as needed by the map databases and applications. This report provides a detailed description of the common vehicle architecture in the following sections.

H.1.2 Common Vehicle Architecture

The Figure H-1 illustrates the common vehicle architecture.

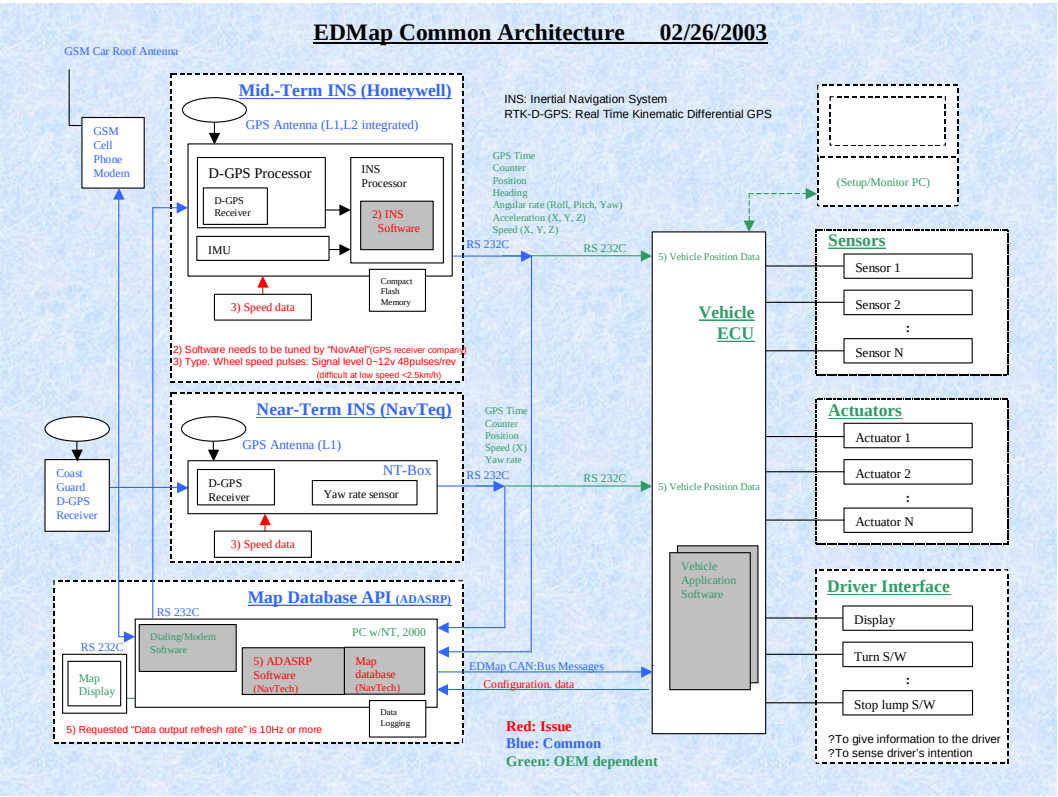

Figure H-1: EDMap common vehicle architecture

For near-term applications, the vehicle system utilizes the NTBox dead reckoning module to obtain vehicle position data while for mid-term applications the vehicle system utilizes the Honeywell Prototype Automotive Positioning System (PAPS). Table H-1 describes the GPS receiver employed with the near- and mid-term applications.

Table H-1: GPS receiver employed by application type

Application Type	GPS receiver employed to execute the application
Near-term	NT-box with SPS GPS receiver that can optionally receive Coast Guard DGPS corrections directly from a CSI Wireless MBX-3 beacon receiver.
Mid-term	Honeywell PAPS unit that receives dual frequency carrier phase DGPS corrections through a Global System for Mobile Communications (GSM) modem that calls a Novatel GPS base station.

Table H-2 describes the ADASRP functions that are common to all demonstration vehicles.

Table H-2: Common ADASRP functions

Function	Description
GSM modem dialing	For the mid-term application only, the ADASRP platform calls the GPS base station by GSM modem.
Vehicle position data	The ADASRP platform receives DGPS corrected vehicle position data from either the NTBox or Honeywell PAPS unit and routes it to the ADASRP software.
ADASRP software host & execution	The ADASRP software resides in ADASRP platform memory. The ADASRP platform executes the ADASRP software to generate CAN messages that contain information regarding map database mapplets relative to the vehicle position information from map matching and/or GPS receivers.
Near- and mid-term map database host	The near- and mid-term map databases are stored in the ADASRP platform.
Communication with application ECU	The ADASRP platform communicates information regarding mapplets derived by the ADASRP software to the vehicle ECU in the form of CAN messages.

H.2 Near-term Vehicle Positioning

The NTBox was designed by NAVTEQ to represent hardware comparable to navigation systems in production today. Given that near-term needs span the period of present day to approximately 2006, there was concern that the NTBox technology was possibly not representative of hardware toward the end of the near-term. A short study was conducted at NAVTEQ. Briefly, here are the results for three of the latest aftermarket DVD based navigation systems:

- Alpine NVE-N851A
  - 8-channel GPS receiver
  - Unable to determine make/model of gyroscope
- Pioneer AVIC-9DVD
  - 8-channel GPS receiver
  - Unable to determine make/model of gyroscope
- Panasonic CN-DV2000
  - 8-channel GPS receiver
  - Matsushita piezoelectric gyro

The Trimble Lassen GPS receiver is comparable in specifications to the receivers in the three aftermarket navigation products. In addition, as far as multipath mitigation is concerned, Trimble claimed that because the SK II was targeted for the automotive market, a significant amount of work to minimize the effects of multipath on the computed position has already been done. The Trimble representative was not aware of any additional multipath mitigation techniques that they could take advantage of based on the fact that Selective Availability (SA) has been turned off. He also pointed out that they are currently supplying BMW, Mercedes, and Fiat with Lassen SK II receivers for their in-vehicle applications. The main concern is the potential for improved accuracy using Wide Area Augmentation System (WAAS) or some other form of code based differential corrections. To cover this contingency, the NTBox was modified to allow RTCM SC-104 corrections to be input to the Trimble receiver.

Although the gyro type being used in the Alpine and Pioneer systems was not determined, odds are that it is also a piezoelectric gyro similar to the one in the Panasonic system. Navigation Technologies did build a limited number of NTBoxes with the Matsushita gyro and found its behavior to be very comparable to the Murata.

Based on what we have observed while test driving these three systems, the overall positional accuracy of the Vehicle Position (VP) tool using the NTBox is as good or better than all of these systems. Therefore, based on these three systems, it appears that the hardware in the NTBox is comparable to the hardware found in today's high-end aftermarket systems.

The GPS receiver outputs the following data:

- Position, velocity, and Dilution of Precision (DOP) information once per second
- Satellite information once every three seconds
- GPS time information once every five seconds

This data is received by the A-Engine and passed through to the host using the Trimble Standard Interface Protocol (TSIP). The A-Engine also samples the analog data from the gyroscope and the temperature sensor ten times per second. This data along with the accumulated speed pulse count and reverse state are transmitted to the host in a separate TSIP packet every 100 milliseconds. The following is a description of the front panel controls from left to right.

Figure H-2: NTBox front panel

Figure H-3: NTBox back panel

Table H-3: NTBox front panel description

Item	Description
Differential GPS serial port	This is a standard RS-232 port that operates at 4,800 baud and permits a differential beacon receiver to be connected to the Trimble GPS receiver for inputting differential correction data in RTCM SC-104 format.
GPS antenna RF Jack	This is the RF antenna jack directly from the Trimble Lassen SK-8 board.
Auxiliary RS-232 serial port	This is a standard RS-232 port that operates at a software configurable baud rate. This port is used for communication between the NTBox and an external sensor box that transmits data serially.
Host RS-232 serial port	This is a standard RS-232 port that operates at 19,200 baud. This port is used for communication between the NTBox and a host computer.
Programming jack	A conventional 3/32 (2.5 mm) phono jack is employed in order to select 'run mode' or 'programming mode'. In 'run mode' the NTBox executes the program stored in the A-Engine's SRAM. In 'programming mode' the NTBox software can be updated by downloading a new executable via the Host serial port. If a phono plug is not installed, then the unit is in 'run mode'. If a phono plug is installed, then the unit is in 'programming mode'.
LED power indicator	Indicates that the unit is powered on.
Vehicle interface plug	This interface plug is used to connect the vehicle inputs to the NTBox. Pin 1 (+12Vdc) +12V DC connection. Connected to the vehicle's ignition switch accessory wire. Pin 2 (GND) Ground connection. Connected to the vehicle's chassis or other suitable ground. Pin 3 (Speed 1) +5V speed pulse connection. Connected to the vehicle's speed sensor. Pin 4 (Video Sync) +5V video synchronization pulse (future use). Pin 5 (Reverse) +12V reverse connection. Connected to the vehicle's backup lights.
Power switch	This switches the +12 volts main power.

An external analog sensor interface plug is located on the back of the NTBox. This interface plug is used to connect additional analog sensors to the NTBox. These sensors might include additional gyroscopes, accelerometers, or inclinometers.

H.2.1 NTBox Specifications

H.2.1.1 Trimble Lassen SK-8 GPS Receiver

General	L1 frequency (1574.42 MHz), C/A code (Standard Positioning Service), 8 channel, continuous tracking receiver, 32 correlator.
Accuracy	Position 25 meters CEP (50%) without SA (Selective Availability) Velocity 0.1 m/sec (1 Sigma) steady state conditions (without SA) Time ±500 nanosecond (nominal) Datum WGS-84 (standard DMA datum set)
Acquisition rate	Cold Start <2 minutes (90%) Warm Start <45 seconds (90%) Hot Start<20 seconds (90%)
Dynamics	Altitude -1000 meters to +18,000 meters Velocity 515 m/sec (maximum) Acceleration 4g (39.2 m/sec^2) Jerk 20 m/sec^3 Operating Temperature -10°C to +60°C

H.2.1.2 Murata ENV-05D Gyroscope

Maximum angular velocity	80 deg/sec
Operating temperature	-30°C to +80°C
Output (angular velocity=0)	2.5 V
Scale factor	22.2 mV/deg/sec
Asymmetry CW & CCW	3 deg/sec
Linearity	0.5 %FS

H.2.2 Coast Guard DGPS Receiver

The Coast Guard DGPS receiver is a CSI Wireless™ model MBX-3 beacon receiver and is used to provide the NTBox with DGPS corrections.

Figure H-4: CSI Wireless™ model MBX-3 beacon receiver

The MBX-3 may be operated in either automatic beacon search (ABS) or manual tune mode. When operated in automatic beacon search mode, the receiver will identify and tune to the station providing the strongest DGPS signal without user intervention. When operated in manual mode, the user specifies the frequency to which the receiver will be tuned.

The default mode of operation for the MBX-3 receiver is ABS mode. The receiver uses two independent channels to identify and lock on to DGPS beacons without interrupting the continuous flow of RTCM data to the receiver. Because the MBX-3 receiver automatically tunes to the strongest DGPS signal, this mode allows for navigation over wide areas without the need for user intervention.

When the MBX-3 is powered up for the first time in ABS mode, it initiates a global search and examines each available DGPS beacon frequency. It records the signal strength of every beacon identified in a Global Search Table. The receiver uses these measured values to compute average signal strength, noise floor and to sort the frequencies in descending order of signal strength. The two channels cooperatively examine the frequencies with the highest signal strength measurements above the computed noise floor to determine which station provides the strongest RTCM signal. The receiver's primary channel locks to the first identified DGPS broadcast while the second channel continues searching in the background for beacon signals of higher quality. If no signal is available, the MBX-3 will initiate a fresh global search and will continue this cycle until it finds a valid beacon.

During the background search, the second channel examines all frequencies to identify beacons possessing superior signal quality. If a DGPS broadcast is identified that exhibits a signal strength 2 dB greater than that of the primary station, the receiver will automatically switch to this beacon. No loss of lock occurs on the primary station during the background scan.

The MBX-3 stores the current primary beacon in memory so that it is available upon subsequent power-up. The user may force a new global search at any time using the display and keypad, or by issuing a proprietary Wipe Search command.

In Manual tune mode, the user may select a specific frequency and bit rate for the receiver to tune to. The user also has the option of specifying just the frequency and allowing the MBX-3 to identify the correct bit rate. The MBX-3 also provides the capability to select a beacon by name from the World Beacon Table stored in the receiver's memory .

H.3 Mid-term Vehicle Positioning

The Honeywell PAPS GPS Receiver represents this advance and is the source of GPS vehicle positioning data for all mid-term applications. The PAPS unit provides the following position accuracy needed for mid-term applications. Figure H-5 illustrates the overall system architecture for the PAPS unit.

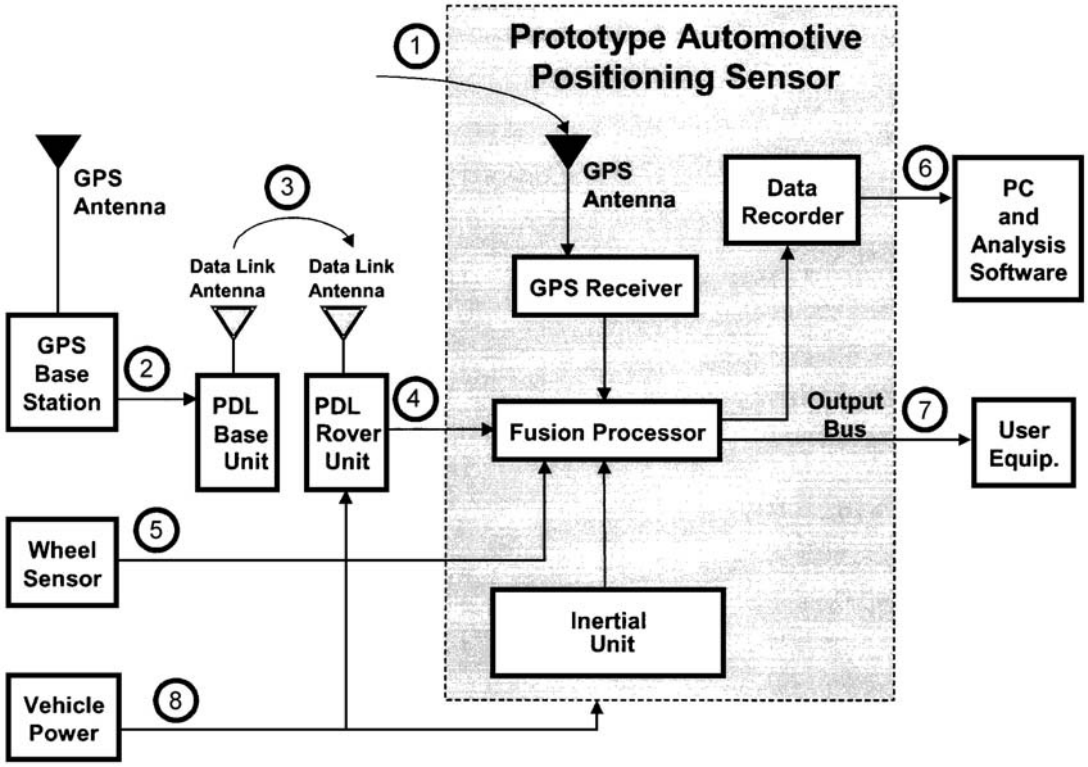

Figure H-5: PAPS system functional block diagram

The eight external interfaces identified in Figure H-5 are defined in Table H-4.

Table H-4: PAPS external interfaces

#	Function	Description
1	GPS Satellite RF Interface	The PAPS unit receives vehicle position data from a GPS satellite constellation.
2	Base Station Output Interface	A number of GPS base stations located in the test areas broadcast differential GPS correction data via the cell phone network.
3	Differential Data Link RF Interface	The PAPS unit receives the differential GPS correction data via a GSM modem that the vehicle operator uses to call a specific base station.
4	Differential Data Link Serial Interface	The GSM modem supplies the PAPS fusion processor with the differential GPS correction data that the base station broadcasts.
5	Wheel Sensor Serial Interface	The Fusion Processor in the PAPS unit receives wheel speed sensor data in the form of a serial data message (message 504) from the vehicle.
6	Data Recorder Media (Compact Flash Card)	The data recorder provides data that can be used for analysis purposes.
7	Prototype Automotive Positioning Sensor Serial Output	The Fusion Processor takes data from the GPS receiver, GPS base station, wheel speed sensor and inertial unit to determine vehicle position. The PAPS unit then outputs this data to the internal data recorder, ADASRP platform and other user subsystems.
8	Vehicle Power Interface	The PAPS unit is powered by the vehicle's DC power system.

A number of base stations located in the test areas broadcast differential GPS-corrections data. The PAPS unit receives this data through an RS-232 serial input bus via a GSM modem. Although the PAPS is capable of receiving data at 115,200 bps, the GSM modem is only capable of providing differential GPS corrections at 9,600 bps therefore the Port setup for the PAPS must be set to the lower speed or the unit will not operate properly. The PAPS also receives wheel speed data through an RS-232 serial input bus (message 504) at 115,200 bps. Each OEM is responsible for providing wheel sensor data in the proper format.

The PAPS provides data through an RS-232 serial output bus at a baud rate of 115,200 bps. The unit provides a 140-byte INS/GPS Output Message (message 502) at a rate of 50 Hz and a 64-byte INS/GPS Detailed Status Message (message 503) at a rate of 1 Hz.

H.3.1 Available Applanix POS Systems

H.3.1.1 POSLV 420

Performance

The POSLV 420 employs a Litton IMU. This IMU has a drift of 1 deg/hr.

POSLV 420	GPS Outage Duration (IARTK/PP/DGPS)														
	0 sec			15 sec			30 sec			1 min			2 min		
	IARTK	PP	DGPS	IARTK	PP	DGPS	lARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS
X, Y (m)	0.035	0.02	1.0	0.07	0.05	1.13	0.013	0.07	1.25	0.20	0.12	1.5	0.30	0.27	1.63
Z (m)	0.05	0.03	1.5	0.07	0.06	1.63	0.10	0.09	1.75	0.15	0.15	2.0	0.20	0.35	2.13
Roll & Pitch (deg)	0.02	0.005	0.02	0.02	0.005	0.02	0.02	0.005	0.02	0.02	0.005	0.02	0.02	0.005	0.02
True heading (deg)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03

IARTK: Inertially-Aided RTK
PP: Post-processed
DGPS: Real-time DGPS

Physical

	IMU	PCS	DMI (Applanix)	Antenna
Size:	204 x 204 x 168 mm	2.5U, 19" Rack Mount (445 x 111 x 350 mm)	153ϕ x 97 mm (not including collets or restraint rod)	160ϕ x 58 mm
Weight:	3.5 Kg	9.4 Kg	2.7 Kg	0.46 Kg
Power:	N/A	120/220 VAC, 60/50 Hz or 12 VDC, 110 W (peak)	N/A	N/A
Temperature:	-40° to +60° C	0° to +50° C	-40° to +85° C	-40° to +70° C
Humidity:	0 to 100 %	5 to 95% RH non-condensing	0 to 100 %	0 to 100 %
Cables:	8 m	N/A	8 m	10 m

Sensors

GPS: 12 channel dual frequency (1-1/1-2), low noise,
12 channel single frequency (1-1), low noise

Ethernet Input/Output (10/100 base -T)

Data: Position, attitude, heading, velocity, track & speed, acceleration, status & performance, raw data. All data has time & distance tags.

UDP Port: Display Port - low rate (1 Hz data)

TCP/IP Ports: Data Port - high rate (1 - 200 Hz data)

Data Port 2 (buffered for data logginq)

Control Port - used by LV-POSView™ (controller software)

Logging Output to Removable PC-Card Disk Drive

Parameters: Position, attitude, heading, velocity, track & speed, acceleration, status & performance, raw data. All data has time and distance tags.

RS232 NMEA Output (DB 9 male)

Parameters: Position ($INGGA)

Heading ($INHDT)

Track and Speed ($INVTG)

Statistics ($INGST)

Rate: 1 - 50 Hz (user selectable)

RS232 High Rate Digital Output (DB 9 male)

Parameters: Roll, pitch, true heading, latitude, longitude and altitude.

Rate: 1 - 200 Hz (user selectable)

RS232 Input (DB 9 male)

Parameters: Auxiliary GPS input

Position ($GPGGA)

DOP ($GPGSA)

Statistics ($GPGST)

Satellites in View ($GPGSV)

Rate: 1 Hz

RS232 Base 1 & Base 2 Input (DB 9 male)

Parameter: CMR, CMR+, RTCM 18/19, RTCM 1, RTCM 9

Other I/0

PPS: 1 pulse-per-second Time Sync output. Normally high, active low pulse where the falling edge is the reference.

Event Input: Two input discretes used to mark external events. Discretes are TTL pulses > 1 msec width where rising or falling edge is time-tagged and logged. (Maximum rate 300 Hz.)

H.3.1.2 POSLV 220

The POSLV 220 employs a Honeywell HG1700 IMU. This IMU has a drift of 3 deg/hr.

POSLV 220	GPS Outage Duration (IARTK/PP/DGPS)														
	0 sec			15 sec			30 sec			1 min			2 min		
	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS
X, Y (m)	0.035	0.02	1.0	0.20	0.05	1.13	0.35	0.08	1.25	0.70	0.15	1.5	1.0	0.60	1.75
Z (m)	0.05	0.03	1.5	0.20	0.08	1.63	0.30	0.12	1.75	0.50	0.20	2.0	0.90	0.70	2.2
Roll & Pitch (deg)	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.06	0.07
True heading (deg)	0.07	0.025	0.07	0.07	0.025	0.07	0.07	0.025	0.07	0.07	0.025	0.07	0.07	0 .03	0.08

H.3.1.3 POSLV 320

The POSLV 320 employs a Litton IMU. This IMU has a drift of 3 deg/hr.

POSLV 320	GPS Outage Duration (IARTK/PP/DGPS)														
	0 sec			15 sec			30 sec			1 min			2 min		
	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS	IARTK	PP	DGPS
X, Y (m)	0.035	0.02	1.0	0.10	0.05	1.13	0.20	0.08	1.25	0.35	0.15	1.5	0.60	0.40	1.63
Z (m)	0.05	0.03	1.5	0.10	0.07	1.63	0.15	0.10	1.75	0.25	0.20	2.0	0.40	0.50	2.2
Roll & Pitch (deg)	0.05	0.02	0.05	0.05	0.02	0.05	0.05	0.02	0.05	0.05	0.02	0.05	0.05	0.02	0.05
True heading (deg)	0.05	0.025	0.05	0.05	0.025	0.05	0.05	0.025	0.05	0.05	0.025	0.05	0.06	0.03	0.06

Notes:

The positional accuracy listed in the tables are RMS values
The accuracy specifications assume good GPS mission planning (when GPS is available)
IARTK performance values are valid at baselines out to 40 km
Specifications are valid as of March 2003

H.4 Delivery of Differential Corrections

The fundamental idea behind differential correction is to estimate certain errors that exist in a GPS position measurement and then correct an originally derived position by those errors. In order to do so, a reference station with a precisely known antenna location is used. Due to the known location of the reference station antenna, the base station receiver can estimate the correction data. Then, this data is transmitted to a second receiver, e.g. in a moving vehicle. Based on the correction data that receiver can correct its position accordingly.

There are two primary kinds of differential corrections, each allowing different levels of accuracy. Code-based differential corrections like those issued by beacon transmitters operated by the United States Coast Guard can provide a GPS receiver with information allowing the receiver to obtain accuracy in the 1 to 5 m ranges. For the mid-term positioning sensor in EDMap, carrier-phase differential correction information allows the GPS receiver to obtain accuracy in the 0.02 to 0.6 m range.

Unfortunately, no source for carrier-phase differential corrections existed at the time of EDMap positioning definition. OmniSTAR (http://www.omnistar.com/) now offers a service that may be used with certain GPS receivers to consistently obtain sub-meter positioning accuracy. This service was not available when EDMap chose its positioning strategy and is not compatible with the current positioning hardware. Additionally, there is an effort underway within the USDOT to investigate the potential of an extended Nationwide Differential GPS (NDGPS) Coast Guard system to provide carrier phase observable differential corrections. The High Accuracy NDGPS work continues, but was not at a level where it could be used in EDMap. The viability of these and other potential sources of differential corrections will be addressed in the Task8b interim report.

A wireless link for transmitting differential corrections is a requirement to demonstrate map-based applications requiring high accuracy positioning in real-time. As a result, the EDMap team defined base stations at each OEM location. Table H-5 outlines the real-time message requirements from the base station GPS receiver to the vehicle mid-term positioning sensor. Overall, the communication link requires an average transmission of 97 bytes per second from the base station to the vehicle.

Message Description	Message Size	Message Frequency
RTCA Standard Type 1	83 bytes maximum	Every 5 seconds
RTCA Reference-Station Satellite Observations	156 bytes	Every 2 seconds
RTCA Reference Station Position Information Type 7	24 bytes	Every 10 seconds

Table H-5: Mid-term differential correction messages

H.4.1 Base Station / Vehicle Setup

For the test setup, the base station transmits the carrier-phase correction data via a landline telephone modem to a moving vehicle equipped with a cellular modem. A Novatel OEM3 or OEM4 receiver (participant dependent) at the base station is configured to generate the RTCA differential correction data. Figure H-6 shows the complete system layout.

The generated differential corrections are then transmitted to a rover GPS receiver. In order to do so efficiently, the base station PC hosts a multi-modem PCI adapter and is connected to a pool of conventional land-base telephone lines. A Java software application on the base station PC then handles incoming calls and routes the correction data to the respective rover unit connected over

the phone line. The Java software and the modem pool configuration of the phone lines allow the base station to handle multiple rover connections at the same time. Hence, each connected rover unit will receive the same differential corrections.

The rover unit then uses a cell modem to connect to the differential base station. The modem has a roof-mounted antenna to improve reception and software on the rover handles placing the cell call as well as serial port routing of the base station data from the cell modem to the rover GPS receiver. The software also handles certain error conditions, e.g. it automatically redials the connection to the base station to minimize the time of a differential correction data outage in case of a dropped cell modem connection.

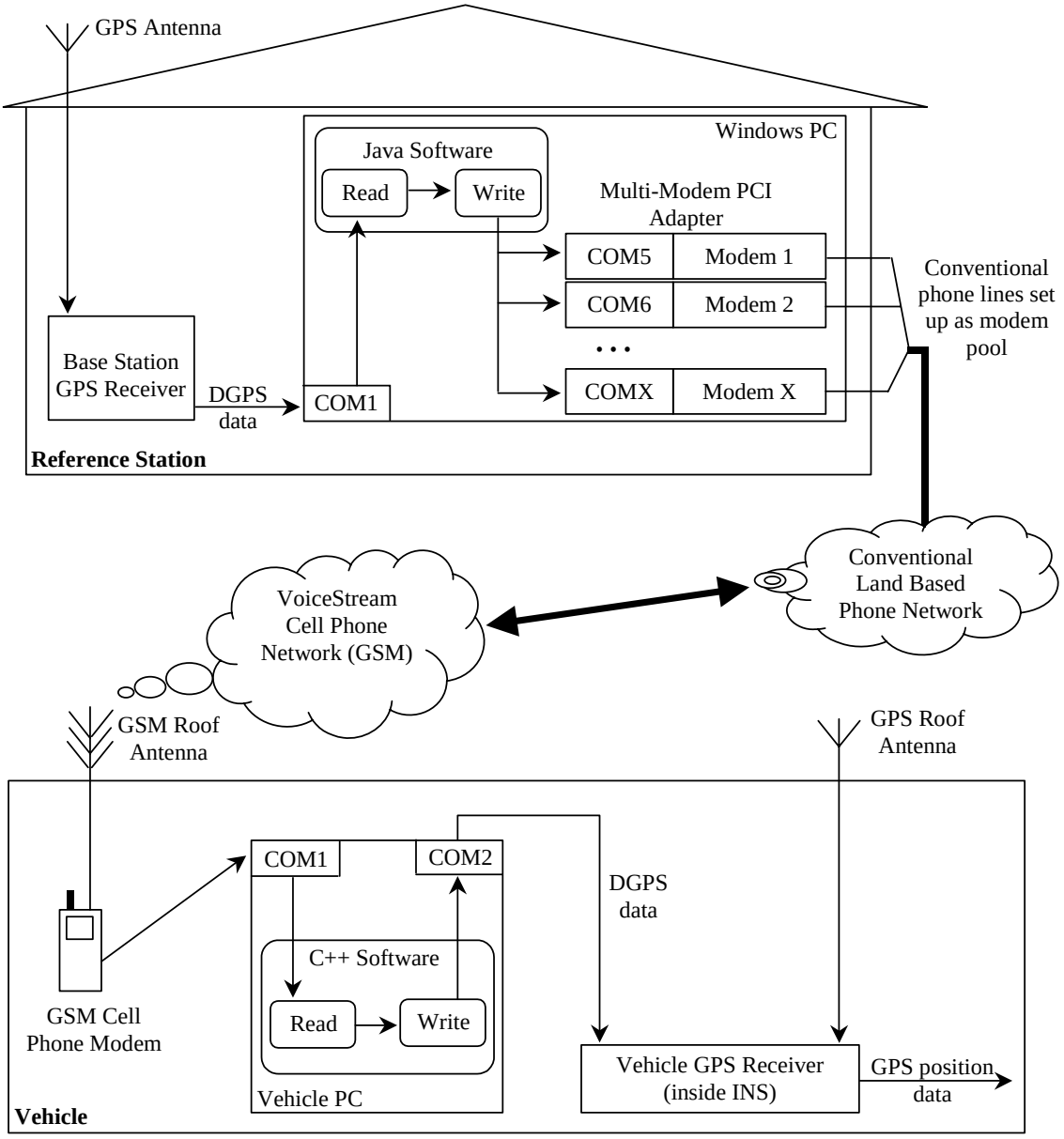

Figure H-6: DGPS correction setup

H.4.2 Base Station Survey

The base station provides measurements used for differential corrections at the roving GPS receiver. For EDMap, a roving GPS receiver is in each of the OEM demonstrator vehicles as well as in the NAVTEQ data collection vehicles. The position solution calculated at any given time sample at the roving receiver is relative to the base station position.

The relative distance calculated using differencing is made absolute using a set of reference coordinates at the base unit. With the base unit coordinates known, the relative distances calculated using differencing are simply added to the base coordinates (ECEF) to determine the coordinates of the rover unit. The coordinates of the base unit can be converted to a common map coordinate system such as NAD83, permitting GPS to be used for survey purposes and navigation.

The key element of a survey is to accurately determine the location of a point or set of points with respect to a known position or network of known positions. Typically, the goal is to determine the location of a set of points, e.g., for a housing development, as shown in the network of survey points in Figure H-7. It is important to maintain consistent accuracy from the known point to all the network points. Accuracy is maintained by measuring the distance from the horizontal control point (HCP) to one of the network points to form a baseline HCP-11. Another baseline is then formed using HCP-12. The first survey stage is accomplished by closing the loop between 11-12, and thereby forming the triangle HCP-11-12. The 11-12 baseline provides increased accuracy by adding a geometric constraint to the individual baselines HCP-11 and HCP-12.

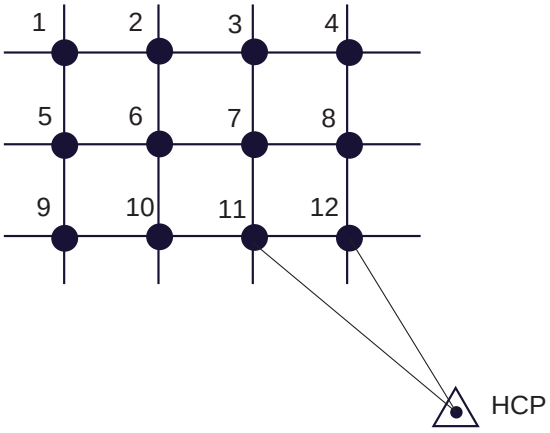

Figure H-7: Network survey representation

The survey proceeds using the 11-12 baseline to create more triangle loops until all network points have been covered. Once all points have been covered, a process called network balancing is performed that uses a least squares adjustment to the errors generated at points where two measurements exist. An example of such a point is location 12 that has baselines 11-12 and HCP-12 pointing to it. A difference between the two measurements for location 12 is mediated by balancing the error through the connected baselines. How much any one point is corrected is determined by statistics (covariance) of the GPS position solution for each point. Using this balancing approach, the network of points can be surveyed to a high level of accuracy from point to point. [Hoffman-Wellenhof, et.al. 1994].

Accordingly, in order to determine accurate positions of the EDMap base stations, HCP sites needed to be identified. There are in-ground HCP locations throughout Michigan as part of the National Geodetic Survey (NGS). However, GPS equipment needs to be set up over the HCP marker to collect data. The alternative used by EDMap was to collect data from Continuously

Operating Receiver Stations (CORS). NGS sponsored CORS sites collect GPS data at pre-surveyed locations, and make the data available via the internet [www.ngs.noaa.gov/CORS/cors-data.html]. The data are time delayed, and therefore not useful for real-time corrections.

The process followed in the Michigan EDMap test area was to collect GPS observations data at each of the EDMap base stations, and process, in conjunction with CORS data, accurate base station positions for the four base stations. Waypoint [www.waypoint.com] survey software was used to calculate the survey. The process followed is summarized in the steps below:

- **Planning** – Good GPS satellite constellation coverage was ensured by using almanac information from [www.navcen.uscg.gov/ftp/gps/archives/yuma]. Waypoint mission planner provides interface to almanac data. The periods of best DOP and number of satellites at a reasonable personnel time were selected as the survey day and time.
- **CORS Data Collected** – CORS sites for the southeast Michigan area were identified based on proximity to the four EDMap base stations to be surveyed. Three were chosen: SIBY (South of Dearborn, MI for Ford), BRIG (near Brighton, MI for CAMP and TTC), and METR (near Auburn Hills, MI for GM and CAMP). GPS observations and related information (coordinates) are downloaded a few hours after the actual EDMap collection due to the data availability delay. In general, CORS sites are known to approximately 1cm in latitude/longitude. Datum NAD83 Epoch 2002 coordinates were used.
- **Collect EDMap Base Station Data** – Using the date and time period established by the almanac, ephemeris and carrier phase measurements were collected for 2 hours (to be used at 15 second intervals).
- **Network Processing** – Waypoint Grafnet software was used to process the EDMap base station data along with the CORS reference data. All EDMap base station observations were added, using one CORS site as the primary control point, and the other CORS sites as balancing nodes. Processing and balancing was an iterative process that continued until baseline residual errors are all under a maximum of 5 cm based on EDMap application needs.

Figure H-8 shows the EDMap network. The three CORS sites (SIBY, BRIG and METR) are shown, along with the four EDMap base stations (TTCLo – Toyota TTC, GMR – GM Research, Ford – Ford Scientific Research Labs, and 212 – CAMP Facility). The triangles highlighted form the survey network with regard to baselines that need to be computed in order to form a minimally constrained network solution. The ellipses around each station is the expected residual error. The calculated base station positions and expected accuracies are shown in **Error! Reference source not found.** and Table H-7, respectively. The results are quite good, and provide a reference from which all EDMap applications and map database collection, especially midterm requirements, can be based.

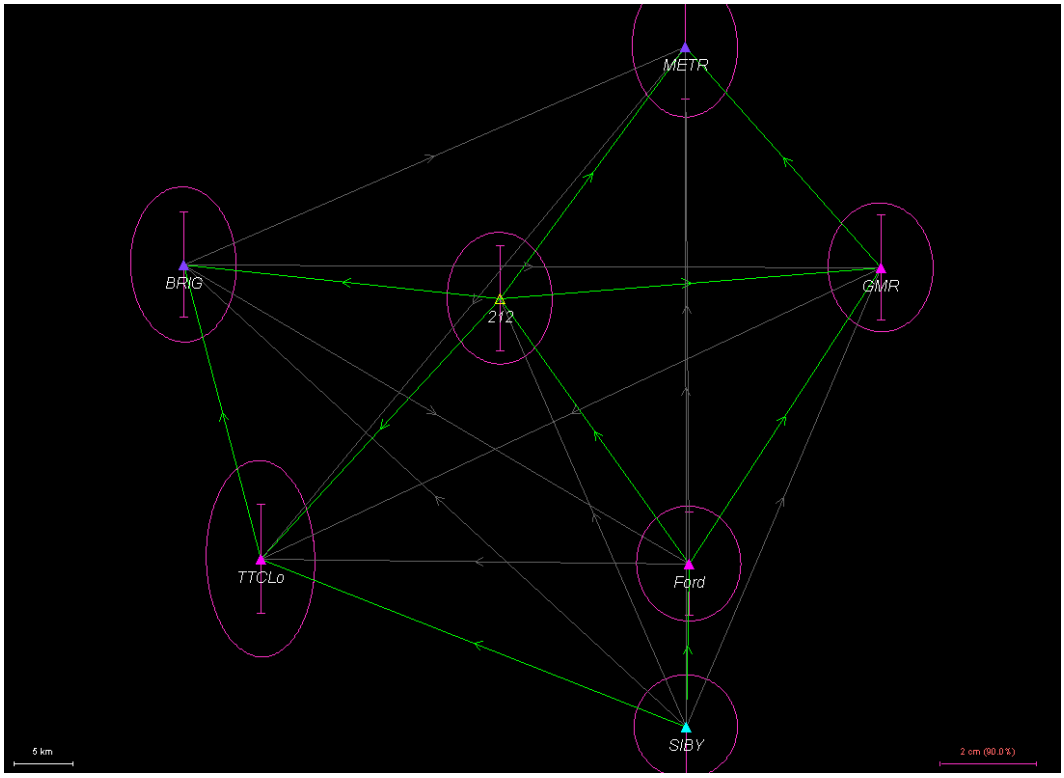

Figure H-8: EDMap base station network for southeast Michigan

Table H-6: Calculated base station positions

Station	**Latitude** **DMS.s** **D.d**	**Longitude** **DMS.s** **D.d**	**ELLHGT (m)**	***Geoid Height MSL (m)**
CAMP	42 29 38.78546 42.494107072	-83 25 58.06541 -83.432795947	243.815	277.554
Ford	42 17 36.26688 42.293407467	-83 14 17.21095 -83.238114153	170.281	204.329
GM	42 31 04.65227 42.517958963	-83 02 30.46258 -83.041795161	165.379	
TTC	42 17 50.87191 42.297464419	-83 40 37.76589 -83.677157191	243.564	278.204
DCX	37 24 56.01401 37.415559447	-122 08 57.5735 -122.14932598	9.204	

Table H-7: Expected base station position errors (90% of errors contained)

Station	North Error (cm)	East Error (cm)	Hgt Error (cm)
CAMP (212)	1.1	1.3	2.2
Ford	1.1	1.2	2.2
GMR	1.1	1.3	2.1
TTC	1.1	2.1	2.2

The base station survey for the Palo Alto region was conducted previously by DCX, but the approach shown here would be readily applied to the DCX base station using appropriate CORS data.

It is interesting to note that standard averaging of GPS (non-differential) data collected at the base stations, typically collected over several days and then averaged, was shown to be insufficient for decimeter level positioning requirements.

H.4.2.1 Investigating Different Means of Differential Correction Delivery

To satisfy the requirement in the EDMap project, the following three wireless technologies for obtaining differential GPS corrections were evaluated under similar testing conditions.

Table H-8: Differential correction delivery methods

Method	Source	License Requirements	For More Information
Spread Spectrum Wireless Modem	Freewave Technologies, Inc.	License free	http://www.freewave.com
35 Watt Radio Modem	Pacific Crest Corporation	License required for 35 watt operation	http://www.paccrst.com
GSM Cellular Modem	Wavecom	License free	http://www.wavecom.com

H.4.2.2 Spread Spectrum Wireless Modem

Two spread spectrum wireless modems were used to test the communications link. The base station modem's antenna was placed on top of the CAMP building located in Farmington Hills, MI. The other modem antenna was mounted on top of a vehicle. A known repeating ASCII string was sent from the base station antenna to the vehicle antenna. Initial testing showed the communications link consistently failed when the vehicle traveled more than 2 miles from the base station location. Since the link was not capable of maintaining a connection over long distances, this technology was deemed not useful for EDMap purposes.

H.4.2.3 35 Watt Radio Modem

Figure H-9 below illustrates the results of a test that General Motors conducted in approximately a 180 square kilometer area in 2002 to assess the radio modem's capability to deliver differential GPS correction data. A 35 watt Pacific Crest Radio transmitter and antenna was placed approximately 50 feet in the air on top of a GM Research building located in Warren, MI. A vehicle was equipped with a radio modem and a roof-mounted antenna. As the vehicle traveled

through the area, GPS locations of the vehicle were recorded along with data received from the base transmitter location. The figure clearly shows that the Pacific Crest Radio modem was extremely susceptible to poor data quality or complete loss of communication as the distance between the base transmitter and receiver grew. Since the loss of differential GPS correction data results in rapid degradation of the vehicle position accuracy, the EDMap team members quickly determined that this method of transmitting differential GPS correction data was wholly unacceptable.

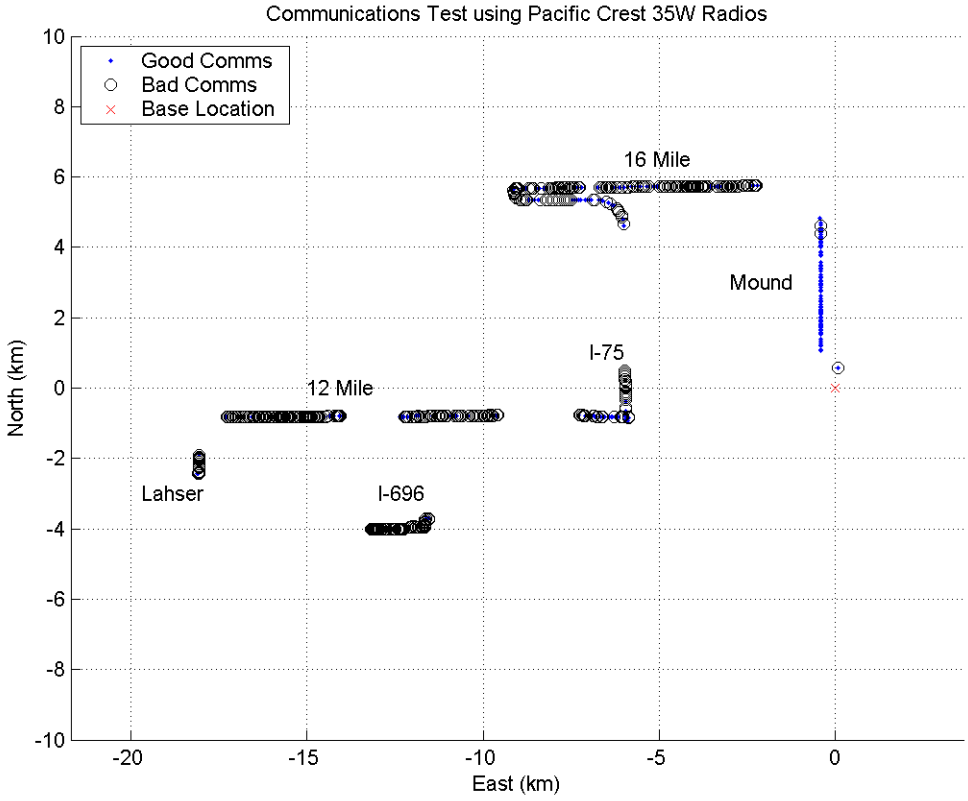

Figure H-9: Pacific Crest 35 watt transmitter test

H.4.2.4 GSM Cell Modem

Figure H-10 below illustrates the results of a test that General Motors conducted in an approximately 4,100 square kilometer area in 2002 to assess the GSM cell modem's capability to deliver differential GPS correction data. A GPS receiver in the vehicle recorded vehicle location as information was transmitted through the cell link from a computer inside a GM Research building. The figure clearly shows a vast improvement in reception of differential GPS correction data over that of the Pacific Crest Radio modem. Instances of bad data receptions were greatly reduced and the area in which differential GPS corrections could be obtained increased by a factor of more than 20 times. The two continuous areas of bad communications are the result of the cell connection being lost requiring a redial. Because of the performance exhibited by the GSM Cell Modem, the EDMap team members adopted it as the method of obtaining differential GPS correction data.

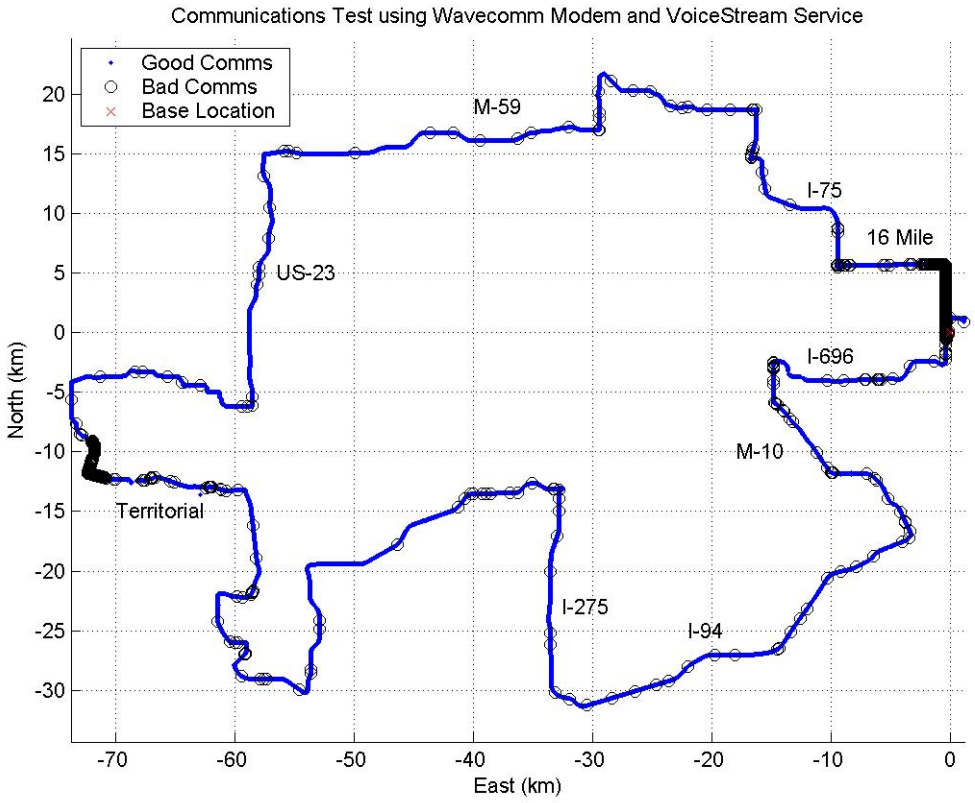

Figure H-10: Wavecom cell modem and T-mobile cell provider test

Figure H-11 and Figure H-12 show the cell modem that the EDMap team chose as the delivery method of differential GPS correction data.

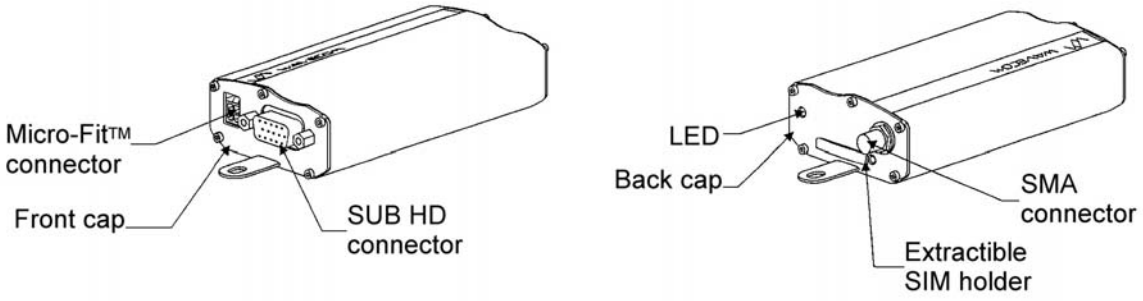

Figure H-11: Wavecom GSM cell modem

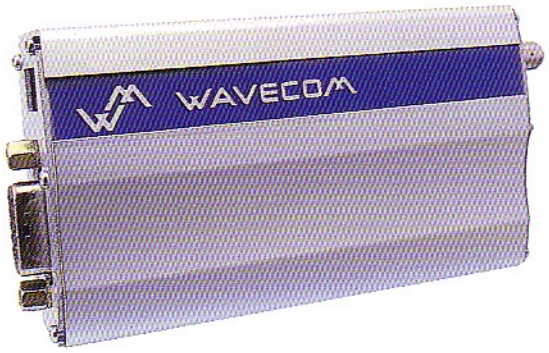

Figure H-12: Wavecom GSM cell modem

H.4.2.5 MEMS Gyro Technology

The Honeywell MEMS gyro, shown in Figure H-13, is based on the Coriolis force. The resonant structure is composed of two elements, called proof masses, driven electrostatically in a plane in opposite oscillatory directions. When the device is rotated about the sensitive axis, the elements are driven to oscillate out of their original plane of motion by an amount proportional to the product of the input rotational rate and the oscillatory drive velocity. Measurements of the mass deflection allow the determination of the rotation rate. Commitment and investment in the Honeywell MEMS gyro remain at a high level and interest from customers has extended well beyond the traditional aerospace market.

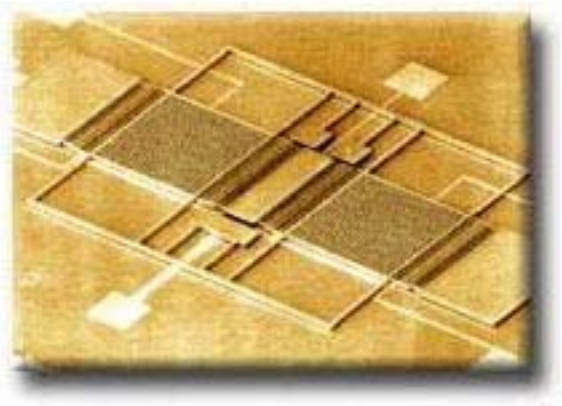

Figure H-13: Honeywell MEMS gyro

The micro-machined mechanisms are fabricated using a dissolved wafer process, depicted in Figure H-14. The critical dimensions are controlled with boron diffusion and dry etch techniques. The silicon wafer is anodically (thermal electrically) bonded to a glass substrate that has been prepared with a metal deposition step to provide all the electrical contacts for the sensor operation. After the unwanted silicon is dissolved away, the mechanism is free to operate. This allows for wafer level probing to map all the mechanisms on a wafer in a single automated process. After mapping, the wafer is diced and the individual mechanisms are vacuum packaged and ready for integration with the sensor electronics.

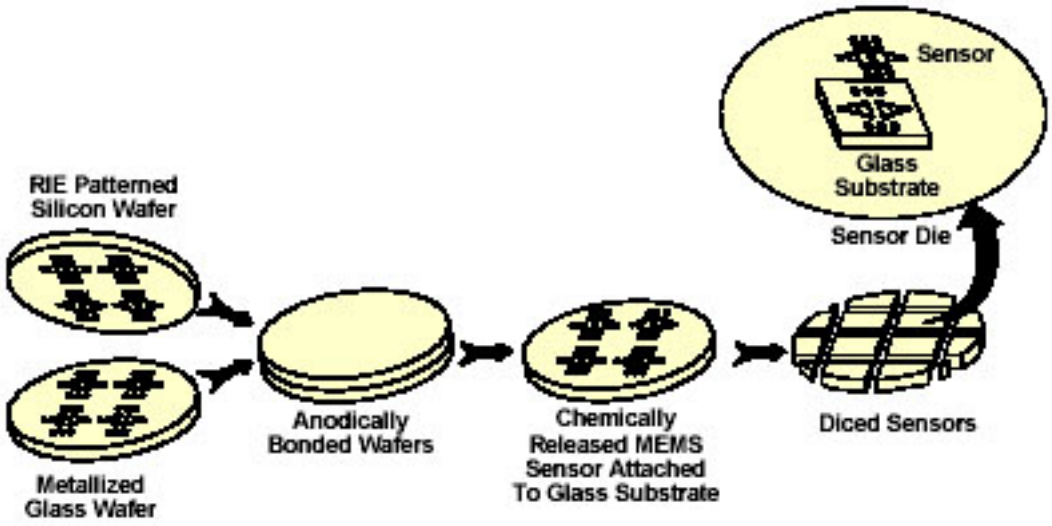

Figure H-14: Wafer level automotive gyro fabrication

The simplicity of this fabrication process makes it possible to build the mechanisms on high volume, low cost MEMS silicon lines.

Appendix I: Task 8A - Deployment Issues

This appendix contains the Task 8A Final Report, published January 31, 2002. It provides an overview of in-vehicle and infrastructure-related equipment and capability that is associated with the deployment of safety-focused applications using enhanced digital map databases.

The Appendix consists of the following sections:

- Executive Summary
- Positioning Study
- Communications Study

TASK 8A – DEPLOYMENT ISSUES - EXECUTIVE SUMMARY

This Executive Overview provides Task 8 motivation and goals, and a brief summary of the take-away points that are of immediate use to the EDMap team and to the DOT. The Honeywell positioning report and the Schaffnit Consulting communication report have been included in their entirety as attachments. The positioning and communications reports each have their own executive summary.

Motivation and Goal

The Task 8 goal is to provide an overview of in-vehicle and infrastructure-related equipment/capability that is associated with the deployment of safety-focused applications using enhanced digital map databases. It is recognized that there are enabling technologies and capabilities that must exist for EDMap safety-focused applications to be deployable in the vehicle market. The EDMap project concentrates on the specification, formation, and maintainability of enhanced digital map databases for vehicle applications with high potential for safety benefit. External to the EDMap project, but implicitly linked to the goal of map-based safety applications, are technologies and capabilities that EDMap applications expect to be in place. These external capabilities, specifically communications and vehicle positioning, are developing along paths not directly related to EDMap. Task 8 reviews these key external capabilities, and provides a reality check on the prospects that the external capabilities will be able to support EDMap applications.

Task 8 is divided in two parts, with the first part, 8a, occurring at the beginning of the EDMap project, and a follow-up analysis, 8b, near project end to address advances made during the project. The Task 8a report, in addition to its purpose of providing advice to the EDMap project, also can serve as a reference point from which external organizations could be approached in order to influence development of capabilities beneficial to DOT and OEM safety application interest.

Independent consultants have been contracted to provide the Task 8a analysis. The key components of the Task 8a report are predictions of positioning and communication capabilities that will be integral to deployment of enhanced maps. The Honeywell Sensor and Products Division and Schaffnit Consulting have provided the respective positioning and communication analyses for this Task 8a report.

Vehicle positioning capability is required to place a vehicle in the map reference frame. Current vehicle navigation systems position the vehicle in a map to enable turn-by-turn

directions. EDMap applications require higher positional accuracy to enable applications that need to know not just what road the vehicle is presently driving, but also just where in the lane the vehicle is driving. Under special conditions, and with expensive equipment, positional accuracy meeting EDMap needs can be met today. However, deployment of this capability to the nationwide road network with relaxed constraints on special conditions needs to be addressed. The Task 8a positioning analysis addresses GPS and DGPS requirements (accuracy, reliability, multi-path mitigation, acquisition times, outages, and differential correction availability) and inertial system requirements (accuracy, reliability, cost, and technology availability).

Communication requirements come from the need to get map and positioning information to (and sometimes from) the vehicle, as well as the inherent communication requirements of some of the EDMap applications themselves. As map databases evolve, the need to communicate map updates to the vehicle is expected to supplant static onboard maps. It is also expected that vehicles will, under certain conditions, transmit information to an externally maintained system to provide real-time traffic and map updates. In addition, several high value applications are enabled by a combination of accurate maps, positioning, and direct car to car and/or car to infrastructure communications. Communication will also be required for the vehicle to receive differential GPS corrections. DGPS corrections, needed to achieve sub-meter position accuracies, are common to both the positioning study as well as the communication study. The Task 8a communications study explores a wide range of potential communication services, and provides additional depth with regard to suitability of meeting EDMap application needs.

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1 Executive Summary

This study investigates the potential for industry to develop a positioning system for automobiles, which can provide accuracies of less than 10 cm with high system availability. The approach taken in this study was to evaluate the ability of high accuracy GPS combined with low cost inertial sensors to achieve continuous sub-meter real-time position determination for automotive applications and to forecast the cost based on the evolving technology and potential market volume. The study identifies the cost, infrastructure and technology trends for positioning systems and evaluates the near, middle and long term prospects for automotive positioning systems.

The study proposes a positioning system that includes a Differential GPS (DGPS) position solution with a nominal accuracy of less than 7 cm. This study investigates local and regional augmentations of GPS and identifies an available DGPS solution, which requires a precision GPS receiver and a differential data link. The study identifies the need for a differential data link, which has a minimum bandwidth of 4.8 kbaud and differential corrections provided by an infrastructure with survey quality.

The study acknowledges that the capabilities and availability of GPS continue to improve. The position sensor performance is enhanced by the prospects of GPS improvements like “GPS III” and alternative systems like Galileo, which will improve the robustness of the navigation signal to interference and the speed in which position solutions recover. In the end, as assumed going into the study, satellite navigation is and will be limited by obstructions in everyday applications.

To overcome this system limitation of GPS, an inertially derived position solution is defined and evaluated. The study shows that such a positioning solution is possible and after investigating a set of expected requirements for the inertial sensors defines a mechanization which meets the objectives laid out for the position sensor.

The study evaluated the potential for a number of inertial technologies and identified an example silicon positioning sensor design, which has a high potential to meet the low cost and high reliability objectives of the automotive industry. The design identified has the ability to provide position errors of < 10 cm for up to 10 seconds at a cost of less than $500. These integrated systems could be available as early as 2006 with a cost driven primarily by volume. The evolution of these technologies is expected to evolve in a similar fashion to GPS receivers.

The study also investigates other methods of providing aiding to the GPS solution including odometer aiding and map matching. The conclusion of the study is that aiding is likely to be included primarily where the costs are low because the benefits to an inertially augmented system are not great in the short term. For systems with outages longer than 10 seconds, aiding is likely and in general expected to be low cost.

Finally, the study is based on a high performance system design. The performance of the design is somewhat scalable in that, if GPS is lost the system will cost graciously to at a rate ratioed to the performance of the system, which calibrated the inertial errors. The system could be based on pure GPS, Wide Area DGPS or Local Area DGPS depending on the infrastructure available and performance required. In all cases of these cases, the cost of the final equipment will primarily be a function of the market volume assuming low cost acceleration and rotation sensors like those described in this study can meet the final system requirements.

1.1 Objectives of the Study

The purpose of this study is to investigate the potential of commercial industries to develop a high accuracy low cost positioning system for automotive use. The approach taken in this study was to evaluate the ability of high accuracy GPS combined with low cost inertial sensors to achieve continuous sub-meter real-time position determination for automotive applications and to forecast the cost based on the evolving technology and potential market volume.

The final conclusions presented in this paper define when equipment will be suitable for use in the automotive market to complete the objectives of the Enhanced Digital Map (EDMap) analysis being performed for the U.S. Department Of Transportation (DOT).

High accuracy GPS, for the purposes of this study, means a GPS solution that has carrier-phase capability and has both code and carrier differential corrections applied to it. Accuracies for position solutions of this type are generally measured in centimeters. This study provides extensive discussion of the GPS solution, performance and limitations. The key objective of the study is to determine potential methods of integration, capable of overcoming the limitations of differential GPS position determination.

Specifically, the GPS limitation of greatest concern is the availability of visible satellites during periods when the sky is occluded by obstacles such as overpasses, buildings, mountains or passing vehicles. The approach taken in this study is to integrate GPS and inertial sensors to maintain high accuracy positioning solutions during periods when the GPS satellites are occluded.

After defining potential solutions, the study evaluates the equipment required to execute the identified solutions. The study then identifies the cost (vs volume) and the time frame in which these solutions are technically feasible.

The approach taken by Honeywell in defining low cost inertial sensors for this study is to evaluate Micro Electro Mechanical System (MEMS) gyros and accelerometers. These sensors, while at the present time export issues exist, offer the greatest potential to reach the automotive cost goals. Finally this study takes into account the inclusion of GPS receivers, automotive wheel sensors and digital maps in identifying a final solution.

1.2 Objective Metrics

The analysis presented in this study considers five key metrics: cost, loss of GPS, accuracy, system update rate and technology availability. The first four metrics are used in this study to aid in the estimation of the fifth metric (technology availability), which is the output of the report.

1.2.1 Cost

Clearly for this technology to be applied to the automotive industry, the cost of the system must be below $500. Currently in today's environment, systems capable of providing centimeter accuracy or inertial navigation capability can cost more than $40,000. This study first identifies a set of performance objectives for automotive applications. Second the study identifies a family of solutions which can be integrated into a single device. Third the study evaluates the potential of the underlying technologies to achieve a truly low cost manufacturing solution given the potential for high volume production of greater than 1,000,000 units/year.

1.2.2 Loss of GPS

The GPS outages vary in time depending on the antenna environment. The minimum duration of time in which an acceptable loss of GPS should occur in an EDMap solution is 10 seconds. This study considers the capability of positioning systems to deal with outages of up to 30 seconds. Single satellite outages, high multipath environments, vehicle dynamics and the complete loss of satellites are considered in this study.

The outage time is defined as the point when the GPS signal(s) is lost and the system begins to coast on the inertial and augmentation position sensors. The outage time ends when the system is no longer coasting only on inertial and the high accuracy GPS solution is recovered. The outage time, therefore, includes the signal re-acquisition time.

The majority of outages in the automotive environment are expected to be due to temporary obstructing objects such as signs and bridges where the duration is very short relative to the 10 seconds.

In addition to the obstruction interval, the 10 second goal is enough time for the system or the operator to respond to a given situation. Ten seconds gives an operator time to react when the systems lose adequate position information.

1.2.3 Accuracy

This study is based on a requirement to maintain position accuracy to better than 10 cm (about 4 inches) both while a DGPS position solution is available and during GPS outages. In addition, the study will evaluate the time frame for which a GPS outage can occur without loss of positioning performance.

The primary reason for the 10 cm accuracy objective is that a position error of less than 10 cm is required to support a positioning solution that remains within about a half wavelength of the GPS carrier signal. This allows the GPS receiver to perform an instant carrier re-acquisition after an outage. Instant or sufficiently fast re-acquisition is key to meeting the accuracy and availability requirements which are expected to be imposed on the automotive industry before key EDMap objectives can be met.

The combination of frequent outages and long re-acquisition times could render the system essentially useless to meet the objectives of the EDMap program. Key to providing an accurate DGPS solution is the integer ambiguity resolution of the differential carrier phase solution, not merely the re-acquisition of the satellite signals. Ambiguity resolution times are generally short when uncertainties are less than 10 cm. However, these ambiguity resolution times grow dramatically with larger position errors, making it key to maintain the solution within 10 cm. In cases where the technique of wide-laning (use of a second frequency) is possible, the half wavelength criteria could be extended to 38 or 43 cm.

The second reason for the 10 cm accuracy goal is that it supports a large number of applications and operational scenarios identified in the EDMap program. For example, applications involving an automobile in a lane would be interested in lateral distances of 10 cm.

In the real world, the outage time will be affected by the integrated system's ability to stay locked on the carrier solution as long as possible. Likewise, the outage time will be affected by the ability of the integrated system to re-acquire quickly when the GPS signal is re-gained. By assuming a 10 cm accuracy goal we significantly simplify the problem of analyzing the GPS reacquisition problem.

The 10 cm accuracy goal is a statistical measure due to probabilistic variations in the GPS and inertial position measurements as well as a large variation in operational scenarios. For purposes of this study we are generally considering the 10 cm objective to be a 50% Circular Error Probable (CEP).

1.2.4 Update Rate

The position solution update rate assumed for the integrated system is 2 Hz (2 outputs of position each second). This is the proposed rate at which the Kalman filter updates all of the corrections based on the GPS measurements. The position output and more importantly the attitude output if required, can occur at a much higher rate because of the introduction of inertial sensors into the system. This implementation allows the update rate of the output to be as high as is required by automotive applications. Typical update rate requirements for automobiles are anticipated to be from 10 to 20 Hz. The output rate of the integrated position solution could be an order of magnitude higher or 100 Hz, if required, as in some aircraft applications.

1.2.5 Technology Availability

The availability of the required positioning technology is based on a number of key factors. An available technology is one in which suitable components can be purchased in the quantities required for a specific application. For this study, there are a number of components to be considered: gyros, accelerometers, processors, memory, Application Specific Integrated Circuit (ASIC) - GPS and inertial, packaging, software algorithms, processes, etc. In addition to cost and availability, automotive environmental requirements must be addressed before a technology can be considered for this application.

1.3 Positioning Background

The first step in the process of executing the vehicle positioning study is to find a low cost positioning technology with global (national) availability. Clearly going into this study, GPS is the strongest potential solution with a global infrastructure. Assuming GPS based solutions open the door to an automotive positioning system, there are a host of GPS shortcomings (well understood in navigation and positioning circles) that must be overcome.

The first requirement identified in the positioning system is positioning accuracy (10 cm). The equipment implementation selected for this study to meet this requirement is a survey quality differential design for the GPS navigation. This in turn requires that the positioning solution include a communications link with a truth reference system in the overall infrastructure of the highway (not directly addressed).

The second significant limitation is the availability of an accurate position. This limitation is addressed by integrating GPS with an inertial positioning solution. The study investigates a number of inertial equipment architectures and ranges of inertial sensor accuracies. The total system defined in the study includes DGPS sensors, inertial sensors (gyros and accelerometers), automotive position/velocity sensors and map data.

1.3.1 Analytical Approach

In order to approach this investigation, several variables had to be dealt with. The key variables used in the study are defined as follows:

- GPS accuracy,
- GPS outage conditions,
- GPS outage duration,
- Gyro and accelerometer performance,
- Positioning sensor integration methodology and
- Vehicle course variation

The potential for large dimensionality of the study caused Honeywell to choose a set of building blocks rather than attempting an all-inclusive analysis. Four specific scenarios have been chosen which represent expected environmental variations. These scenarios have been analyzed in detail. These four scenarios combine the course of the vehicle with the GPS outage and are repeated for several different system integration methods and several different MEMS accuracy levels.

This approach has the advantage of illustrating the impact of specific conditions on the system performance. The approach also allows the study to provide a detailed look at the impact of real world environmental factors in the analysis.

1.3.2 Development of Scenarios

Four scenarios were developed and presented to the EDMap team. These scenarios are described in detail in the following paragraphs. The scenarios represent a vehicle traveling through dynamics consistent with typical roadways and dynamics, which challenge typical strapdown navigation solutions, while experiencing GPS outages or degraded solutions.

In order to strain the inertial navigation position determination, the turns in the scenarios are specified at 90°. In addition to the four scenarios selected, each scenario is preceded by a pre-scenario calibration phase, which is executed prior to the scenario under investigation. The pre-scenario calibration is used to initiate the internal state in the simulations used.

1.3.2.1 Scenario One – “10 Second Outage on a Straight Roadway”

Scenario one, shown in Figure 1.3.2.1, investigated the impact of signs and overpasses by conservatively assuming complete outages of less than 10 seconds. The outages occur while the vehicle is on a straight section of road prior to and following and following a 90° curve. A pre-scenario calibration is assumed prior to the start of this scenario.

This scenario a simple scenario, which provides a conservative, look at the most common outages. Ten seconds is expected to be longer than most of the typical outages experienced on a highway but it is long enough to allow us to view the error propagation during the inertial coasting segment.

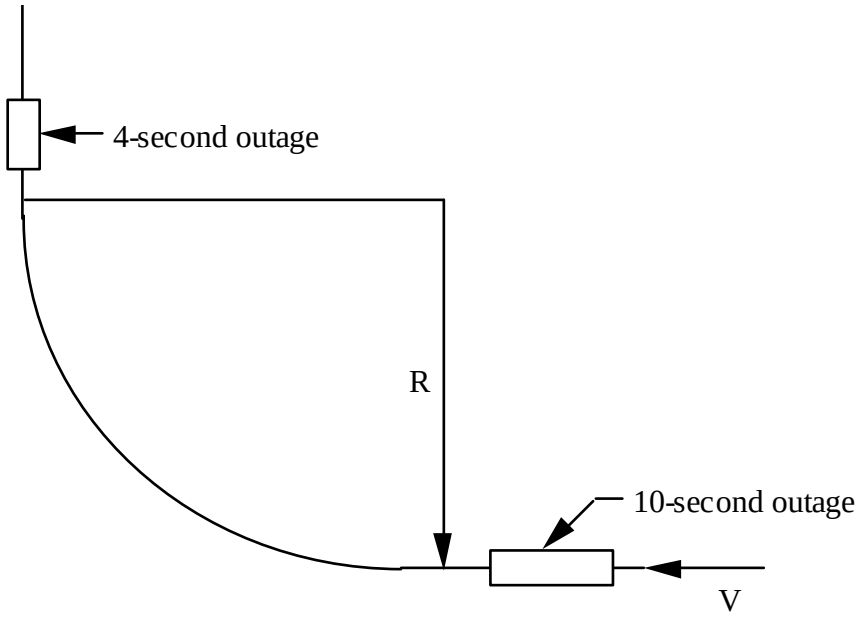


Figure 1.3.2.1 10 Second Outage on a Straight Roadway

1.3.2.2 Scenario Two – “Partial Outage on a 90° Curve”

Scenario two investigates the impact of vehicles approaching an obstruction such as a building or other structure to the side of the road as shown in Figure 1.3.2.2 . As the vehicle approaches the obstruction, individual satellites become occluded based on the obstruction sitting in the line of sight to the satellite. As the vehicle continues around a curve past the obstruction some satellites come back into view while others become occluded. As the distance from the obstruction increases the obstruction no longer interferes with visibility to any satellites. A pre-scenario calibration is assumed prior to the start of this scenario.

This scenario addresses the impact of stationary objects temporarily blocking individual satellites. By including a 90° curve during the partial outage two additional elements are addressed, 1) a dynamic blockage condition and 2) vehicle dynamics that expose system errors, specifically, inertial sensor errors.

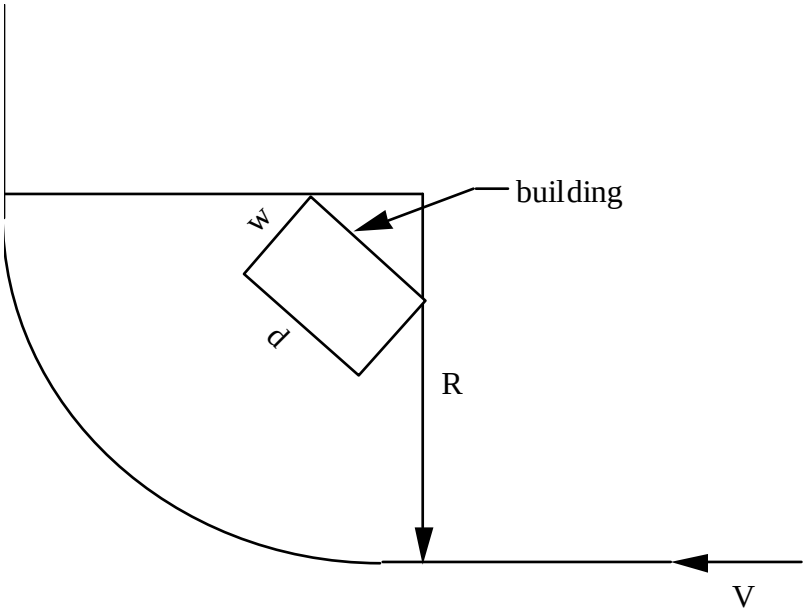


Figure 1.3.2.2 Partial Outage on a 90° Curve

1.3.2.3 Scenario Three – “30 Second Outage During a 90° Curve”

Scenario three investigates the impact of vehicles entering a tunnel that causes a long GPS outage as shown in Figure 1.3.2.3 . The tunnel requires 30 seconds to traverse. There is a 90° curve in the tunnel designed to impact the inertial solution. A pre-scenario calibration is assumed prior to the start of this scenario.

This scenario is meant to be extremely difficult for the system because the outage is complete and long and the system also experiences a turn while it is coasting on the inertial.

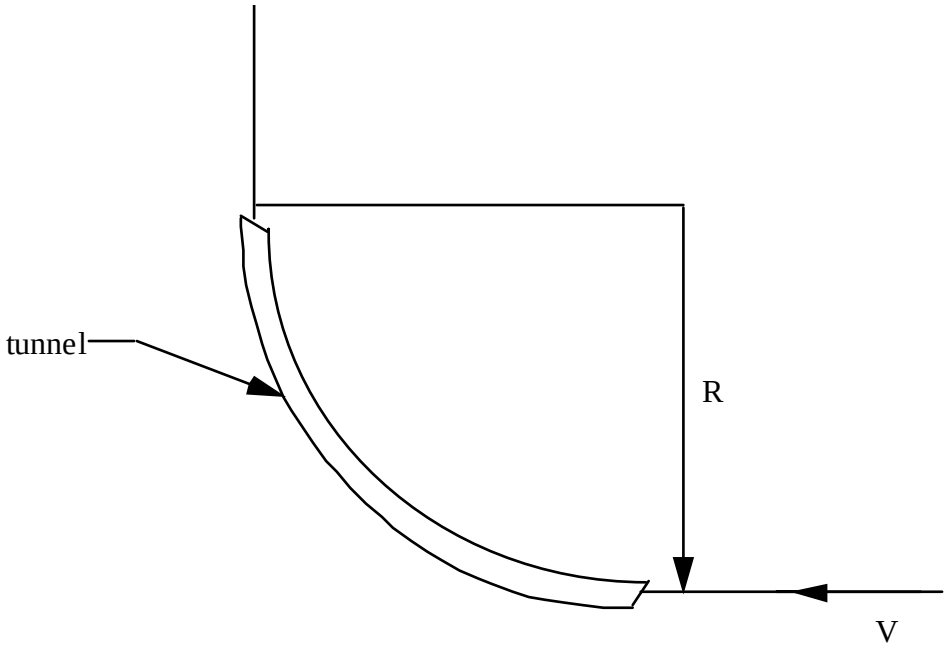


Figure 1.3.2.3 30 Second Outage During a 90° Curve

1.3.2.4 Scenario Four – “GPS Degradation during a 90° Curve”

Scenario four is similar to scenario 2 except that instead of individual satellite blockages the system receives reflections that simulate multipath effects. The scenario is shown in Figure 1.3.2.4 . A pre-scenario calibration is assumed prior to the start of this scenario.

This scenario illustrates the affect of multipath on the proposed positioning systems.

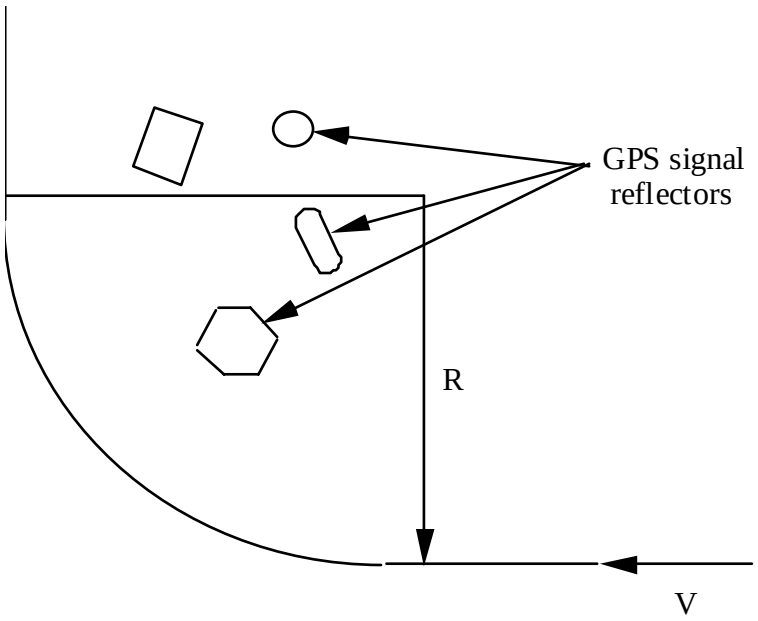


Figure 1.3.2.4 GPS Degradation during a 90° Curve

1.3.2.5 Pre-Scenario Calibration Phase

When the system has high accuracy GPS available, the system can estimate certain inertial (and wheel sensor) errors and calibrate the system to eliminate the impact of the errors on the integrated solution. We assume in this study that prior to each of the scenarios, there is a pre-scenario calibration phase. The errors that are calibrated in this phase are sensor errors that are stable relative to the timeframe of 30 seconds. Also, in order to calibrate these errors there must be certain dynamics that allow the errors to be visible to the system. An example of dynamics would be accelerations and turns.

In the analysis section we have defined a specific pre-scenario calibration trajectory that precedes each of the four scenarios. It includes an acceleration, some turns, a hump that provides pitch axis rotation and a banked curve that provides some roll axis rotation.

The study assumes that it is reasonable that any particular trip will begin with a few maneuvers such as backing out of a driveway, accelerating, executing a couple of 90° turns and having a hump or bank here and there enabling the system to calibrate an initial state.

2 Study Results

The study identifies and analyzes a family of potential positioning systems which can be appropriately configured to accurately determine vehicle location (< 10 cm) for use as part of the Crash Avoidance Metrics Partnership (CAMP) program. The study evaluates the potential for the proposed systems to reach an affordable cost and conform to the automotive market on a reasonable timeline given the state of the art in navigation technologies.

2.1 System Performance

This study investigates the fusion of navigation technologies and begins with an evaluation of the state of the art in DGPS systems. As a side evaluation, the study considers also the infusion of other satellite based navigation systems.

Following a discovery of the limitations, the study explores the capability of inertial navigation systems to be fused with GPS and determines the level of performance might be achieved. In order to meet the cost goals, a MEMS-based inertial system aided by differential carrier-phase GPS is assumed and analyzed. Four positioning mechanizations, each implemented with three different qualities of MEMS sensors, were evaluated across the set of representative scenarios specifically designed to expose the performance characteristics of the positioning mechanizations.

The assumptions regarding the performance level that could be expected from a differential carrier-phase receiver, in terms of both positioning accuracy and clock stability, are considered to be compatible with anticipated low-cost GPS receiver evolution.

Specific conclusions clearly suggested by the study results are the following:

- This study is based on DGPS for the inherent position accuracy. The analysis assumes survey quality GPS equipment as a baseline. The cost of survey quality GPS receivers should go down when the market reaches the volume levels defined for the automotive positioning sensor.
- The DGPS element of the system will require a differential correction source, which will have a direct impact on the system. Issues such as differential update rate, reference grids, data link and link antenna requirements will have to be integrated into the final system analysis.
- Second-generation inertial sensors (denoted as “MEMS-2”) statistically provide the desired performance to meet the objectives of this study.
- A six degree of freedom inertial mechanization (designated “Mechanization - 1”) is the preferred system implementation identified in this study (Mechanizations 1, 2 and 3 each meet the requirements assumed in this study). This preference depends only on inertial sensors, and the level of GPS measurement accuracy offered by differential carrier-phase GPS. This eliminates the risks and complexities associated with additional sensors.
- The use of odometer aiding is of benefit for GPS outages of 20 seconds or greater. The benefit is minimal for outages less than 20 seconds and therefore has minimal impact on system availability (System availability is enhanced the greatest when outages of 10 seconds or less are eliminated).
- The performance of an odometer-aided system depends on a basic performance parameter associated with the error in cumulative distance traveled. Since this error

parameter is poorly understood at the accuracy level of interest, considerable analysis and testing is necessary to properly characterize this error.
Note: The odometer creates a number of risks resulting from the need to properly characterize the measurements applied to the Kalman filter, however, odometer aiding is of minimal cost and would probably be included in a final system design.

- The use of zero-up-slip and zero-side-slip constraints is of benefit for GPS outages of 10 seconds or greater. The benefit is minimal for outages less than 10 seconds and therefore has minimal impact on system availability.

  Note: Zero-up-slip and zero-side-slip aiding is of minimal cost and would probably be included in a final system design.

- The performance analysis shows that the ability of the system to calibrate itself while in operation, as opposed to undergoing factory calibration, appears excellent. This capability only requires normal vehicle maneuvering and speed changes and results in the elimination of a significant system cost element which is a part of navigation systems today (2002).
- A digital map is not required to achieve the position sensor performance described in this study, however, once the cost and availability of maps reaches low cost (nearly free) and high accuracy (< 10 cm) they will be incorporated into the position sensor to aide performance and integrity.

2.2 System Cost and Timeline Forecast

Given the analytical results identified in the performance section of this analysis, this study concludes that a system which would meet the requirement of the CAMP program would be a “Mechanization 1” architecture with “MEMS-2” sensors. Section 3.2 defines two systems which are potentially available. The first could be based on “MEMS-1” sensors and manufactured in low volume in 2003 and the second requires some additional component integration and is more likely to be available with “MEMS-2” sensors in the 2008 time frame. The exact timeframe in which performance will transition from “MEMS-1” to MEMS-2” will depend on ongoing technological achievements.

The objective of position sensors, which meet the performance requirements and the cost objectives (< $500) requires the manufactured volume of components to exceed 100,000 devices/year.

Because the features available from the EDMap program and industry regulation will significantly impact the speed at which the market will absorb the product, the study can only conclude that these products become possible some time between 2005 and 2009. Figure 2.2 shows the volume vs price prediction for the positioning system given the hardware definition provided in Section 3.2 .

Finally, the positioning sensor is based on “dual use” (Military/Commercial) technologies. GPS, inertial navigation and MEMS sensors are all of significant value to the government and as the government invests in the evolving technologies, the capabilities of the positioning systems, which use it, continue to accelerate in performance. On the other side of the coin, the government will frequently control a technology’s, limiting the ability of commercial enterprises to absorb the full potential of the technology.

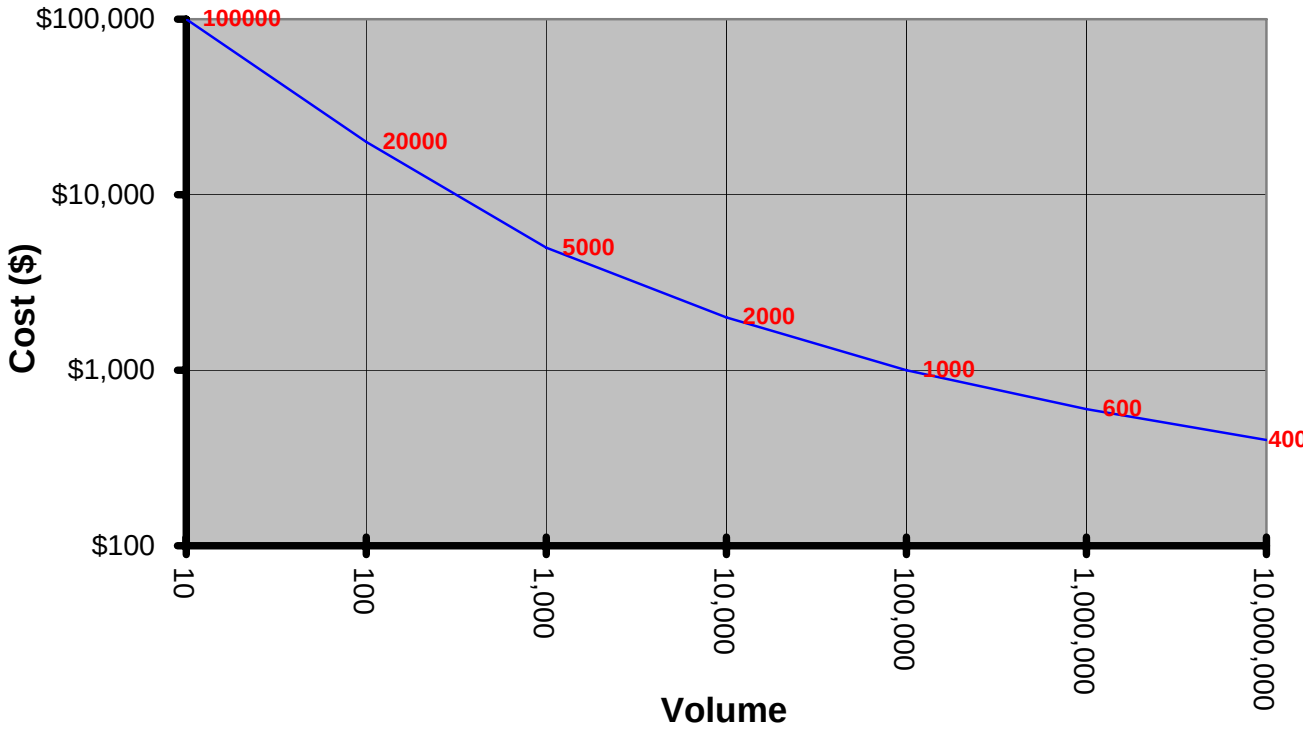


Figure 2.2 Position Sensor Cost/Volume Curve

2.3 Exportability

While significant obstacles to export of inertial sensor technologies (including: laser gyros, fiber optic gyros, MEMS gyros, pendulous accelerometers and silicon accelerometers) exist today (2002), it is expected that the future commercial needs for GPS and inertial sensors coupled with the obvious cost benefits to the military resulting from volume production of navigation components will drive the State and Commerce Departments to create controls which will facilitate both technology security and commercial opportunity.

Honeywell is working with the government on a number of levels to clarify the future export requirements of inertial technologies and based on that effort it is the expectation of this study, that the products defined in Section 3.2 are feasible and will be exportable by 2006.

2.4 Conclusion

It is the conclusion of this study that position sensors based on GPS, differential corrections and inertial measurements could be developed for the automotive industry. The cost objective of obtaining positioning sensors for less than $500 could be achieved given the volumes identified in Figure 2.2 . These positioning sensors would have an error of less than 10 cm CEP, these systems could be available in 2006.

Finally, based on ongoing developments in the navigation industry, it is the conclusion of the study that further reductions in size and cost are inevitable and that future module level components will be available if a market need is created.

3 Positioning System

This study is based on the positioning system shown in Figure 3 and comprised of a:

- Navigation Satellite Constellation,
- Differential Ground Reference System and
- Automotive Positioning System

The Automotive Positioning Sensor is comprised of the following six subcomponents:

- Digital Communications Link,
- GPS Receiver,
- Inertial Positioning Sensor Package,
- Digital Maps,
- Automotive Motion Sensors and
- Fusion Processor

This analysis assumes an acceptable Digital Communication Link (required for carrier level DGPS), Automotive Motion Sensors and Digital Maps as specified are available. The study considers a number of navigation environments for the positioning sensor package.

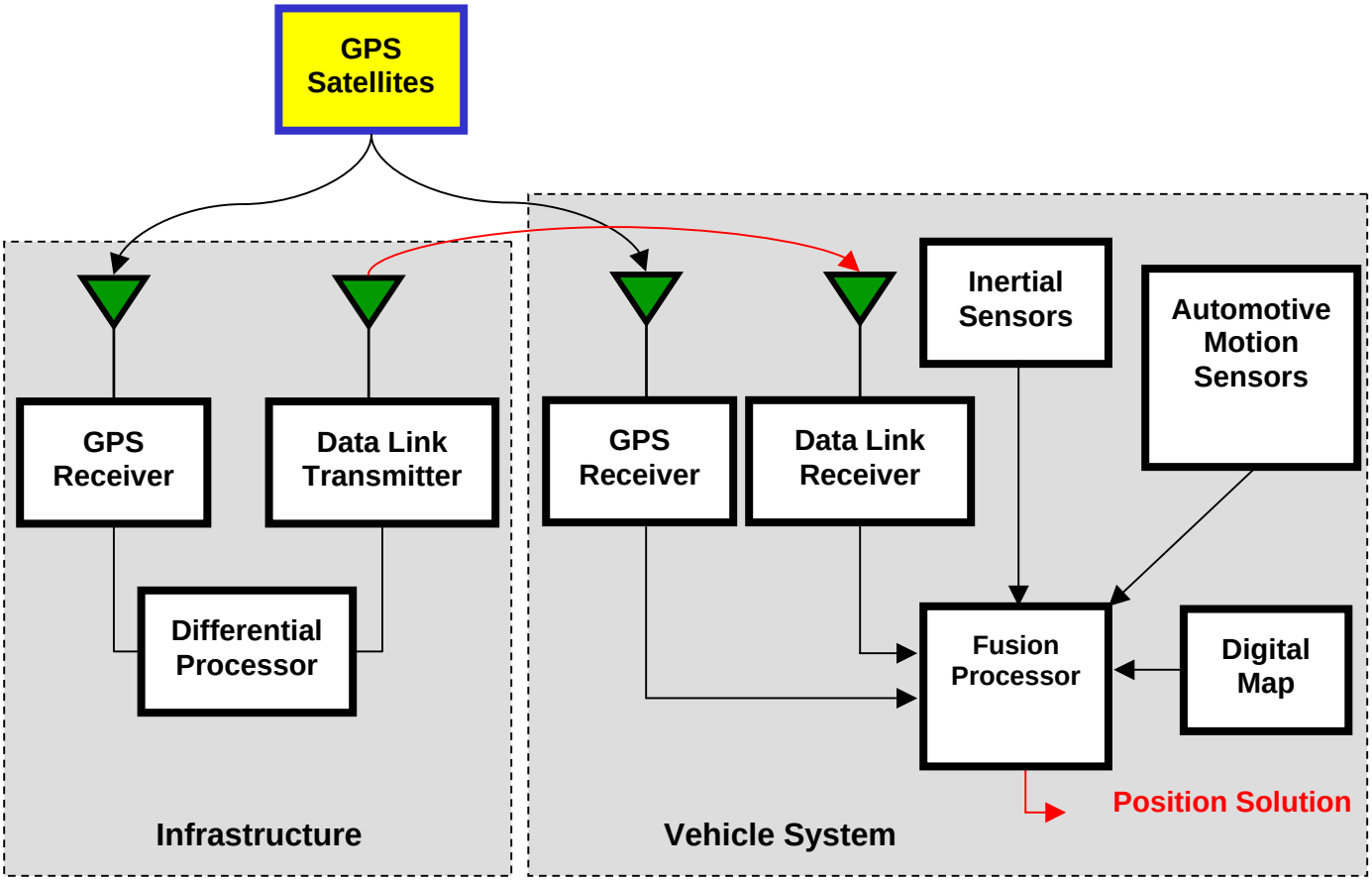


Figure 3 Automotive Positioning System

3.1 Satellite Navigation

At the time of this writing (2002), the U.S. Global Positioning System (GPS) is the only complete and operational Global Navigation Satellite System (GNSS). GPS supports both military and civilian applications. This section of the report focuses on the civilian aspects of GPS. Military features of GPS and other GNS Systems (G LONASS, WAAS, Galileo, …) will be discussed briefly for completeness.

3.1.1 Background

GPS (and satellite navigation in general) is divided into three major segments: a space segment, a user segment, and a control segment. The GPS space segment consists of nominally 24 satellites, orbiting 10,900 nautical miles above the earth (4 satellites in each of 6 orbital planes). The user segment consists of the receivers and antennas. The control segment consists of ground control stations that monitor and upload data to the satellites. There are five ground control stations; they are located in Hawaii, Kwajalein, Diego Garcia, Ascension Island, and Colorado Springs, Colorado.

According to the Standard Positioning Service (SPS) Performance Standard, for any point on the earth at any time, there is an average of more than 8 satellites visible, assuming the nominal 24 satellite constellation. Using these same assumptions, 6 or more satellites are visible 99.9% of the time, while, at the time of this writing, there were 28 healthy satellites (the nominal 24 satellites plus 4 active spares) in orbit. For this analysis 24 satellites are assumed for the nominal environment.

3.1.1.1 Definitions

To ensure a common understanding, we will define a few terms for this study.

Pseudorange (PR) is a code-based measurement of the time difference between the user receiver and satellite clocks (signal delay). After removing the time difference in the clock sets, the measurement represents the magnitude of the vector from the user receiver to a satellite in time. This magnitude can be converted to a distance (range) using the signal speed of travel (speed of light).

Delta Range (DR) is a carrier-based measurement of the satellite signal (phase difference). It is the number of periods of the carrier (scaled into distance units using the wavelength of the carrier) received between measurement updates.

Dilution of Precision (DOP) is the ratio of navigation solution error to measurement error. It is the “goodness” of the satellite constellation. A lower DOP indicates less dilution and therefore more precision. Various DOPs can be defined that provide insight to specific parameters. Geometric DOP (GDOP) is all encompassing – it is four dimensional (X, Y, and Z Cartesian coordinates, and Time). Position DOP (PDOP) is three dimensional (X, Y, and Z); Horizontal DOP (HDOP) is two dimensional (X and Y); Vertical DOP (VDOP) and Time DOP (TDOP) are each one dimensional (Z and T, respectively).

GDOP (for a four-satellite set) is inversely proportional to the volume of the tetrahedron defined by unit vectors between the user and each satellite (tetrahedron nodes are at the satellite end of unit vectors). Statistically, position error equals PR error times DOP, and velocity error equals DR error times DOP (assuming straight and level flight).

Figure of Merit (FOM) is the radius of a circle about the current indicated GPS (measured) position that the actual position will stay within to a probability of at least 95%. This number assumes no failures in the tracked satellites. FOMs are a current assessment of position accuracy. For navigation, Horizontal FOM (HFOM) and Vertical FOM (VFOM) are commonly used.

Integrity Limits are the radius of a circle (or half a line segment, in the case of a vertical integrity limit) about the current indicated position within which the actual position will stay with a probability of at least 99.9%. This number assumes an undetected failure in the worst case satellite (the tracked satellite that will cause the largest position error before the error is detected). Integrity limits are a current assessment of position integrity that are calculated by Receiver Autonomous Integrity Monitor (RAIM) algorithms.

Navigation System Error (NSE) is the difference of the position calculated by the navigation equipment and the actual position. NSE contains both Signal in Space (SIS) errors and user equipment errors.

Hazardously Misleading Information (HMI) is any output data that results in an NSE larger than the current integrity protection level (or integrity limit) without an annunciation within the time-to-alert. HMI is caused by undetected failures.

3.1.1.2 Signal Structure

Currently, GPS satellites transmit on two frequencies, L1 and L2. Various codes and navigation data are organized in 5 subframes and is modulated onto the L1 and L2 carriers. The frequency standard used in the system is 10.23 MHz.

The civil GPS signal is a spread spectrum signal which utilizes digital pseudorandom noise (PRN) codes that are 1023 bits in length and unique for each satellite. It is transmitted at 1.023 Mbits/sec, repeating once every 1.0 msec. These PRN codes, also called Gold codes, are balanced -- that is, the total number of 1's and 0's differ by only one, which helps to decrease the chance of cross-correlation. The structure of these Gold codes, known as the Coarse/Acquisition (C/A) code, were not originally intended for navigation, but were designed to provide acquisition and transition to the more precise P-code.

The current military signal (Precision Positioning Service, or PPS) utilizes a single 37 week long PRN code known as the P-code; each satellite transmits a different 7-day segment. Each unique P-code segment is about $6x10^{12}$ (six trillion) bits, and transmits at 10.23 Mbits/sec. The P-code is typically encrypted to prevent unauthorized access and is referred to as the Y-code or simply P(Y) code.

The L1 (1575.42 MHz = 10.23 MHz x 154) and L2 (1227.60 MHz = 10.23 MHz x 120) right hand circular polarized (RHCP) carrier waves have the PRN codes modulated onto them using biphase-shift-key (BPSK) modulation. The C/A code is modulated onto the in-phase component of L1; the P-code is modulated onto the quadrature (90° rotated) component of L1, 3 dB down from the L1 C/A code signal level. The P-code is modulated alone onto L2 (on current satellites) at 6 dB down from L1 C/A code levels. The 50 bit/sec navigation data message is superimposed on the C/A and P codes using modulo 2 addition (an exclusive-OR function). There is a data bit transition once every 20 periods of the complete C/A code. The BPSK modulation results in a spread spectrum signal centered on the carrier. This spread results in power levels that are an average of 30 dB down from where they would be with non-spread spectrum modulation.

The envelope of the power spectral density (PSD) of the signal is proportional to sinc x = [sin x / x] ^{2}. The power of the C/A code is contained in impulses spaced every 1.023 MHz / 1023 bits = 1 kHz. The spectral content of each PRN is slightly different (i.e. the magnitude of the spectral lines vary slightly from PRN to PRN). The power of the P-code is more evenly spread because the length of the P-code is large (increasing the randomness) relative to its frequency.

GPS receivers use code division multiple access (CDMA) to distinguish one satellite from all others, since all satellites transmit on the same frequency.

3.1.1.3 Additional GPS Concepts

A short discussion of a few significant GPS concepts follows. These concepts are helpful in understanding GPS position determination.

3.1.1.3.1 Doppler

The received signal experiences a doppler shift due to satellite (and possibly user) motion. For a stationary user, doppler offsets can be as much as ±6 kHz. A satellite at zenith with respect to the user has no doppler shift; a satellite on the horizon, moving toward or away from the user, has maximum doppler. Receiver tracking loops must account for the doppler shift to maintain lock on the satellite signal.

3.1.1.3.2 Cross Correlation

Code tracking within a receiver employs the concept of autocorrelation – correlating the received code with an internally generated version of the same PRN code. Cross correlation occurs when a received PRN code correlates with an internally generated but different PRN code, such that the output level is great enough for the code tracking loop to close or “lock onto the satellite”. Large measurement errors may occur as a result, leading to large user position error.[jpc1]

The maximum cross correlation power between two C/A codes is about 24 dB down from the autocorrelation power if they have the same doppler. For other than identical dopplers, the peak cross correlation power is about -22 dB. Because the P-code has a longer sequence, cross correlation power is about 127 dB down, and is therefore not an issue.

If two satellites have different dopplers, a receiver’s cross correlation condition won’t last for long. For example, if the dopplers differ by 1 kHz, the two codes will shift in time by one chip every (1575.42 MHz / 1 kHz) / 1.023 Mbps = 1.54 seconds, and once the codes have shifted by one chip, cross correlation power will be reduced beyond what can be tracked. If the two satellites have the same doppler, the code and carrier tracking loops will be coherent, and the cross correlation condition may persist for some time.

3.1.1.3.3 Smoothing

Carrier phase smoothing is a process that uses carrier phase measurements (that are ambiguous, but have little high frequency noise) to smooth out code phase measurements (that do contain high frequency noise caused by small errors in the code meadurements).

Carrier smoothed PRs can be calculated (assuming 1 Hz measurements and a 100 sec smoothing constant):

PR(smooth) = 0.01 * (raw PR measurement) + 0.99 * (previous PR(smooth) + carrier)

The carrier measurement is the number of carrier cycles received between successive code measurements.

Since position is calculated from smoothed PRs, successive samples are correlated. Since velocity is calculated in high quality receivers only from the carrier-derived DRs, successive samples are independent.

3.1.1.3.4 Geodetic Models

GPS employs the WGS-84 model of the earth. An ellipsoid is an ellipse rotated around its minor axis -- it can be easily defined mathematically. A geoid is a (irregular) surface of equipotential gravity -- the WGS 84 (DOD World Geodetic System 1984) geoid is a first order approximation of Mean Sea Level (MSL). The difference between the WGS 84 geoid and the WGS 84 ellipsoid is defined, by the Defense Mapping Agency, as heights at discrete points on a grid of the earth. Intermediate points can be interpolated. The WGS 84 geoid and ellipsoid origins are both at the true center of the earth.

In most receivers, GPS positioning is performed in X, Y, Z Cartesian coordinates. These can be transformed into ellipsoidal (geodetic) coordinates (e.g. latitude, longitude, altitude). At this point, altitude is referenced to the ellipsoid -- a WGS 84 type look-up table is needed to convert it to a geoid (MSL) reference.

Geodetic coordinate systems are with respect to the local plane tangent to the ellipsoid; geocentric coordinate systems are with respect to the center of the earth.

3.1.1.3.5 Sidereal Day

A sidereal day is the time the earth takes to rotate referenced to the stars (360°), rather than the sun (since the earth moves each day with respect to the sun). It is the time for the earth to rotate once, less the time required to make the fraction of a revolution around the sun that it completes in one day. The GPS orbit planes are fixed with respect to the stars, not the earth/sun reference. GPS satellites have a period of one half a sidereal day, which is 11 hours, 58 minutes, 2.0045 seconds of mean solar time. Because of this, the satellite constellation shifts approximately 4 minutes per calendar day, such that the group of satellites in view at a particular location will be in view 4 minutes earlier the next calendar day.

3.1.1.3.6 Orbital data

Keplerian orbital parameters define the satellite orbits and also the position of the satellite within its orbit. This data, contained within the navigation data message transmitted by each satellite, is available in two formats -- almanac and ephemeris.

The almanac message, 10 parameters per satellite, is nominally updated twice per week. The satellite ephemeris message, about 20 parameters per satellite, is updated every four hours nominally. The almanac provides satellite position accuracy of a few hundred meters whereas the ephemeris provides accuracy of a few meters. The ephemeris is contained in subframes 1, 2, and 3 and the almanac is contained in subframes 4 and 5.

Each satellite transmits its unique ephemeris data and also transmits the almanac data for the entire constellation. The almanac data for the entire constellation consumes 25 “pages” of data and is transmitted by cycling through each page. Given the navigation data rate of 50 bps and 1500 bits per frame, it takes 12.5 minutes to transmit all 25 pages of data. If a

receiver does not contain a valid almanac (typically stored in non-volatile memory), it can usually find at least one satellite, download the almanac data and then know where to “look" for the other satellites. Having a valid almanac stored in NVM decreases the Time to First Fix (TTFF). Modern day receivers update their almanac whenever it changes or at least once per week.

3.1.1.3.7 Code/Carrier Divergence

Code/carrier divergence occurs as the GPS signal passes through the ionosphere. The code delay is actually a group delay (the modulation envelope is delayed with respect to the L1 carrier), and the carrier delay is a phase delay. The propagation velocity of the code (modulation envelope) times the propagation velocity of the carrier equals the speed of light squared (therefore, in the case of divergence, it is said that the carrier has “advanced”).

There is a tradeoff in setting the carrier smoothing time constant, which must be resolved when designing the filter. A large (long) time constant allows the smoothed pseudorange to drift away from the true pseudorange due to the divergence, but a small (short) time constant passes too much of the pseudorange measurement noise through.

3.1.2 Differential Augmentation

One method to increase the accuracy of autonomous GPS is to employ differential corrections, commonly known as Differential GPS (DGPS). DGPS uses independent satellite measurements from a reference receiver at a fixed, known location. Because the reference position is known, a predicted pseudorange can be calculated. Corrections are generated by differencing the predicted and measured values. These corrections are then broadcast to mobile GPS receivers that apply the corrections to measured pseudoranges. Differential corrections are applied in the measurement domain, rather than in the navigation solution domain, since a user may be calculating a navigation solution based on a subset of the measurements used in the reference station.

Differential corrections will remove the effects of errors whose sources are common to both the reference and user receivers (i.e. common-mode errors). Examples of common-mode errors are unmodeled satellite clock and ephemeris errors (including SA), and unmodeled atmospheric (ionospheric and tropospheric) delays. Examples of non common-mode errors are multipath and receiver thermal noise. For high accuracy applications, it is important to utilize design considerations that will limit differential mode errors, such as:

- Multipath limiting antennas. These can be expensive, so their use may be limited to reference stations. Receivers in motion do not require the same level of multipath mitigation as stationary receivers.
- High quality receiver hardware. Examples are low voltage standing wave ratio (VSWR) and low insertion loss RF filters, low noise figure components, high quality oscillators, large automatic gain control range, fine analog-to-digital resolution, high order intermediate frequency (IF) filters, and dual frequency capability.
- Sophisticated tracking loops. Examples are optimal discriminators, narrow or strobe correlators, adjustable loop bandwidths, inertial velocity aiding and carrier aiding of the code loop.
- Sophisticated navigation algorithms. Examples include carrier phase smoothing and ranging source weighting.

Differential GPS accuracy is reduced as the distance to the nearest reference station increases (spatial correlation) or the age of the differential corrections increase (temporal correlation). A system may use a weighted average of corrections from multiple reference stations.

3.1.2.1 Code Phase

Differential corrections applied to code phase measurements (pseudoranges) can produce corrected measurements with tens of centimeters of noise, assuming the reference station is not more than 10 or 20 km away, and the corrections are not more than a few seconds old. The resulting position solution would have less than one meter of error (2 drms).

Scalar PR corrections (a single correction that compensates for the effects of all combined error sources) are usually used for local area systems, and vector PR corrections (individual corrections for each significant error source) are used for wide area systems. Multipath and receiver noise are the only significant remaining error sources; multipath is almost always dominant.

The correction calculation must be based on the same ephemeris that the user receiver uses in its navigation solution; therefore, corrections for both the current and the previous sets of ephemeris must be broadcast to cover operation during ephemeris transitions. A complete ephemeris takes a minimum of 30 seconds to download, and a user receiver may require several attempts to successfully download a complete set of data (e.g. if there is partial or momentary satellite signal blockage).

Since carrier phase measurements have two to three orders of magnitude less noise than code phase measurements, carrier smoothing of the code measurements is used in high quality receivers. The smoothing filter emphasizes the carrier measurement much more than the (most recent) code measurement. Ionospheric induced code/carrier divergence and carrier phase cycle slips add error to this smoothing process. Dual frequency receivers can calculate the ionospheric delay and remove the code/carrier divergence problem, allowing longer smoothing time constants. Additional civilian signals available in the near future (L2CS and L5) will allow dual frequency use without the current level of degraded performance associated with codeless and semi-codeless L2 designs. If the cost of dual RF front ends is not prohibitive, they should be used. Dual frequency systems provide the ionosphere error related benefit described here, but they also provide a major enhancement in carrier integer ambiguity resolution, to be discussed in Section 3.1.2.2.2 .

3.1.2.2 Carrier Phase

Differential carrier phase is currently used in survey systems (both post-processed, and Real Time Kinematic, or RTK) and also in attitude and heading systems that use multiple antennas on a vehicle.

A single difference can be performed on satellite measurements between

- receivers (two receivers, one satellite, same measurement time),
- satellites (one receiver, two satellites, same measurement time) or
- epochs (one receiver, one satellite, two distinct measurement times).

A double difference can be performed using any two of the single difference cases. For survey systems, the two receiver and two satellite cases are combined to remove clock errors. Carrier phase measurements are low noise but ambiguous; code phase

measurements are unambiguous, but higher noise. A double difference solution using carrier smoothed code measurements is unambiguous and low noise.

3.1.2.2.1 Integer Ambiguity

All differential carrier phase systems must resolve the signal integer ambiguity. Integer ambiguity is the unknown number of whole carrier wavelengths between the two GPS antennas. There is much written on methods to solve integer ambiguity. The method chosen for a given system will depend on many specific variables of that system.

One popular aid to ambiguity resolution method is known as the wide-lane technique. A second frequency (e.g. L2 or L5) in combination with L1 provides a “beat frequency” with a longer effective wavelength (e.g. 86 cm or 75 cm, vs 19 cm), greatly decreasing the number of possible solutions within the solution space.

Integrity of the integer ambiguity solution is important. There is always some non-zero probability that a system will initially choose the wrong set of possible solutions. To avoid the generation of HMI, an integrity monitor should be used in the ambiguity resolution process. Several schemes have been proposed, such as multiple solution calculations over time, or use of an overdetermined solution similar to RAIM.

3.1.2.2.2 RTK Systems

Real Time Kinematic systems apply the carrier phase corrections and solve for the integer ambiguity in real time for a user receiver in motion. Typical measurement errors are 1 to 5 cm (1σ) for wide-laning systems. If the system reverts to L1 only after the integer ambiguity is resolved, then typical measurement errors can be reduced to 0.2 to 1 cm (1σ).

Assuming a 10 km distance between the user and the reference station, and a 1 Hz correction update rate, expected horizontal accuracy is on the order of 4 cm (2 drms), and expected vertical accuracy is on the order of 6 cm (2σ). Post processed (not real time) systems can achieve better accuracies. System accuracy is dependent on multipath, the dominant error source. A well designed system will take steps to minimize multipath at the reference stations. Receiver errors (thermal noise, cycle slips, etc) are the only other significant error source. At the vehicle receiver, up to one-quarter wavelength (5 cm at L1) of measurement error is possible due to multipath before cycle slips will occur.

The main issue with RTK is rapid resolution of integer ambiguities. The vehicle receiver is able to calculate its position relative to the ground station, and since the ground station’s location is surveyed and known accurately, the vehicle’s absolute position can be calculated. Code phase measurements can be used to limit the solution space, while differential code phase measurements can reduce the solution space even further. Initial ambiguity resolution times can range from tens of seconds to several minutes, depending on conditions (number and placement of satellites, vehicle motion, etc).

RTK requires corrections to be broadcast at a rate of 1 Hz or faster to maintain accuracy. Bandwidths to support the necessary data rates are available in the VHF and UHF bands. Assuming a vehicle antenna height of 1.5 m, and reference station transmitting antenna height of 7 m, the maximum range should be about 10 miles to maintain the accuracies noted above. Signal blockage by buildings or terrain can affect range. A link budget analysis must be performed to determine the necessary transmit power and receiver sensitivity.

Measurements from four satellites are required for static double difference solutions. A valid assumption is that a minimum of 4 satellites is needed for code phase aiding of ambiguity resolution, and 5 satellites for good results. If five satellites are used after ambiguity is resolved, the solution can be maintained if one satellite is lost due to masking or multiple cycle slips or loss of lock.

The system should estimate position quality and only allow the navigation solution to be used for critical applications such as lane-keeping when a minimum threshold has been achieved. This can easily be accomplished using information from the Kalman filter and digital maps.

One important issue to note is that many current dual frequency RTK systems use a semi-codeless technique for tracking the P(Y) code signal on L2. Since the complete PRN code is not used, the receiver's ability to remain locked onto the signal is degraded by several dB. Future dual frequency systems could be L1/L2CS or L1/L5, effectively removing this need for codeless tracking.

3.1.2.2.2.1 Broadcast Corrections

The Radio Technical Commission for Maritime Services (RTCM) Special Committee 104 has defined standardized message types for RTK systems. Used in pairs, receivers will utilize RTCM SC-104 Message Types 18 and 19 or 20 and 21. Message type 18/19 contains raw code and carrier phase measurements; message type 20/21 contains code and carrier corrections. Either of these message type pairs requires 2,280 bits per epoch, assuming code and carrier data for nine satellites. Differential solutions based on corrections broadcast in this format can achieve centimeter level accuracies.

3.1.2.2.3 Attitude Systems

Feeding signals from multiple GPS antennas mounted on a single vehicle into a compatible receiver can produce heading or attitude solutions. Two antennas can provide heading; four antennas can provide a complete attitude solution. While this is a differential carrier phase system, the solution is produced without using broadcast corrections.

A good rule of thumb for predicting one sigma heading accuracy is arctan (0.5 cm / baseline). This predicts that a system can provide about 0.5° accuracy (2σ) on attitude outputs with a 1 meter baseline (separation of antennas).

Since the antennas are physically close to each other, effects of error sources that are spatially correlated are removed in the solution. And since there is no broadcast of corrections, there is no latency issue. Again, multipath and receiver noises are the only significant measurement error sources that remain.

The baseline (distance between two antennas) establishes the solution space as a hollow sphere. This sphere has one antenna at the center and radius equal to the baseline (this sphere is actually a hollow shell with some thickness). A low-grade inertial device can provide nominal level data that reduces the solution space to a horizontal slice of the hollow shell -- sort of a donut shape. Heading data from a magnetometer ($\pm 10°$, or even $\pm 45°$) can limit the solution space even further to a wedge of the donut. If initial pitch, roll, and heading are known to within $\pm 5°$, there is no integer ambiguity for a 1 meter baseline. User motion also provides data to solve the integer ambiguity. Any rotation over 5° is usually sufficient. GPS track angle can be used as a source of pseudo heading data.

There are a few considerations that must be made when evaluating system requirements. The antennas used should have phase center variations that are known and consistent – this may be a cost driver. True Phase Locked Loop (PLL) carrier tracking loops are necessary. Cycle slips can be a continuity problem, but won't affect the integrity of the solution. Utilizing only measurements with high C/No's would help limit the occurrence of cycle slips impacting the solution.

3.1.3 Differential Infrastructure

3.1.3.1 Wide Area Augmentation System

The FAA's Wide Area Augmentation System (WAAS) augments GPS with three services: additional ranging, differential corrections, and integrity monitoring. There is an emphasis on providing a quick warning of satellite failures.

Currently, GPS (and GEO) satellite measurements are taken at 29 WAAS Reference Stations (WRSs) across the U.S. WAAS data is created from these measurements, and transmitted via transponders on two Inmarsat III Geosynchronous satellites (GEOs): AOR-W (Atlantic Ocean Region - West) and POR (Pacific Ocean Region). Coverage is the continental U.S. (CONUS), although only the West Coast currently receives signals from both GEOs. Since GEOs have a limited lifetime, this is expected to change over time.

WAAS employs code corrections only, which are comprised of satellite clock, ephemeris data and ionospheric corrections. The corrections are divided among the error sources to conserve bandwidth – corrections for slowly changing error sources can be transmitted at a rate lower that for those corrections for quickly changing error sources.

The system emphasis has been placed on integrity so that aircraft systems do not generate potentially harmful misleading information. System accuracy available at the time of this writing is about two meters. System integrity levels (a bound on the position solution that provides a probability of misleading data of 10^{-7} per hour) available are currently better than 50 m vertically and 40 m laterally. This is an improvement from unaugmented RAIM, which provides horizontal integrity levels that are typically below a few hundred meters. The 10^{-7} bound is derived from the missed detection probability of 10^{-3} that applies once a satellite has failed. The probability of a satellite failure is accepted to be 10^{-4} per hour per constellation. The WAAS time-to-alert is 6 seconds. Coverage is about 90% of the CONUS; the uncovered areas are primarily on the CONUS fringes -- some of Alaska, southern Florida, parts of Maine, etc.

The FAA announced on 24 May 2000 that WAAS is available for non-safety-of-life uses. The FAA believes the signal-in-space will be certified for safety of life uses by the end of 2003. After Initial Operating Capability (IOC) is declared, system upgrades are planned to increase performance, including:

- Dual frequency (L1/L5) for the GEOs
- A total of four GEOs
- 22 more reference stations across the U.S. (51 total)
- A reduction of measurement noise at the WRSs (through the use of multipath limiting antennas, etc)

These upgrades will have only a modest impact on system accuracy; however, system integrity levels should be reduced to 12 m vertical and 10 m horizontal.

Both Europe and Japan have systems similar to WAAS under development. Several other countries are evaluating the merits of creating their own WAAS-type system.

3.1.3.2 Nationwide Differential Global Positioning System

The U.S. Department of Transportation (DOT) maintains a Nationwide Differential Global Positioning System (NDGPS) for public and private applications. The U.S. Coast Guard (USCG), under the DOT, manages the NDGPS. The network of stations includes NGS's Continuously Operating Reference Stations (CORS). CORS are maintained by the National Geodetic Survey (NGS), an office of National Oceanic and Atmospheric Administration (NOAA)'s National Ocean Service.

Over 70 individual NDGPS sites are managed by the U.S. Coast Guard, NOAA, NASA/Jet Propulsion Lab, United States Army Corps of Engineers, United States Department of Transportation, various state and local governments, universities, and even private companies. Many sites have been converted to U.S. Air Force Ground Wave Emergency Network (GWEN) sites. Single coverage for the entire U.S. is currently expected sometime in 2003 or 2004. Dual coverage is required to achieve the availability goal.

System performance requirements are 10 m (2 drms) accuracy, integrity alarms (alert limit is 8 m, 2 drms) with 10 sec time to alert, and availability of 99.7%. Actual accuracy has been found to be about 2 m plus 7 ppm of the baseline. The reference standard is the National Spatial Reference System. Because NDGPS transmits in the 285-325 kHz band, receiving antenna size may be an issue for automotive applications.

The Interagency GPS Executive Board (IGEB) has funded a High Accuracy DGPS Demonstration Project, with a goal of 20 cm (90%) accuracy. Code and carrier measurements with update rates of two seconds will be broadcast to meet this higher accuracy goal. Both the standard DGPS service and the higher accuracy service will be broadcast from each station. The broadcast signal will be RTCM SC-104 compliant.

3.1.4 GPS Modernization

The GPS program is currently going through a modernization phase. Current satellites nominally transmit the civil C/A code and the military P(Y) code on the L1 frequency, and P(Y) code alone on L2 (the capability does currently exist to deviate from this norm). Additional capabilities will be placed on future satellites, while maintaining the existing codes. L2CS is a new civil code that will be broadcast on the L2 signal. M-code is a new military code that will be broadcast on both L1 and L2. A third signal, L5 (1176.45 MHz set at 10.23 MHz x 115), will provide another civil code to be added in the future.

Satellites orbiting the earth today belong to the Block II, IIA, and IIR (for replenishment) families. New launches consist of block IIR satellites. L2CS and M-code will be implemented into as many of the block IIR satellites as possible, probably 10-12 (these are referred to as block IIR-M, for modified). These block IIR-M satellites are scheduled to be launched between 2003 and 2006. Lockheed Martin has a contract to create up to 12 IIR-Ms from existing IIRs – the final number will depend on the necessary replenishment rate.

The new L5 civil code (as well as L2CS and M-code) will be transmitted from block IIF (for follow-on) satellites that are scheduled to be launched beginning in 2005, although the program is currently thought to be about 1 year behind schedule. There will be a total of 12 block IIF satellites launched and some of the new features of the L5 civil signal are summarized in Table 3.1.4 .

An entirely new generation of “Block III” GPS satellites are scheduled to begin launching in 2009 or 2010. Studies are currently underway to define the features of the block III satellites, and a production contract is scheduled to be granted in 2005.

L2CS will be comprised of two new time-shared alternating codes:

- CM, a 10,230 chips code (20 msec period) with data, and
- CL, a 767,250 chips code (1.5 sec period) with a coherent carrier (i.e. without data)

CM and CL are perfectly balanced (equal number of 1’s and 0’s). The combined chipping rate is 1.023 MHz. Single frequency users (e.g. cell phones) will most likely use the shorter code; high performance dual frequency users will likely use the longer code. The CM design provides for fast acquisition, the CL design provides for good cross correlation protection. IOC of a new feature is scheduled to occur when 18 compliant satellites are in orbit. L2CS and M-Code IOC should be in 2008, and L5 IOC should be about 2013.

Table 3.1.4 Features of the New L5 Civil Signal

Feature (Compared to C/A Code)	Benefit
Higher power (+6 dB from L1 C/A)	Less susceptibility to interference
Higher chipping rate (10.23 Mbps as compared to 1.023 Mbps for C/A)	Better accuracy resulting from lower susceptibility to waveform distortion resulting from multipath.
QPSK vs BPSK modulation	Both data and data-less signal capability
In-phase component (I) contains PRN + data Quadrature component (Q) contains (an independent) PRN only	More robust carrier phase tracking on Q and therefore tracking is possible at lower C/No
PRN in message	Lower cross correlation probability
Longer codes (10230 chips as compared to 1023 chips)	An average of 10 dB less cross correlation power.
Forward error correction (FEC), 10-bit Neuman-Hoffman encoding on I, 20-bit N-H encoding on Q	13 dB less effect from CWI, (the error correction and encoding result in spectral lines at (10.23×10^6 chipping rate) / (10230 x 20 effective code length) = 50 Hz, rather than the 1 kHz that the chipping rate and code length would suggest), Improved cross correlation and bit sync properties
Five 300 bit messages vs subframes	More efficient use of bandwidth
CRCs rather than parity	Stronger data protection

3.1.5 Galileo and GLONASS

3.1.5.1 Galileo

Galileo is an initiative of the European Union (EU) and the European Space Agency (ESA). GNSS applications are substantial, and they support large pieces of countries' infrastructure. The current existing operational system, GPS, is single sourced, non-European, and U.S. military controlled. As a result, Galileo was conceived. The intent is for Galileo to be compatible with, but independent from, GPS.

PricewaterhouseCoopers recently completed a study for Galileo. The report stated that the likely system cost is €3.6B, and that the cost/benefit ratio is greater that 1:4. It also recommended that revenue come from primarily two sources: royalties from chipset sales and revenue from service providers.

As of the writing of this paper, Galileo has been funded by the EU and the ESA to a level of a few hundred millions euros. The ESA committed in November 2001 to fully fund €550M for its portion of the full engineering phase of the project. In December 2001, the EU Council of Ministers delayed an expected funding decision on a matching €550M due to uncertainties of the private funding aspect of the project.

The current design baseline is for 30 Medium Earth Orbit satellites (MEOs) at 23,200 km in three orbital planes inclined at 56°, and maybe some GEOs. Plans call for the first satellite in orbit in late 2003, and system operational capability in 2008 (this schedule is now in doubt, of course, due to the delay in funding). Galileo plans to provide three levels of service: Open Access (free, basic), Commercial (encrypted data, chargeable), and Safety of Life (additional accuracy and integrity, chargeable).

Ground-generated integrity data is uplinked to "selected" MEOs, which in turn incorporate this information into their navigation data messages. There is a planned system guarantee that two of these "selected" satellites will always be above 25° elevation for any user. This integrity data could be used by safety of life systems.

Current plans are for Galileo to use three 24 MHz signals: E5a (overlayed with GPS L5), E5b, and E6. In addition, four smaller bandwidth signals will be employed: E2 and E1 (neighboring GPS L1), and E3 and E4 (neighboring GPS L2).

Data on E5a (1176.45 MHz = 10.23 MHz x 115, same as GPS L1) and E5b (1196.91 or 1207.14 MHz = 10.23 MHz x 117 or 118) will be identical. The I-channel on E5a will be modulated with a code plus 50 Hz navigation data -- the code will have a marker at 20ms intervals to indicate a possible bit transition (code length will be a multiple of 20 msec). The Q-channel on E5a and E5b will both have data-free 10230 length codes. I's and Q's will be power balanced on E5a and E5b.

The E6 carrier (1278.75MHz = 125 x 10.23 MHz) will provide three signals:

- channel A is BOC(10,5) (binary offset carrier) 5.115 Mcps with data
- channel B is 10230 bit code modulated with BPSK at 5.115 Mcps with 1000 symbols per second (sps) data
- channel C is 10230 bit code modulated with BPSK at 5.115 Mcps without data

The E2-E1 carrier (1587–1591 and 1559–1563 MHz) will provide three signals:

- channel A is BOC(n,m) chipped at a variable rate with data
- channel B is BOC(2,2) modulated at 2.046 Mcps with data
- channel C is BOC(2,2) modulated at 2.046 Mcps without data

The minimum received power level near the surface of the earth will be -132 dBm for E5a+E5b, E6, and E1+E2 for elevation angles above 10°. These compare to the power on the C/A code carried on the GPS L1 of –130 dBm for elevation angles above 5°.

Since Galileo is being designed to be compatible with GPS (e.g. a common 10.23 MHz frequency standard, a common WGS-84 geodetic model), the systems should work well together. System availability of both accuracy and integrity would be boosted significantly. Different carriers provide frequency diversity that would give effective protection against intentional and unintentional interference. The uncertain funding future is the greatest risk to system deployment.

3.1.5.2 GLONASS

GLONASS (GLObal NAvigation Satellite System) is Russia's GNSS. The GLONASS system has two navigation signals: the standard precision navigation signal (SP) and high precision navigation signal (HP). A full GLONASS constellation consists of 24 satellites with 19,100 km orbits at an inclination angle of 64.8 degrees. Each satellite completes an orbit in approximately 11 hours 15 minutes.

GLONASS satellites transmit in the 1591-1610 and 1240-1256 MHz bands. Each satellite transmits on a unique center frequency, separated by a minimum of 562.5 kHz.

Recently, Russia has struggled for funding to manufacture and launch satellites. The satellites average 3 years operational in orbit (GPS satellites average 7-10 years). As of November 2001, there were 6 healthy satellites in orbit. Three new GLONASS satellites were sent into orbit on 1 December 2001.

3.1.6 Pseudolites

Pseudolites are ground-based transmitters that broadcast a satellite-like signal. In general, pseudolites are used to provide increased availability and/or continuity in a localized area. They can also be used in pairs as integrity beacons, helping to resolve carrier phase integer ambiguities.

Despite the potential benefits of pseudolites, other problems are also introduced. A ground-based transmitter operating at L1 could easily be seen as a GPS jammer. Depending on the type of transmission scheme chosen, a receiver will have to take special precautions to deal appropriately with the pseudolite signal. If the pseudolites transmit relatively high power in a burst mode, a receiver will have to employ pulse blanking and have adequate dynamic range to handle the varying signal strengths.

3.1.7 GNSS System Performance

Navigation performance can be specified in terms of accuracy, integrity, continuity, and availability.

3.1.7.1 Accuracy

Accuracy is the degree of conformance between the measured position of a platform at a given time and its true position. System accuracy is usually given as a statistical measure of system error and is specified as:

- predictable (accuracy with respect to earth's geodetic coordinates)
- repeatable (accuracy with which position coordinates agree with a previous measure at the same location)
- relative (accuracy of one position solution with respect to another location's position solution, regardless of true position error).

Precision relates how well repeated measurements agree with themselves, whereas accuracy defines how well measurements agree with a reference, like truth. High precision implies a small variance (σ^2).

Vertical GPS accuracy is affected significantly by user latitude; it decreases rapidly above 60° latitude (for a user at the North or South Pole, no satellites are directly overhead). In

addition, vertical accuracy is always worse than horizontal accuracy because there are no satellites below the user (assuming the user is within the earth's atmosphere). Horizontal accuracy varies slightly as a function of latitude. GPS accuracy (especially vertical) is a function of user longitude due to ephemeris uploads that occur over the U.S. (satellite position error is a function of ephemeris age).

3.1.7.2 Integrity

Integrity is the ability of a navigation system to provide timely warnings to users if and when the system should not be used. It is the probability of an undetected failure of the specified accuracy – it is really "integrity of accuracy". Integrity can have three components: probability of HMI, time-to-alert, and alert limit. Integrity is gained through the use of monitors. Implicit in monitor performance is the missed detection and false detection (alert) probabilities. Long duration false alerts can negatively impact system continuity.

In the case of GPS, integrity can be achieved using several methods. Stand-alone receivers can employ Receiver Autonomous Integrity Monitor (RAIM), and augmentation systems may supply integrity independently. RAIM is possible if the solution is overdetermined -- algorithms compare satellite measurement residuals to detect satellite faults, and also to calculate integrity limits. In general, four satellite measurements are necessary to solve for 3D position and time (4 equations, 4 unknowns); a fifth measurement is necessary for RAIM to detect a failed satellite, and a sixth satellite measurement is necessary to exclude the failed satellite (and remove its measurements from the navigation solution). RAIM will detect a satellite failure independent of the failure dynamics (e.g. ramp, step, etc).

Augmenting the satellite measurements with other measurements, such as pressure-derived altitude can enhance the capability of RAIM, or (in the case of a ground vehicle) altitude obtained from a digital terrain elevation map combined with approximate horizontal position data.

3.1.7.3 Continuity

Continuity is the ability of a navigation system to perform its function without interruption during the intended operation. It is the probability that navigation performance will be maintained at the required level for the duration of a operation, assuming the system was available at the beginning of the operation. Since a system can provide accuracy and integrity independently, there is both "continuity of accuracy" (continuity of navigation) and "continuity of integrity" (continuity of fault detection). A third continuity that addresses accuracy and integrity together is "continuity of function" (COF) or "continuity of service".

3.1.7.4 Availability

Availability is the percentage of time that the system is to be used for navigation during which reliable information is presented to users. It is the percentage of time the necessary signals are available for use. It is "availability of integrity" or "availability of integrity of accuracy". It is also possible to define an "availability of accuracy" that may be useful if integrity is not a system priority. The integrity in "availability of integrity" can be refined to either detection or exclusion.

Availability of detection: the detection function is considered available when the satellite geometry allows the *missed alert* and *false alert* requirements to be met [*missed detection* and *false detection* are the two incorrect outcomes of the detection function]. The detection

function is considered available for a given operation when the integrity limit is less than the alert limit.

Availability of exclusion: the exclusion function is considered available when satellite geometry allows the *failed exclusion* requirement to be met, and prevent the indication of either a positioning failure or a loss of the integrity monitoring function. Also useful is "availability of detection after exclusion".

Coverage defining the service volume and service period are integral in the availability calculation. This applies to both the GPS satellite signals and the differential correction signals.

3.1.7.5 Acquisition times

A system integrator must be concerned with several different acquisition times.

3.1.7.5.1 Unaugmented GPS Time To First Fix (TTFF)

When first powered up, a receiver will acquire and track GPS satellites and generate a position fix. Assuming the receiver is out of the differential correction coverage area, this solution will provide about 10-20 m (2 drms) horizontal accuracy in an SA-off environment [this assumes 5-10 m (1σ) code measurement error, and an HDOP of 1.0]. To shorten the TTFF, a receiver can store its last known position, and assume that location at power up. For this to be useful, the receiver must also store the almanac in non-volatile memory, and it must have some source of time initialization (e.g. a real time clock with a battery back-up). With this time and position initialization, TTFF should be expected to be about 1-2 minutes (95%) with a generally unobstructed view of the sky.

3.1.7.5.2 Code differential TTFF

Many times at power up, a receiver will have code-based differential corrections available (e.g. WAAS, NDGPS). Applying these corrections will have little impact on the TTFF. The solution will have horizontal position accuracy of about 2 m (2 drms) [this assumes 1 m (1σ) code measurement error, and an HDOP of 1.0].

3.1.7.5.3 Initial carrier differential TTFF (initial ambiguity resolution time)

If available, the receiver will shrink the possible solution space by applying the code differential corrections. Assuming the receiver employs optimal techniques to the ambiguity resolution problem (e.g. wide-laning), the ambiguity resolution process will add an additional block of time that is tens of seconds to several minutes in duration, depending on conditions (e.g. number and orientation of tracked satellites, signal interference levels, etc). Resulting horizontal accuracy should be better than (less than) 10 cm (2 drms).

3.1.7.5.4 Ambiguity resolution after GPS outage

Statistically, ambiguity resolution time is a function of the position error that exists at the time the GPS measurements again become available. Position error grows as a function of time since the start of a GPS outage, and is highly dependent on inertial performance. If the position error has not grown beyond half a wavelength (9.5 cm for L1; 43 cm if wide-laning with L1 and L2), then the ambiguity resolution time will be nearly instantaneous once GPS is reacquired. If the position error has grown to a few wavelengths, the ambiguity resolution time should be just a few seconds. It is assumed that the receiver's code and carrier

tracking loops will not move significantly during a short duration outage, such that the acquisition of all satellites will occur immediately once the masking is over. It may be desirable for a system to use wide laning techniques to shorten the ambiguity resolution time, and then shift to L1-only operation to achieve increased accuracy.

It is important to note that receiver clock performance is a significant factor in the ambiguity resolution time following a GPS outage. Receiver clock bias is removed as part of the navigation solution, but the accuracy of the clock bias estimate will degrade over time during an outage. Clock stability will determine the rate of this accuracy degradation. Any error in the clock bias estimate will skew the initial guess of the integers, and therefore the size of the search space must be large enough to accommodate this error. Obviously, a larger search space results in a longer resolution time.

3.1.7.6 Interference

Susceptibility to interference is probably GPS' largest weakness. This susceptibility is due to the fact that the received signal power is extremely low – below the noise floor. The minimum received power is –130 dBm, which translates to 0.01% of a picoWatt. The fact that the signal is spread spectrum provides for some increased immunity to jamming and spoofing.

GPS interference is caused by both intentional and unintentional sources. Major unintentional interference sources include over-the-horizon (OTH) radar, television (the channel 23 video signal is broadcast such that its third harmonic is 525.25 MHz x 3 = 1575.75 MHz, which is only 330kHz away from the GPS L1 center frequency), and VHF broadcast such as taxi dispatch systems. Intentional interference (i.e. jamming or spoofing) could be caused by anything from simple pranksters to terrorists or unfriendly nations intending to disrupt the U.S. infrastructure. In general, jamming is a continuity risk, but not an integrity risk, unless spoofing is employed, which is a non-trivial undertaking.

If Continuous Wave Interference (CWI) is located on one of the PRN spectral lines, it is likely to interfere with tracking of that satellite.

L1 and L5 are within internationally protected frequency bands; L2 is not. Internationally, the International Telecommunication Union (ITU) manages spectrum through World Radio Conferences (WRCs). The UN has responsibility for the ITU. In the U.S., the NTIA (National Telecommunications and Information Administration) manages government allocated spectrum, and the Federal Communications Commission (FCC) manages commercial allocated spectrum.

There are technologies that will aid in interference rejection. A first line of defense, of course are RF bandpass filters on the receiver input, allowing only desired frequency content to pass unattenuated.

Deep integration with inertial systems provides additional help. Inertial data (e.g. velocities) can be fed into either the code tracking loop, or both the code and carrier tracking loops to allow narrowing of the tracking loop bandwidths, reducing the effects of interference by about 10 dB. Even deeper integration using correlator I's and Q's as inputs to the hybrid solution can provide an additional 6 dB or so of interference resistance.

Another technology that is effective in rejecting interference uses antenna arrays. Null-steering phased arrays allow antenna nulls to be "pointed" in the direction of a detected interference source, effectively decreasing the received noise power. It is also possible to point nulls at detected multipath sources, reducing measurement error. More difficult to implement is beam forming antenna arrays that allow beam lobes to be "pointed" towards

satellites, effectively increasing the received signal power. These technologies all require larger and more complex antenna arrays and replication of GPS receiver RF-section electronics. Cost impact is significant, but no other approaches can provide comparable levels of interference rejection capability (on the order of 40 to 60 dB).

3.1.7.7 Error sources

The error sources that are present in unaugmented GPS measurements can be summarized as follows:

- Satellite clock and ephemeris
- Ionosphere
- Troposphere
- Multipath
- Receiver noise

Prior to May 2000, the U.S. DOD added noise to the satellite signals such that the statistical error present in the navigation solution was inflated. This noise, termed Selective Availability (SA), was accomplished by two means. The ε-process manipulated satellite position in the ephemeris portion of the navigation data message. And τ-dither, also called the δ process, manipulated the satellite clock frequency. It is thought that the ε-process was used early in the life of GPS, but was later discontinued. SA was first turned on in March 1990, then turned off during the Gulf War and again during the 1994 Haiti occupation. SA was turned to zero at 0407 UTC on 2 May 2000. It is expected that SA will remain set to zero, but user equipment must continue to monitor its level to ensure integrity of the navigation solution.

When SA was on, civil GPS users experienced satellite clock and ephemeris errors of 23-33m (1σ). At the time of this writing, those error sources represent 2-3m of measurement error.

Civil industry knowledge of other error sources is somewhat limited because, until recently, the effects of SA masked those sources. The largest single remaining error contributor is the ionosphere. The GPS master control station monitors the ionosphere-induced group delay of the GPS signal. The delay is modeled for single frequency receivers using equation coefficients that are broadcast in the satellite navigation data message. Applying this model to pseudorange measurements removes about 50% of the ionospheric delay error. The remaining ionospheric measurement error is 6-10m, except during periods of high solar activity. At these times, solar coronal mass ejection's (CMEs) can cause single frequency measurements errors as high as 30m. Long term solar activity is cyclical with an eleven year period; the most recent peak occurred in 2000/2001. Iono-induced error is highest in the equatorial ($\pm 20°$ geomagnetic latitude) and auroral ($65° <$ geomagnetic latitude $< 75°$) regions; it peaks between sunset and local midnight. Using the ionospheric error corrections in the WAAS signal removes about 90% of the ionospheric delay error. Since the signal delay through the ionosphere is a function of frequency, dual frequency receivers can remove about 99% of the iono-induced error.

Ionospheric disturbances will typically change slowly with respect to time and location. One exception to that is ionospheric scintillation -- a rapidly fluctuating disturbance in the ionosphere. It focuses the satellite signal such that amplitude and phase variations in the signals may cause a receiver to lose lock on most satellites. An optical analogy to

ionospheric scintillation is the light and dark patches present at the bottom of a swimming pool when there are small waves on the surface.

Tropospheric delay can be modeled such that the residual measurement error is typically less than 1m (1σ).

Satellite and atmospheric errors are common mode for differential systems; their effects are almost completely removed by application of the corrections. Remaining are errors caused by effects that are seen differently by the user and reference (differential) receiver. As stated earlier, this is only multipath and receiver noise. It is important to design differential systems that reduce multipath and receiver noise. A well designed receiver can achieve receiver noise in the centimeter level. Multipath errors are caused by signal reflections, and are therefore installation dependent. Careful placement of reference station antennas is of the highest concern. Multipath rejection technologies are available for use in both reference station and mobile antennas.

There is some chance that civilian receivers will be able to utilize the GPS P(Y) code after the M-code has achieved full operational capability (FOC). Receiver thermal noise and multipath have ten times less effect with P-code because its data stream rate (10.23M chips/sec) is ten times higher than the C/A code. Cross correlation is not a concern when using the P-code.

Per the SPS Performance Standard, typical unaugmented SIS ranging errors are less than 2m rms when averaged over a one week period. Instantaneous total ranging errors are higher, of course. Because the sources are independent of each other, a statistical total ranging error can be found by RSS'ing the individual terms discussed above.

3.1.8 GPS Antenna

Many parameters must be evaluated when selecting GPS antennas. Among these are size and weight, cost, power needs and signal noise figure (for active antennas), environmental considerations (e.g. operating temperature and vibration range, weather-proofness), interference rejection, multipath mitigation, phase center variation, and signal compatibility (e.g. impedance, VSWR, polarization).

Multipath rejection can be achieved by surrounding the antenna with a ground plane, or a choke ring assembly. Other methods include employing antennas with low gain at negative elevation angles (e.g. phased arrays). Signal processing within the receiver can also reduce the impact of multipath on the measurements. Automotive applications requiring small-size and low-cost solutions may limit the selection to microstrip patch antennas. Some antenna manufacturers produce specialized patch antennas, and claim multipath rejection performance equivalent to choke rings.

The electrical phase center of an antenna (the physical three dimensional point where the range measurement is applicable) will move as a function of the incoming signal direction. This phase center variation is typically dependent on satellite elevation more than azimuth. Phase center variations of several centimeters are common, and this effect must be mitigated to achieve a high accuracy solution. If the variation is repeatable, a phase center offset table can be used when generating the line-of-sight vectors for the navigation solution.

If an antenna with an integral low noise amplifier is used, it is important that the noise figure is low (2-3 dB, including filter insertion loss). This will help ensure the signal-to-noise ratio does not fall below the sensitivity limit of the receiver when tracking or attempting to acquire low power satellites in the presence of interference.

3.2 Inertial Navigation Sensor

Honeywell is in the process of developing an integrated GPS inertial navigation system for the aviation marketplace. As part of that work integrated with this study, this analysis investigates two configurations of equipment: positioning hardware likely available in the near term (2004-2005), shown in Figure 3.2 and a second future configuration likely available in the mid term (2007-2008), described in Section 3.2.4 .

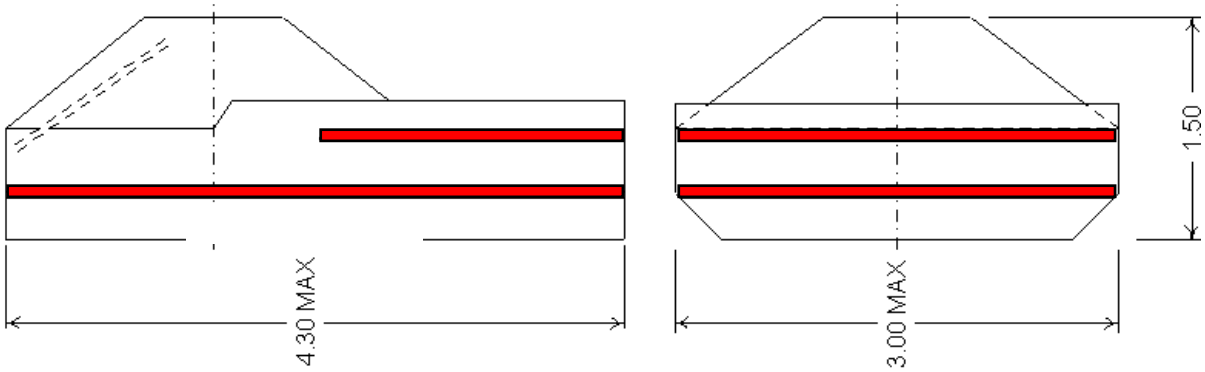


Figure 3.2 Positioning Sensor Unit

3.2.1 Inertial Sensor Mechanical Configuration

The Position Sensor Unit is comprised of two primary mechanical elements: an Inertial Sensor Assembly (ISA) shown in Figure 3.2.1 and the electronics module which contains the processor ASIC assembly and the I/O buffer assembly. The mechanical configuration of the Position Sensor Unit was previously shown in Figure 3.2 .

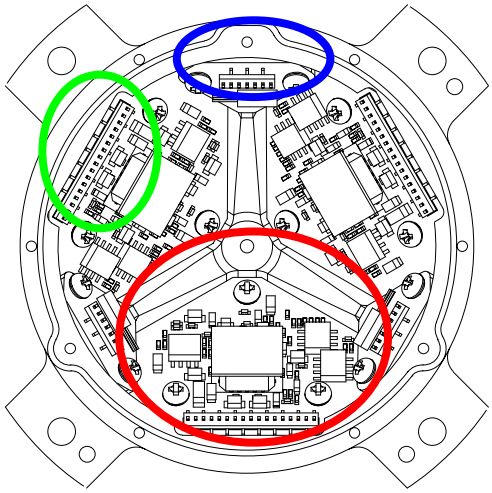


Figure 3.2.1 Position Sensor Inertial Sensor Assembly (ISA)

The mechanical configuration of the ISA provides a rigid orthogonal mount of the three gyros and accelerometers isolated from aircraft vibrations. This configuration was

developed for military munitions and has been demonstrated to withstand more than 500 g's without loss of performance. The ISA mounts to the processor ASIC assembly through the connectors located on each of the gyro and accelerometer assemblies.

The region of Figure 3.2.1 inside the lower red oval is a MEMS gyro assembly, the region inside the upper blue oval is a MEMS accelerometer assembly and the region inside the green oval on the left is a connector on one of the three gyro assemblies. The package shown is used on the Honeywell HG 2200 integrated position system demo equipment.

The selection of MEMS based inertial sensors is not key to the performance analysis of this report. It is possible to select any one of a number of sensors today to develop the system defined here. Included in the possibilities are cavity and fiber laser gyros, spinning mass gyros or quartz rotation sensors along with pendulous or vibrating beam accelerometers. It is the position of this paper that silicon sensors will have the lowest cost and highest reliability and performance in the mid and long term of the CAMP study (8 to 13 years).

The proposed hardware assemblies and system components analyzed in this study were based on MEMS sensors in both the gyro and accelerometers. Alternate sensors are feasible, however, the it is unlikely that the mature production cost of those alternate sensors will be lower cost than the MEMS type designs identified in this report due to the additional cost of manufacturing complex components (not developed in silicon). Some of the sensor technologies, which are inherently small like Quartz Rate Sensors (QRSs), could provide a nearly as low cost/almost as small alternate.

3.2.2 Electronic Architecture

The electronic architecture of the positioning sensor is shown in Figure 3.2.2. As shown in Figure 3.2.2, the positioning sensor includes a GPS receiver of the type required to obtain centimeter accuracy, inertial sensors required to maintain the navigation solution during an outage and interfaces to the automotive velocity sensor and power systems. It is certainly conceivable that this device could include the communications equipment and the required GPS and communications antennas as integral parts of the device.

3.2.2.1 Electronic Component Assumptions

The positioning sensor consists of an oscillator, a GPS receiver, a data link receiver, MEMS gyros and accelerometers, a processor, memory and power conditioning. Additionally, the device antennas could be made integral parts of the equipment.

The oscillator is a frequency source that drives both the GPS receiver and the microprocessor and digital electronics. The GPS receiver requires a fairly stable oscillator as compared to a microprocessor. Higher stability tends to increase cost and techniques at the system level such as double-difference, discussed in Section 3.1.2.2, will be used to minimize any increased cost. The assumed performance of the oscillator is listed in Table 4.3-2 .

The GPS receiver consists of an RF section and a GPS engine that has both code and carrier correlator functions. The GPS receiver includes a significant amount of software and includes a digital interface to the processor.

The technology is available today from a number of suppliers for the GPS receiver to be contained on a single chip. In fact, the technology exists today for the processor and digital

electronics to also be combined on that same chip. A single chip (or few chip) solution for the GPS and processor would lend itself to a low cost solution.

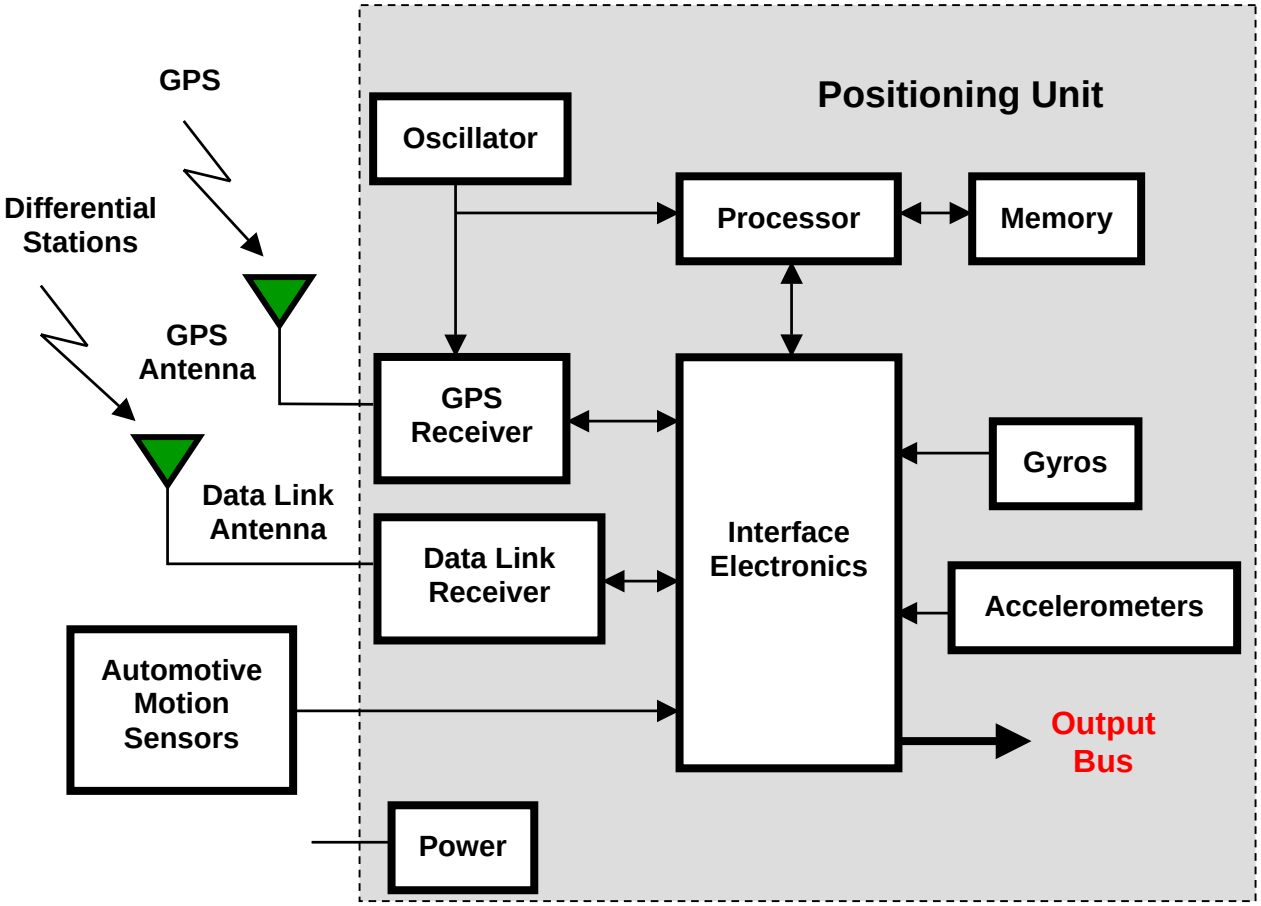


Figure 3.2.2 Positioning Sensor Electronic Architecture

Currently the Data Link receiver is a separate external radio, however, several benefits can be derived from incorporating the Data Link receiver into the Position Unit. First, it saves a processor and support electronics and therefore reduces cost. Second, it allows the fusion of various sensors and aiding sources into a single processor and single solution.

The MEMS gyros and accelerometers consist of a sensor mechanism on a silicon chip and an ASIC that electrically drives the mechanism and produces the measurement signal. Both the fabrication of the mechanisms and the ASIC have been designed for low cost.

The Positioning unit contains 6 inertial sensors, of which, three are gyros and three are accelerometers. Each of the gyros measures rotational rate about an input axis. Each of the 3 accelerometers measure linear acceleration in the direction of an input axis. The 6 inertial sensors must be configured such that they measure rotational rate and linear acceleration in three orthogonal directions in order to compute position in three dimensions.

The inertial sensors would be mounted on a single assembly in order to accomplish the lowest possible cost. The 6 sensors could be mounted on a single plane if the inertial

sensors were designed in configurations that measure motion in-plane and out-of-plane. Developments are under way at Honeywell of both in-plane and out-of-plane configurations.

An interface electronics section buffers digital data from sensors and aiding sources for use by the processor in the System solution. It also provides a serial output bus for users of the position information. An industry standard bus would be used. The interface electronics consists of digital cells in an ASIC.

The power section provides power conditioning and DC power conversion for the unique needs of the digital electronics and the inertial sensors. This hardware is minimal since the all of the components would be designed to run on 5 volts or less.

3.2.3 MEMS Sensors

3.2.3.1 Automotive Sensors Today

Inertial sensors today, which have achieved the cost and performance goals required for automotive applications, are generally used to measure acceleration or rotation rate directly. They are not integrated into systems that measure position. The accuracy of current gyros is in the neighborhood of 1°/sec (or 3600°/hour). The accuracy of current accelerometers is in the neighborhood of 200 mg.

In order to meet the goals of this study the inertial sensors must contribute 2-3 orders of magnitude less than current automotive sensors today.

3.2.3.2 Factory Calibration

One of the methods employed to reduce sensor errors is factory calibration. Factory calibration involves tilting and spinning the sensors at known rates, reading the measured values from the sensors and then computing (calibrating) the measured sensor errors. This procedure is then repeated at different temperatures. With many sensors a factor of 10-20 improvement can be achieved through factory calibration because most sensors have large temperature sensitivities.

Factory calibration also takes care of errors associated with the mis-alignment of the sensors input axis to the expected input axis. The expected input axis of the sensor is usually determined by its mounting position.

Factory calibration involves capitol equipment, test time and engineering support, which is costly. To achieve the cost goals of this study factory calibration would have to be avoided or at least minimized to seconds of test time.

3.2.3.3 In-Vehicle System Calibration

Systems, which integrate GPS with inertial sensors, can continuously calibrate inertial sensor errors. High accuracy GPS can calibrate these sensor errors to a high degree and do it very quickly. This is discussed in detail in the System Analysis section but is also broached here because the system determines which sensor errors are of interest.

The Tables 3.2.3.3-1 and 3.2.3.3-2 illustrate how some initial sensor errors, which may be quite large, can be calibrated by the System. These sensor errors are therefore of less interest than other sensor errors. Table 3.2.3.3-1 depicts a set of initial sensor errors. Fairly large values have been chosen to represent sensors that have had minimal or no factory

calibration. These sensor errors would exist only when there has been no System calibration in the vehicle as well. This analysis shows that the in-vehicle calibration improves the sensor performance by orders of magnitude.

Table 3.2.3.3-1 Uncalibrated Sensor Errors

Parameter	Value 1σ	Units
Gyros		
Initial Bias	1,000	deg/hr
Initial Scale Factor	10,000	ppm
Initial Misalignment	3,000	arc sec
Accelerometers		
Initial Bias	80	mg
Initial Scale Factor	20,000	ppm
Initial Misalignment	2,400	arc sec

The impact of In-Vehicle System calibration has been analyzed and the results are depicted in Table 3.2.3.3-2 . The In-Vehicle System calibration occurs during the pre-scenario calibration phase described in the Scenario discussion above. Table 3.2.3.3-2 illustrates how these initial errors are calibrated during the pre-scenario calibration phase.

Table 3.2.3.3-2 Post Calibration Sensor Errors

Parameter	Value 1σ	Units
Gyros		
Initial Bias	5	deg/hr
Initial Scale Factor	1000	ppm
Initial Misalignment	100	arc sec
Accelerometers		
Initial Bias	4	mg
Initial Scale Factor	1000	ppm
Initial Misalignment	440	arc sec

Additionally, some of the post-calibration errors are offsetting and therefore do not have the impact on the system performance that would be suggested by the individual values listed in the table. For example, the accelerometer bias and the accelerometer misalignment errors are offsetting errors in most conditions.

The details of the analysis for the In-Vehicle calibration are in the system analysis section. There is a lot of background on the system design that should be read prior to understanding these results however they are tabulated here to drive the focus of our attention away from the raw initial sensor errors and toward the short term sensor errors.

3.2.3.4 Honeywell MEMS Sensors

Honeywell is an industry leader in the tactical, navigation and precision segments of inertial products for the aerospace market. This success is primarily due to the high quality and reliability of Honeywell inertial sensors. Honeywell is also a leader in inertial system design. The mature and highly reliable Ring Laser Gyros (RLGs) have been offered in numerous products in volume production since the early 1980's.

Honeywell's strategy has been to maintain this leadership position in the inertial marketplace that is characterized increasingly by smaller size, lower weight, lower power, and lower cost. Honeywell has, therefore, augmented its existing sensor technology with silicon MEMS inertial technology to meet these emerging market requirements.

3.2.3.4.1 MEMS Gyro Technology Acquisition

Honeywell performed an extensive worldwide assessment of MEMS technologies in 1998, including reviews of MEMS capability at ten leading companies and laboratories. This assessment led to the conclusion that the spectacular demonstrated performance, and proposed performance enhancement approach, that was achieved by Boeing North American in partnership with Draper Laboratory, offered the best combination of gyro performance, maturity and cost.

Honeywell acquired this technology from Boeing in 1999 and immediately commenced a high priority program to transfer the technology to Honeywell. The MEMS technology acquisition was extensive. It included all intellectual property, designs, processes, and trade secrets relating to the MEMS sensors that have been developed under the license agreement between Draper Laboratory and Boeing.

In addition, Honeywell has also acquired the Draper Laboratory license agreement with all its rights including those to intellectual property developed by Draper previous to the agreement with Boeing. This agreement links Draper Laboratory and Honeywell together with complementary roles of advanced technology development and product development/production, respectively.

The Honeywell MEMS gyro, shown in Figure 3.2.3.4.1, is based on the Coriolis force. The resonant structure is composed of two elements, called proof masses, driven electrostatically in a plane in opposite oscillatory directions. When the device is rotated about the sensitive axis, the elements are driven to oscillate out of their original plane of motion by an amount proportional to the product of the input rotational rate and the oscillatory drive velocity. Measurements of the mass deflection allow the determination of the rotation rate. This is not new physics; macroscopic tuning fork gyroscopes have been used for many years and are well understood.

Further developments at Honeywell over the last 3 years have achieved truly impressive results. Commitment and investment in the Honeywell MEMS gyro remain at a high level and interest from customers has extended well beyond the traditional Aerospace market.

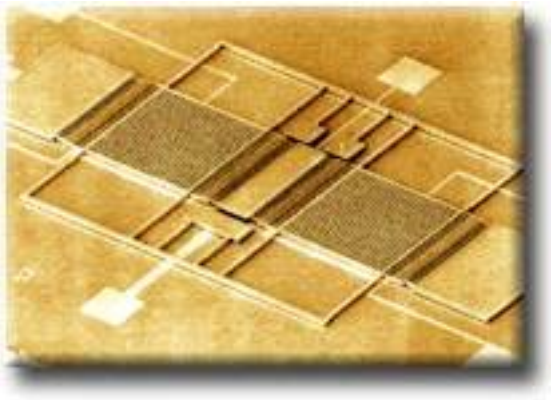


Figure 3.2.3.4.1 Honeywell MEMS Gyro

3.2.3.4.2 Gyro Manufacturing Process

The micro-machined mechanisms are fabricated using a dissolved wafer process, depicted in Figure 3.2.3.4.2 . The critical dimensions are controlled with boron diffusion and dry etch techniques. The silicon wafer is anodically (thermal electrically) bonded to a glass substrate that has been prepared with a metal deposition step to provide all the electrical contacts for the sensor operation. After the unwanted silicon is dissolved away the mechanism is free to operate. This allows for wafer level probing to map all the mechanisms on a wafer in a single automated process. After mapping, the wafer is diced and the individual mechanisms are vacuum packaged and ready for integration with the sensor electronics.

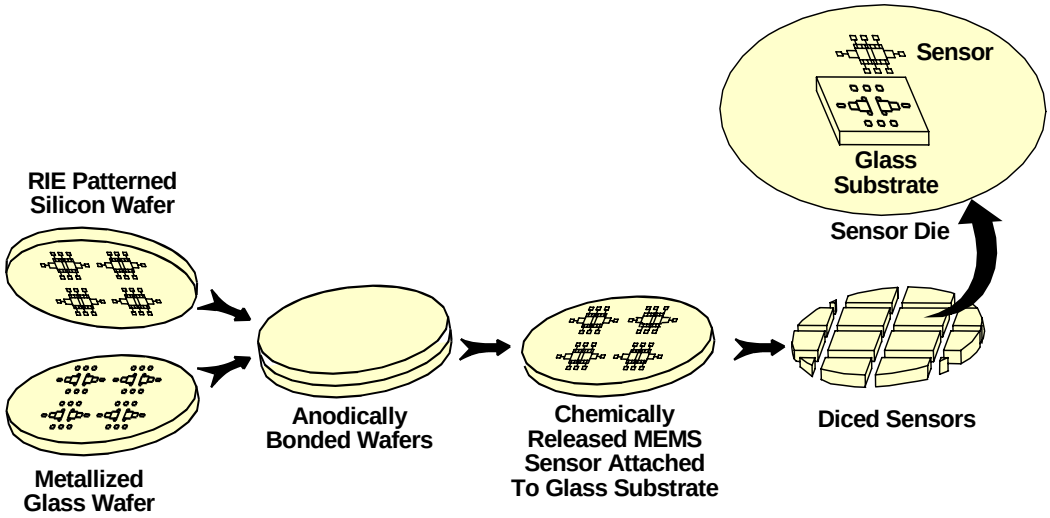


Figure 3.2.3.4.2 Wafer Level Automotive Gyro Fabrication

The simplicity of this fabrication process makes it possible to build the mechanisms on high volume, low cost MEMS silicon lines. Honeywell has produced nearly 90,000 die up to this time as a part of their mechanism design, silicon process development and product demonstrations.

3.2.3.4.3 Honeywell MEMS Accelerometers

Prior to the MEMS technology acquisition, Honeywell had already begun developing a MEMS accelerometer. The Honeywell MEMS accelerometer senses linear acceleration and outputs a digital signal proportional to that acceleration. The Honeywell MEMS accelerometer is in production today for Tactical markets.

The Honeywell MEMS accelerometer is mechanized in the Double Ended Tuning Fork (DETF) configuration. The DETF vibrates like a piano wire when clamped at both ends. An unloaded DETF will oscillate at a fundamental frequency. Extension, or tension, causes an increase in frequency while relaxation, or compression causes a decrease in frequency. The DETF is attached to a mass that is susceptible to gravity or acceleration. The DETF frequency of oscillation is proportional to the applied acceleration.

In addition, new MEMS accelerometer developments are under way in conjunction with the MEMS gyro developments.

3.2.3.4.4 MEMS Levels of Performance

For purposes of this study Honeywell has identified 3 levels of inertial sensor performance. These 3 levels of performance represent 3 generations of sensor development. We have chosen the nomenclature of MEMS-1, MEMS-2 and MEMS-3 to represent these 3 levels of performance. MEMS-1 comes earlier in time than MEMS-2 or MEMS-3.

The following table identifies an error budget for the 3 levels of MEMS sensor performance. Only the short-term errors are of interest at this point since the System has been able to calibrate other sensor errors as explained in the In-Vehicle System Calibration section above.

Table 3.2.3.4.3 Short Term Sensor Error Budgets

Parameter	MEMS-1 (1σ)	MEMS-2 (1σ)	MEMS-3 (1σ)	Units
Gyros				
Bias Stability	10.0	3.0	0.3	deg/hr/root-hr
Bias G-sensitivity	3.0	0.5	0.2	deg/hr/g
Scale Factor Stability	175	50	25	ppm/root-hr
Misalignment Residual	75	50	20	arc sec
Noise (Angular Random Walk)	0.20	0.10	0.05	deg/root-hr
Accelerometers				
Bias Stability	0.20	0.15	0.08	mg/root-hr
Scale Factor Stability	150	75	25	ppm/root-hr
Scale Factor G-sensitivity	10	10	10	ppm/g
Misalignment Residual	60	30	10	arc sec
Noise (Velocity Random Walk)	0.40	0.15	0.10	ft/sec/root-hr

There is a certain art to developing an error budget and understanding the terms. One element that is not progressing as well can sometimes be traded off for another that is doing better. These budgets may change somewhat over time. The way that the elements are tested and analyzed may also change. The units may also change to be more understandable by parties that are involved. For purposes of this study, the important thing is the overall level of performance and its impact on the System.

3.2.3.4.5 Current Honeywell MEMS Performance

MEMS-1 performance represents an error budget that has largely been achieved in the laboratory in 2001. Some progress towards MEMS-2 has also been made in the lab. The following figures are given as evidence and examples of this performance.

Figure 3.2.3.4.4-1 shows gyro bias stability over a 3 hour time period. In order to observe bias stability the data must be averaged over 5 minute periods so that the data is not dominated by the noise. This data is of a single gyro as an example. The data was taken at a constant temperature because we are really concerned with bias stability over a much shorter period of time, such as 30 seconds, and that leaves little time for temperature fluctuations. Three hours of data give a larger sample bias stability data.

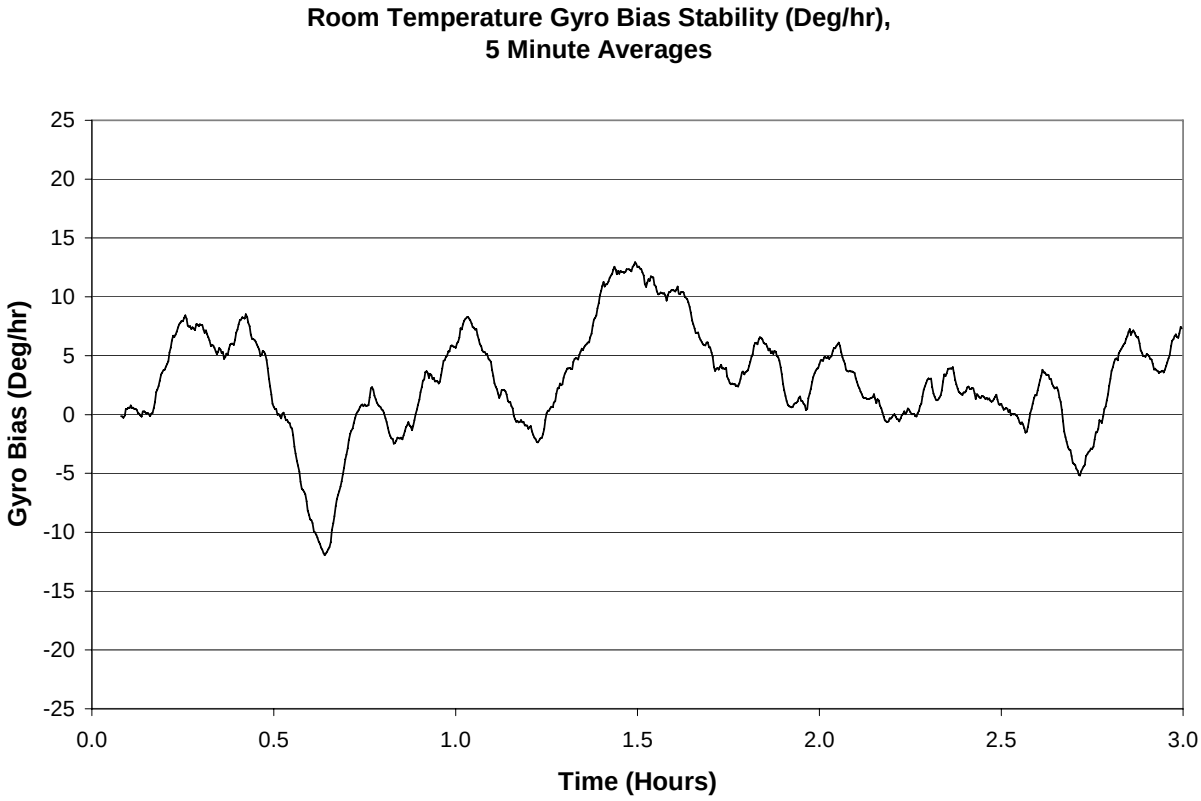


Figure 3.2.3.4.4-1 Gyro Bias Stability

Figure 3.2.3.4.4-2 shows gyro noise over a 1 hour time period. In order to observe the noise the data is sampled at 12 second intervals. At 12 second intervals the gyro noise is fairly obvious, however, some bias stability can also be seen. In Table 3.2.3.4.3, gyro noise is expressed as Angular Random Walk (ARW) so we have included the RMS equivalent of ARW on this graph for comparison purposes. The noise is essentially the envelope of the width indicated around the bias, which moves gradually up, down and up again across the graph.

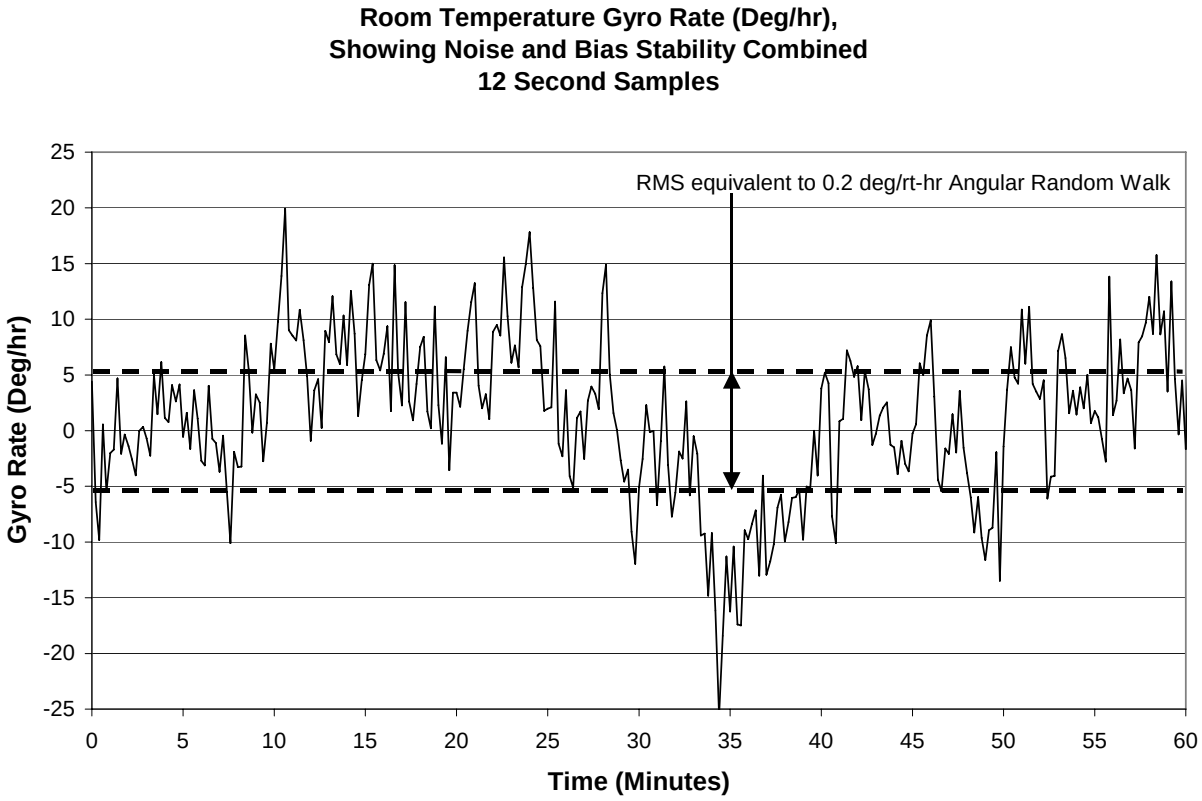


Figure 3.2.3.4.4-2 Gyro Noise

3.2.3.4.6 MEMS Performance Trends

Figure 3.2.3.4.5 depicts an estimate of MEMS inertial sensor performance trend over time. The X-axis is calendar years with the tick mark representing the beginning of the year. The Y-axis is a composite measure of performance that includes all of the elements in the 3 levels of MEMS performance from the table. The Y-axis is on a logarithmic scale and the tick marks are approximately an order of magnitude of performance.

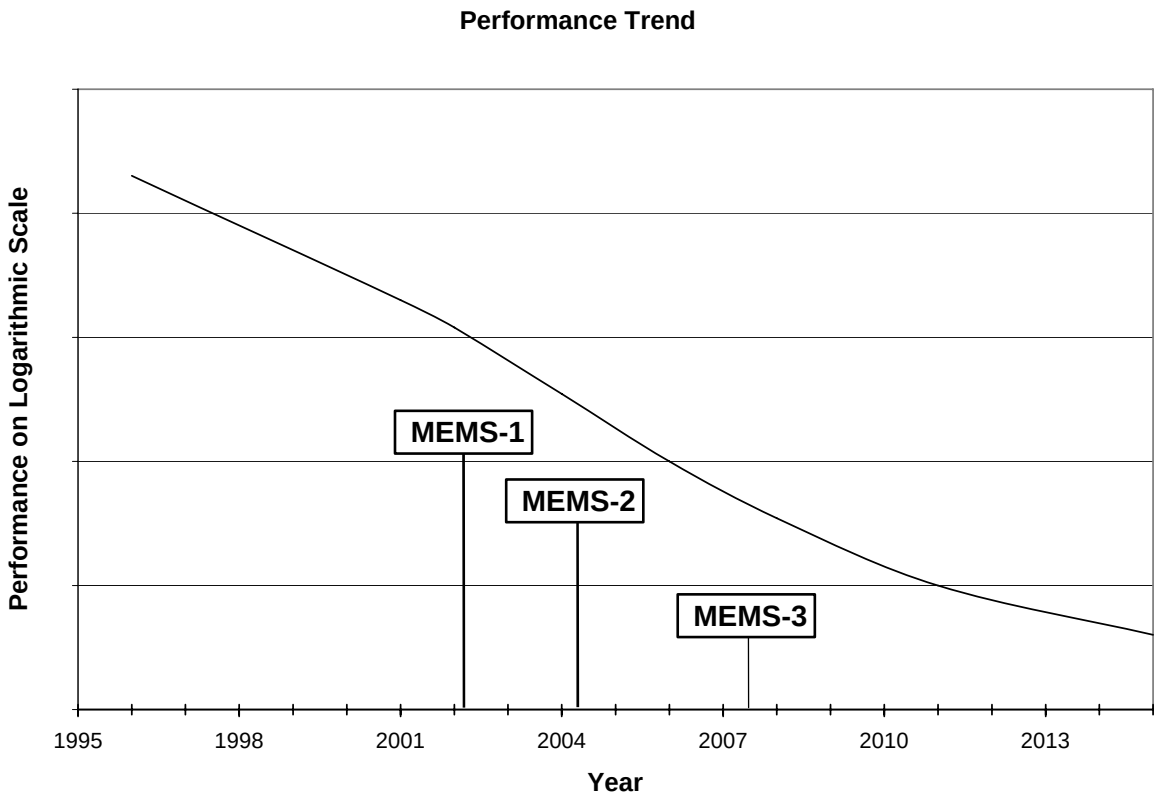


Figure 3.2.3.4.5 MEMS Inertial Sensor Performance Trend

The MEMS-1, MEMS-2 and MEMS-3 blocks indicate when the level of performance is achieved on a consistent basis in the laboratory. Bringing this level of performance to production in a cost effective way can be a formidable task that would be expected to take at least 2 years and may, under some circumstances, take as much as 5 years.

3.2.4 Future Positioning Equipment

Clearly the objective of this study is to determine when a device suitable for the high volume automotive market would be available. As presented in Sections 3.2.1 and 3.2.2, positioning systems could be made to nearly meet the design requirements for the automotive industry today (2002), however, they would not meet the volume availability and cost requirements. The key benefit to the approach taken in this study is that the position sensor is comprised of “chips”, “housing”, “antennas” and “connectors”. Devices, which can be described this way, can generally be developed to be “low cost”, “high reliability” and “high volume” when the manufacturers can see significant volume and the technology crosses a feasibility point.

For this technology that point is approximately 2 to 3 years away or 2005. Stable designs will exist with the key performance features desired by the automotive industry. Following the initial implementation additional technology breakthroughs will occur like the integration of multiple sensor axis into a single chip for the gyros and accelerometers, development of

single ASICs which combine processors, memory and sensor electronics, new power considerations and reliability enhancements. By 2008 products similar to that shown in Figure 3.2.3.1 could be available assuming a significant market develops. These products would integrate GPS, communications, inertial, processing and interface components and the required antennas.

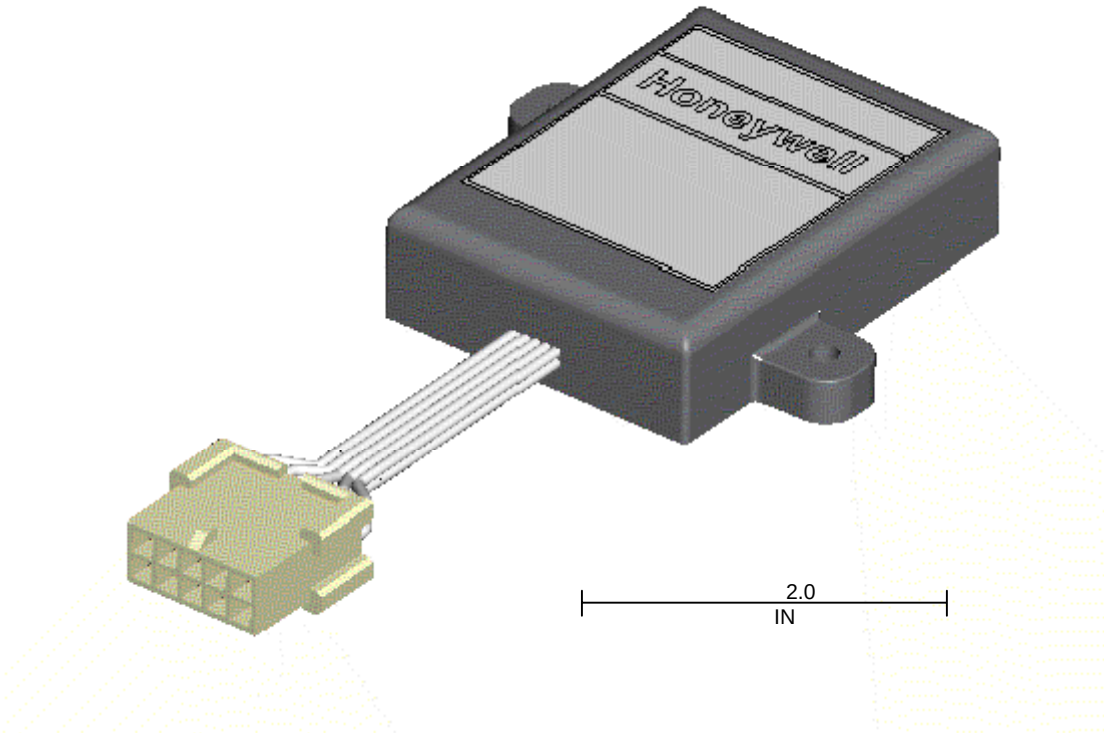


Figure 3.2.3.1 Future Position Sensor

3.2.4.1 Equipment Availability

For the purpose of this study, Honeywell has assumed that a capable technology can be productized and qualified in 30 months following the finalization of industry requirements.

3.2.5 Exportability

Inertial navigation systems (INS) have for many years been closely controlled by export regulations, both in the United States and in the majority of countries with the technical capability to produce them, because of their clear application to weapons system development. Within the United States, these controls range from US State Department International Traffic in Arms Regulations (ITAR) control to Department of Commerce Export Administration Regulations (EAR) control for commercial end items. ITAR controls apply to certain specially defined technologies and for those items, which were either specifically designed for use in military applications or funded by the US government with ITAR restrictions applied. Very similarly controls exist for navigation systems within thirty–two other countries who have signed onto the Wassenaar Arrangement, which is concerned with

technology which could be used in weapons development, and by the 28 countries in the Missile Technology Control Regime. Between these two international agreements, navigation systems and related sensor technology is controlled for the most active countries in automotive production including France, Japan, Great Britain, South Korea and Germany.

Up to now, inertial navigation systems has been relatively large, expensive and difficult to produce. Military and airborne applications, due to their specific needs and ability to afford INS, have not had a problem with these limitations. The advent of GNS made accurate position determination both affordable and common, and made possible the combining of relatively low grade inertial sensors with the GNS solution to yield a robust navigation grade product. MEMS and other solid state sensors are becoming commonly available and will allow the affordability to enter into new markets.

Once commonly applied in consumer applications, MEMS based inertial systems as described in this paper will become too numerous to prevent diversion of individual units to weapons systems. For that reason, the US Government in consultation with industry and experts in the field, are determining what specific parameters are appropriate to control in order to prevent missile development, tactical and armament related applications from being successfully generated from the low cost inertial systems described here. The ability to successfully control this technology against those threats will rely on cooperation from key partner countries, which are engaged in development or will be in coming years.

3.3 Digital Maps

Digital roadway maps providing coverage of the U.S. are available from sources such as Navigation Technologies and Tele Atlas. These maps, actually computer data bases, can be expected to provide 10-12m accuracy for major metropolitan areas, and 50m accuracy for outlying areas.

It would likely be technically and fiscally efficient to use a third party to provide the link between the map supplier and database storage hardware. Companies such as Telcontar are able to apply compression algorithms to the database file and format the output to be compatible with specific receiver hardware. A file providing maximum resolution for the entire U.S. would likely be hundreds of megabytes in size, so a system integrator may chose to limit the size of the area that is represented with the highest resolution data.

Applications such as lane-keeping would, of course, require much higher fidelity maps. No known commercial source of this type of data exists at the time of this writing.

Map matching is a technique that has been utilized in a number of land navigation applications. The basic concept is that the inertial system registers (via its attitude matrix, velocity vector, and position vector) a description of the vehicle trajectory. When the trajectory derived from the inertial solution is correlated with possible trajectories defined by a digital map, periodic corrections to the inertial solution are possible. However, a number of important limitations are inherent in the map-matching concept.

First, the trajectory taken by the vehicle generally has significant variations relative to the centerline of the road (for example, lane changes or normally encountered “lane wandering”). These trajectories require a fairly long correlation window for effective correlation of the vehicle trajectory and the digital-map-derived road, which limits the accuracy of the position fixes provided by the map-matching technique.

A second major factor that limits accuracy of the position fixes available from map-matching techniques is the distinctiveness of the vehicle trajectory over the correlation window. Clearly, events such as 90-degree turns, would produce the most accurate position fix, since

the ability to correlate this type of event with a possible map feature of the same type would be excellent. However, such events are relatively infrequent and, more typically, there is a much less distinctiveness in the trajectory over a given correlation window.

Still another factor that limits the accuracy of the available position fixes is inherent in the resolution of the map data itself. Since it is necessary to limit the number of data points used to represent successive segments of a road, a basic limitation will be imposed on the achievable accuracy for a given correlation window size. Generally, for the accuracy of vehicle positioning desired in the present application, map-matching techniques do not appear to offer a viable approach to improving performance.

A second application of map matching is to derive vehicle altitude from the map data base; that is, given the vehicle 2-dimensional horizontal position derived from the inertial navigation solution, altitude becomes the dependent variable. This does not involve correlation techniques, as defined above, but has similar limitations affecting accuracy. Here also, for the accuracy of vehicle positioning desired, the use of a digital map to derive altitude does not appear to offer a viable approach to improving performance. (Positioning accuracy in both the horizontal and vertical directions are discussed in detail in Section 4).

3.4 Equipment Cost

The Position Sensor defined in this study has already been implemented as a federated prototype. The concept is that of a simple silicon device. In addition, calibration (required on existing equipment today - 2002) should be eliminated with the inclusion of a "full time" GPS receiver as part of the system. As a consequence of this approach, the cost of the equipment is primarily a function of manufacturing volume, equipment capitalization and development cost.

While the production volume remains low (< 100,000 devices/year) the product cost will remain high. When the production volumes become significant (> 1,000,000 pieces/year) the cost of the position sensor will become compatible with the automotive market.

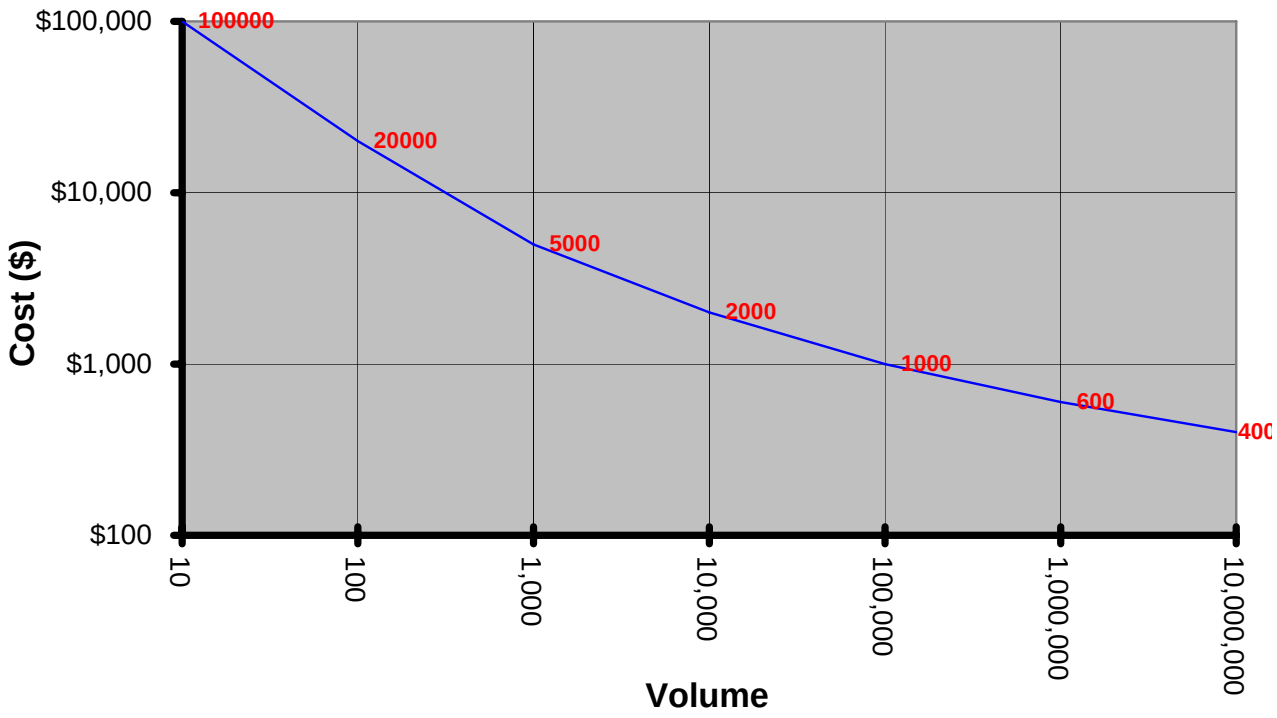


Figure 3.4 Position Sensor Cost/Volume Curve

4 System Design and Analysis

This study focuses on the ability of a low cost inertial system to augment a survey quality DGPS system for numerous automotive applications. The study analyzes specifically high performance requirements which are the most difficult to satisfy like lane keeping. Lower performing positioning solutions could be developed using the same concept of augmenting the inertial solution with a lower accuracy GPS solution and the results would be scaleable to these (the position solution would degrade slowly over a short period of GPS outage).

The study considers four mechanization concepts, all of which assume differential carrier phase GPS aiding. No specific requirement exists in this analysis for dual frequency DGPS equipment, although it is the expectation that the automotive industry will maintain a fairly high quality GPS technology and will include dual frequency system as soon as they become cost effective. The four mechanization concepts are summarized as follows:

4.1 Navigation System Mechanization Concepts

GPS-Aided Position/Attitude Reference System – This is a conventional strapdown inertial navigation system implemented with a triad of strapdown gyros, and a triad of strapdown accelerometers. This configuration, denoted “Mechanization 1”, is depicted in Figure 4.1-1.

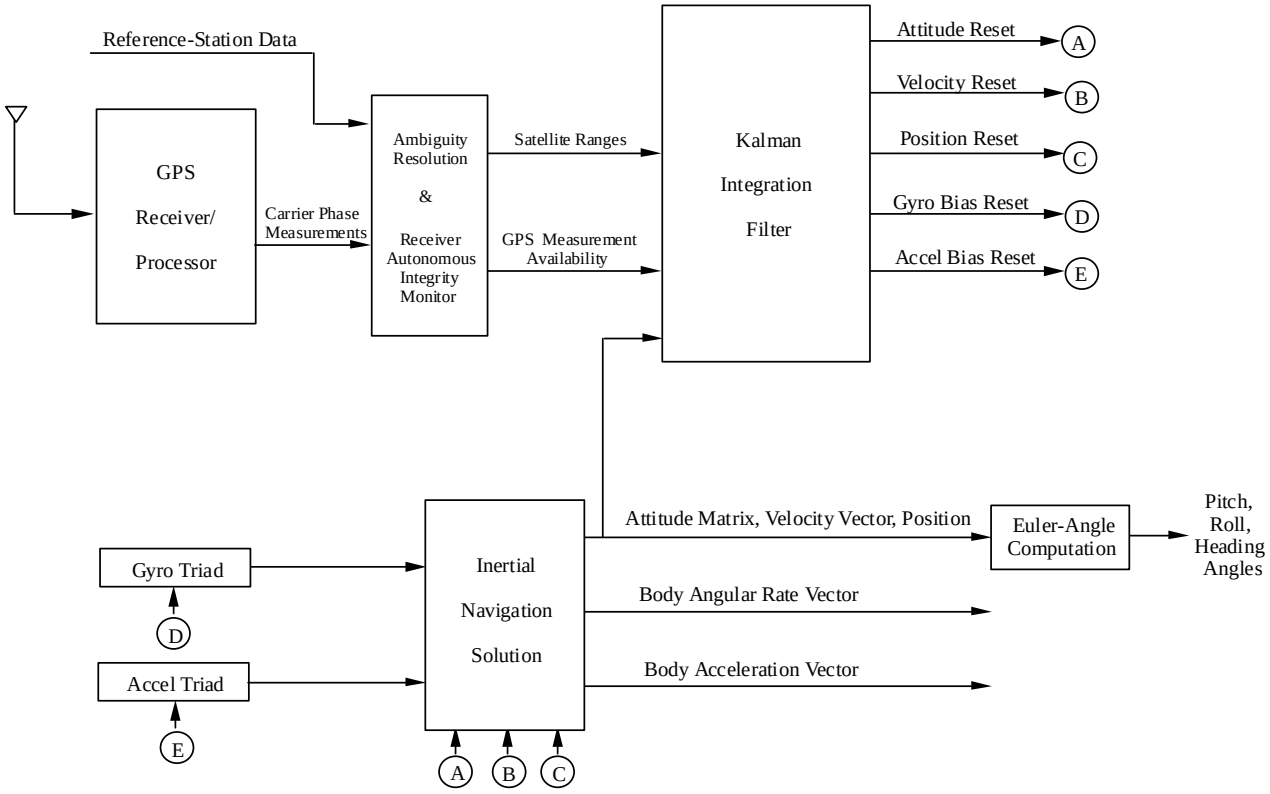


Figure 4.1-1 System Mechanization 1

GPS-Aided Position/Attitude Reference System With Zero Sideslip and Upslip Constraints – This is a conventional strapdown inertial navigation system implemented with a triad of strapdown gyros, and a triad of strapdown accelerometers, and using the two (nominally zero) velocity components computed normal to the vehicle body frame as an aiding source. This configuration, denoted “Mechanization 2”, is depicted in Figure 4.1-2.

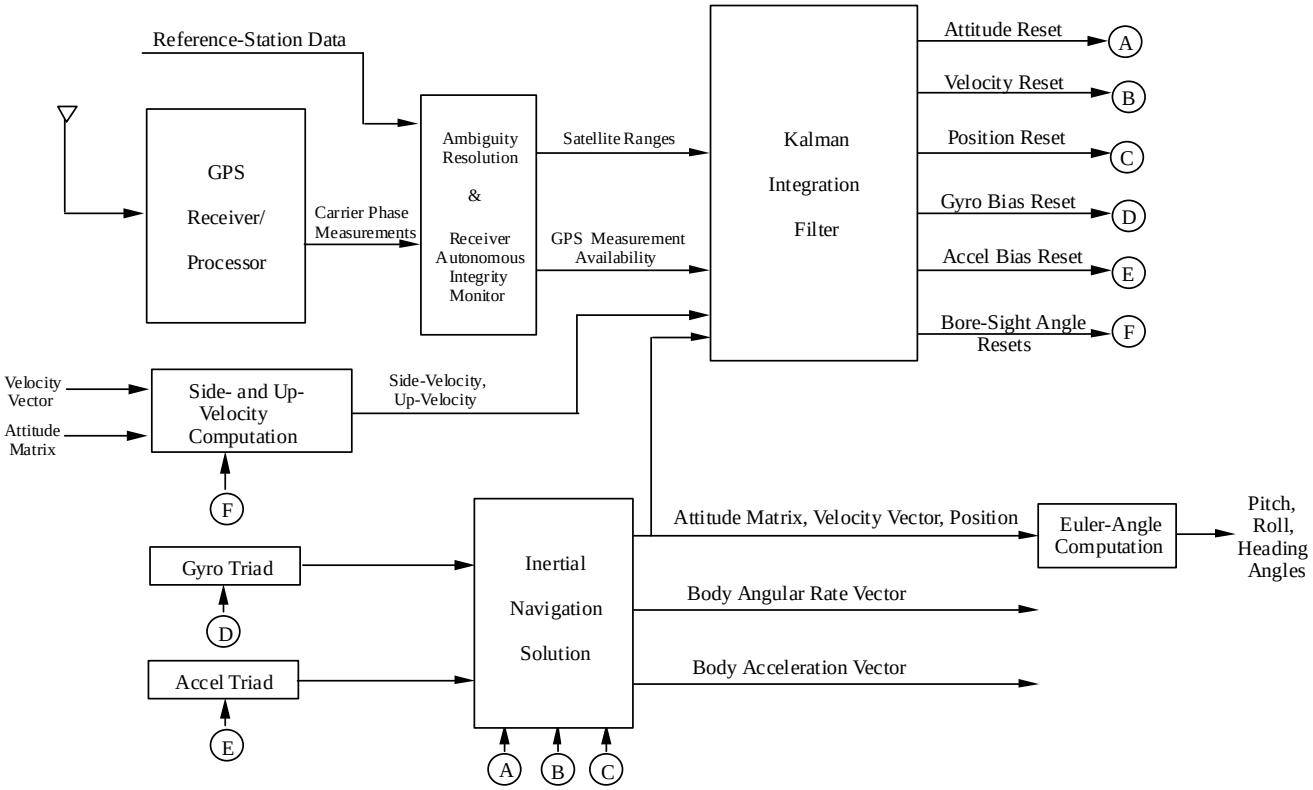


Figure 4.1-2 System Mechanization 2

GPS-Aided Position/Attitude Reference System With Use of Dead Reckoned Position – This is a conventional strapdown inertial navigation system implemented with a triad of strapdown gyros, and a triad of strapdown accelerometers, with the use of a 3-dimensional dead-reckoned position vector as an aiding source. This configuration, denoted "Mechanization 3", is depicted in Figure 4.1-3.

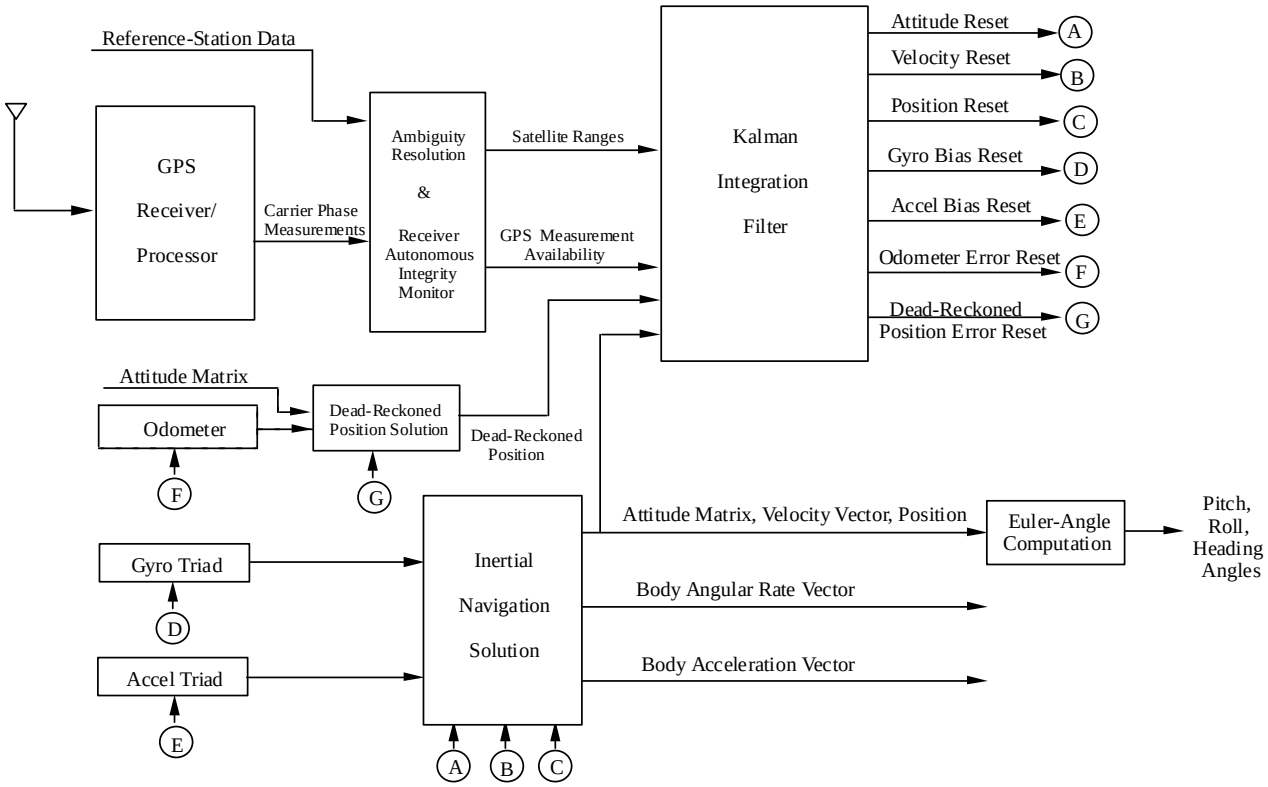


Figure 4.1-3 System Mechanization 3

GPS-Aided Dead-Reckoning System – This is a configuration of three inertial sensors, and an odometer measurement. The inertial sensor triad can consist of either a set of three strapdown gyros, or a strapdown triad consisting of two nominally level accelerometers and a heading gyro. The latter configuration provides a means of obtaining the vehicle attitude matrix when the accelerometer measurements are compensated by odometer-derived corrections for vehicle non-gravitational acceleration. This configuration, denoted "Mechanization 4", is depicted in Figure 4.1-4.

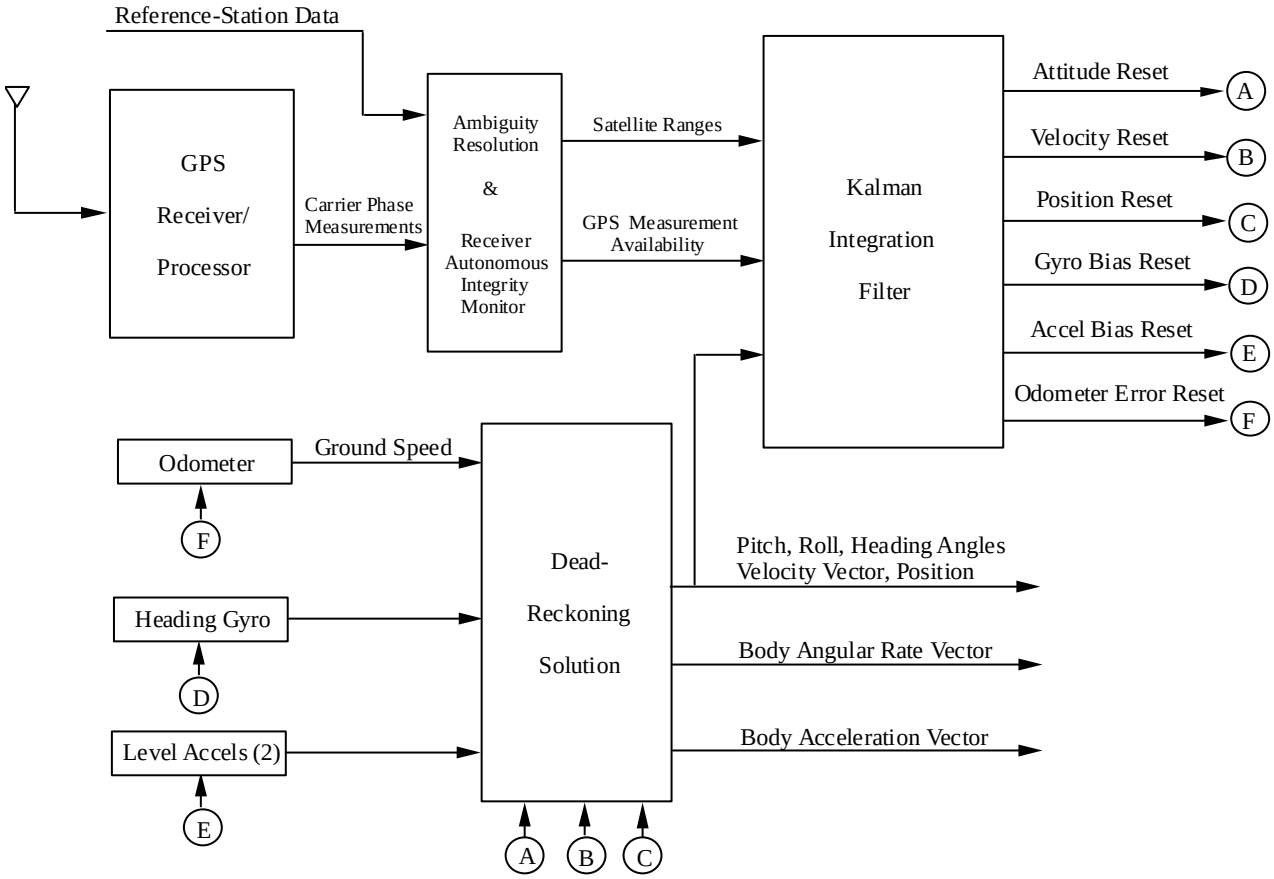


Figure 4.1-4 System Mechanization 4

All four mechanization concepts assume the use of a Kalman Filter approach as the means of integrating the information from the navigation system and the aiding sources. Each of the mechanization concepts also assumes the availability of a signal from a reference station that allows a differential carrier-phase capability.

4.2 Performance Evaluation Methodology

An assessment of the performance associated with each of the four mechanization concepts assumed in the study makes use of the following:

Error Analysis Capability – The error analysis approach commonly utilized in evaluating the performance of an integrated navigation system is via linear error covariance analysis techniques. Such a technique is described in Appendix C. The approach is based on the

use of linear error models for the navigation system, the sensors, and the measurements. The methodology also requires the use of a trajectory generator that provides the vehicle kinematic state required to define the coefficients of the linear error model differential equations. The present study takes advantage of mature tools available at Honeywell in carrying out this aspect of the study.

System Error Budget – The error analysis assumes that an error budget applicable to each of the major system elements (sensors, aiding devices) in the integrated system is available. The error budgets utilized in the present study are provided in the following subsection of the report.

Scenarios – The performance evaluation assumes that a specific set of scenarios is defined that, even though limited in scope, adequately defines the performance of the system for the various system configurations considered. In the present study, four such scenarios are defined – each of which utilizes its own trajectory, and considers a uniquely specified use of GPS and odometer aiding. The vehicle trajectory and the four scenarios are discussed in detail in a subsequent section of the report.

The results of the performance analysis allow comparison of the various mechanization options over a set of inertial sensor error budgets for the selected scenarios. This leads to an assessment of the ability of different levels of sensor performance (associated with three generations of MEMS technology) to satisfy the desired accuracy objectives for the system.

4.3 Error Budgets

The error budget for the MEMS inertial sensors are shown in Table 4.3-1. Projected error budgets for three generations of MEMS sensors (designated “MEMS-1”, “MEMS-2” and “MEMS-3”) are defined in the table. The sensor errors given in the Table are the principal one associated with MEMS sensors, and are all associated with linear error mechanisms. However, other error mechanisms of a nonlinear nature also exist (such as scale factor nonlinearly and asymmetry). However, it is beyond the scope of the present work to evaluate the effect of these additional nonlinear error mechanisms on system performance.

Table 4.3-1 MEMS Inertial Error Budget

		MEMS-1	MEMS-2	MEMS-3
1 – sigma gyro errors	bias (deg/hr)	25	7.5	.50
	Bias stability (deg/hr/hr ^{½})	10	3	.25
	Scale factor (ppm)	250	125	50
	Scale factor stability (ppm /hr ^{½})	175	50	25
	Non-orthogonality (arc sec)	75	50	20
	Random walk (deg/hr ^{½})	.20	.10	.05
	Bias g-sensitivity (deg/hr/g)	3	.50	.20
1 – sigma accelerometer	Bias (micro-g)	3000	1500	350
	Bias stability (micro-g/hr/hr ^{½})	200	150	75
	Scale factor (ppm)	500	250	100
	Scale factor stability (ppm/hr ^{½})	150	75	25
	Non-orthogonality (arc sec)	60	30	10
	Misalignment (arc sec)	60	30	10
	Random walk (ft/sec/hr ^{½})	.40	.15	.10
	Scale factor g-sensitivity (ppm/g)	10	10	10

A second category of errors is that associated with the aiding devices (GPS, Odometer, Zero-Slip Constraints). The error budgets, assumed for the aiding devices, are defined in Table 4.3-2. The GPS error parameters assume that the carrier-phase ambiguities have been resolved prior to the time the performance of the system is being evaluated. It is also assumed that other potential GPS error mechanisms (such as the offset between the antenna and the inertial system) may be compensated using available sensor and offset information, together with the appropriate compensation model. The odometer errors are predicated on what would nominally be achievable in state-of-the art systems. The 1σ value assigned to the odometer "slippage/undulation" error parameter (see also Appendix D) is a reflection more of what is considered reasonable, rather than on experimental data. This error mechanism is dependent on the condition of the road surface (wet or dry), the condition of the tires, the number of wheels instrumented, the geometry of the road surface (localized along-track and cross-track undulations), and the vehicle dynamics. All of these contribute in a very complex way to the error in odometer-derived distance traveled. Lacking theoretical or experimental models, the study makes what is considered a reasonable assumption regarding the 1σ value assigned to this error parameter.

Table 4.3-2 Aiding Device Error Budget

Aiding Device Error	Value 1σ	Correlation Time
GPS Random Range Measurement Error	2 cm	
GPS Clock Frequency Random-Walk Error*	0.25 meter/sec/ sec $^{1/2}$	
GPS Clock Phase Random-Walk Error*	0.25 meter/sec $^{1/2}$	
Odometer Scale Factor Error	1%	0.5 hour
Odometer Quantization Error	0.25 feet	
Odometer Boresight Error	1°	0.5
Odometer Slippage/Undulation Error	2.5 ft @ 1 mile	
Zero Side-Slip and Up-Slip Residual Errors	0.1 feet/sec	

*** Clock frequency and phase errors are expressed as equivalent range-rate and range errors**

The following assumptions were used in defining the GPS Random Range Measurement Error budget:

- The distance to the nearest reference station is not more than a few tens of kilometers; the latency of the differential corrections is not more than a few seconds
- Multipath at the reference stations is minimized through standard techniques: multipath limiting antennas, optimal antenna siting, narrow/strobe correlators, calibration of installation, etc.
- Phase-stable antennas are used

- The GPS receivers have been designed to keep receiver errors small (e.g. high quality hardware, sophisticated tracking loops and navigation algorithms)

4.4 Trajectory and Scenarios

The performance associated with each of the four mechanization concepts assumes a specific trajectory that is composed of two distinct segments. The first segment consists of a 20-minute calibration phase in which the vehicle is exposed to dynamic maneuvering typical of an urban environment (accelerations, decelerations, stops, right- and left-hand turns, turning on a cloverleaf). This phase of the mission assumes that GPS carrier-phase aiding is continuously available, and serves to calibrate the inertial sensors, as well as odometer, and GPS user's clock. The second segment consists of a single 90-degree turn, preceded and followed by straight segments. This phase of the mission is intended to expose the system error propagation characteristics associated with various degradations in the GPS measurement accuracy (due to outages, occlusions, and exposure to multipath effects). The trajectory description for the two mission phases is as defined in Table 4.4. This trajectory specification is utilized in defining the complete kinematic state of the vehicle, via a trajectory generator, which constitutes an important element in the performance evaluation methodology described in Appendix C.

Table 4.4 Trajectory Specification

Description of Vehicle Maneuver	Maneuver Parameters
Acceleration from a stopped condition	ΔV =60 feet/sec over 10 sec @ t =1 sec
Left-hand turn	$\Delta\Psi$ = 90° over 5 sec @ t =100 sec
Deceleration from a cruise condition	ΔV = 60 feet/sec over 10 sec @ t=175 sec
Acceleration from a stopped condition	ΔV = 60 feet/sec over 10 sec @ t=200 sec
Right-hand turn	$\Delta\Psi$ = 90° over 5 sec @ t=300 sec
Left-hand turn	$\Delta\Psi$ = 90° over 5 sec @ t=450 sec
Right-hand turn	$\Delta\Psi$ = 90° over 5 sec @ t=600 sec
Deceleration from a cruise condition	ΔV = 60 feet/sec over 10 sec @ t=800 sec
Acceleration from a stopped condition	$\Delta\theta$ = 80 feet/sec over 10 sec @ t=850
Pitch up	$\Delta\theta$ = 10° over 15 sec @ t=625 sec
Pitch down	$\Delta\theta$ = 10° over 15 sec @ t=15 sec
Coordinated turn on cloverleaf	$\Delta\Psi$ = 20° over 15 sec @ t=700 sec
Turn for scenarios 1-4	$\Delta\Psi$ = 90° over 30 sec @ t=1200 sec

Note: Variations in the calibration pitch maneuver had a minimal impact on the results

The four scenarios utilized in carrying out the system performance evaluation are as depicted in Figure 4.4-1. Each of the scenarios assumes the nominal 6-satellite GPS constellation depicted in Figure 4.4-2. The nominal HDOP of the identified satellite constellation is 1.25 without any occlusions. This is a typical satellite configuration. It is also assumed that during each of the approximately 20-minute missions, the GPS constellation is fixed. This is a convenient assumption that should not restrict the generality of the results obtained. The four scenarios are defined as follows:

Scenario 1: This scenario consists of two GPS outages – one of 10-second duration occurring just before a 90° turn, and one of 4-second duration occurring just after a 90-degree turn. In both cases GPS differential carrier phase measurements are assumed to be totally absent due to the vehicle passing through a tunnel. A similar loss of GPS carrier-phase capability could also occur if the reference station signal was totally occluded due to a physical or geographic obstruction.

Scenario 2: This scenario consists of a sequence of satellite occlusions – each of 2-second duration occurring during a 90-degree turn. The scenario assumes a tall building, located as depicted, which causes satellites 1, 2, 3 and 4 to each be occluded in turn. The number of satellites utilized in the aided solution varies from six prior to the curve, to five during the turn, to six again subsequent to the curve.

Scenario 3: This scenario consists of a single GPS outage of 30-second duration occurring during the 90-degree turn, the outage resulting from the vehicle passing through a long tunnel. As in Scenario 1, loss of GPS measurements could also occur if the reference station signal is totally occluded due to a physical or geographic obstruction.

Scenario 4: This scenario consists of a sequence of GPS measurement degradations occurring during a 90-degree turn. The scenario assumes a set of GPS signal reflectors, located as shown, which causes the carrier phase signals received from satellites 1, 2, 3 and 4 each to be degraded in turn by multipath for a 2-second interval. A degradation factor of 10 is assumed for the range accuracy of the affected satellite transmission (that is, the range accuracy is assumed to have a 1σ error of 20 cm while the affected satellite signal is being exposed to multipath).

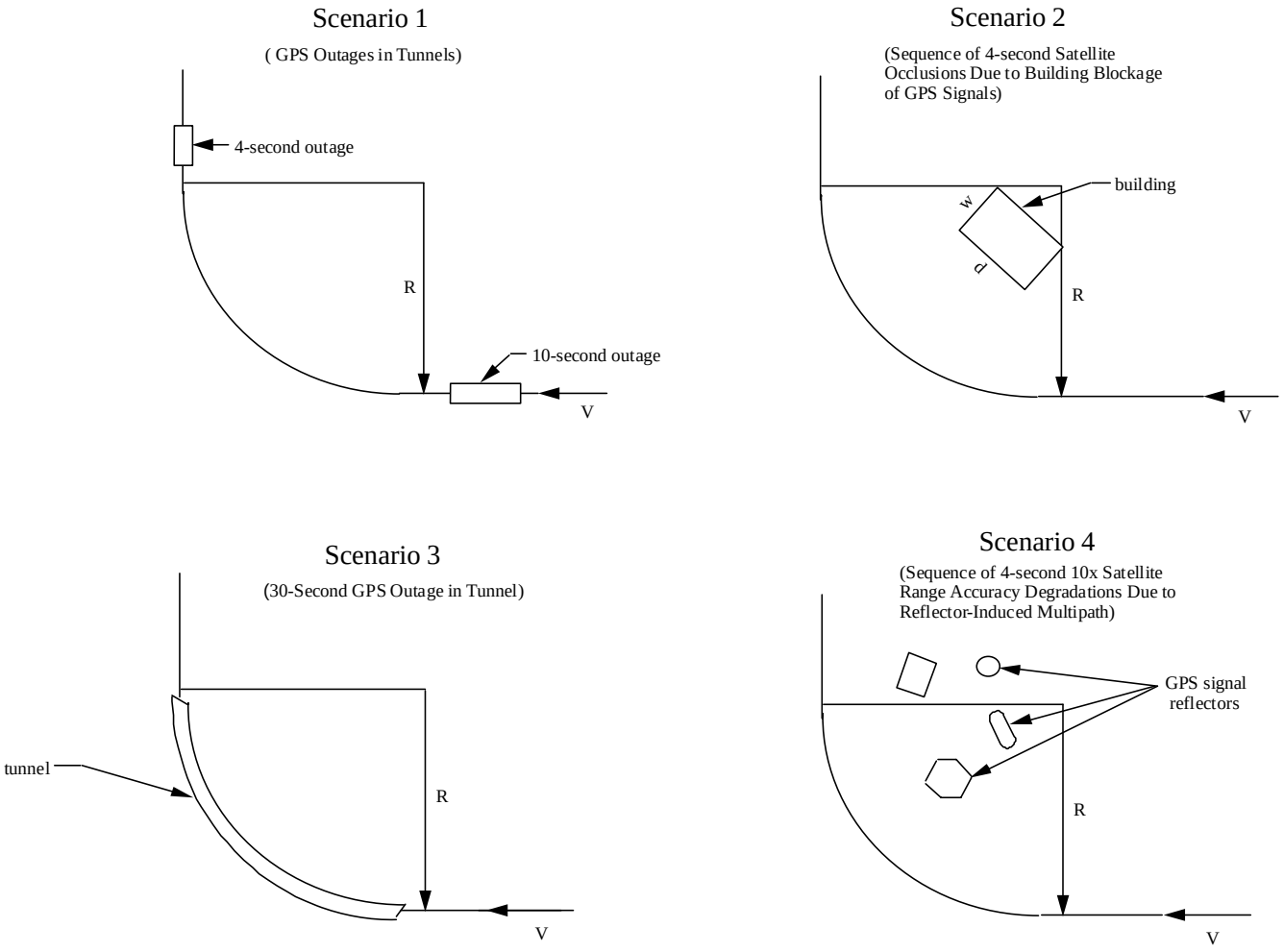
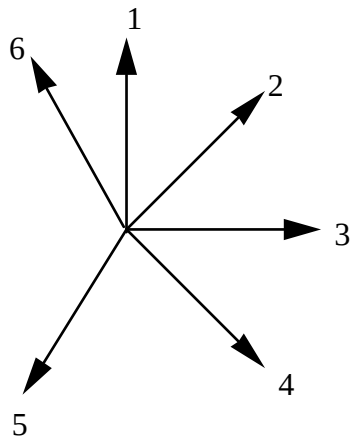


Figure 4.4-1 Illustration of Scenarios 1 – 4

The four scenarios described above were selected as containing basic elements of major importance in the application of interest. The evaluation of system accuracy during and after a GPS outage is very relevant to the question of the likelihood of reacquiring the carrier phase signal subsequent to a GPS outage. Clearly, if the position error after a GPS outage is less than a half wavelength (approximately 10 cm, or around 1/3 foot), the carrier phase will be reacquired almost instantaneously without need for ambiguity resolution. This is also essentially true when the position error is on the order of a single wavelength, in which case the ambiguity resolution should typically be very rapid. As the position error subsequent to a GPS outage becomes progressively larger, the ambiguity resolution time increases commensurately. The evaluation of system accuracy during GPS measurement accuracy degradations is very relevant to the question of lane-keeping accuracy. The position accuracy during such events provides an important insight into how well the lane-keeping function can be performed during periods of non-optimal GPS performance – independently of any consideration of carrier-phase reacquisition, which is associated strictly with GPS outages.

Unit Vectors to Nominally Visable Satellites



Satellite Azimuth & Elevation Angles

sat	azim	elev
1	0	30
2	45	45
3	90	60
4	135	30
5	225	45
6	315	60

Figure 4.4-2 Satellite Geometry for Scenario 1-4

4.5 Scenario 1 and 3 Results

It is natural to group the performance results for Scenarios 1 and 3 together since, in fact, both scenarios deal with the ability of the navigation system to “coast” though GPS outages of various durations. A set of results is given in Table 4.5 for the three different GPS outages embodied in Scenarios 1 and 3. The results define the Circular Error Probable (CEP), which is the radius of the circle containing half of the possible outcomes for the system positioning error in the level plane.

Table 4.5 Results from Scenarios 1 and 3

		After 4-Second GPS Outage (CEP – cm)	After 10- Second GPS Outage (CEP – cm)	After 30-Second GPS Outage (CEP – cm)
Mechanization 1	MEMS-1	6	19	201
	MEMS-2	4	11	91
	MEMS-3	3	7	43
Mechanization 2	MEMS-1	5	16	76
	MEMS-2	4	10	55
	MEMS-3	3	7	37
Mechanization 3	MEMS-1	5	14	46
	MEMS-2	4	9	37
	MEMS-3	3	7	27
Mechanization 4	MEMS-1	15	26	64
	MEMS-2	15	26	64
	MEMS-3	15	26	64

Mechanization 1: INS (3 gyros, 3 accels) + Differential Carrier-Phase GPS

Mechanization 2: INS (3 gyros, 3 accels) + Differential Carrier-Phase GPS + Zero-Slip Constraints

Mechanization 3: INS (3 gyros, 3 accels) + Differential Carrier-Phase GPS + Dead-Reckoning

Mechanization 4: Dead Reckoning (1 gyro, 2 accels) + Differential Carrier-Phase GPS

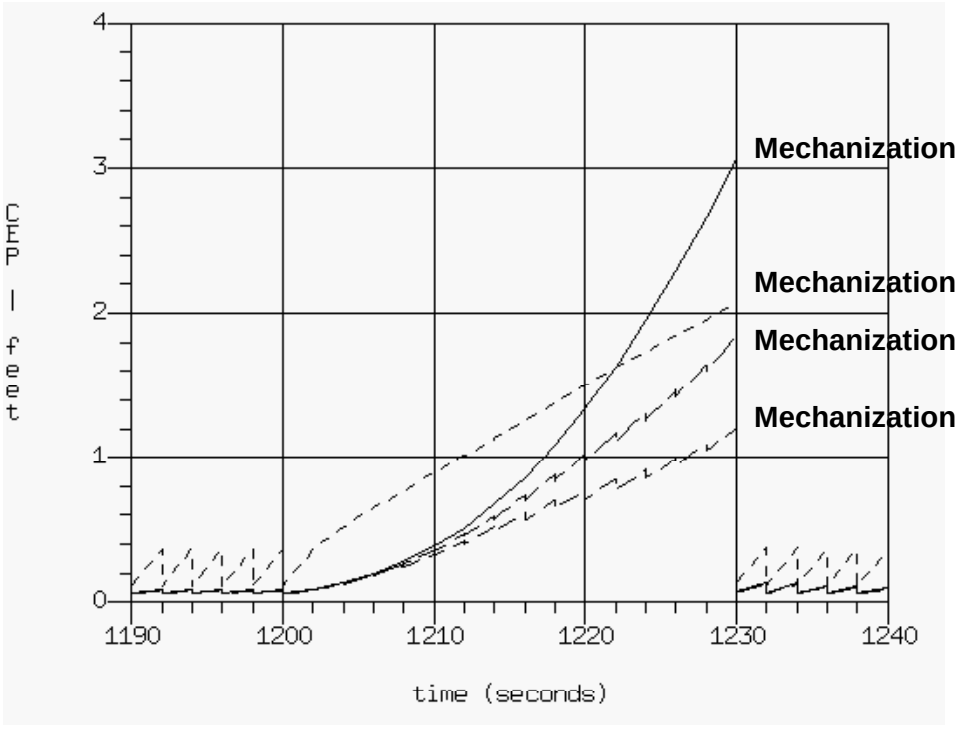
As expected, Table 4.5 shows a pronounced effect on the position error caused by varying outage durations for all four mechanization options. This is also true for the three sensor error budgets. The variation of position error for a given outage duration also manifests considerable variation across the four mechanization concepts. The results show that MEMS2 and MEM-3 sensor sets integrated in mechanizations 1, 2 or 3 can meet the 10 second goal.

The impact of outage duration for the four mechanization concepts is effectively demonstrated by the set of curves shown in Figure 4.5. The first set of curves shows the variation of CEP, for MEMS-2, as a function of time, for the four mechanization options. Reference to the curves shows a fundamentally different shape for the CEP variation associated with Mechanization 4, relative to that manifested by Mechanizations 1, 2 and 3. The first three mechanization concepts manifest a CEP error growth rate, which is very low

for short outage times, and then increases quite rapidly as the GPS outage interval increases. In contrast, the CEP error growth rate for Mechanization 4 starts out at a substantially higher value than for Mechanizations 1, 2 and 3, and then begins to diminish. This is due to the cumulative error in the odometer-derived distance traveled, which is modeled as a random-walk process. The importance of this difference in error propagation characteristics is clear. Assuming that a large percentage of GPS outages will be of relatively short duration (say, less than 3 seconds), it is clear that Mechanization 4 will require carrier-phase reacquisition in a much larger percentage of occurrences of a GPS outage than Mechanizations 1, 2 or 3. Because this, in turn, suggests that a greater amount of total road time would need to be devoted to ambiguity resolution, system availability would be potentially reduced significantly relative to Mechanizations 1, 2 and 3.

Figure 4.5 also shows the variation of the 1σ altitude error for the four mechanization options as a function of outage duration. Here, as noted, the 1σ altitude error for Mechanizations 1, 2 and 3 are fairly consistent – with relatively little difference being observed; whereas, Mechanization 4 manifests a uniquely different variation. Again, because the altitude error grows at a faster rate for Mechanization 4 than for the other three mechanization options, it is evident that the probability of loss of carrier–phase lock at the end of the period of GPS outage is greater for this mechanization (given that the ability to maintain carrier-phase lock depends on the 3-dimensional position error when GPS carrier-phase measurements are restored).

In Figure 4.5 the scenario begins at time 1200 seconds.



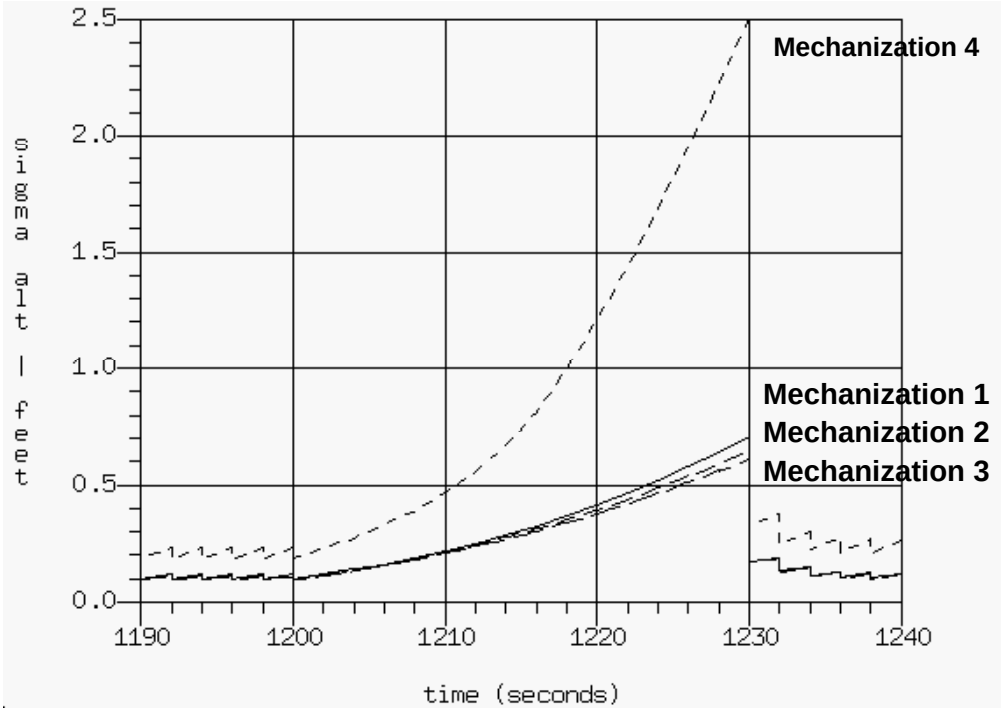


Figure 4.5 Horizontal Position Error (CEP) and Altitude (1σ) Error Following a GPS Outage for the Four System Mechanizations (MEMS-2)

4.6 Scenario 2 and 4 Results

It is natural to group the performance results for Scenarios 2 and 4 together because both scenarios deal with the ability of the navigation system to maintain positioning accuracy in the presence of GPS measurement accuracy degradation. The degradations are a result of one or more satellites being temporarily occluded or one or more satellite carrier signals being temporarily contaminated by multipath effects from nearby reflectors.

A set of results is given in Table 4.6 for Scenarios 2 and 4. The results define the CEP after a sequence of individual satellite occlusions, each persisting for 2 seconds.

These are the Scenario 2 results. Table 4.6 shows very little difference between the CEP values observed for Mechanizations 1, 2 and 3, but a fairly large difference when compared to Mechanization 4. The effect of sensor quality is not a major factor for any of the mechanization options, but it is interesting that Mechanization 4 results are invariant with respect to sensor quality. This reflects the fact that the inertial sensor errors are being completely dominated by odometer related errors. For Mechanizations 1, 2 and 3 the position errors are at a level that suggest excellent lane-keeping accuracy (on the order of 4 cm). In contrast the CEP for Mechanization 4 is at a considerably higher level (on the order of 11 cm).

Table 4.6 also provides accuracy results for Scenario 4, which is intended to expose the system sensitivity to GPS measurement accuracy degradation. The results are obtained for the case where the carrier-phase signals from satellites 1, 2, 3 and 4 are sequentially degraded by a factor of ten for a period of 2 seconds. The evaluation is carried out differently for Scenario 4 than for the other three scenarios to reflect the fact that the integration Kalman Filter is based on an assumed nominal measurement accuracy for GPS carrier-phase measurements. In reality, however the accuracy is degraded, and the degradation factor is unknown by the filter. Therefore, in the evaluation of this scenario, a “real-world/filter-world” evaluation needs to be carried out (Appendix D). This constitutes a 2-step process, with the Kalman Filter being predicated on the nominal carrier-phase measurement accuracy, but the evaluation of the filter’s real performance being based on the true carrier-phase measurement accuracies. Table 4.6 shows essentially no performance difference (in terms of CEP) between the first three mechanization options, but with a somewhat higher level of position error associated with Mechanization 4. The effect of sensor quality is also noted in the Table for Mechanizations 1, 2 and 3, but Mechanization 4 results are invariant with respect to sensor quality. As for the Scenario 2 results, this reflects the fact that the inertial sensor errors are being completely dominated by odometer related errors. The position accuracy (CEP) associated with all four mechanization options are at a level for Scenario 4 that would suggest acceptable lane-keeping accuracy for most applications.

Table 4.6 Results from Scenarios 2 and 4

		After GPS Satellite Occlusion Outage (CEP – cm)	After GPS Satellite Multipath (CEP – cm)
Mechanization 1	MEMS-1	4	11
	MEMS-2	3	9
	MEMS-3	2	8
Mechanization 2	MEMS-1	4	11
	MEMS-2	3	9
	MEMS-3	2	8
Mechanization 3	MEMS-1	4	11
	MEMS-2	3	9
	MEMS-3	2	8
Mechanization 4	MEMS-1	11	14
	MEMS-2	11	14
	MEMS-3	11	14

Mechanization 1: INS (3 gyros, 3 accels) + Differential Carrier-Phase GPS

Mechanization 2: INS (3 gyros, 3 accels) + Differential Carrier-Phase GPS + Zero-Slip Constraints

Mechanization 3: INS (3 gyros, 3 accels) + Differential Carrier-Phase GPS + Dead-Reckoning

Mechanization 4: Dead Reckoning (1 gyro, 2 accels) + Differential Carrier-Phase GPSTable 1

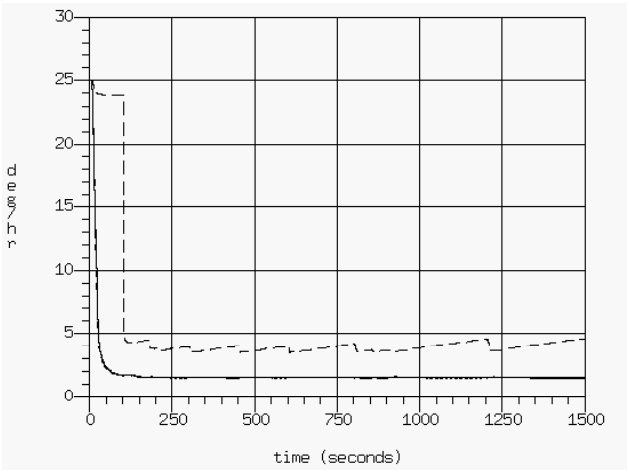
4.7 Sensor Calibration Results (Pre-Scenario Calibration Phase)

A natural concern in any low-cost system is the cost associated with factory testing and/or calibration of the system prior to shipping. Such costs, if not properly controlled, can represent a major impediment to achieving the low production cost that is intended. In the automotive application of interest, a natural function that is continuously performed is system calibration. This is made possible by the availability of high precision GPS carrier-phase measurements, in combination with the natural excitation of the sensor errors by normal vehicle maneuvers. The combination of these two factors makes possible a high level of sensor calibration on essentially a continuous basis, as required by the relatively high levels of sensor bias random variations over time and temperature. This same inherent ability to maintain the sensors in a continuously calibrated state may also provide the means

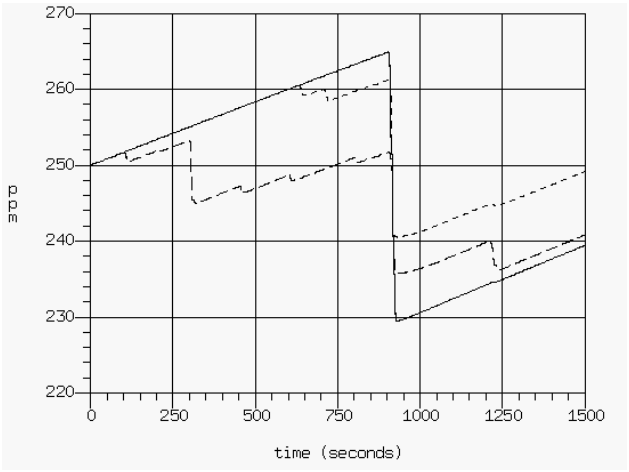
by which initial sensor calibration may be carried out, in lieu of factory calibration. Having such a capability effectively eliminates a source of system cost and is therefore, highly desirable.

To test the possibility of performing initial sensor calibration during first use of the system two sets of calibration results were generated, each assuming the trajectory defined in Table 4.4. A calibration interval of 1500 seconds was also assumed. The two sets of calibration results are shown in Figures 4.7-1 through 4.7-4.

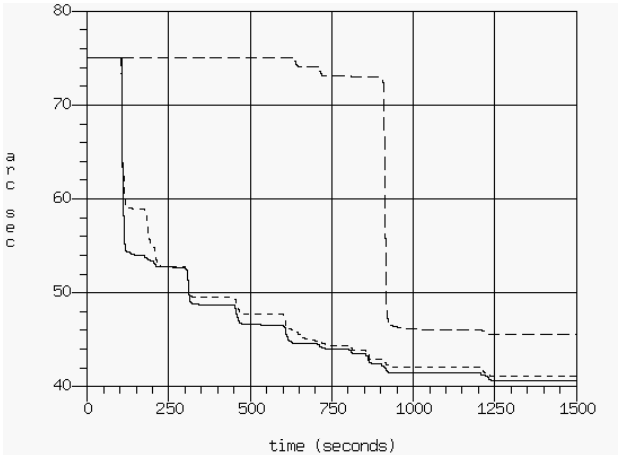
Figures 4.7-1 and 4.7-2 show the calibration results for a MEMS-1 system, as defined in Table 4.3-1. These results are characteristic of what would be expected from a system already having undergone some level of calibration, which is then being further refined. Figure 4.7-1 shows how the 1σ gyro calibration errors vary during the calibration period, while Figure 4.7-2 shows how the 1σ accelerometer errors vary during the same calibration period. For both the gyro and accelerometer errors, the achievable level of calibration, even over a fairly short interval with only modest maneuvering, is quite good.



Gyro Bias Errors

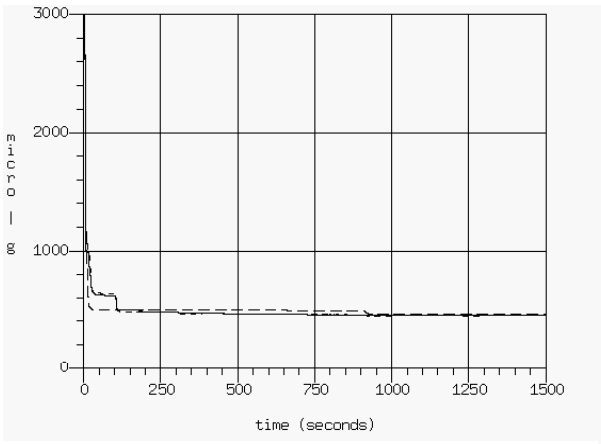


Gyro Scale-Factor Errors

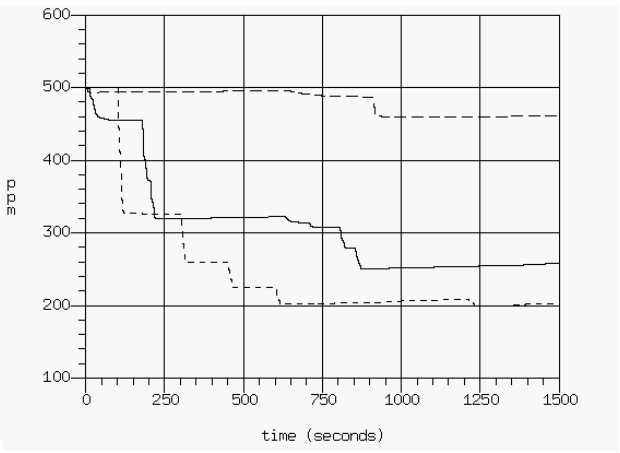


Gyro Input-Axis Non-Orthogonality Errors

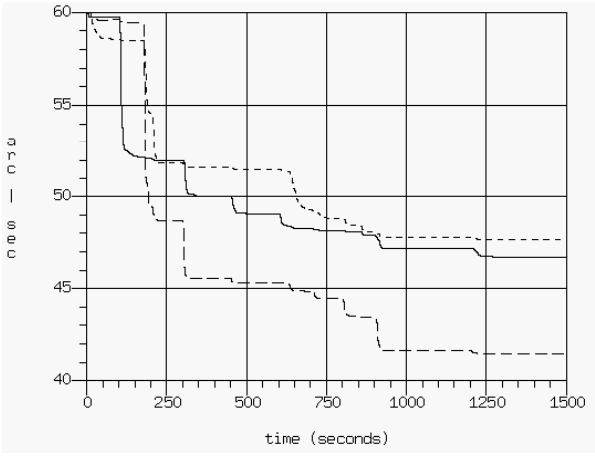
Figure 4.7-1 Gyro Calibration Errors For System Which Has Undergone Factory Calibration (MEMS-1)



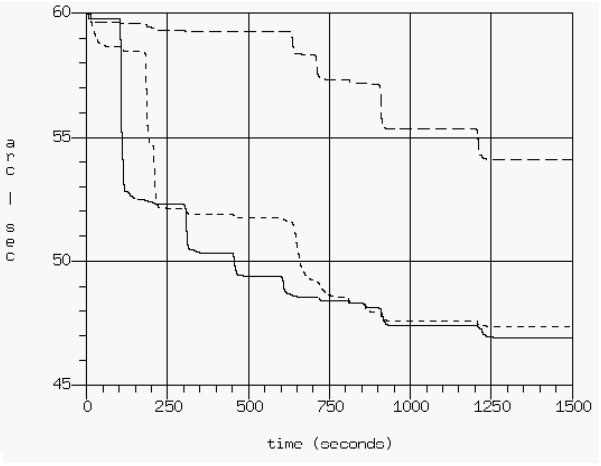
Accel Bias Errors



Accel Scale-Factor Errors



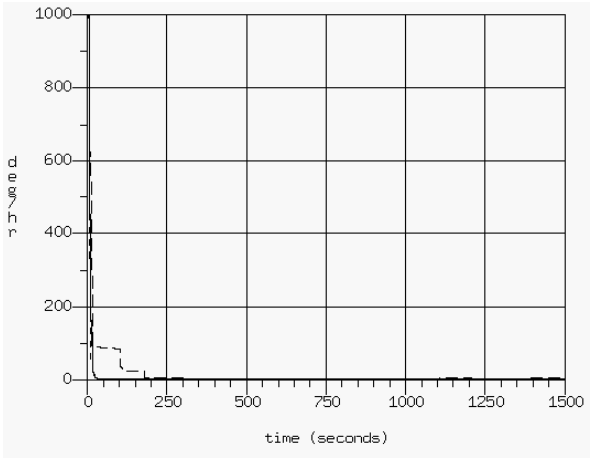
Accel Input-Axis Non-Orthogonality Errors



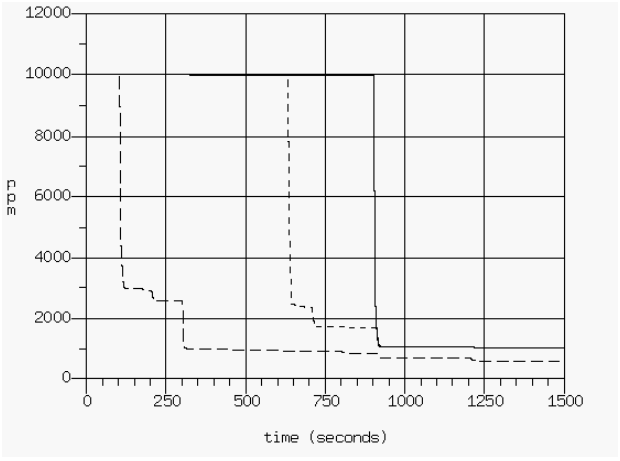
Accel Input-Axis Misalignment Errors

Figure 4.7-2 Accelerometer Calibration Errors For System Which Has Undergone Factory Calibration (MEMS-1)

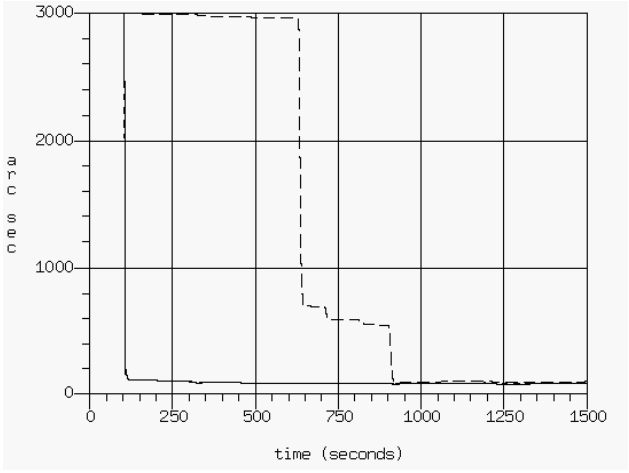
Figures 4.7-3 and 4.7-4 show the calibration results for the same MEMS-1 system, but with a 10 times increase in the initial fixed gyro and accelerometer 1σ errors (bias, scale-factor. etc.). Figure 4.7-3 shows how the 1σ gyro calibration errors vary from these larger initial uncertainties during the calibration period, while Figure 4.7-4 shows how the 1σ accelerometer errors vary. For both the gyro and accelerometer errors the final levels of uncertainty, although not as low as the levels associated with a calibrated system, is nonetheless quite good. The same set of runs also showed the performance associated with Scenarios 1, 2, 3 and 4 to be virtually the same for the initially calibrated and initially uncalibrated systems. This is an encouraging result that strongly suggests that factory calibration of the sensor assembly may be eliminated, or greatly simplified, without performance penalty.



Gyro Bias Errors

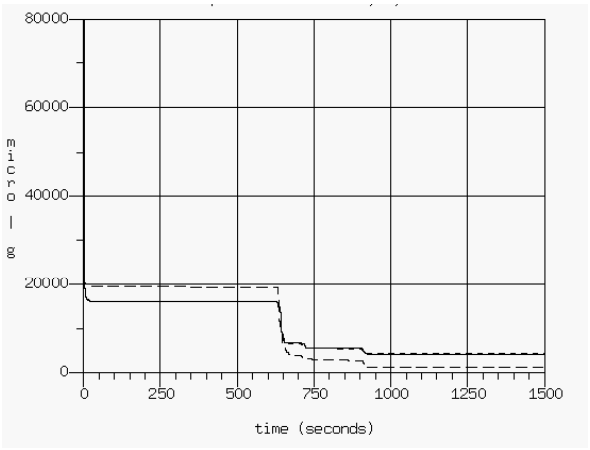


Gyro Scale-Factor Errors

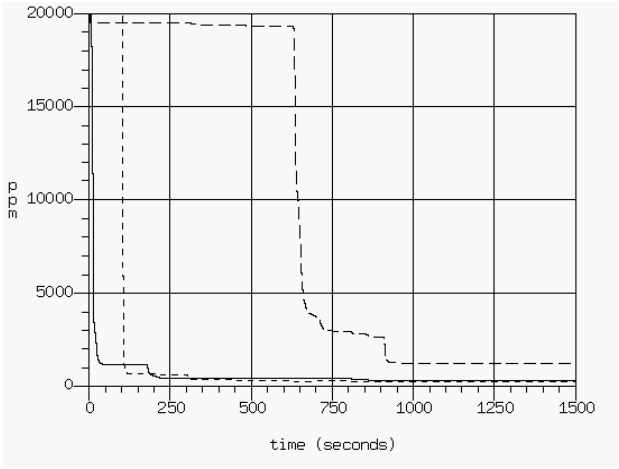


Gyro Input-Axis Non-Orthogonality Errors

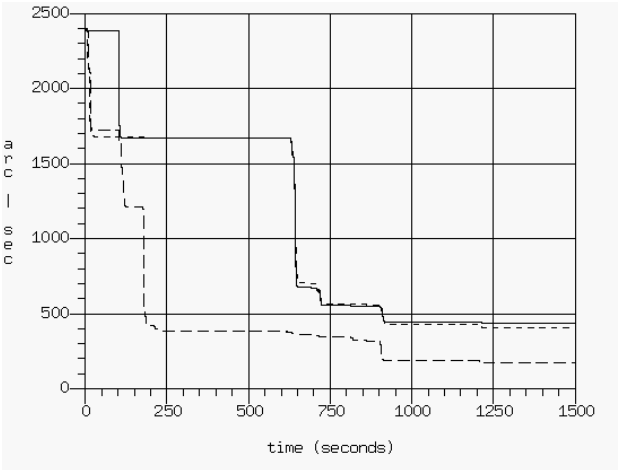
Figure 4.7-3 Gyro Calibration Errors For System Having Minimal or No Factory Calibration (MEMS-1)



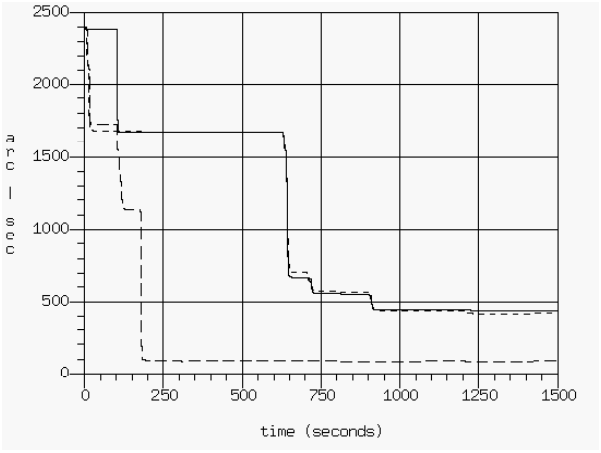
Accel Bias Errors



Accel Scale-Factor Errors



Accel Input-Axis Non-Orthogonality Errors



Accel Input-Axis Misalignment Errors

Figure 4.7-4 Accelerometer Calibration Errors For System Having Minimal or No Factory Calibration (MEMS-1)

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Appendix A. Navigation System Mechanization Equations

This appendix defines the mechanization equations associated with an inertial navigation system and a dead-reckoning system. Both of these mechanization concepts are incorporated into the four system implementations evaluated in the main body of the report.

A.1 Coordinate Frames

Before proceeding, a number of coordinate frames will need to be specified in a fairly general way suitable for the needs of the development to follow. Five coordinate frames, key to the development, are as follows:

- Inertial Frame - A frame that is non-rotating with respect to inertial space, and is coincident with a set of earth-centered axes at $t = 0$. This frame is designated by "i".
- Earth Reference Frame - A frame that coincides with the inertial frame at $t = 0$ and, thereafter, rotates at a fixed rate (earth's sidereal rate of 15.04 degrees/hour) relative to the inertial frame. One axis of this frame is coincident with the earth's spin axis, with the other two being perpendicular to the first, and defining the earth's equatorial plane. This frame is designated by "e".
- Local-Vertical Computational Frame - A frame having two axes level, with the third being coincident with the direction of the local vertical. The two level axes are rotated from the North and East directions respectively by an azimuth rotation, α, which is referred to as the "wander-azimuth angle". This frame, which is also referred to as the "wander-azimuth frame", is designated by "c".
- Sensor Reference Frame - A frame that establishes the reference for the inertial sensors, and serves as the reference frame for the purpose of the strapdown computations. This frame, which is designated by "r", is nominally coincident with the vehicle body frame,
- Vehicle Body Frame - A frame that establishes the reference for the vehicle, and is nominally coincident with the vehicle body frame established by the rear axle and wheels of the vehicles. This frame, designated by "b", is that in which the odometer measurement is naturally expressed.

The navigation system implementation equations to follow assume a geocentric vertical. The navigation solution will also be predicated on a free-inertial vertical position computation, and blending of the inertial system's vertical axis information with that obtained by a secondary source (usually provided by a barometric altimeter) is not assumed.

A.2 Strapdown Navigation Equations

In general terms, an inertial navigation system functions by continuously measuring the components of vehicle non-gravitational acceleration and angular velocity in three orthogonal sensor reference axes and, simultaneously, integrating the set of differential equations defining vehicle attitude, velocity, and position that have these measurements as inputs. In the case of a dead reckoning system, the output of a triad of gyros is integrated, together with the output of an odometer, to derive vehicle position.

In the following development, the particular mechanization approach assumed for the navigation system is a strapdown system mechanization, expressed in a wander-azimuth coordinate frame. This choice of navigation frame convention is convenient since it is the most frequently employed frame convention, but the results to be obtained do not depend in any way on the specific frame convention utilized.

The complete strapdown solution, as expressed in a wander-azimuth coordinate convention, is defined by four time-varying entities. This includes: an attitude matrix that defines the transformation between the sensor reference frame and the local-vertical computational frame, a velocity vector, a matrix that accounts in a general way for vehicle horizontal position, and an equation that defines the vehicle vertical position. The equations solved in the navigation computer are the following:

$$dC/dt = C\{\omega^r\} - \{\Omega^c + \rho^c\}\, C \qquad \text{(A-1)}$$

$$\mathrm{d}V^c/dt = C\,A^r - \{2\Omega^c + \rho^c\}V^c + g^c \qquad \text{(A-2)}$$

$$dD/dt = D\{\rho^c\} \qquad \text{(A-3)}$$

where

C = transformation matrix from sensor reference frame to local-vertical frame

D = transformation matrix from local-vertical frame to earth reference frame

V^c = velocity vector

Ω^c = angular velocity vector of earth with respect to the inertial frame

ρ^c = angular velocity of local-vertical frame with respect to the earth reference frame

ω^r = angular velocity vector of sensor reference frame with respect to the inertial frame

A^r = non-gravitational acceleration vector of vehicle

g^c = apparent or "plumb-bob" gravity vector

and the convention is used here and throughout that the particular frame in which a vector is realized is designated by its superscript. Another convention used in (A-1), (A-2), (A-3), and throughout, is that a quantity of the form, $\{\mathrm{v}\}$, denotes the skew-symmetric matrix formed from the components, v_i, of the enclosed vector, v, according to

$$\{\mathrm{v}\} = \begin{bmatrix} 0 & -\mathrm{v}_3 & \mathrm{v}_2 \\ \mathrm{v}_3 & 0 & -\mathrm{v}_1 \\ -\mathrm{v}_2 & \mathrm{v}_1 & 0 \end{bmatrix}$$

The plumb-bob gravity vector is composed of the sum of a mass-attraction component and a centripetal component, with the mass-attraction component being defined by an inverse-square law.

To complete (A-1) and (A-2), the earth-rate vector, expressed in the local-vertical computational frame, is defined by

$$\Omega^c = D^T\Omega^e\,. \qquad \text{(A-4)}$$

Where Ω^e is the constant earth-rate vector, expressed in the earth-reference frame.

The use of direction cosines in the navigation solution is based strictly on convenience in the development to follow, and does not restrict the results to be given - which are equally applicable to quaternion-based systems as well.

A.3 Dead-Reckoning Navigation Equations

The function of a dead-reckoning system is to compute the location of the vehicle in the computational reference frame using the accurate attitude information that is available from the solution of the attitude matrix, together with the incremental output of the odometer. The basic position differential equation is defined by

$$dR/dt = CV_o \quad . \tag{A-5}$$

Where

$C =$ vehicle attitude matrix

$R =$ position vector

$V_o =$ odometer derived velocity vector

and C is the instantaneous attitude matrix available from the solution of (A-1). A discrete update equation for the variation of the position vector, which accounts for the fixed offset between the sensor reference and vehicle body frame is given by

$$R_n = R_{n-1} + \Delta s_n C_n \begin{bmatrix} k_o \\ \alpha_0 \\ \beta_0 \end{bmatrix} \tag{A-6}$$

where

R_n = position vector at the end of the n^{th} iteration interval

C_n = attitude matrix at the end of the n^{th} iteration interval

Δs_n = odometer incremental output at the end of the n^{th} iteration interval

k_o = odometer scale-factor

α_0, β_0 = boresight angles

The nominally known odometer scale-factor and boresight angles are corrected in system use via the precision aiding information provided by GPS differential carrier-phase measurements.

The attitude matrix may be continuously defined using the output of a triad of gyros or, alternatively, using the output of a set of two level accelerometers, and a single heading gyro. Equation (A-6) applies to either of the two approaches.

Appendix B. Navigation Error Equations

This appendix defines error models for the various elements in the system. The error models are of important for two reasons:

- They provide key elements required in implementing the Kalman Filter used to integrate information from the various subsystems
- They provide the basis for assessing the performance possible from the integrated system

The following subsections deal with error models for the inertial navigation solution and the odometer-derived position.

B.1 Inertial Navigation Error Model

The solution of (A-1), (A-2), and (A-3) will be imperfect due to errors introduced through the sensor inputs, errors in the initial conditions on $C, \mathrm{V}^c,$ and D and errors in modeling the earth's gravity field. The errors associated with these quantities are defined as the differences between the erroneous solution variables, and their counterparts when the equations are solved with perfect sensors, exact initial conditions and the true value of the earth's gravity vector.

A commonly used error model is based on the differences between the derived earth-referenced variables of the perfect and imperfect navigators. This formulation of the strapdown error model, referred to as the "ψ-angle" error model, is defined by the following set of vector differential equations:

$$d\psi^c / dt = -(\rho^c + \Omega^c) \times \psi^c - C\,\delta\omega^r \qquad \text{(B-1)}$$

$$d(\delta V^c) / dt = C\,\delta A^r - \psi^c \times A^c - (2\Omega^c + \rho^c) \times \delta V^c + [M - \{\Omega^c\}^2]\,\delta R^c + \gamma_m^c \qquad \text{(B-2)}$$

$$d(\delta R^c) / dt = \delta V^c - \rho^c \times \delta R^c \qquad \text{(B-3)}$$

where

$\psi^c =$ attitude error vector

$\delta V^c =$ velocity error vector

$\delta R^c =$ position error vector

$\gamma_m^c =$ gravity anomaly and deflection error vector

and the matrix *M* is defined by

$$M = \begin{bmatrix} -\omega_s^2 & 0 & 0 \\ 0 & -\omega_s^2 & 0 \\ 0 & 0 & 2\omega_s^2 \end{bmatrix}$$

in which ω_S is the Schuler frequency defined by

$$\omega_s^2 = g_m / r$$

The term $\{\Omega^c\}^2\delta R^c$ in (B-2) is included for completeness but, due to its small numerical value, may be ignored in most applications.

The attitude, velocity, and position error equations defined by (B-1), (B-2), and (B-3) provide a complete description of the error propagation characteristics of a strapdown inertial navigation system.

B.2 Dead-Reckoning Error Model

The attitude and velocity error equations defined by (A-1) and (A-2) provide a description of the error propagation characteristics of the strapdown inertial navigation system. In addition the error propagation equation for the dead-reckoned position is required. This is derived from the basic dead-reckoning equation defined by (A-5). Taking the differential of both sides leads to

$$d(\delta R)/dt = \delta C V_o + C\delta V_o$$
$$= -\{\psi^c\}CV_o + C\delta V_o = -\{\psi^c\}V^c + C\delta V_o \qquad \text{(B-4)}$$

The error in the odometer-derived velocity vector is expressed as

$$\delta V_o = s\begin{bmatrix} k \\ \alpha \\ \beta \end{bmatrix} + \begin{bmatrix} \eta_o \\ 0 \\ 0 \end{bmatrix} \qquad \text{(B-5)}$$

where

s = vehicle speed

k = odometer scale-factor error

α = lateral boresight error

β = normal boresight error

η_o = white-noise error in speed measurement error

In vector/matrix format (B-4) is expressed as

$$\frac{d}{dt}\begin{bmatrix} \delta R_x \\ \delta R_y \\ \delta R_z \end{bmatrix} = -\begin{bmatrix} 0 & -\psi_z & \psi_y \\ \psi_z & 0 & -\psi_x \\ -\psi_y & \psi_x & k_o \end{bmatrix}\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}\left\{\begin{bmatrix} sk \\ s\alpha \\ s\beta \end{bmatrix} + \begin{bmatrix} \eta_o \\ 0 \\ 0 \end{bmatrix}\right\}$$

or, equivalently

$$\frac{d}{dt}\begin{bmatrix} \delta R_x \\ \delta R_y \\ \delta R_z \end{bmatrix} = \begin{bmatrix} 0 & V_z & -V_y \\ -V_z & 0 & V_x \\ V_y & -V_x & 0 \end{bmatrix}\begin{bmatrix} \psi_x \\ \psi_y \\ \psi_z \end{bmatrix} + \begin{bmatrix} sc_{11} & sc_{12} & sc_{13} \\ sc_{21} & sc_{22} & sc_{23} \\ sc_{31} & sc_{32} & sc_{33} \end{bmatrix}\begin{bmatrix} k \\ \alpha \\ \beta \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}\begin{bmatrix} \eta_o \\ 0 \\ 0 \end{bmatrix} \qquad \text{(B-6)}$$

in which V_x,V_y and V_z are the vehicle velocity component in the computational reference frame.

B.3 Inertial Sensor Error Models

The error vectors $\delta\omega^r$ and δA^r, in the navigation error equations account for the angular rate and linear acceleration errors originating from errors in the outputs of the inertial sensors. To complete the overall inertial system error model, a model for these errors needs to be provided.

The errors in the inertial sensor may be defined as falling into two categories. The first category, which may be referred to as "sensor-level" errors, are those errors that are not dependent on the sensor's position or orientation in the system. The principal errors that fall into this category are sensor bias, scale-factor, and random drift errors. The remaining errors, which may be referred to as "system-level" errors, arise from misalignments of the sensor input axes when they are assembled into a system. Basic error models applicable to the gyro and accelerometer sensor- and system-level errors are given in the following.

Gyro Errors

The error in a given gyro's output, due to bias, scale-factor, and random errors is expressed as

$$\delta\omega = b_g + k_g\ \omega + \xi_g \tag{B-7}$$

where

$\delta\omega$ = error in measured angular rate

b_g = gyro bias error

k_g = gyro scale-factor error

ξ_g = gyro random drift rate error

ω = angular rate measured by gyro

The angular rate error expressed in the sensor reference frame due to gyro input-axis misalignment errors is expressed in general as

$$\delta\omega^r = \begin{bmatrix} 0 & k_{12}^g & k_{13}^g \\ k_{21}^g & 0 & k_{23}^g \\ k_{31}^g & k_{32}^g & 0 \end{bmatrix} \omega^r \tag{B-8}$$

where the k_{ij}^g are the gyro input-axis misalignments. The misalignment matrix can be decomposed into the sum of a symmetric and a skew-symmetric matrix, which leads to the alternate error expression

$$\delta\omega^r = \left\{ \begin{bmatrix} 0 & -\mu_3^g & \mu_2^g \\ \mu_3^g & 0 & -\mu_1^g \\ -\mu_2^g & \mu_1^g & 0 \end{bmatrix} + \begin{bmatrix} 0 & \delta_3^g & \delta_2^g \\ \delta_3^g & 0 & \delta_1^g \\ \delta_2^g & \delta_1^g & 0 \end{bmatrix} \right\} \omega^r \tag{B-9}$$

The δ_i^g account for the non-orthogonality (skew) in the gyro input axes, while the μ_i^g account as a group for a small-angle misalignment (rotation) of the gyro triad with respect to the sensor reference frame. The latter error can be made identically zero by choosing a specific sensor reference frame for which there is, by definition, no pure rotation component

of the misalignment error. The result is that the pure rotation component of the misalignment error is absorbed into the initial attitude error.

The random uncorrelated noise sequence, ξ_g, in the gyro error model characterized by a standard deviation or, equivalently, by a "random-walk" coefficient. The latter is a commonly used error parameter that applies to the cumulative gyro output angle. The error in the cumulative angle output, due to the random drift rate, ξ_g, may be expressed in the form

$$\sigma_\theta = k\, t^{1/2}$$

where

σ_θ = standard deviation of error in cumulative angle (rad)

k = random walk coefficient (rad/sec$^{1/2}$)

t = elapsed time (sec)

The random-walk parameter is typically used as a measure of the gyro white noise drift, expressed in the convenient units of deg/hour$^{1/2}$.

Accelerometer Errors

The error in a given accelerometer's output, due to bias, scale-factor, and random errors is expressed as

$$\delta A = b_a + k_a\, A + \xi_a \qquad \text{(B-10)}$$

where

δA = error in measured angular rate

b_a = accelerometer bias error

k_a = accelerometer scale-factor error

ξ_a = accelerometer random drift rate error

A = nongravitational acceleration measured by accelerometer

The linear acceleration error expressed in the sensor reference frame due to accelerometer input-axis misalignment errors is expressed as

$$\delta A^r = \begin{bmatrix} 0 & k_{12}^a & k_{13}^a \\ k_{21}^a & 0 & k_{23}^a \\ k_{31}^a & k_{32}^a & 0 \end{bmatrix} A^r \qquad \text{(B-11)}$$

where the k_{ij}^a are the accelerometer input-axis misalignments. The misalignment matrix can be decomposed into the sum of a symmetric and skew-symmetric matrix, which leads to the alternate error expression

$$\delta A^r = \left\{ \begin{bmatrix} 0 & -\mu_3^a & \mu_2^a \\ \mu_3^a & 0 & -\mu_1^a \\ -\mu_2^a & \mu_1^a & 0 \end{bmatrix} + \begin{bmatrix} 0 & \delta_3^a & \delta_2^a \\ \delta_3^a & 0 & \delta_1^a \\ \delta_2^a & \delta_1^a & 0 \end{bmatrix} \right\} A^r \qquad \text{(B-12)}$$

If the sensor reference frame had been defined such that the gyro triad, by definition, consists only of skew errors in its input axis orientations, the accelerometer misalignment errors must be retained in the general form define by (B-12). However, it is also possible to define the sensor reference frame in a manner such that the accelerometer input-axis errors consist only of a set of skew errors, with the pure rotation component of the misalignment error being absorbed into the attitude error. When such is the case, the general set of six misalignment errors must be associated with the gyros. In either case, a minimal realization of errors associated with sensor input-axis misalignment results.

As for the gyro, the random uncorrelated error in the accelerometer output is typically defined by a random-walk coefficient characterizing the error in the cumulative output of the sensor. The accelerometer random-walk parameter is usually expressed in the convenient units of ft/sec/hour$^{1/2}$.

B.4 Odometer Error Model

In many land-navigation applications use is made of measurements derived from an odometer. The odometer nominally measures incremental distance traveled, along the arc of travel, over some interval of time. The measurement will be in error due to a number of sources, the principal ones being: (a) Odometer Scale Factor Error; (b) Slippage/Undulation Error; (c) Readout Quantization Error; and (d) Boresight Error

The odometer scale-factor error originates from the fact that the nominal wheel diameter assumed in the conversion of wheel incremental rotation pulses into distance is not correct due to wheel wear or tire pressure variations, and will also manifest effects from prevailing vehicle dynamics. In some applications each wheel is instrumented, and the overall odometer scale-factor error will be the average of the four individual values. The overall odometer scale factor error is modeled as a slowly varying random bias, with a characteristic correlation time.

The slippage error originates from the fact that the incremental distance traveled will generally be in error due to a small level of slippage that occurs essentially on a continuous basis, even when turns and/or accelerations are absent. Wheel slippage causes a negative error in the odometer reading; that is, the reported value of incremental travel will be less than the actual value. The undulation error originates from the fact that the actual incremental arc length traveled by the wheel is not the same as the CG of the vehicle due to small local undulations of the road. The road undulation error will lead to a positive error in the odometer reading since the value of incremental distance traveled will be greater than the value experienced by the vehicle CG. When all four wheels are instrumented, the overall slippage/undulation error will reflect the mean of the four values being experienced by the individual wheels. The cumulative slippage/undulation error is modeled as a random-walk process in which the1σ error in total distance traveled along the arc of the path varies as the square root of the distance traveled.

The readout error originates from the fact that the incremental distance traveled is measured by a number of pulses that are generated by magnets distributed around the circumference of the wheel. Each pulse represents an increment of wheel rotation and, therefore, the actual distance reported would be in error by a random quantity – which is the quantization error. The fractional pulse that is not reported is never lost since, in fact, it is “saved” by the wheel position itself, and becomes part of subsequent outputs. The cumulative quantization

error is modeled as a random (uncorrelated) sequence of errors in the total distance traveled, and will have a maximum error of one pulse.

The boresight error is not directly an odometer error but in applications in which the odometer-derived distance traveled is compared with that derived from an inertial navigation solution, a system-level error needs to be accounted for. This is the so-called “boresight” error. The boresight error is modeled as a set of two misalignment errors between the vehicle frame (in which the odometer measurement is naturally expressed) and the sensor reference frame (in which the inertially derived attitude, velocity and position are expressed). The two boresight angle errors are modeled as slowly varying biases with a characteristic correlation time.

Appendix C. Covariance Analysis and Kalman Filtering

This appendix provides a description of the covariance-based performance analysis methodology used in the study, and the Kalman Filter technique that is utilized as the means of integrating information from the various subsystems. The methodology described is referred to within Honeywell as "NAVCAD", which has been widely utilized for the past 20 years.

C.1 Covariance Analysis Methodology

Performance analysis, as applied to inertial navigation systems, is the process of determining the attitude, velocity, and position accuracies associated with a given system implementation concept. It constitutes an essential step in most system design tradeoffs that have as their objective the optimization of a particular complement of inertial sensors, aiding devices, and integration filter. The methodology commonly utilized in carrying out such performance evaluations is based on modern covariance analysis techniques, which provides a very effective and efficient means of establishing the performance associated with both autonomous and externally-aided inertial navigation systems. .

Covariance analysis techniques are predicated on the use of linear error models for the navigation system, the inertial sensors, and the auxiliary measuring devices utilized in aiding the navigation system. Once the system error propagation characteristics have been reduced to a set of linear equations, the generalized techniques of linear analysis may be evoked, allowing the time-varying ensemble error statistics for the navigation system to be derived and the overall system errors to be established.

Covariance analysis techniques provide the basis of the performance analysis methodology depicted in Figure c.1. The methodology assumes the availability of the following elements:

- A trajectory generator that converts a mission profile into the time-varying kinematic state of the vehicle, which is essential in synthesizing the transition matrix for the navigation and sensor error models.
- A comprehensive error model for the navigation system (strapdown, platform, or space-stable).
- A repertoire of sensor error models (bias, scale-factor, input-axis misalignments, etc.).
- A repertoire of error models for the auxiliary aiding devices (GPS, Odometer, etc.).
- A repertoire of analysis capabilities (covariance analysis, sensitivity analysis, and real-world/filter-world analysis).

The typical procedure is to define one or more trajectories which are representative of those anticipated in the given application. For each, the complete time-varying kinematic state is established, via the trajectory generator, and stored for later use. Once having accomplished this, a sensor error budget for the inertial sensors and aiding devices is defined in terms of 1σ errors, correlation times of exponentially correlated errors, and spectral intensities of white-noise error sources. The final step is to computationally determine the time-varying covariance and sensitivity matrices to allow the system attitude, velocity, and position accuracies to be established as a function of time.

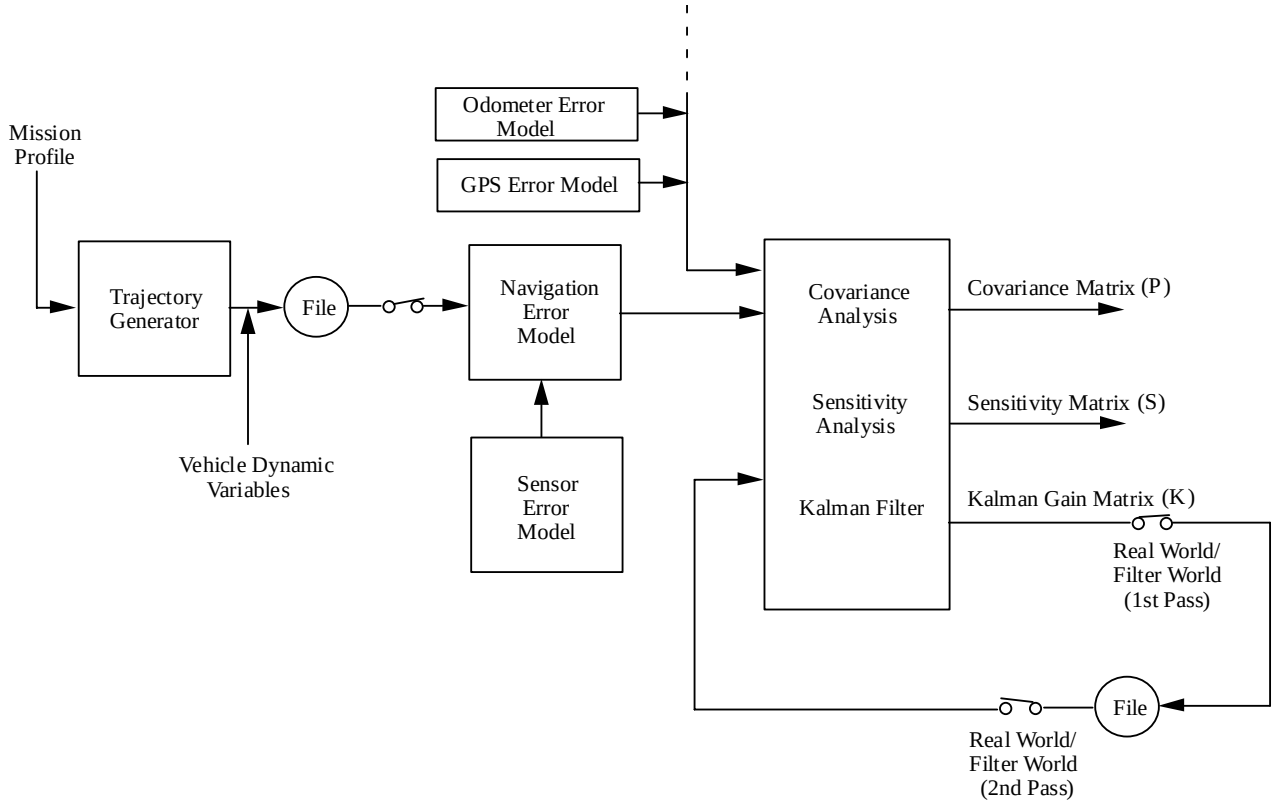

Figure C.1 Schematic of Performance Analysis Methodology

The main ideas associated with the covariance analysis techniques, which provide the basis of the performance analysis methodology, are described below.

The Kalman Filter processes measurements consisting of the difference between quantities derived from the aiding devices (GPS, Odometer, etc.) and the corresponding quantities derived from the navigation solution. The Kalman Filter structure is such that all information is blended (i.e., integrated) in an optimal fashion and is closely related to the more familiar concept of recursive least-squares estimation. Effective use of the Kalman Filter requires knowledge of the following important elements:

- A model for the dynamic variations in the state. This takes the form of a set of differential or difference equations.
- A model for the constant and random errors that act as the forcing functions to the dynamic state.
- A model for the constant and random errors that appear in the measurements which augment or "aid" the navigation solution.

The outstanding attribute of the Kalman Filter is that it allows all of the above elements to be accounted for in a very systematic and formalized way, making it ideal for implementation in a digital computer. The following discussion summarizes the steps implicit in the implementation of the Kalman Filter.

C.2 Error Covariance Matrix Propagation

Consider a system whose behavior is defined by the following set of discrete linear equations:

$$X_n = \Phi_n X_{n-1} + B_n \eta_n \qquad \text{(C-1)}$$

where

X = vector of states

η = vector of random (zero-mean) noise sequences

Φ_n = state transition matrix from $(n-1)^{th}$ to n*th* update points

B_n = noise distribution matrix

For a given η and *B*, the state *X* will have a time variation determined by the particular noise sequence, η, and initial condition, X_0, which in general is taken to be a randomly distributed quantity. Since the noise sequence, η, has an infinite number of realizations, and the initial condition error can assume an infinite number of values, the system given by (C-1) has an infinite number of solutions. Because this is true, attention must be focused on the statistical behavior of Equation (C-1) rather than on specific solutions.

The most natural and useful way of characterizing the behavior of (C-1) is to compute the statistical parameters that define the bounds on the state vector, *X*. The statistical bounds on the components of *X* are found by solving the covariance matrix equation associated with (C-1), which takes the recursive form:

$$P_n = \Phi_n P_{n-1} \Phi_n^T + B_n Q_n B_n^T \qquad \text{(C-2)}$$

where *P* is the error covariance matrix of the state vector, *X*, defined explicitly by:

$$P = [P_{ij}]$$

and

$$P_{ij} = E(x_i x_j)$$

in which *E* denotes the expectation operator. It is seen that the individual variances of the components of *X* are defined by the diagonal elements of *P*, with the joint expectations being defined by off-diagonal elements of *P*. The matrix *Q* in (C-2) is the covariance matrix of the driving noise vector, η, defined by:

$$Q = [q_{ij}]$$

in which

$$q_{ij} = E(\eta_i \eta_j)$$

C.3 Optimal Kalman Filtering

Consider the case where the discrete process defined by (C-1) represents the true dynamic propagation characteristics associated with a given linear system. For this case, assume that a measurement is made at the n^{th} measurement update time employing an external

measuring device, which allows a specific linear combination of the states to be directly monitored. A general way of stating this in mathematical terms is as follows:

$$y_n = H_n X + \xi_n \qquad \text{(C-3)}$$

where

y_n = vector of measurements

H_n = measurement matrix at nth measurement update time

ξ_n = measurement noise vector applicable to n^{th} measurement

and it is assumed that, in the general case, a number of independent measurements may become available simultaneously.

The optimal utilization of information introduced through a series of measurements of the form given by (C-3), to estimate the state vector X in a sequential fashion, is the central problem addressed by Kalman estimation theory, and has the following solution. After each measurement (or a sequence of measurements), the estimate of the state, X, is refreshed by the two-step procedure:

$$\hat{X}_n^- = \Phi_n \hat{X}_{n-1} \qquad \text{(C-4)}$$

$$\hat{X}_n = \hat{X}_n^- + K_n [y_n - H_n \hat{X}_n^-] \qquad \text{(C-5)}$$

where

$\hat{X}_n^-$ = optimal estimate of vector X just before the n^{th} measurement is processed

$\hat{X}_n$ = optimal estimate of vector X immediately after n^{th} measurement is processed

K_n = Kalman gain matrix at n^{th} measurement update with K_n defined by

$$K_n = P_n^- H_n^T (H_n P_n^- H_n^T + R_n)^{-1} \qquad \text{(C-6)}$$

in which

P_n^- = apriori error covariance matrix of vector X

R_n = measurement noise error covariance matrix and the apriori error covariance matrix, P_n^-, is computed from (C-2) over the interval t_{n-1} to t_n.

After processing the n^{th} measurement, the error covariance matrix of the state X is modified to reflect the benefit of incorporating new information introduced by the measurement, by means of:

$$P_n = (I - K_n H_n) P_n^- \qquad \text{(C-7)}$$

where P_n is the aposteriori error covariance matrix. The form given by (C-7) is applicable when the Kalman Filter is fully optimal; that is, when it is a full-state filter in which all components of X are fully accounted for in the mathematical model and, further, are re-estimated after each successive measurement is made available.

C.4 Suboptimal Kalman Filtering

Consider the case where, for computational simplicity, the state model associated with a given dynamic process is deliberately simplified by excluding one or more states. This type of simplification will lead to a state transition matrix having a reduced dimension to accommodate a state vector *X* similarly reduced in dimension.

Suppose that a Kalman filter of the optimal form expressed by (C-1) through (C-6) is used in conjunction with a modified reduced-state transition matrix, $\tilde{\Phi}$. The filter will compute a gain matrix ($\tilde{K}$) and apriori and aposteriori covariance matrices ($\tilde{P}^-, \tilde{P}$); however, these quantities are clearly different than would have been computed were the full-state representation of the process dynamics used. It is also true that the Kalman filter that corresponds to the reduced-state system no longer correctly predicts its own performance; that is, its covariance matrix does not convey a correct statistical measure of the errors in the components of *X*.

In order to account for the effect introduced by the ignored states of the dynamic system, it is necessary to perform a so-called "real-world/filter-world" evaluation. This constitutes a two-step process in the performance analysis. In the first step, the reduced-state mode that is actually implemented in the Kalman filter is used to establish $\tilde{K}, \tilde{P}^-,$ and $\tilde{P}$. These are the design (filter-world) quantities. As the filtering process evolves in time during the first step, the design gain matrix, $\tilde{K}$, is stored in a computer file for later access. In the second step of the procedure, the dynamic process is restored to full dimension, and a covariance analysis carried out to establish the real-world performance of the design Kalman filter. In this step, the apriori error covariance matrix [as defined by equation (C-2)] is computed using the full-state transition matrix. At a measurement update point, the gain matrix $\tilde{K}$ is read from the file created in the first step and used to compute the true (real-world) aposteriori error covariance matrix from :

$$P_n = (I - \tilde{K}_n H_n) P_n^- (I - \tilde{K}_n H_n)^T + \tilde{K}_n R_n \tilde{K}_n^T \qquad \text{(C-8)}$$

Equation (C-8) is the generalized form for the aposteriori error covariance matrix. This form (referred to as the "stabilized" or "Joseph's" form) reduces, when the filter is fully optimal, to the form expressed by (C-7). The covariance matrix computed in this manner then defines the true performance associated with the reduced-state design Kalman filter. The suboptimal filter evaluation approach is depicted in Figure c.2.

In doing the real-world/filter world evaluation, according to the methodology depicted in Figure c.2, certain precautions need to be taken to ensure a valid result. The methodology illustrated in Figure c.2 is not completely general, but provides a limited real-world/filter world capability that suffices for most problems. It is possible to mismatch the filter world and real world in any manner that does not produce a mismatch in either the state transition matrix, Φ, or the measurement matrix, *H*. Doing either invalidates the result. However, a great deal of flexibility exists within the context of these constraints to allow the desired mismatches to be produced. For example, a common mismatch that is desired is one where the design filter eliminates a number of sensor errors and states associated with the aiding device. This can be accomplished by setting the initial variance associated with each of these states to zero, with the variance of its driving noise also set to zero - which leads to a condition of complete "invisibility" of the state. On the second pass, the previously ignored error states are activated by setting the initial uncertainties and noise variances to their actual values so that the states are properly accounted for.

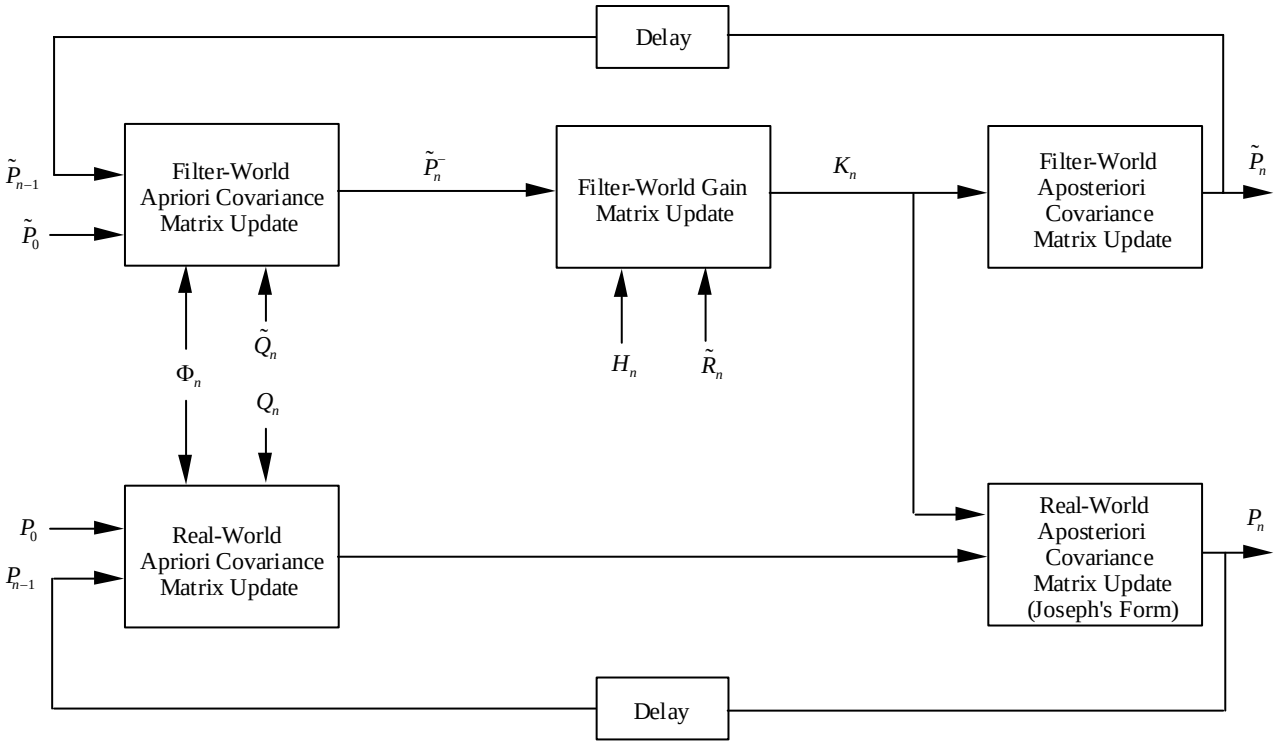

Figure C.2 Real World/Filter World Methodology

Appendix D. Measurement Error Models

This appendix derives linear error models applicable to satellite range measurement errors and their dependency on: satellite transmission errors, user receiver and clock errors, and inertially derived and odometer-derived position errors. The types of measurements assumed in the study, the linear error models of, which provide the basis for establishing system performance.

D.1 GPS Measurement Model

The Global Position System is a satellite based navigation system that provides measurements for a visible subset of 24 satellites. Each satellite transmits a carrier signal, which is modulated with a pseudo-random noise code that is synchronized with the satellites clock reference. The user's receiver generates an identical code, and the detected time shift in this code relative to that transmitted by the satellite allows the range to the satellite to be approximately determined. The measured range ("pseudo-range") will be in error due to: (a) user and satellite clock errors; and (b) ionospheric and tropospheric refraction errors. The satellite clock is an atomic clock, which receives periodic corrections from ground tracking stations and, for most practical purposes, may be considered perfect. The user's clock, on the other hand, is generally of lower accuracy and needs to be continuously adjusted via the measured GPS ranges utilizing a suitably chosen linear error model for the clock. Ionospheric refraction errors are correctable in some receivers (those having two transmitted frequencies), and tropospheric refraction errors may be partially compensated using empirical correction models.

In addition to pseudo-range, most receivers can also provide pseudo-range-rate measurements via the doppler shift in each satellite signal, that is the measured signal frequency is compared to the nominal transmitted frequency. Further, precise satellite ephemeris data is modulated on the transmitted signals, so that satellite position may be precisely established at all times.

Three principal factors; (a) receiver correlation accuracy, (b) travel delay errors and (c) satellite geometry establish the inherent position and velocity estimation accuracy possible with GPS. This third factor, which is the geometric determinant of position and velocity accuracy, is referred to as "GDOP" (geometric dilution of precision.

The basic outputs of the GPS receiver are, as noted, pseudo-range, pseudo-range-rate and ephemeris data. These allow the satellite's instantaneous position relative to the earth to be computed. The pseudo-range ($\tilde{\rho}$) is related to the true range (ρ) according to:

$$\tilde{\rho} = \rho + \lambda \frac{\delta\phi}{2\pi} + \eta_\rho \qquad \text{(D-1)}$$

where

$\delta\phi =$ clock phase error

$\lambda =$ wavelength of carrier signal

$\eta_\rho =$ random atmospheric refraction error

The range from the user to a given satellite may also be determined directly from the positions of the user and the satellite according to

$$\rho_c^2 = \rho_c \cdot \rho_c = (R^s - R) \cdot (R^s - R) \qquad \text{(D-2)}$$

where

R^s = vector from earth's center to satellite, expressed with coordinates in the local-vertical computational frame

R = vector from earth's center to the receiver, expressed with coordinates in the local-vertical computational frame

The error in the range, as computed in this manner, is given by:

$$\delta\rho_c = \frac{1}{\rho_c}[\delta R^c \cdot (R^s - R)]$$

$$= \delta R^c \cdot U_\rho \qquad \text{(D-3)}$$

where U_ρ is the unit vector defining the line connecting the receiver and the satellite, and the satellite's position is assumed to be known via its ephemeris data without error.

With (D-1) and (D-3), it is possible to express the measurement error equation for GPS range measurements as follows:

$$y = \delta\tilde{\rho} - \delta\rho = \lambda\frac{\delta\phi}{2\pi} + \delta R^c \cdot U_\rho + \eta_\rho \qquad \text{(D-4)}$$

Equation (D-4) constitutes the basic measurement error equation for GPS range measurements. The above relationship can be cast in a form suitable for Kalman Filter implementation as follows:

$$y = Hx + \eta \qquad \text{(D-5)}$$

where, in the case of interest here, the navigation error state vector is given by

$$x = (\psi_x^c \ \psi_y^c \ \psi_z^c \ \delta V_x^c \ \delta V_y^c \ \delta V_z^c \ \delta R_x^c \ \delta R_y^c \ \delta R_z^c)^T \qquad \text{(D-6)}$$

and the measurement matrix is defined as

$$H = [0 \ 0 \ 0 \ 0 \ 0 \ 0 \ U_{\rho_x} \ U_{\rho_y} \ U_{\rho_z}] \qquad \text{(D-7)}$$

where

$U_{\rho_x} \ U_{\rho_y} \ U_{\rho_z}$ = components of the pointing vector to the satellite, expressed with components in the local-vertical computational frame

To complete the linear error model for GPS range measurements, it is necessary to define a model for the variation for the receiver clock error states. Such a model is defined by the block diagram in Figure D.1 .

δf = clock frequency variation

$\delta\phi$ = clock phase variation

η_1, η_2 = white noise functions

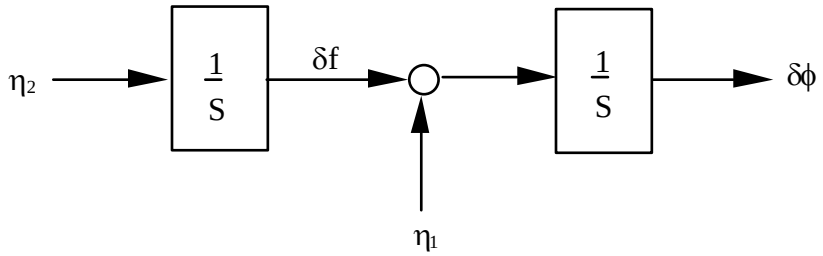

Figure D.1 GPS Clock Model

The model is composed of two integration processes that model the receiver clock phase error. The first integrator is driven by a white noise process, and creates a clock random-walk frequency error. The second integrator integrates the frequency error, together with a second random noise process, to create the clock random phase error. The spectral intensities are chosen in a manner that reflects the clock frequency and phase stabilities associated with a particular class of clocks.

D.2 Differential Carrier Phase GPS Measurement Equation

The most accurate use of GPS involves using the phase angle of the carrier signal together with a signal of the same frequency transmitted by a reference station having a precisely known position. Then instead of using the basic pseudo-range data, as defined above, the GPS carrier signals are used for position determination. This is accomplished in the following manner.

By comparing the carrier phase of the GPS transmitted signal, and the phase of the reference signal, a phase angle difference is obtained that, analogously with (D-4) is expressed as

$$y = \delta\tilde{\phi} - \delta\phi = N + \delta\phi_c + \delta R^c \cdot U_\rho + \eta_\phi \qquad \text{(D-9)}$$

where

$N =$ the integer number of carrier wave lengths between the user and the reference station

$\delta\phi_c$ = the clock phase error

$N_\phi =$ carrier phase measurement error due to multipath effects

It is seen then that, if the integer number of cycles, N, can be resolved and removed, a much more precise measurement will have been obtained relative to that defined by (D-4). This is due to the fact that the latter measurement is contaminated only by a random multipath error, whereas, the former is contaminated by a much larger random atmospheric refraction error. In all other respects the two measurement error equations are identical

insofar as they have the same contribution from receiver clock error, and from vehicle position error. An implicit assumption here is that the reference-station clock is of a much higher accuracy than the clock which would typically be included in the vehicle system.

D.3 Dead-Reckoned Position Measurement Equation

The measurement relationship for GPS aiding of the dead-reckoned position is analogous to that used for GPS aiding of the inertially derived position [Equation (D-4)]. The measurement error relationship is expressed for this case as:

$$y = \delta\tilde{\rho}_d - \delta\rho = \lambda\frac{\delta\phi}{2\pi} + \delta R \cdot U_\rho + \eta_\rho \qquad \text{(D-10)}$$

where

$\delta\rho_d =$ error in the range to a satellite based on use of dead-reckoned vehicle position and the known satellite position

$\delta R =$ error in the dead-reckoned position, as defined by Equation (B-7)

By comparing the carrier phase of the GPS transmitted signal, and the phase of the reference signal, a phase angle difference is obtained that, analogously with (D-9) is expressed as

$$y = \delta\tilde{\phi}_d - \delta\phi = N + \delta\phi_c + \delta R \cdot U_\rho + \eta_\phi \qquad \text{(D-11)}$$

where

$\delta\tilde{\phi}_d =$ phase angle based on dead-reckoned position

Equation (D-11) then provides the desired measurement error equation to be utilized in the integrated solution.

Appendix E. EDMap Task 8a Description

In the box below there is listed the initial description of the task of this study. This was given to Honeywell from the EDMap group. It is included here for reference.

EDMap Task8a Deliverables:

Provide an analysis of in-vehicle and infrastructure technology/capabilities that are part of current vehicle positioning systems, and predicted components of potentially deployable systems.

Deliverable 1 – Vehicle Positioning

A study of the current and future positioning systems shall be conducted. The purpose of this study is to identify factors and technology that will influence the OEM's ability to deploy precise vehicle positioning systems. This review shall, at a minimum, address:

1. GPS (Galileo, GLONASS, …) capabilities (accuracy, reliability, multi-path mitigation, acquisition times, differential corrections, cost, etc.).

2. Inertial system capabilities (accuracy, reliability, cost).

3. Integrated positioning system capabilities (GPS+INS, tight vs. loosely coupled, and other aiding approaches).

Appendix F. Acronyms

ASIC	Application Specific Integrated Circuit
AOR-W	Atlantic Ocean Region – West
BPSK	Bi Phase-Shift-Key
C/A	Course / Acquisition
CDMA	Code Division Multiple Access
COF	Continuity of Function
CONUS	Continental U.S.
CORS	Continuously Operating Reference Stations
DGPS	Differential GPS
DOD	U.S. Department of Defense
DOP	Dilution of Precision
DOT	Department of Transportation
DR	Delta Range
EDMap	Enhanced Digital Map
FCC	Federal Communications Commission
FOC	Final Operating Capability
FOM	Figure of Merit
GEO	Geosynchronous Orbit satellite
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GWEN	Ground Wave Emergency Network
HMI	Hazardously Misleading Information
IGEB	Interagency GPS Executive Board
ITU	International Telecommunication Union
IOC	Initial Operating Capability
L2CS	The new Civil Signal in the GPS L2 band
M-code	The new Military code signal to be transmitted on GPS L1 and L2
MEMS	Micro Electro Mechanical Systems
MEO	Medium Earth Orbit satellite
NAP	NDS Analysis Package
NDGPS	Nationwide Differential Global Positioning System
NDS	Nuclear Detection System

NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NSE	Navigation System Error
NTIA	National Telecommunications and Information Administration
POR	Pacific Ocean Region
PLL	Phase Locked Loop
PPS	Precise Positioning Service
PR	Pseudorange
PRN	Pseudo Random Noise
PSD	Power Spectral Density
PVT	Position, Velocity, and Time
QPSK	Quad Phase-Shift-Key
RHCP	Right Hand Circular Polarized
RTCA	Requirements and Technical Concepts for Aviation
RTCM	Radio Technical Commission for Maritime Services
SA	Selective Availability
SatNav	Satellite Navigation or GNSS
SIS	Signal in Space
SPS	Standard Positioning Service
TTFF	Time To First Fix
TSE	Total System Error
USCG	United States Coast Guard
UTC	Universal Coordinated Time
WAAS	Wide Area Augmentation System
WRC	World Radio Conference

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Conducted and Prepared by Schaffnit Consulting Inc.

for:

Crash Avoidance Metrics Partnership (CAMP)

IVI Enhanced Digital Map Project

January 31, 2002

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Chapter 1

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Executive Summary

Four major technology trends are having a cumulative effect in the area of wireless communications. These four trends are: increased processing capabilities, increased data storage capabilities, higher frequencies, and higher data rates. The net effects of these trends in the wireless realm are potentially much lower device costs, and increased bit rate capabilities.

Throughout the course of the wireless communications research conducted for the EDMap project, it has become increasingly obvious that there is unlikely to be a single wireless technology that meets the requirements of all EDMap applications. Instead, as the efficiencies and resulting economics of various wireless technologies are matched to appropriate applications over time, it is most likely that multiple communications technologies will be used in each vehicle.

Many automotive applications planners have assumed that cellular technologies will provide the only wireless communications channel for telematics and other automotive applications. While it seems obvious that many telematics applications will use cellular communications, there are limits to the applicability of this technology. The network latency, even with the newer 2.5G (transition from second generation (digital) cellular) data capabilities, will likely preclude the use of cellular systems to support many of the EDMap applications. In addition, the transition from 2.5G to 3G (third generation digital cellular technologies) cellular technologies in the ten-year time frame is likely to be fairly inconsequential for EDMap applications. Data rate expansion will be the main benefit of this transition in technologies, and EDMap applications do not seem to require high bandwidth communications.

Bluetooth gateways may allow personal digital assistants (PDAs), cell phones and laptops to effectively interface with the vehicle. Potentially, information available on the vehicle bus could be utilized in applications running on PDAs and cell phones, to provide virtual integration between carry-on devices and the vehicle. Although the operational parameters of Bluetooth limit its role in supporting most of the EDMap identified applications, it could be used to update navigational databases while the vehicle is parked in the garage, for example, or to download turn-by-turn directions for a driving destination.

DSRC (dedicated short range communications) technology will likely be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles in the 300 meter range, as well as between vehicles in close

proximity (most likely in the 100 meter range). As well, most of the applications identified by EDMap that require wireless communications are likely to require the enhanced capabilities of the 5.9 GHz (gigahertz) DSRC systems.

Automotive implementation cost considerations have not been the highest priority for the DSRC standards being developed, with the result that, for example, a requirement for three separate DSRC transceivers on each vehicle was being considered to provide vehicle-to-vehicle communications, intersection collision avoidance and emergency vehicle notification. The next two years will likely prove critical for the development of the full range of 5.9 GHz DSRC standards, with the next six-to-nine months representing the most intensely critical period. These DSRC standards have the potential to provide support for many automotive safety-related applications, but if detailed standards are not optimized for automotive applications, safety-related applications may be too costly, or too inefficiently supported, to become widely available at the earliest possible time. *Deployment of enhanced DSRC systems is likely to be one of the largest pacing items on the critical path for implementation of EDMap-envisioned applications in the United States*.

The potential for data broadcasting (one-way data transmissions from a single transmitter to many receivers, i.e., point-to-multipoint) from stratospheric platforms has particular relevance for EDMap applications. In-vehicle map databases could be continuously updated in this way, providing support for EDMap applications that require high accuracy database support with more dynamic information elements at the local/regional level. As location databases become more accurate, they also necessarily become more detailed. As the level of detail increases, the dynamic component of the database information increases significantly. Thus, increasing the accuracy of location databases requires more frequent, detailed updates to the database.

Although there are lingering questions concerning the long-term economic viability of Satellite Digital Audio Radio Services (SDARS) systems, if these systems do prove to be viable, they could be very important for EDMap safety applications. If satellite radio receivers become an integral, factory-installed part of every new vehicle, then SDARS has the potential to become an important, pre-existing communications channel into vehicles on a mass, point-to-multipoint basis.

There are a significant number of telematics-type applications that could potentially use terrestrial digital radio datacasting (shortened term for data broadcasting) to most efficiently and effectively communicate with vehicles. These types of applications are generally point-to-multipoint in nature, where the same information is sent to all the vehicles at the same time. In the ten-year time frame, a very effective potential use of datacasting over terrestrial radio systems is near real time, continuous updates of on-board geographical databases. Low-bandwidth, variable information, like work zone locations, lane closures, detours, malfunctioning traffic signals and time-of-day restrictions, for example, might best be conveyed to the vehicle databases through such point-to-multipoint systems.

In the five-year time frame, 802.11b systems (an Institute of Electrical and Electronic Engineers (IEEE) standard for wireless local area networks (LANs)) are likely to become nearly ubiquitous for home LANs. This will offer the opportunity for 802.11b-equipped vehicles to upload and download data through the home LAN while the vehicles are parked in the garage, assuming that the on-board systems can be powered at this time.

In the five-year planning horizon, one-meter positioning accuracy can be expected to be widely available from the combination of GPS (global positioning system) / NDGPS (nationwide differential GPS) signal reception and more processing power in receivers.

This should enable many of the applications identified by EDMap, assuming that navigational databases of sufficient detail and accuracy are also available in this time frame. Since the basic research on high accuracy capabilities is being conducted over the next year, it is not yet clearly determined if the planned NDGPS system will be sufficient to allow centimeter-level accuracy for receivers in moving vehicles in the longer-term.

Besides sensor applications, radar technology can also be used to communicate data from a roadside beacon to vehicles. With a high likelihood of at least forward-looking radar capabilities on future vehicles (in conjunction with adaptive cruise control (ACC)), a standards-based method of providing messaging capabilities for these systems could extend the vehicle's capabilities for deriving useful information from the roadside. These capabilities may be very complementary to DSRC capabilities, although some overlap is likely.

Safety applications, like those being studied by the EDMap project, generally require reliable wireless communications channels. As well, these safety applications generally require interoperability between the vehicles of different manufacturers, and between these vehicles and the road infrastructure. Remote Keyless Entry (RKE) systems, as they are currently designed, could not effectively support either of these requirements.

Access to two-way wireless data communications, with ubiquitous coverage over the continental US (as well as extended global coverage), provides a strong argument to consider two-way satellite services for applications that require ubiquitous wireless connectivity for vehicles. None of the EDMap applications appear to require ubiquitous coverage, however. Although not of particular relevance to EDMap applications, two-way broadband satellite systems should be reaching operational status in the ten-year planning horizon, if they are deployed at all.

The low-cost, small size characteristic of Ultra Wide Band (UWB) devices, coupled with their potential use as an integrated communications, positioning and radar solution, makes UWB a reasonable candidate to monitor for further developments facilitating its use for EDMap applications. One of the crucial hurdles facing the deployment of UWB is the potential for these systems to create harmful interference for existing services, especially GPS. Further research and experimentation is required to better understand the likely impact of UWB deployment within spectral ranges already licensed and/or assigned to other services.

A number of promising wireless technologies are being implemented, or planned for implementation, within the EDMap project planning horizon. *The wireless communications research has uncovered no fundamental wireless technological impediments to the deployment of the types of automotive safety applications being proposed.* There are, however, significant opportunities to exert positive influences on the development of specific wireless technologies that are likely to be the most critical components for support of the automotive safety applications identified by the EDMap project. *Current opportunities exist to exert positive, timely influence on the development of public policies and technological standards for DSRC and terrestrial digital radio. As well, there appears to be an immediate opportunity to encourage and facilitate the acceleration of research and development of high accuracy NDGPS, and potentially accelerate the deployment of this technology if the proposed level of accuracy proves to be achievable in practice.*

Chapter 2

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Introduction

This report documents wireless communications research that was conducted by Schaffnit Consulting, Inc. for the Crash Avoidance Metrics Partnership (CAMP) Enhanced Digital Map (EDMap) project during the second half of 2001.

Project Objectives:

The EDMap project is a three-year effort to develop map database specifications that enable or improve driver safety assistance systems. The main objective of the portion of the EDMap project (Task 8a) that is relevant to the wireless communications research is to "Provide an analysis of in-vehicle and infrastructure technology/capabilities that are part of current vehicle positioning systems, and predicted components of potentially deployable systems."

The wireless research conducted was focused upon Deliverable 2 – Vehicle-to-Infrastructure Communication under Task 8a in the EDMap Statement of Work. Specifically, the objective of Deliverable 2 is to "Provide an analysis of future wireless communication paths between infrastructure and vehicles for real-time position corrections, probe vehicle communication, and map information to vehicles." The research included consideration of wireless communication capabilities potentially suitable for vehicle-to-infrastructure and infrastructure-to-vehicle use to support, among other safety-related applications, probe vehicle data and map updates to vehicles.

Based upon existing wireless technologies, planned enhancements, emerging technologies, wireless technology trends and the industry experience of Schaffnit Consulting, eleven different wireless technologies (and technologies with a significant wireless component) were proposed for specific inclusion in this wireless research. These technologies were presented to the EDMap team at the project kick-off meeting. During initial stages of the research, two additional wireless technologies – NDGPS and RKE - were suggested for inclusion by members of the EDMap team.

These thirteen wireless technologies were analyzed to determine relevance both to the vehicle environment and the EDMap applications in the five and ten-year time frames (five and ten years after the completion of the EDMap project). The detailed results of these analyses are described in the following report. Later in the report, the results are

summarized and integrated into likely scenarios for the wireless environment for vehicles in the five and ten-year time frames. In the final section of the report, conclusions derived from the wireless research are presented.

A parallel research effort, conducted by Honeywell, has addressed the necessary GPS and DGPS developments to support the real time positional requirements, related to the map databases, that are necessary to enable the identified safety-related applications. In regards to wireless communications, the Honeywell research has addressed the reception of the GPS satellite signals, as well as reception of the Wide Area Augmentation (WAAS) signals. The interpretation of the GPS signals in conjunction with on-board positional sensors has also been incorporated in the research. The wireless research conducted by Schaffnit Consulting, and described in this report, includes consideration of the wireless reception of National Differential GPS (NDGPS) differential correction data. During coordination discussions between Honeywell and Schaffnit Consulting, the potential for integration of NDGPS capabilities into the proposed Honeywell ASIC was viewed as an important consideration.

The EDMap applications that have been used for the wireless research have been taken from the Task 1 report, and represent those applications that have communications requirements. These safety-related applications have been rated by the automotive manufacturers as having benefit when augmented by map databases.

Wireless Technology Trends:

All four of the following major technology trends are having a cumulative effect in the area of wireless communications. The net effects of these trends in the wireless realm are potentially much lower device costs, and increased bit rate capabilities (which generally translate into lower airtime costs per bit).

Increased Processing Capabilities: “Moore’s Law” predicted a doubling of processor capabilities every 18-24 months. This has been realized for microprocessor chips within the computer industry for many years, and is expected to remain realizable for at least the next ten years. Besides the increased processing capabilities, which enable totally new applications, decreased costs have been an important result of this technological progress. As well, the increased processing power has allowed the creation of small, low powered devices which contain significant amounts of computation abilities. Personal Digital Assistants (PDAs) and current generation cell phones are examples of this situation being applied to practical devices. Major progress in this direction is expected to continue for at least the next decade, fostering many applications which are currently not practical.

Increased Data Storage Capabilities: Along with data processing capabilities, data storage capabilities continue to escalate. The decreased cost of data storage has already enabled many new applications from digital cameras, through MP3 players, to vehicle on-board map databases. This trend is also expected to continue well into the future.

Higher Frequencies: The rapid developments in digital technologies have enabled a rapid escalation in the practical upper limits of radio frequencies. This has allowed the useable spectrum to be greatly expanded, and greatly increased the bandwidth available for wireless communications systems. This trend can be expected to continue in the foreseeable future.

Higher Data Rates: Besides the opening of new spectrum through expansion to higher frequencies, recently available digital technologies have enabled much more efficient use of available spectrum at all frequency ranges. The most revolutionary shift has been

conversion from analog technologies to digital technologies, which is almost complete for cellular systems, and is currently underway for television and radio broadcasting. The conversion from analog to digital typically allows five times more data to be carried over the same spectral allocation. After deploying digital communications systems, the rapidly advancing capabilities of digital signal processing can be utilized to continually increase spectral efficiency. With higher data rates and digital technologies, most media (including video, music, voice, graphics, computer files and email, for example) can be carried in digital format, allowing further increased efficiencies through bit stream multiplexing over common digital communications links.

Chapter 3

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Wireless Technology Areas

In this chapter, each of the thirteen sub-sections covers a wireless technology area. Each particular technology is described in detail, and projections on expected developments and deployments are provided. These sub-sections also include discussions of the expected relevance of each technology to the vehicular communications environment in five and ten years, with a focus on communications between infrastructure and vehicle, as well as between vehicles.

These detailed technology subsections are summarized in textual format in Chapter 4 and in tabular format in Chapter 5. Tables 5.1 and 5.2 in Chapter 5 provide a high level comparison view of the various wireless technologies' capabilities and costs in the five and ten year planning horizons.

2.5-3G PCS and Digital Cellular

The so-called "Third Generation" (3G) of cellular telephone technology has generated great expectations, as well as great confusion. The marketing focus for many wireless carriers has been to characterize their approach to new services as "3G", regardless of the underlying technology. The definition of 3G is therefore not widely agreed, and this has created quite a bit of misunderstanding regarding 3G wireless technologies and capabilities.

The International Telecommunications Union (ITU) has approved a standard for 3G – called IMT-2000 - that supports three over-the air technologies: Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA) and a combination CDMA/TDMA. The IMT-2000 standard represents a single international "umbrella" standard for future wireless communications. The ITU hopes to facilitate an "evolution along converging paths" that will support the deployment of low-cost, multi-mode, multi-band 3G handsets, allowing global roaming. The data rate target for 3G systems is 2 Mbps (megabits per second), with 384 Kbps (kilobits per second) for full speed mobile operations. http://www.itu.int/newsarchive/press/releases/1999/99-24.html, http://www.itu.int/imt/

Technology:

2.5G

The most significant, unifying concept for 2.5G technologies is the addition of data services to the existing over-the-air technologies of Global System for Mobile (GSM), TDMA and CDMA networks that are currently in use by wireless carriers in the US. These are called 2.5G to indicate that they represent a step from existing second generation wireless networks (2G) toward the 3G wireless networks defined by IMT-2000.

General Packet Radio Service (GPRS)

The standards for GPRS have been developed by the European Telecommunications Standards Institute (ETSI). GPRS uses a packet-mode technique to transfer digital data and signaling in an efficient manner over GSM radio networks. This protocol stack software provides the ability to pass Transmission Control Protocol/Internet Protocol (TCP/IP) or X.25 packet data across the air link, through the GSM/GPRS network and to/from the Internet. GPRS is therefore the immediate 2.5G packet data communications solution for GSM.

GPRS is also appropriate for other digital cellular technologies that use TDMA. In the US, IS 136 digital cellular (the US-only TDMA technology) will support GPRS. The US carriers using TDMA are therefore expected to implement GPRS.

This data solution allows for the use of the basic, existing digital cellular (GSM or IS 136) network structure, but requires major design changes in handsets and transceivers. For GSM networks, it is expected that GPRS will initially use 2 time slots and provide 19.2 Kbps data capacity. Even with the use of additional time slots, data rates above 50 Kbps are likely to be difficult for the GPRS technology to achieve. One additional, serious consideration is that GPRS suffers from high latency – in the range of 1.5 – 3.5 seconds.

Enhanced Data rates for GSM Evolution (EDGE)

EDGE is the next step beyond GPRS planned for US TDMA (and possibly GSM) networks. This packet data technology promises speeds up to 384 Kbps. EDGE uses the existing TDMA frame structure, but requires significant hardware and software changes to the existing network infrastructure. This transition affects the basic modulation scheme of the networks, which also places a linearity requirement on the power amplifiers at each cell site. EDGE achieves higher speeds by allocating more time slots to a single user, which significantly limits the number of high-speed data users within a channel. Although it is currently an important aspect of US TDMA carriers' plans, EDGE does not represent progress toward the W-CDMA 3G solution, and, if implemented, is likely to become another US-only technological anomaly in the 3G world. Of course, as discussed elsewhere in this report, 3G may be significantly delayed in the US because of the lack of available 3G spectrum, in which case the EDGE solution may have longer-term viability for the TDMA-based carriers.

CDMA2000 1x

1x is the first phase of CDMA2000 (the CDMA approach to 3G), and just means "one carrier". The 1x term was originally 1xRTT, which just meant "radio transmission technology." (http://www.cdmatech.com/about_cdma/faq/1x.html)

1x is a CDMA-based technology that provides qualitatively higher capacity and data transmission speeds using existing CDMA 1.25 MHz carriers. This means that current CDMA-based wireless carriers deploy this technology in their existing spectrum. Since 1x does not meet IMT-2000 3G requirements, it is considered a 2.5G technology. 1x does not require any changes to existing CDMA (cdmaOne) network radio hardware, but does require changes to network baseband hardware, as well as network software. The new technology is backward compatible with existing CDMA equipment, which allows existing cdmaOne handsets to be used with the new 1x networks. In comparison to cdmaOne, 1x allows voice capacity to be doubled, handset standby time to be improved by up to 50%, and bi-directional data transmissions up to 144 Kbps to be supported.

High Data Rate (HDR), 1x Evolution (1xEV)

HDR is a proprietary solution developed by QUALCOMM to provide high-speed data support via existing 1.25 MHz CDMA carrier channels. HDR is specifically designed to support IP-based (packet-switched) data. “The Telecommunications Industry Association (TIA) recently adopted a specification based on HDR, known as TIA/EIA/IS-856 "CDMA2000, High Rate Packet Data Air Interface Specification". This is also known as 1xEV. The 1xEV specification was developed by the Third Generation Partnership Project 2 (3GPP2), a partnership consisting of five telecommunications standards bodies: CWTS in China, ARIB and TTC in Japan, TTA in Korea and TIA in North America. QUALCOMM is pleased to have HDR move forward as 1xEV, part of the CDMA2000 technology family.” (http://www.qualcomm.com/hdr/about.html)

There is still a bit of confusion concerning the naming of this technology, and whether it can be properly considered 3G compliant. Many still consider it to be 2.5G, however, since it uses only one 1.25 MHz channel. The name of the technology has also been listed as “CDMA2000 1X Evolution Data-Optimized (1xEV-DO)”, but this is the same industry standard. 1xEV technology segregates voice and data onto separate channels, allowing for each channel to be optimized for its intended application – voice or data – and this allows higher capacity for each channel. A single 1.25 MHz channel optimized for data through 1xEV technology allows a maximum data rate of 2.4 Mbps in the download direction, and 307 Kbps for uploading data. The 1xEV data rate is actually faster than the 2 Mbps required for IMT-2000. This highlights the issue of whether or not IMT-2000 3G will be required in the US. As with cdma2000 1x technology, 1xEV requires new software and baseband hardware throughout the network, but uses existing 1.25 MHz radio components.

3G

“True” or “real” 3G refers to technologies meeting the ITU IMT-2000 standards, even though these standards have not yet been completed at the detailed network level. Although there are multiple technological approaches that seemingly meet IMT-2000 standards, the two that are most likely to be implemented are described in the following sections.

Wideband CDMA (W-CDMA)

W-CDMA (or WCDMA) was selected by ETSI (along with the hybrid TD-CDMA approach) as Europe’s universal mobile telecommunications system (UMTS) solution. W-CDMA also appears to be the preferred evolution path to 3G for most other GSM networks. W-CDMA uses the "direct spread" (DS) radio technique. Direct spread means

that W-CDMA will spread its transmissions over a wide, 5MHz carrier. Each of the 5 MHz channels that W-CDMA uses will support 100 simultaneous 8 Kbps voice calls, or 50 simultaneous packet data users at up to 384 Kbps of "bursty" data each.

CDMA2000 3x

CDMA2000 uses from one to three 1.25 MHz carriers to support high-speed data capabilities. The version with three carriers – CDMA2000 3x is a "true" IMT-2000 solution, since it meets all the established high level specifications of the ITU 3G standard. CDMA2000 3x is backward compatible with cdmaOne, allowing legacy handsets to be supported, but it requires new baseband and radio frequency hardware throughout the network, as well as new software. The joint facts that W-CDMA deployment is farther advanced than cdma200, and that 1xEV can provide faster data rates than W-CDMA using much less spectrum, mean that CDMA2000 3x may develop further still before being widely deployed. This could provide a further evolution path for US wireless carriers as 3G spectrum eventually becomes available in the US, and in other countries for W-CDMA networks that need to use their allocated spectrum more efficiently to carry more traffic.

Expected Developments:

The two 3G technologies that are expected to become dominant (W-CDMA and CDMA2000 3x) both use CDMA technology. Initial implementations are likely to have data capacity in the 144 Kbps range with full mobility. This data capacity is matched by the already-realized data capacity of CDMA2000 1x. Considering that a majority of Internet households and a significant portion of small businesses connect to the Internet through dial-up modems at a maximum data rate of 56 Kbps, the potential for wireless data connections over 2.5G and 3G networks seems to have a potential market. This assumes that the wireless airtime charges can be comparable to wireline costs. This is a significant question mark, since the costs of auctioned spectrum and new network equipment will need to be recovered through airtime charges.

The figure at the end of this section labeled "US Evolution of 2.5G / 3G" illustrates the likely development and deployment of wireless network technologies in the US in the five year planning horizon. There remain a number of questions even in this time frame, so the ten-year view has only been provided in textual format.

Likely Deployments:

A test version of 3G mobile telecommunications services, based on the W-CDMA version of the ITU IMT-2000 standards, was launched in May 2001 in Japan by DoCoMo. This was expanded to a limited commercial service offering in October. There have been a number of technical problems with the rollout of the commercial service, so this implementation seems a bit more like a beta test of proposed technology. It is always difficult to deploy systems for which the detailed standards have not yet been developed, and the detailed level of IMT-2000 and W-CDMA standards have not yet been fully completed. However, there are expected to be significant network implementations of 3G in Japan and Europe within the next year or two. One obstacle to the rapid rollout in Europe is that the spectrum auctions in most of Europe were very expensive and they consumed most of the capital available to the wireless carriers. Many of the European wireless carriers are therefore having a hard time raising the necessary capital for the new network equipment necessary for 3G.

In the US, new spectrum for 3G has not yet been made available by the Federal Communications Commission (FCC). The plan was to recover the television broadcast spectrum that is currently being used for analog television transmissions, and use that for 3G. The television broadcasters are supposed to vacate this spectrum in 2006, but have already begun lobbying to extend this date. Another proposal for US 3G involves spectrum that is currently used by the military. The argument against this approach is that it would be very expensive for the military applications to move to higher frequencies, and would take at least ten years. So this approach is probably less likely than the analog television spectrum. Without a clear view of when spectrum may become available for 3G in the US, wireless carriers are concentrating on improving the performance of their systems within their existing spectrum allocations. This is basically the 2.5G approach.

Relevance to Vehicle Communications Environment:

Many automotive applications planners have assumed that cellular technologies will provide the only wireless communications channel for telematics and other automotive applications. Since two-way voice services have driven the rollout of wireless networks in the US, it can be readily projected that systems designed to support voice applications will be readily available for vehicle communications applications.

While it seems obvious that many telematics applications will use cellular communications, there are limits to the applicability of this technology. In the US, cellular systems (as described above) are in the midst of constant change. One common standard has not been applied for these systems – an approach that encourages innovation, but hinders interoperability. The average lifecycle of a wireless handset is around two years, in contrast to the much longer average lifecycle of an automobile. The continuous, rapid turnover in handsets allows the networks systems to be changed frequently, introducing more features and capabilities.

The limited geographic coverage of cellular systems remains a significant issue for automotive applications. Most current “mayday”-type applications use analog cellular technology, since this is the most widely deployed in terms of geographic coverage. Even so, it is estimated that a substantial percentage of the geographical area of the US is not covered by these systems. This is one of the reasons that Volvo recently announced that their mayday service would be augmented with a two-way packet data system using Orbcomm satellite capabilities. As the new wireless technologies are deployed, the new services or capabilities are often targeted toward major urban centers, where population density, network congestion (and demand for new capabilities) are highest. The newer technologies generally make more efficient use of available spectrum, thus allowing more users to be supported on the same portion of spectrum. Unless there is a significant economic incentive to install newer technology in rural areas, the wireless carriers are generally content to leave older, existing systems in place, since system capacities are generally not being challenged by the low-density rural user base.

Many telematics applications have basically point-to-multipoint wireless communications requirements. Such telematics applications will therefore operate with much greater efficiencies (and lower costs) by using data broadcasting technologies, rather than “force-fitting” the required point-to-multipoint communications onto historically point-to-point technologies, like cellular. Real-time traffic information service is a good example of this observation. This service can currently be supported by datacasting over frequency modulation (FM) subcarrier technology (www.cue.net), or by using a cellular phone to call a voice portal or concierge-type service. During a traffic jam, or emergency situation, affected cellular sites often become overloaded, and access to traffic information, or

recommended emergency responses is unobtainable by cellular phone. The data broadcasting approach, however, simultaneously sends the same message to all the vehicles within transmission range, and depends upon intelligence in the vehicle to sort through the data to provide only pertinent information to the user.

Cellular networks have historically been inherently point-to-point technologies – one phone calls another phone. The standards for GPRS data include some provisions for point-to-multipoint data transmissions, but it is not certain if such capabilities will be implemented in US 2.5 and 3G cellular systems. It is also not clear if this point-to-multipoint capability is spectrum efficient, or is an example of "force fitting" the capability on top of the point-to-point technologies.

Five-Year:

In the five-year planning horizon, 2.5G cellular systems are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas. Also at this time, 3G systems will likely begin to be installed in major markets in the US. Interfaces to allow mobile devices to interconnect with vehicle network systems will become widely available in vehicles. This will allow, for example, web-based driving directions and maps to be downloaded for potential display using the vehicle's human-machine interface. Entertainment-type telematics services are also likely to be supported by the data communications capabilities of the 2.5-3G cellular systems in this time period.

Ten-Year:

High-bandwidth 3G systems are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas in the ten-year time frame. "Always on" packet data connectivity over these systems is likely to allow vehicles, by this time, to become as "connected" to the Internet as the typical small office, home office is today with DSL or cable modem connection. This connectivity will come at a price, however, since the very high expenses of auctioned spectrum and new network equipment will need to be repaid through compensatory airtime charges. Rural areas are expected to lag years behind in the deployment of new network technology, so "networked vehicle" connectivity is unlikely to be ubiquitous in the US within the foreseeable future. Additionally, there are still likely to be a number of competing technologies being deployed in the US, so region-by-region (and carrier-by-carrier) differences in wireless technologies are likely to be prevalent. Any critical wireless applications in vehicles that use primarily cellular communications will need to have alternative wireless communications channels to use whenever they are out of range of their main systems.

As the efficiencies and resulting economics of various wireless technologies are matched to appropriate applications over time, it is most likely that multiple communications technologies will be used in each vehicle. Applications, like entertainment, traffic information, or database updates, that can effectively use less expensive point-to-multipoint wireless communications technologies are likely to adopt this approach for cost reasons. The intelligence in the vehicle will be expected to transparently integrate data received through multiple communications channels into a cohesive set of information to present to the driver (or passengers). A similar "hybrid" data delivery approach is also likely to be used for fixed locations in this time frame, so the mobile developments will mirror wider trends in data communications technologies.

Relevance to EDMap Applications:

The “always on” packet data capabilities of the 2.5-3G cellular technologies will virtually eliminate the call set-up delays of data connections over current cellular systems. However, end-to-end latency is likely to remain in the range of at least several seconds, due to the server processing required in the mobile location registers, and the multiple packet forwarding necessary to deliver data to/from dynamically changing cellular sites. As well, data communications over these networks tend to be lower priority than voice communications, so data packets can be expected to encounter buffer-based latency if the networks are busy with voice traffic. These latency limitations will likely preclude the use of cellular communications for the majority of the EDMap applications’ wireless requirements.

Five-Year:

With widespread deployment of high-speed cellular data communications in major metropolitan areas, this technology may potentially be used to download location database updates. This could be useful for the types of updates that are in a limited dynamic range, but not instantaneous. GPRS, for example, has been designed to support both point-to-point and point-to-multipoint communications. If such point-to-multipoint capabilities are implemented in the US cellular networks and their respective handsets/transceivers, then 2.5G may provide an effective wireless medium over which location database updates could be downloaded.

If the point-to-multipoint capabilities for cellular data transmission are not widely deployed in the US, database downloads would be a bit awkward, since the database update server would be required to send the same update through separate unique messages to each individual vehicle. However, this approach is similar to the current Internet operation, where the detailed information is resident on an Internet server, and upon request from the client software (web browser), an up-to-date version of a specific view of the data (web page) is set to the client. Since the majority of EDMap applications require a high-accuracy location database to be on-board, however, the web-view model (delivered over cellular data communications) seems inappropriate for supporting EDMap database updating applications.

Besides the potential for locations database updates, there are two EDMap applications that might be readily supported through cellular communications in the five-year time frame, these applications are:

“Enhanced Route Planning and Guidance”; and

“Road Maintenance Aid”.

For the first application, one implementation scenario that lends itself to cellular communications is the utilization of a query-driven, network server-based architecture containing the necessary intelligence, with the vehicle-side interface being basically a “dumb terminal”.

In the case of the “Road Maintenance Aid” application, this might be a:

1. A query-drive request for roadside maintenance; or

2. An indication of maintenance work zone locations, requiring only a daily location database update.

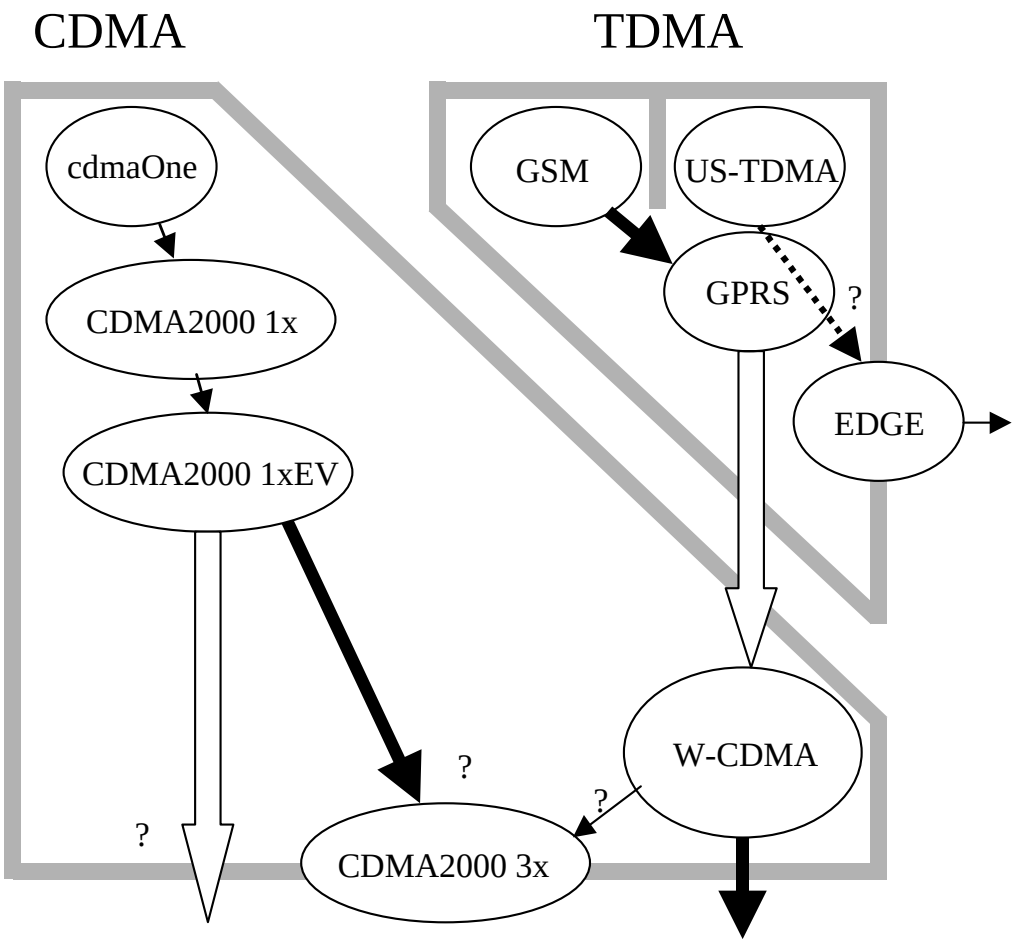
In either case, 2.5G cellular communications could be used to support the application.

Ten-Year:

For EDMap applications, the transition from 2.5G to 3G cellular technologies in the ten-year time frame is likely to be fairly inconsequential. Data rate expansion will be the main benefit of this transition in technologies, and EDMap applications do not seem to require high bandwidth communications. The network latency is unlikely to improve through this transition to 3G, so the relevance for EDMap applications is likely to be virtually the same as in the five-year perspective – that is, potentially downloading location database updates, and marginally support for the two applications described in the previous section.

US Evolution of 2.5G / 3G

"G"	Yr	Kbps
2	01	8-64
2.5	02	19.2-144
2.5+	03	384-2400
⇩	04	⇩ ?
3	05	2000-?



Source: Schaffnit Consulting, Inc.

Bluetooth

Bluetooth is an emerging industry group *de facto* standard that has the support of major telecommunications equipment manufacturers. “The Bluetooth Special Interest Group (SIG), comprised of leaders in the telecommunications, computing, and network industries, is driving development of the technology and bringing it to market. The Bluetooth SIG includes promoter companies 3Com, Ericsson, IBM, Intel, Lucent, Microsoft, Motorola, Nokia and Toshiba, and more than 2000 Adopter/Associate member companies.” (http://www.bluetooth.com/sig/sig/sig.asp)

This specification is designed to facilitate small-form factor, low-cost, short-range radio links between mobile PCs, mobile phones and other portable devices. It will allow the simple connection of a wide range of computing and telecommunications devices. Bluetooth supports rapid ad hoc connections, and the possibility of automatic, unconscious, connections between devices (http://www.handytel.com/technology/bluetooth01.htm).

Intended applications include wireless links between miniature headsets and cell phones, connections between PDAs and cell phones, laptops to printers, and generally replacement of cables interconnecting electronics devices. Implicit in these intentions is the need for extremely low-cost radio modules, and the parallel deployment of sufficient Bluetooth-enabled devices to create a viable community-of-interest to drive the market adoption of this technology.

Technology:

This technology represents a "multiple piconet structure" for radio frequency communications in the 2.45 GHz industrial, scientific and medical (ISM) band at data rates up to 1 Mbps (http://www.howstuffworks.com/bluetooth5.htm). This frequency is nearly universally available as unlicensed spectrum. The Bluetooth air interface is based on a nominal antenna power of 0dBm (decibel milliwatt), which meets the requirements for unlicensed operation in the ISM band.

Bluetooth offers both point-to-point and point-to-multipoint communications at a range of up to ten meters, but its range can be extended to more than 100 meters by increasing the transmit power. This increased power will be subject to power control and other more specific regulations for unlicensed operation in the ISM band, so cannot be considered reliable or predictably available at the 100 meter range. As well, the power amplifiers necessary to achieve 100 meter range will make the higher-powered units more expensive than the 0 dBm units.

nThe system can penetrate non-metallic obstacles, therefore line-of-sight is not required for communications. Bluetooth supports both isochronous and asynchronous communications, providing flexible support for both Internet protocol (TCP/IP) packets and voice channels, for example (http://www.handytel.com/technology/bluetooth05.htm). Security is provided within the protocol at the link layer, and the inherent frequency hopping arrangement makes over-the-air data interception difficult.

Expected Developments:

The main developments urgently required at this time are reductions in costs for Bluetooth modules. Many of the market projections have been based on a module price of approximately $5, but the current prices seem to be 4-5 times this amount. The higher powered versions of Bluetooth are estimated to be in the $20 per module range in the longer term. The Bluetooth standard is complete enough to allow standardized manufacturing to proceed, however, and prices should be able to be reduced as manufactured quantities increase.

Likely Deployments:

The first round of Bluetooth devices has now reached the marketplace. For example, Dell now carries a Bluetooth PC Card for laptops. Several of the cell phone manufacturers, like Nokia and Ericksson, now have Bluetooth-enabled cell phones available at the retail level.

The deployment of this technology seems to be best targeted toward uses that allow a long acquisition time (in the range of seconds) and lengthy "hold" times (in the range of hours) while connected to the network, much like the LAN technology characteristics.

Nokia predicts that: "In the future, Bluetooth is likely to be standard in tens of millions of mobile phones, PCs, laptops and a whole range of other electronic devices." (http://www.nokia.com/bluetooth/whatis.html)

Relevance to Vehicle Communications Environment:

Bluetooth shares the 2.4 GHz ISM band with many other unlicensed devices, including cordless phones, 802.11b devices, and a growing number of wireless consumer products. This means that Bluetooth communications have to accept interference and signal loss due to other devices operating at the same frequencies. Due to these characteristics of Bluetooth, it is viewed primarily as a way to connect mobile devices together. In the vehicle environment, this could take the likely form of a Bluetooth "gateway" to/from embedded vehicle networks. Such a gateway would provide the equivalent of a standard physical and electrical interface for connecting third party devices to the vehicle, as well as offering a virtual applications programming interface (API). This would allow PDAs, cell phones and laptops to effectively interface with the vehicle. Potentially, information available on the vehicle bus could be utilized in applications running on PDAs and cell phones, to provide virtual integration between carry-on devices and the vehicle.

An additional role can also be cast for Bluetooth as a vehicle to/from infrastructure communications channel for stationary vehicles in close proximity to the desired communications point. The long set up times and interference from other devices on the ISM band would not prevent Bluetooth from supporting electronic payments at fast food drive-thrus, for example, or communications between a garaged vehicle and the house. The stationary nature of these communications scenarios would allow sufficient time for the connection to be established, and long enough "hold" times to allow multiple repeats of messages when packet loss is experienced due to interference.

Five-Year:

In five years, widespread adoption of Bluetooth is expected (as long as prices can be reduced to the $5 range). Automotive Bluetooth gateways may provide the flexible connection necessary to support various modules for the multiple channels of wireless communications that are expected to be necessary to effectively and efficiently support telematics services. This arrangement would also allow for upgraded wireless communications modules to be easily installed to replace obsolete units. This is especially desirable with typical wireless technology progress creating 18 month product life cycles, and automotive product life cycles in the 8-10 year range.

Ten-Year:

In the 10-year horizon, Bluetooth could become ubiquitous after having time to meet cost targets. In another future scenario, however, Bluetooth could be outflanked by 802.11 developments, or supplanted by a new technology. Assuming that Bluetooth is able to meet its cost targets and become widely deployed, its relevance to vehicle communications is likely to remain in the connection of mobile devices to the vehicle network systems, due to set up times and packet loss through interference of other devices on the ISM band.

Relevance to EDMap Applications:

The operational parameters of Bluetooth, in terms of set up time and interference on the ISM band, limit its role in supporting critical safety applications, like most of the EDMap identified applications. However, like 802.11b LAN technology, it could be used to update navigational databases while the vehicle is parked in the garage, or download turn-by-turn directions for a driving destination (for example).

Five-Year:

If it occurs as planned, the widespread deployment of Bluetooth should be well-underway in the 5-year planning horizon. This means that inexpensive, low power, short-range communications within “pico-nets” could be assumed for the vehicle environment, as well as in general. If the Bluetooth gateway function is implemented in vehicles, functional components, like sensors, that support the EDMap applications could be connected to vehicle networks through Bluetooth channels.

Ten-Year:

In the 10-year time frame, no major enhancements are expected that would make Bluetooth any more likely to support EDMap identified applications. In this case, the relevance to EDMap applications would be essentially the same as in the 5-year view.

Dedicated (Digital) Short Range Communications (DSRC)

DSRC stands for Dedicated Short Range Communications, although it is also sometimes called Digital Short Range Communications. The title is fairly self-descriptive of the intentions for this category of wireless communications capabilities. Since this type of communications relates primarily to infrastructure-to/from-vehicle and vehicle-to-vehicle applications, there is an on-going attempt to create standards so that interoperability can be achieved.

Technology:

This communications systems category – DSRC – includes current deployments that are mainly used for Electronic Toll Collection (ETC) and various commercial vehicle identification applications. Technology has recently progressed to the point where much-higher frequencies have become commercially-viable for these systems, allowing planning and standards development to proceed for next-generation systems in the 5.8-5.9 GHz range. The current situation regarding DSRC plans to use these different frequencies is presented in the following subsections.

900 MHz:

Current DSRC systems in the United States use the 902 – 928 MHz frequencies for Location and Monitoring Services (LMS) on a "shared use" basis. IEEE Std 1455-1999, Standard for Message Sets for Vehicular/Roadside Communications, as well as ASTM standards at the physical and link layers, have been developed to provide a standard approach toward implementation of DSRC systems. However, "The ETTM (Electronic Toll and Traffic Management) field is rapidly evolving, and ETTM systems across North America use a variety of incompatible Dedicated Short Range Communications products. Plus, several Commercial Vehicle Operations mainline screening systems are now in operation and use incompatible data definitions." (http://standards.ieee.org/announcements/twoitsstds.html) In general, the 900 MHz systems of different manufacturers are not compatible with each other. This situation creates many scenarios where end-users need to install multiple tags to use contiguous systems. This condition has been noted for both electronic toll collection and commercial vehicle applications. In order to make progress toward standardization, the ITS Joint Program Office of U.S. DOT (Department of Transportation) has initiated a proposed rule-making to select available ASTM standards and relevant options at the physical and link layers, and IEEE Std 1455 at the applications layer for commercial vehicle operations (CVO) applications nationwide (http://www.its.dot.gov/tcomm/dsrc1299.htm). If adopted, this rule-making will only apply to new installations, so legacy (incompatible) systems are likely to remain for quite some time.

5.9 GHz US:

A number of standards development activities relating to DSRC were listed as "critical standards" for ITS by the U.S.DOT in 1999 (http://www.dot.gov/affairs/1999/fhwa4599.htm). Technology has recently progressed to the point where frequencies much higher than 900 MHz have become economically-viable for DSRC systems, allowing planning and standards development to proceed for next-generation systems. In 1999, as a result of efforts by ITS America, the FCC allocated 75

MHz of spectrum (5.850 – 5.925 GHz) for ITS applications, with ITS as a co-primary user. Other users sharing this spectrum are "some military radars and some satellite communications systems". The reasoning behind this priority use of spectrum is that many of the intended DSRC applications are potentially life-critical. Non-preferential spectrum use (like the international standards at 5.8 GHz) may create situations where other devices and services that share the spectrum could interfere with the critical DSRC applications and cause life-threatening results (http://www.its.dot.gov/tcomm/specqa.htm). All 17 of the critical standards identified for ITS in 1999 were completed and published by January 2001, except the DSRC standard at 5.9 GHz, so a great deal of pressure has been applied for the development of the 5.9 GHz DSRC standard.

The intended uses for the 75 MHz of spectrum in the 5.9 GHz range allocated by the FCC in 1999, in terms of applications, as well as the band plan and other technical standards, are presently under intensive development (please see next paragraph). The short-range communications capabilities represented by 5.9 GHz DSRC are viewed as extremely necessary to support many of the location-specific telematics services being planned. This type of system has the bandwidth and, potentially, other beneficial performance characteristics, to be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles, as well as between vehicles in close proximity, if the correct technological choices are made for the standards to be used in this spectrum.

In August, 2001, the DSRC 5.9 GHz Standards Writing Group, a sub-group of ASTM E17.51, selected the IEEE 802.11a R/A (roadside applications) as the standard physical layer to be used for 5.9 GHz DSRC. The fundamental advantages of this approach are that the 802.11a R/A physical layer uses the same Medium Access Control (MAC) layer as other 802.11-family physical layers, there are basic chip sets already available, and market momentum already exists for consumer devices utilizing 802.11a technology. A very recent proposal has been made for another task group within IEEE to develop the appropriate DSRC lower layer standards under a "fast track" approach. If this approach is followed to accelerate the standards development, there is a risk that compatibility with 802.11 may be compromised.

The ASTM E17.51 subcommittee has developed an action plan to complete the necessary standards for DSRC, ready for balloting in the various standards development organizations, in the next six-to-nine months. The committee plans to meet at least monthly, support a number of concurrent task forces, and work in close cooperation with the IEEE and other, related standards development organizations to coordinate all aspects of DSRC standards in this aggressive time frame. The committee has included active participation from Canadian delegates, and is soliciting more active participation by Mexican participants, in order to ensure North American harmonization. There has also been an effort for active liason with European DSRC standards development organizations to help foster global harmonization.

The DSRC standards groups met from October 30th through November 1st, 2001, to organize task forces, assign chairmen, and agree on the proposed 5.9 GHz North American DSRC Band Plan for immediate recommendation to the FCC. The present band plan being proposed for the 5.9 GHz DSRC spectrum is for seven 10 MHz channels (in the US). These channels are to be categorized into "Public Safety" channels, "Private" channels, and "shared" (Public Safety and Private) channels (please see attached band plan diagram). The definition being proposed for "public safety services" and licensing eligibility for DSRC is that found in Section 337(f) (1) of the 1997 Communications Act. The DSRC standards group most recently met from December 4th through 6th

5.8 GHz International:

The International Telecommunications Union – Radio Sector (ITU-R) has recommended DSRC standards at 5.8 GHz for adoption (http://www.itsa.org/85256201003EFA03/0/1782651806D9A1C48525671D0057A1BC?Open&Highlight=2,DSRC). These standards were basically developed by the European Telecommunications Standards Institute (ETSI) in 1999 to provide support for DSRC applications in the 5.8 GHz Industrial, Scientific and Medical (ISM) band (http://www.etsi.org). These standards basically represent testing procedures for type-approval of DSRC devices. Japan DSRC standards also use the 5.8 GHz ISM band, and have been included in the ITU-R recommendations, so there is a movement toward worldwide harmonization for DSRC on the 5.8 GHz ISM band. The European Committee for Standardization (CEN) prepared a standard (CEN ENV 12253) to define the Road Transport and Traffic Telematics (RTTT) services that were to be supported by DSRC. However, there appear to be fairly flexible options available for different countries to use in terms of specific frequencies and modulations. Thus these standards do not yet ensure interoperability between systems. As well, there has been an effort for the 5.9 GHz DSRC standards development group in the United States to communicate with the DSRC standards groups elsewhere in the world, in the hopes of fostering international harmonization.

Expected Developments:

It appears likely that there will be effective worldwide DSRC standards in the 5.8 - 5.9 GHz range in the longer-term, as the member country differences in frequency and modulation are gradually harmonized. There are likely to be remaining options within the standards for quite some time, however, since legacy systems represent a substantial investment. The incentive to switch to a unified standard approach is one of economies of scale. In practice, it is generally true that the larger the market for a particular device, the lower the price.

The developments in the United States on 5.9 GHz are being studied by the ETSI group responsible for DSRC standards, with a view toward possible harmonization. The international community was able to find a nearly-universally available frequency range in the 2.4 GHz range for Bluetooth deployment, so it may be possible to locate a harmonized worldwide DSRC service at a fairly consistent frequency range in the 5.8-5.9 GHz range. If it does occur, this would be expected to be a longer-term development (10-15 years).

In the United States there is likely to be agreement on the major components of a 5.9 GHz set of standards for DSRC by the summer of 2002. These standards for the major components of 5.9 GHz DSRC are being planned to be presented for balloting within the various standards development organizations (SDOs) by the mid-2002 time frame.

A strategic consideration for enhanced DSRC at 5.9 GHz is that a slow rollout of systems, due to either slow standards development or unfavorable economics, could allow less effective and less efficient wireless communications technologies to be used to support some DSRC-type applications. This is possible because commercial telematics services of value to the end users will use whatever wireless communications channels are readily available to handle their immediate communications needs. Then, DSRC-type

applications that are desired by the end users will be added to the commercial systems (most likely in a proprietary format).

There are two separate strategic paths that could be pursued to help ensure the success of DSRC communications systems dedicated to ITS applications, if this is deemed to be a desirable outcome. The first strategic option is to have the government mandate the inclusion of standards-compliant enhanced DSRC devices in all new vehicles sold, and mandate the installation of standards-compliant enhanced DSRC transceivers in all new roadway infrastructure construction projects receiving federal funding. Automotive manufacturers are unlikely to find this approach desirable, because of the cost and engineering considerations. The government mandate approach may be more feasible in Europe and Japan, but even a major regional initiative of this nature might achieve a critical mass for enhanced DSRC deployment worldwide.

The second strategic option, perhaps more palatable in the United States, is to foster and facilitate commercially-viable services that would be able to use the capabilities of the enhanced DSRC systems to support profitable services, thus generating the economic justification for the installation of DSRC systems that can also be used to support safety-type applications. This objective could be accomplished through public-private partnerships, or through large-corporate direct involvement in facilitating innovative new telematics service providers.

Likely Deployments:

The current situation in the United States, with legacy systems (and their respective manufacturers) well-entrenched in ETC and CVO deployments, indicates a very-lengthy conversion to enhanced systems, unless additional compelling applications (which cannot operate over the legacy systems) are developed and aggressively marketed. If things move along smoothly at expected pace in the United States, fairly widespread deployment of enhanced DSRC systems is possible in the 2007 time frame. However, successful local and regional deployments are quite likely to be very noticeable within specific geographic areas in this time frame.

European and Japanese deployment of enhanced DSRC capabilities is likely to proceed more rapidly, since the telematics market is more advanced in these areas, and the respective governments are likely to strongly support the new telematics capabilities. As well, there are already 5.8 GHz standards-compliant devices being manufactured. However, compelling applications that depend upon the enhanced DSRC capabilities will be the critical deployment factor in this case, as well as in the United States. The DSRC standards work at 5.9 GHz in the United States is being closely monitored by the global community. If the United States standard proves to be successful, then there is a strong potential for it to be emulated, or duplicated, as an international standard. If the 802.11a R/A physical layer and related protocol stacks that are being set as standards in the United States are adopted in Europe and Japan, this could delay enhanced European and Japanese DSRC deployment to be more in line with the United States DSRC deployment timing. However, this development would help to ensure a homogenous global approach, which could create larger economies of scale and potentially be very beneficial for automotive manufacturers.

Relevance to Vehicle Communications Environment:

The short range communications capabilities represented by DSRC are viewed as extremely necessary to support many of the location-specific telematics services being

planned. This type of system will likely be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles, as well as between vehicles in close proximity. Current estimates are for vehicle-to-vehicle communications in the 50-100 meter range, routine infrastructure-to-vehicle communications in the 300 meter range, and emergency communications from stationary units, or units mounted on emergency vehicles, that can be received within a 1000 meter range.

The band plan being proposed in the United States for the 75 MHz of spectrum in the 5.9 GHz range has been under development for some time. It appears that 75 MHz of spectrum, due to frequency re-use with short range transmissions, will support a large number of concurrent applications for a great number of vehicles. Determination of whether the DSRC system currently being designed through the standards process will be able to provide sufficient bandwidth for all proposed applications must await further testing. However, this plan contains some aspects that may prove sub-optimal for the economical deployment of safety-related automotive applications. More elegant designs for on-board equipment (OBE) with current costs in the $250 range have been proposed. Alternately, less-capable OBEs (in the estimated current cost range of $80-100) could be specified. In the five year time frame, these costs could easily be reduced to one-third of the current cost levels, but $80+ manufacturers' cost for DSRC OBE could easily preclude the ready adoption of DSRC by the automotive industry, so cost is another potential "show stopper" for DSRC.

At a very preliminary level of evaluation, the automotive safety-related applications appear to have fairly low data rate requirements, but some require very low latency. Other interests that are well-represented in the DSRC standards group have agendas to promote high bandwidth, higher latency capabilities, and the higher bandwidth requirements may drive OBE prices higher. The standards process is an effective forum for the development of compromise solutions among participants with very different agendas. However, active participation in the standards development process at a sufficient level of technical detail is required to significantly affect the outcome of the standards process. The DSRC standards group has been soliciting more active involvement by automotive manufacturers, but has thus far not generated much active participation from the automotive industry. The DSRC standards group has included a number of obviously safety-related applications in their deliberations, but their deployment assumptions may or may not prove to be valid for mass-produced automotive applications.

Automotive implementation cost considerations have not been a high priority for the DSRC standards being developed, with the result that, for example, a requirement for three separate DSRC transceivers on each vehicle was being considered to provide vehicle-to-vehicle communications, intersection collision avoidance and emergency vehicle notification. As well, new safety-related applications with wireless communications requirements may be precluded from using 5.9 GHz DSRC communications, just because the DSRC standards are being developed without specific, detailed knowledge of these potential applications. This may slow, or even prevent, the timely introduction of valuable, new safety-related applications. *In general, automotive manufacturers have not been actively involved in the detailed development of the 5.9 GHz band plan, or other aspects of DSRC standards, in spite of the fact that they will be the ones mainly responsible for implementing the safety-related applications.*

The next two years will likely prove critical for the development of the full range of 5.9 GHz DSRC standards, with the next six-to-nine months representing the most intensely critical period. As of January, 2002, much of the fundamental lower layer structure for DSRC has

already been proposed by the DSRC group. For example, the diagram at the end of this section contains the proposed DSRC band plan that has been submitted to the FCC. This band plan inherently assumes the use of a control channel with designated switching to other service channels. This approach has been analyzed only at the most basic levels, and will require sophisticated simulation testing in order to even theoretically estimate the potential latency for critical safety applications. If this latency proves to be too long in cases where the DSRC channels are "loaded up" with a large number of vehicles and applications using this form of communications, then critical safety applications may not be able to be supported. This is a potential "show-stopper" for DSRC implementation by automotive manufacturers.

In addition to the basic uncertainties of the proposed lower layer DSRC structure, critical details for the DSRC standards (for example, layer management within the protocol stack and security) have only begun to be discussed. For safety applications in particular, the security considerations, like authentication of emergency broadcasts, are likely to take well over a year to reach the state of proposed standardization. The time required to complete the detailed work on these vital components of the DSRC standards suggests that a consistent, active participation by the automotive manufacturers would be very valuable in ensuring that the complete DSRC standards fully address the needs of automotive safety applications.

These DSRC standards have the potential to provide support for many automotive safety-related applications, but if detailed standards are not optimized for automotive applications, safety-related applications may be too costly, or too inefficiently supported, to become widely available at the earliest possible time. This situation could result in the unnecessary loss of life through accidents that are preventable by the earliest possible deployment of automotive safety-related applications. For this reason *it has become an urgent priority for automotive manufacturers, on a pre-competitive basis, and in close cooperation with the public sector, to actively participate in the development and testing of DSRC standards and technologies, especially within the next six-to-nine months.*

Five-Year:

If the automotive manufacturers are able to provide effective input into the DSRC standards development process to ensure cost effective DSRC systems that fully support the desired automotive safety-related and telematics applications, then the likelihood of significant deployment of these systems by 2007 increases dramatically. Due to the extensive infrastructure component, as well as the relatively slow (compared to consumer electronics devices, for example) turn-over in the installed base of automobiles in the United States, ubiquitous deployment of these systems is likely to take longer than five years. However, there are likely to be extensive deployments within certain geographical areas, particularly where desirable commercial applications have been effectively deployed and marketed. In the United States, there are also likely to be an increasing number of fairly simple commercial services, like electronic payments for gas, fast food, parking, etc., that depend upon the existing, basic 900 MHz systems.

In the five-year time frame, 5.8 GHz systems are likely to be gaining a significant installed base in Europe, Japan and other areas. These enhanced systems are likely to provide large bandwidth communications capabilities for vehicles at very specific locations. This capability is most likely to provide a complementary communications channel to the two-way, wider area wireless communications systems, like 3G, that will also be available in many vehicles. Of course, if the rest of the world decides to adopt the DSRC standards

being developed in the United States, then the deployment time frame in these regions could be expected to be similar to that in the United States.

Ten-Year:

By 2012, the United States is likely to experience fairly widespread deployment of enhanced DSRC, assuming that the standards development work progresses according to plan, and that the automotive manufacturers are able to provide effective input into the standards development process. This short range communications channel is most likely to be integrated into the vehicle, along with other multiple wireless communications channels, in order to provide the most efficient and effective wireless channel for each safety-related and telematics application, based upon the specific communications needs of each individual application.

Relevance to EDMap Applications:

DSRC, or a similar short range system, is a necessary component of many of the applications areas identified by EDMap (approximately 45% of EDMap applications, by rough estimates). For example, although some functions in “Enhanced Route Planning and Guidance” could be provided through a 3G communications channel, it is likely to be much more efficient and effective (and economical) to support these through DSRC channels. In another example, “train timing” information in the “Railroad Collision Avoidance” application might be able to fairly reliably exist in the navigation database, however, DSRC is likely to be a safer approach, since real time data of approaching trains could be used, rather than planned times. In other cases, like “traffic signal status”, only other immediate, real time systems could provide this information effectively. For the “Cooperative Collision Warning/Avoidance” application, the “communication with infrastructure” and “communications between vehicles” functions demand an immediate, real time communications system. *If detailed standards are developed correctly, then DSRC is likely to be about the only wireless communications system that can reasonably support such functions.*

To the credit of the DSRC standards development group, a number of potential automotive safety-related applications have been identified and analyzed for communications requirements. The diagram following the band plan diagram at the end of the DSRC section lists the applications under consideration by the DSRC standards group. By comparing this list with the EDMap list of applications, it becomes apparent that much more work remains to be completed to analyze the communications requirements of the additional applications identified by EDMap, and to actively insert these requirements into the basic requirements for DSRC, as well as the more detailed DSRC standards (like security) that will be developed over the next several years. Since much of the potential implementation of DSRC involves equipment that is functionally integrated with automobiles, the automotive manufacturers must be involved in the development of these detailed portions of the DSRC standards over the next two years. Much of the work over the next two years should involve hands-on automotive testing and verification, with prototype equipment and antennas mounted in actual vehicles, since, for example, antenna performance on various vehicle shapes and sizes would be very difficult to predict using theoretical methods.

Five-Year:

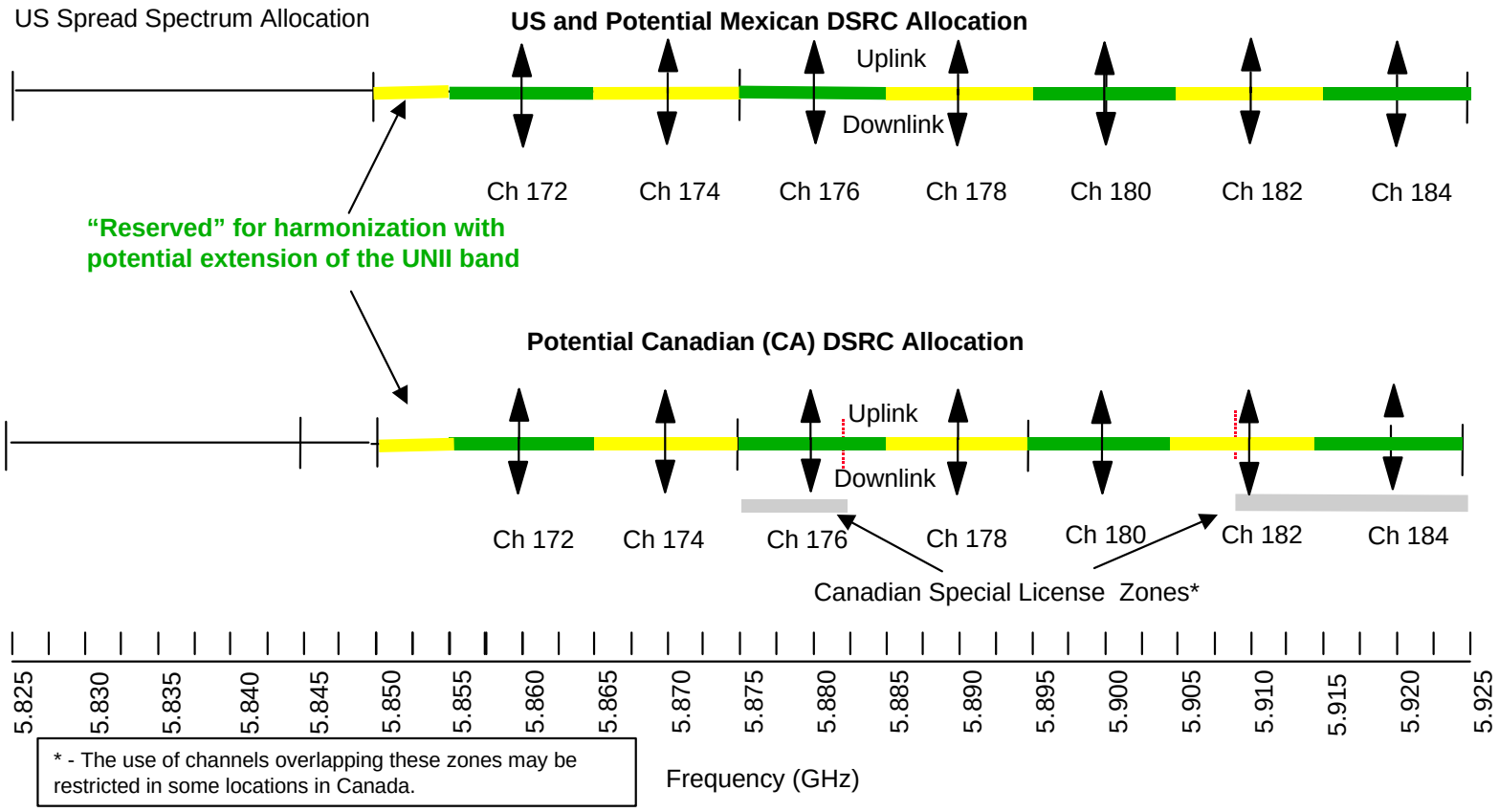
Even the basic 900 MHz DSRC systems (that are likely to continue to represent the bulk of DSRC systems deployed in the United States in five years) could be effectively used as vehicle probes, for example. Most of the applications identified by EDMap that require wireless communications, however, are likely to require the enhanced capabilities of the 5.9 GHz DSRC systems. Thus, *deployment of enhanced DSRC systems is likely to be one of the largest pacing items on the critical path for implementation in the United States of the roughly 45% of the EDMap-envisioned applications that have a potential communications requirement.*

Assuming that Europe and Japan proceed along the technology paths that they have currently set, some of the applications envisioned by EDMap are likely to be able to be implemented sooner in these regions, due to the widespread availability of high bit-rate, enhanced DSRC systems in the five-year time frame. The success of these services in Europe and Japan may even provide the impetus for more-rapid adoption of enhanced DSRC in the United States. There may be issues related to shared use of the 5.8 GHz spectrum, however, that encourage these regions to adopt the United States DSRC approach of dedicated spectrum for safety-related applications. If this is the case, then the DSRC roll out in these regions is most likely to closely approximate the United States roll out timing.

Ten-Year:

Assuming that automotive manufacturers are able to provide effective inputs to the DSRC standards development process to ensure cost effective systems, then widespread use of high bit-rate, 5.9 GHz DSRC systems seems very likely in the ten-year horizon. The expected wide availability of such systems in this time frame is likely to enable many of the applications envisioned by EDMap to be effectively implemented. The earlier success of such applications in Europe and Japan, if these regions continue with their current plans, is very likely to provide solid motivation for rolling out these applications in the United States.

5.9 GHz DSRC CHANNEL FREQUENCY ASSIGNMENTS (10 MHz CHANNELS)



Source: "5-9GHz_FCC_Rules_Brf_01_15_02" document discussed at DSRC meeting January 22-24, 2002

PUBLIC SAFETY and PRIVATE APPLICATIONS share the band

PUBLIC SAFETY

- PROBE DATA COLLECTION
- **TRAFFIC INFORMATION**
- TOLL COLLECTION
- **IN-VEHICLE SIGNING**
  - **WORK ZONE WARNING**
  - **HIGHWAY/RAIL INTERSECTION WARNING**
  - **ROAD CONDITION WARNING**
- **INTERSECTION COLLISION AVOIDANCE**
- **VEHICLE TO VEHICLE**
  - **VEHICLE STOPPED or SLOWING WARNING**
  - **VEHICLE-VEHICLE COLLISION AVOIDANCE**
  - **IMMINENT COLLISION WARNING***
- **ROLLOVER WARNING**
- **LOW BRIDGE WARNING**
- MAINLINE SCREENING
- BORDER CLEARANCE
- ON-BOARD SAFETY DATA TRANSFER
- DRIVER'S DAILY LOG
- VEHICLE SAFETY INSPECTION
- **TRANSIT VEHICLE DATA TRANSFER (gate)**
- **TRANSIT VEHICLE SIGNAL PRIORITY**
- **EMERGENCY VEHICLE SIGNAL PREEMPTION**
- **EMERGENCY VEHICLE VIDEO RELAY**
- **EMERGENCY VEHICLE APPROACH WARNING**
- **TRANSIT VEHICLE DATA TRANSFER (yard)**
- **TRANSIT VEHICLE REFUELING**

PRIVATE

- **ACCESS CONTROL**
- GAS PAYMENT
- DRIVE-THRU PAYMENT
- **PARKING LOT PAYMENT**
- **DATA TRANSFER (IDB, J1708, J1939, PCI, etc.)**
  - **ATIS DATA**
  - **DIAGNOSTIC DATA**
  - **REPAIR-SERVICE RECORD**
  - **VEHICLE COMPUTER PROGRAM UPDATES**
  - **MAP and MUSIC DATA UPDATES**
- **RENTAL CAR PROCESSING**
- **UNIQUE CVO FLEET MANAGEMENT**
- **CVO TRUCK STOP DATA TRANSFER**
- **LOCOMOTIVE FUEL MONITORING**
- **LOCOMOTIVE DATA TRANSFER**

ATIS - Advanced Traveler Information Systems
CVO - Commercial Vehicle Operations
EV - Emergency Vehicles
IDB - ITS Data Bus

THRU – Through
REGULAR – Current 915 MHz Applications / Future Dual Mode .915 and 5.9 GHz Applications
BOLD - New 5.9 GHz Applications with Two-Way Communication
GREEN - New 5.9 GHz Applications with One-Way Communication

* - NEW as of 1/11/02

Source: "5-9GHz_FCC_Rules_Brf_01_15_02" document discussed at DSRC meeting January 22-24, 2002

Digital Television (DTV)

Digital Television (DTV) is the general term used to describe all digital television broadcasts and formats, including High Definition Television (HDTV), Standard Definition Television (SDTV) and the use of digital data broadcasting. DTV transmissions carry a high-speed bit stream, which can include packets of encoded video, audio, data and system information. As part of the ten-year conversion to DTV in the US, DTV is transmitted within the same frequency bands used for analog television, but broadcasters have each been given an additional channel to simulcast in analog and digital throughout the conversion period.

Technology:

The Advanced Television Systems Committee (ATSC) Digital Television Standard (A/53), was adopted by the FCC in 1996 as the DTV standard for the US. This standard utilizes the 8-Level Vestigial Side-band (8-VSB) modulation method as the basis for digital transmissions. The ATSC is an international standards development organization specializing in advanced television systems (http://www.atsc.org/). The ATSC DTV Standard has also been adopted by Argentina, Canada, S. Korea, and Taiwan. Other areas in the world are deploying a DTV standard based upon the Coded Orthogonal Frequency Division Multiplex (COFDM) modulation method. Comparison performance testing of the two standards conducted at the request of the FCC in 1999 indicated that 8-VSB has about a five percent data rate advantage over COFDM. The 8-VSB modulation, however, is not applicable to mobile reception, while COFDM is well-suited for mobile applications. Since mobile reception was not an established criterion for DTV in the US, the FCC reaffirmed the ATSC standard including 8-VSB modulation after the 1999 testing.

Expected Developments:

Continuous improvements in the DTV receivers are expected to improve system performance over time, particularly in the areas of indoor reception and signal acquisition. There are no obvious efforts underway to facilitate the use of the ATSC system for mobile applications.

Likely Deployments:

By 2006, DTV is planned to totally replace analog television in the US. The FCC requires that broadcasters vacate their analog spectrum by 2006, although lobbying has already begun to extend this date. Whatever the outcome of the lobbying efforts, however, it is expected that there will be extensive deployment of DTV transmissions, and that DTV receivers will be widely available, by 2006.

Relevance to Vehicle Communications Environment:

The vestigial sideband approach adopted for the ATSC DTV standard is not readily applicable for mobile applications. Without major technological breakthroughs in antennas and receivers, the vestigial sideband DTV system will not be at all relevant to the vehicle communications environment.

Five-Year:

In the US, the ATSC system will be just reaching market penetration in the five-year time frame. Since this system is not useful for mobile applications, no relevance is expected in this time frame.

Ten-Year:

In the ten-year time frame, there is a potential for new technologies to be developed that would replace the ATSC system, or allow that system to be used for mobile applications. If these events occur, then DTV could provide high bandwidth, one-way data broadcasting channels to vehicles. This development would probably be most applicable for multimedia-type, entertainment applications in the vehicle.

Relevance to EDMap Applications:

In the US, DTV is not expected to be relevant for EDMap applications through the medium-term. Longer-term relevance is contingent upon technological developments for antennas and receivers, or else the development and adoption of a totally new DTV technology to replace the ATSC system (which is unlikely).

Five-Year:

Since the ATSC system is not useful for mobile applications, no relevance is for DTV in the US is expected in this time frame.

Ten-Year:

In the ten-year time frame, the most likely scenario for DTV's relevance to EDMap applications would be if new technologies are developed that would allow the ATSC system to be used for mobile applications. If this development is achieved, then DTV could provide high bandwidth, one-way transmissions to vehicles. However, EDMap applications are not expected to require high bandwidth, one-way communications, so, unless such wireless requirements arise for EDMap applications, DTV seems to be basically irrelevant.

High Altitude Platforms

There are presently several concepts under development to place a communications payload in the stratosphere over major population centers. High altitude platforms (HAPS) refers to systems currently being developed to place large, stationary, lighter-than-air platforms at stratospheric altitudes (around 70,000 feet) over major metropolitan areas for the purpose of providing wireless communications services. A US company called Sky Station is pursuing this approach on a global basis. (http://www.skystation.com) These large, remotely/automatically piloted platforms would be put into station-keeping flight for extended periods (years at a time). The current plans call for solar powered platforms over 500 feet long.

Another approach, using High Altitude Long Operation Aircraft (HALO™) flying over major metropolitan areas between 50,000 and 60,000 feet is being pursued by Angel Technologies. (http://www.angeltechnologies.com) These aircraft will be piloted and flown in multiple shifts per day to provide 24/7 service.

Technology:

Both of the identified companies are focusing on wireless broadband technologies and markets initially. Sky Station has secured spectrum in the 47/48 GHz range from the FCC in the US, and has been successful in having this same spectrum designated for HAPS on a worldwide basis by the World Radiocommunications Conference 2000 (WRC-2000), the worldwide spectrum authority of the International Telecommunications Union (ITU).

Angel Technologies is planning to use Local Multipoint Distribution System (LMDS) spectrum in the 28 GHz range that has already been auctioned for terrestrial use for wireless broadband. Angel Technologies hopes to be able to partner with existing license holders to gain the use of this spectrum in the desired locations.

Sky Station has also gained some WRC support for using HAPS as a 3G terrestrial platform. This approach could allow a very rapid implementation of 3G technology in a major metropolitan area, followed by build-out of more closely-spaced terrestrial cell sites as subscriber density develops.

Some of the most significant advantages of stratospheric communications in comparison to satellite services are the low latency (less than 0.5 millisecond compared to about 250 milliseconds for GEO-based services) and none of the hand-off problems that LEO-based technologies encounter.

Expected Developments:

Development of stratospheric communications systems has been underway for over five years, however, this is still very new technology. It is expected that prototypes of the platforms will fly within the next year or two. The 28 GHz wireless communications technologies are already available for terrestrial wireless broadband, but the 47 GHz equipment is at a more preliminary stage of development.

Likely Deployments:

If the prototype platforms prove to be successful, deployment of commercial platforms could follow very rapidly. Unlike satellite systems, deployment can proceed on a city-by-city basis. It is estimated that 250 stratospheric platforms could provide global coverage (presumably of population, since all major population centers would be included). With up to 75 miles radial coverage from each platform, significant geographical coverage would also be achieved.

The advantages of having a "cell tower" at 70,000 feet over a major metropolitan area are obvious. It is expected that, if regulatory hurdles can be overcome, new wireless technologies (like 3G) may be rapidly deployed using a stratospheric platform for initial deployment. As the number of subscribers increases to the point where the single "cell site" becomes overloaded with traffic, a second stratospheric platform could be added. At some point of desired frequency reuse, smaller terrestrial cell sites would likely become more economical. This would allow the stratospheric platforms to be re-deployed with another new technology. This may be a sensible approach with the expected short life cycle for new cellular technologies.

One strength of the stratospheric platform approach is that multiple wireless communications technologies could be simultaneously supported on a single platform. The main limitations would be antenna spacing/interference between different technologies, and power and weight considerations. The anticipated payload capacity of each platform is in the 1700-2200 pound range. This capacity should allow multiple transceivers to be supported. By having a number of different wireless systems on board, the operation of the stratospheric platform can be supported by multiple applications, allowing costs to be distributed among the various applications. Since a system of stratospheric platforms is estimated to be an order of magnitude less expensive than a satellite-based system, such cost sharing could lead to affordable airtime rates.

Relevance to Vehicle Communications Environment:

The initial wireless broadband technologies that are being planned for the stratospheric platforms are unlikely to be useful for mobile applications. If 3G wireless technology is deployed on these platforms, however, this could provide high-bandwidth mobile communications capabilities for vehicles. For vehicular applications that require high-bandwidth, two-way communications capabilities, 3G communications using stratospheric platforms could provide a fairly rapid deployment path in major metropolitan areas.

Another significant consideration is the potential for data broadcasting (point-to-multipoint) from stratospheric platforms. This capability could be especially appealing for sending regional information to vehicles. Such local/regional information as traffic, weather, road work zones, as well as commercially-significant location-based information, could potentially be very well-supported by wireless datacasting from stratospheric platforms.

Five-Year:

If platform prototypes fly successfully in the next year, it is possible that commercial versions could be significantly deployed within the five-year time frame. The most likely scenario, however, is that roll-out will be delayed while the airborne transceivers and matching ground-based, end-user equipment for the 28-48 GHz "main application" of wireless broadband access is developed and commercialized.

Ten-Year:

Since the stratospheric platform approach represents very new technology, there is a real risk that the entire concept may not prove to feasible. However, if this is a feasible approach, then the ten-year time frame should allow enough time for these platforms to be deployed for most major metropolitan areas in the United States, at the least.

Relevance to EDMap Applications:

The potential for data broadcasting (point-to-multipoint) from stratospheric platforms has particular relevance for EDMap applications. In-vehicle map databases could be continuously updated in this way, providing support for EDMap applications that require high accuracy database support with more dynamic information elements at the local/regional level. As location databases become more accurate, they also necessarily become more detailed. As the level of detail increases, the dynamic component of the database information increases significantly. Thus, increasing the accuracy of location databases requires more frequent, detailed updates to the database.

Data broadcasting can accomplish this objective of detailed database updates in near-real time. In fact, with the low latency of stratospheric platform wireless data broadcasting (or terrestrial data broadcasting), these systems may be able to meet the most extreme low latency requirements for many of the EDMap applications. If the overall system latencies do not prevent this, then some of the infrastructure-to-vehicle communications could be accomplished in a “centralized” way by using data broadcasting. One example might be traffic signal status information. It is conceivable that sufficient data broadcasting bandwidth could be available from a stratospheric platform to send the instantaneous status of all traffic signals in a metropolitan area to all vehicles in the area. This might be a much more economical approach, and much quicker to implement than equipping all traffic signals with short-range wireless transmitters, for example.

Five-Year:

In the most likely deployment scenario these systems are not expected to be widely-deployed in the five-year time frame.

Ten-Year:

In the ten-tear time frame, however, the potential relevance for EDMap applications becomes much higher. If the technology is actually proven to be successful, then nationwide coverage of major metropolitan areas could be accomplished very rapidly, certainly within a three-year period. Once the stratospheric platform technology is proven, then the main pacing item for deployment will likely be finding enough revenue-generating wireless applications to support a rapid-deployment business plan. The end result could be nationwide coverage of major metropolitan centers in the US within the ten-year horizon. If many of the EDMap applications being deployed in this time frame require high accuracy location database support, then there may be good synergy with the stratospheric platform deployment.

IEEE 802.11 Wireless LAN

The Institute of Electrical and Electronic Engineers (IEEE) Project 802 is targeted toward providing standards for Local Area Networks (LANs) and Metropolitan Area Networks (MANs). This portion of the IEEE is also called the LAN / MAN Standards Committee (LMSC). This standards effort comprises around 600 technical representatives who meet every four months to further the standards-setting developments. Subgroups within the LMSC work on standards for LANs and MANs using wireline and fiber connections, as well as wireless. The 802.11 Working Group is focused strictly on wireless LANs.

Technology:

The 802.11 standards were developed by the IEEE to support wireless LANs. These standards are focused toward the first two layers of the Open Systems Interconnection (OSI) Basic Reference Model (7 layer protocol model). There is a common 802.11 Medium Access Control (MAC) layer, representing OSI layer 2 functionality. There are also three physical layers (PHYs) in the existing 802.11 standards (infrared (IR), 2.4 GHz Frequency Hopping Spread Spectrum (FHSS), and 2.4 GHz Direct Sequence Spread Spectrum (DSSS)), while extensions to these physical layers are currently under development. The standard for 2.4 GHz spread spectrum wireless LAN was first agreed by the IEEE in 1997. In 1999, 802.11 was also agreed as an International Organization for Standardization (ISO) standard.

802.11a:

Task Group a (TGa) was tasked to develop a new 802.11 PHY for high speed operation in the newly available unlicensed national information structure (U-NII) bands in the 5GHz range. An orthogonal frequency division multiplexing (OFDM) system was chosen, and this PHY was agreed and added to the 802.11 standard as a supplement in 2000 (IEEE Std 802.11a-1999).

Although some modifications to 802.11 were also required, this PHY also operates with the 802.11 common MAC, so applications that have been built on top of the MAC can be supported on the new PHY. 802.11a offers data rates up to 54 Mbps. OFDM mitigates multipath and intersymbol interference at high data rates by simultaneously transmitting multiple subcarriers on orthogonal frequency channels. Each subcarrier is modulated at a low symbol rate. This allows higher data rates in total, with much less interference.

Some of the advantages of 5 GHz, compared to 2.4 GHz are: the unlicensed 5-GHz spectrum is available throughout much of the world; the broader spectrum allocation at 5 GHz enables higher data throughput; and, regulations limit interference from applications that require higher power levels (such as wireless local loop). Chip sets that implement 802.11a are currently becoming available, and some enterprise networking equipment that uses these new chips has reached the marketplace. It is likely to be several more years before this system reaches wide deployment, as costs need to be reduced and applications that require the additional bandwidth need to become more common.

802.11a R/A:

802.11a R/A (roadside applications) represents a variation of 802.11a that is optimized for highly mobile wireless communications, such as vehicle-from/to-infrastructure at highway speeds. This version of 802.11a recently achieved high visibility (August 2001) when the DSRC 5.9 GHz Standards Writing Group (a sub-group of ASTM E17.51) selected IEEE 802.11a R/A as the preferred technology to provide national interoperability for DSRC Public Safety-based applications.

This selection enables the initiation of the detailed standards work necessary to support short-range vehicle-to/from-infrastructure, and vehicle-to-vehicle, safety applications. The use of the 802.11 framework allows portability of applications that have been written for other 802.11 wireless LAN standards, as well as the use of existing development tools and libraries.

802.11b:

In 1999, 802.11 was updated, and the 802.11b standard for higher data rate PHY at 2.4 GHz was included. This new PHY extension uses high rate direct sequence spread spectrum to boost the maximum data throughput to 11 Mbps from the maximum of 2 Mbps in the original 802.11 standard. Also in 1999, 802.11b was embraced by Apple Computer for its commercial AirPort wireless LAN system. Since 1999, this standard has been widely adopted for home and office wireless LAN equipment. Internal modems for desktop computers and PC Card modems for laptop computers are now widely available to consumers. Using these modems in conjunction with a base unit provides a multi-user wireless LAN within an indoor range of approximately 30 meters. The range is much further (over 1000 meters) for line-of-sight communications outside.

This technology is based upon a mature standard, and there are receivers available from Lucent, Apple, Cisco and others in the $100-200 range (see http://shop1.outpost.com/product/61910 for example). The 802.11b wireless gateways are priced in the $200-1000 range. The units operate in the unlicensed 2.4 GHz band (the same as Bluetooth and HomeRF systems). It is commercially-available wireless broadband, operating in a part of the spectrum that, unlike third-generation, or 3G, mobile telephony, requires no license. This is the wireless technology that is currently being installed in Starbuck's coffee shops to support customers' wireless email and web browsing.

Expected Developments:

802.11b has become widely deployed in both offices and homes over the past two years. Further work is underway to add standards to support more security features, access points and other features that will improve 802.11b. In the longer term, the IEEE has established Task Group g (TGg) to "develop a higher speed(s) PHY extension to the 802.11b standard. As is the case within the 802.11 "family" of standards, the new PHY extension must be compatible with the IEEE 802.11 MAC. The maximum PHY data rate targeted by this project is at least 20 Mbps. The new extension shall implement all mandatory portions of the IEEE 802.11b PHY standard." (http://grouper.ieee.org/groups/802/11/index.html).

With the high data rates already possible within the 802.11a standard, this technology is likely to be enhanced with additional features as the development of equipment continues. With many new chipsets just becoming available, 802.11a equipment will become more widely available and less expensive.

Since 802.11a R/A has been chosen as the wireless communications standard to support 5.9 GHz DSRC, detailed development of this standard is expected to proceed fairly rapidly. Major portions of this standard are expected to be completed in the 6-9 month time frame, with completion of the detailed portions of the relevant standards likely over the subsequent 12-18 months.

The IEEE intends to ensure compatibility between systems operating on the same frequencies, particularly for newer standards which enhance older standards. This should help to facilitate the development of a gradual evolution of these systems toward more features and higher throughput.

Likely Deployments:

For 802.11b, the deployment of systems is expected to grow rapidly as more homes and small offices decide to network multiple computers with shared resources (the original rationale for office LANs), like printers, file servers and high-speed Internet access. In many of these cases, the installation of Category 5 wiring, for example, to support a wired LAN solution would be expensive or unsightly, or both. The wireless connectivity provided by 802.11b currently equals Ethernet 10baseT (basic 10 Mbps Ethernet) wired systems, and allows for flexible rearrangement of the terminal equipment throughout the wireless coverage area.

In the case of applications, like video, requiring higher speed connectivity, 802.11a will increasingly be deployed. This is most likely in larger offices initially, but could easily become more common in homes if these types of applications become common.

Relevance to Vehicle Communications Environment:

802.11a has been promoted for use in DSRC systems operating in the 5 GHz range. It became apparent, however, that modifications would need to be made to the standard to allow acquisition to be accomplished in a sufficiently short time with vehicles travelling at highway speeds. At a fixed location, like a home or office situation, there is no particular urgency for a “new” device within the range of a wireless LAN to identify itself to the network, log onto the network, request services, provide proper authentication, secure permission to access the requested services and exchange desired data. For a vehicle traveling at 60 miles per hour, however, 30 seconds of “handshaking” dialog to gain access to the network could put the vehicle out of wireless range before the desired data exchange could occur. Preliminary testing of the adaptation of 802.11a known as 802.11a R/A, indicates that the further development of this standard will be able to resolve these issues and provide a viable option for DSRC communications for vehicles at highway speeds.

One of the interesting implications of the choice of 802.11a R/A for DSRC is that there is a reasonably good chance that the same transceiver could be used for DSRC and 802.11a. This would open the possibility of DSRC equipment in vehicles also using the 5.8 GHz UNII band in slow speed or stationary situations for non-life-critical applications. This

flexibility could be used to add commercial applications to provide additional economic justification for the inclusion of on-board, unified DSRC/802.11a transceivers.

Both 802.11a and 802.11b (depending upon data rates required) could support the inclusion of vehicles in wireless home LANs. Such home systems could provide extensive data downloads to garaged vehicles, as well as allowing the vehicles to download non-time-critical information to wider area networks. If 802.11a R/A capabilities become commonly installed in vehicles, then this communications mode is likely to also be employed for garaged vehicle communications with home network systems, as would be possible with a unified DSRC/802.11a system.

Five-Year:

In the five year planning range, 802.11b systems are likely to become fairly ubiquitous in homes and small offices, and public “wireless islands” are likely to become very common. Some of these islands are likely to be targeted toward vehicles in slow, or parked, operation. Entertainment content, from games, to music, to movies, will be downloaded to vehicles in this manner, and web browsing and Internet email will also be supported this way.

If 802.11a R/A systems are able to be rapidly developed and implemented for vehicle applications, then these systems are likely to be achieving significant market penetration in the five-year time frame. As other technologies in the 5 GHz range reach technical maturity, the prices are likely to continue to fall. If significant interference is encountered on the unlicensed 2.4 GHz band (from microwave ovens, cordless phones, garage door openers and Bluetooth rollout), then 802.11a may become the preferred technology, if prices become competitive with 802.11b systems.

Ten-Year:

With the rapid changes in wireless LAN technologies, as evidenced in the rapidly evolving IEEE 802.11 standards since 1997, more radical changes can be expected. In the 10-year time frame, some of these radical innovations beyond 802.11a will have had time to develop into agreed standards, have chips and equipment manufactured, and build market presence. Although the exact nature of these developments is unclear, the past trends have been toward increased data throughput and higher frequencies. These trends probably provide clues toward the future directions of wireless LAN technological progress.

Relevance to EDMap Applications:

Because design parameters for wireless LANs typically enhance data speed at the cost of high speed mobility and acquisition time, for example, the main expected use of the 802.11b systems for EDMap applications is for navigational database downloads and updates while vehicles are parked, or moving very slowly. However, some basic testing of 802.11b systems have shown fairly good performance for moving vehicles as long as the network log-on/handshaking functions are disabled.

The expected rapid development of 802.11a R/A, in conjunction with the 5.9 GHz DSRC standards development activities in the United States, may provide a very effective short range wireless capability for the vehicle-to-vehicle and vehicle-to/from-infrastructure communications requirements of a number of the safety –related applications identified by the EDMap project (see also DSRC section). In order to ensure that these wireless

capabilities meet the communicaitons requirements of the EDMap and many other safety-related applications, effective collaboration will be required over the next several years among the automotive OEMs, standards development organizations (SDOs) and public sector organizations.

Five-Year:

In the 5-year time frame, 802.11b systems are likely to become nearly ubiquitous for home LANs. This will offer the opportunity for 802.11b-equipped vehicles to upload and download data through the home LAN while the vehicles are parked in the garage, assuming that the on-board systems can be powered at this time. Just using the first minute after startup, however, nearly an entire CD of data can be downloaded to the vehicle at 11 Mbps.

If 802.11a R/A systems are developed and implemented as rapidly as possible for vehicle safety applications, there should be significant availability of the technology components in the five-year time frame. *Although commercial applications may help drive the market penetration of 802.11a R/A technologies, it will require a concerted, long-term effort from automotive OEMs and public sector organizations to enable the type of mass deployment necessary to achieve the kinds of safety benefits identified by the EDMap project.*

Ten-Year:

In the 10-year horizon, higher data rates and higher frequencies are likely for wireless LAN systems. If the automotive OEMs and public sector organizations can establish an effective collaboration to foster 802.11a R/A deployment to support safety-related applications, this technology (and further, forward and backward compatible enhancements within the spirit of the IEEE 802 Working Group) could become ubiquitous within the ten-year horizon. This would then support the achievement of the types of benefits (savings in terms of lives and injuries) that have been identified by the EDMap project, both for applications identified by EDMap and other safety-related applications that require wireless communications but do not depend upon on-board map databases.

Nationwide Differential Global Positioning System (NDGPS)

The Global Positioning System (GPS) is a worldwide, satellite-based radio-navigation system developed by the United States Department of Defense. GPS was developed to support military applications, but the government then made the system available for limited accuracy civilian use. In May 2000 the intentional degradation of the GPS signals that limited accuracy for civilian users was removed. GPS is a worldwide system that is available 24/7 in any weather conditions.

The U.S. Coast Guard Navigation Center (NAVCEN) operates the maritime and nationwide differential GPS systems, comprising two control centers and over 60 remote broadcast sites. The differential GPS systems provide additional data to GPS receivers to improve the accuracy beyond what is possible with satellite-based GPS data alone (http://www.navcen.uscg.gov/dgps/default.htm). The Coast Guard is "part of the seven-agency partnership for the Department of Transportation's Nationwide Differential GPS expansion initiative to provide DGPS signals for public safety services. The Coast Guard brings its expertise in building, operating and maintaining DGPS sites to the partnership. The other members of the project include; U.S. Air Force, Federal Railroad Administration, U.S. Army Corps of Engineers, Federal Highway Administration, National Oceanic and Atmospheric Administration, and the Office of the Secretary of the DOT." (http://www.navcen.uscg.gov/dgps/ndgps/default.htm)

Technology:

The GPS system uses 24 satellites that broadcast their identification and very accurate time information. The satellites transmit on two L-band frequencies: L1 = 1575.42 MHz and L2 = 1227.6 MHz (http://tycho.usno.navy.mil/gpsinfo.html). Since the orbits of the satellites are very precisely known, triangulation algorithms can be used by GPS receivers to determine very precise location information, based upon reception of signals from at least four satellites (http://www.trimble.com/gps/triangulating1.html). This "raw" GPS data is able to provide around 20 meter accuracy, since "selective availability" (intentional degradation of the GPS signals to non-U.S. military users) was removed in May 2000 (http://www.navcen.uscg.gov/news/archive/2000/May/SA.htm). Garmin, one of the best-known manufacturers of GPS receivers, claims an average of 15 meter accuracy for its receivers (http://www.garmin.com/aboutGPS/), but actual field results in the 5 – 10 meter range are typical. Also according to Garmin, "newer receivers with WAAS (Wide Area Augmentation System) capability can improve accuracy to less than three meters on average" (http://www.garmin.com/aboutGPS/).

When fully deployed, the NDGPS system will use differential GPS reference station transmitter systems located throughout the country to broadcast additional information that can be used by GPS receivers to generate more accurate location estimates. These DGPS transmitters currently broadcast in the 450 KHz frequency range. Using NDGPS to augment the GPS system currently provides accuracy in the one-meter range for "good quality" receivers that are moving (such as those located in vehicles).

By using stationary DGPS receivers and recording the data for some time, then comparing this recorded data to standard reference data (this procedure is called "post-processing"), survey-quality receivers can provide sub-centimeter accuracy at the present time. By using carrier phase timing to enhance the pseudo random code at the receiver level (enabled by smaller, more capable and less expensive computing power), sub-centimeter accuracy for stationary receivers is well-established, without resorting to post-processing.

The Trimble web site is good resource for more details about this technique (http://www.trimble.com/gps/advanced3.html).). A more thorough examination of DGPS and GPS capabilities is in the positioning portion of the report.

Expected Developments:

The rapid adoption of GPS technology for commercial uses demonstrates the inherent usefulness of accurate positional information. System enhancements are likely to continue to be developed which will enable inexpensive receivers to achieve sub-centimeter accuracy over time.

A high accuracy demonstration project, funded by the Interagency GPS Executive Board, is currently underway, with active participation from the US Coast Guard and the Federal Highway Administration. The first phase of the project, which is already underway, involves using a single site corrections approach with test broadcasts from a single station. One additional test station has been proposed to be added, possibly in 2002, but funding seems to be the current constraint limiting the rate of progress. "The ultimate goal of High Accuracy DGPS is to provide 20 cm, three dimensional accuracy, with a 90% confidence level throughout the completed NDGPS network. High Accuracy DGPS will accomplish this by using the characteristics of the GPS frequency to provide decimeter level corrections. In order to achieve this level of accuracy both carrier and code phase observables will be broadcast on a different frequency than the current NDGPS Service." Approximately 100 KHz of spectrum in the 450 KHz range (just below the commercial AM broadcasting band) is available to this service. It is estimated that the necessary corrections data can be sent within approximately 1Kbps. This allows both portions of the NDGPS to operate within the same 100 KHz of available spectrum. As well, this arrangement will allow the use of a diplexer to simultaneously use the same antenna for both transmissions [http://www.navcen.uscg.gov/dgps/ndgps/Enhancements0106.htm].

In the January/February 2001 issue of Public Roads, James A. Arnold – a research electronics engineer with the Federal Highway Administration's Office of Operations Research and Development - states: "It is expected that immediate positioning will be routinely accurate to within 5 to 10 centimeters, which is the degree of accuracy that many transportation vehicles and transportation support services need to operate safely and successfully." [http://www.tfhrc.gov/pubrds/janfeb01/newapps.htm]. In a recent telephone conversation, Mr. Arnold, who has been actively involved in GPS technology planning and management for over seven years, re-iterated his belief in the ability of the NDGPS system to be enhanced to provide 5 to 10 centimeter accuracy by using multi-site techniques in conjunction with the proposed additional high accuracy NDGPS transmission capabilities that are currently under test.

At this point in time, it is not yet clear whether or not the planned NDGPS system, even with the high accuracy capabilities currently being researched, coupled with increased receiver processing power, will be sufficient to allow centimeter-level accuracy for receivers in moving vehicles. At some point, it may become necessary to establish micro-DGPS reference stations and transmitters at close intervals near the roadways upon which critical applications requiring this level of accuracy will be implemented. This is similar to the extremely high accuracy systems being deployed in the immediate vicinity of airports to provide positioning information for automated aircraft landing. In the case of motor vehicle applications, these local transmitters could use next generation DSRC communications, for example. Another option, which may be technically and economically possible, is to establish DGPS reference stations at future digital radio stations and use the digital data channel to broadcast the differential corrections information.

Likely Deployments:

With many public sector users having a vested interest in accurate DGPS, and the U.S. DOT having a leading role in the NDGPS rollout, rapid progress is expected in deployment of this system. However, there is some concern about achieving the desired rate of deployment, due to current funding levels: “Funding for this year is about half of the administration's request. Single coverage expected in 2002 is now hoped for the year 2003.” (http://www.navcen.uscg.gov/dgps/ndgps/default.htm)

It also appears that current funding levels are insufficient to rapidly determine if high accuracy NDGPS will be capable of providing a practical system to support positional accuracy of 20, 10 or 5 centimeters in moving vehicles. The development of high accuracy correction algorithms using a multi-reference-site approach will require additional research. Only upon the culmination of this research will the practical accuracy limits become apparent for differential corrections provided over a 300-400 kilometer radius (the distance range for current NDGPS beacons).

Relevance to Vehicle Communications Environment:

Very accurate positioning is a critical component for future vehicle systems. GPS satellite receivers can be expected to be a core component of the future vehicle communications requirement. In addition, for more critical positional applications, it seems certain that vehicles will require at least DGPS reception in order to approach the degree of positional accuracy desired, thus the NDGPS system, hopefully with carrier phase corrections, (or another one of the high-accuracy systems being tested) must be deployed to enable EDMap positioning requirements. The NDGPS system currently broadcasts this data in the 450 KHz frequency range, potentially requiring a dedicated receiver (and antenna). In addition, a potential need has been identified for the reception of supplementary DGPS information on a more localized basis than that likely to be provided by the currently planned NDGPS system. Potential candidate communications technologies for transmitting this additional positioning information are radio datacasting (both hybrid and terrestrial digital), and next generation DSRC.

Five-Year:

Within the view for 2007, NDGPS deployment can be expected to reach the point of dual-station coverage for the majority of the United States, assuming adequate funding becomes a stronger priority.

In this time frame, it will become apparent whether or not the NDGPS transmissions, high accuracy enhancements, and improved on-board receivers are capable of providing sufficiently accurate positioning for moving vehicles. However, this may be too late to begin planning for the implementation of supplementary DGPS systems, if necessary. Focused research would seem to be required to determine this need at an earlier time, so that any necessary planning could be completed in a timely manner. It appears that acceleration of the high accuracy NDGPS research could be achieved with increased funding priority.

Ten-Year:

It appears feasible to expect that vehicles will have sub-meter accuracy positioning capabilities by 2012. This is expected to require multiple (at least two) wireless communications capabilities for vehicles, and may also require very localized infrastructure development. If the DGPS is required to be extremely localized in terms of infrastructure, then vehicle applications that are dependent upon highly accurate positioning will likely be limited to major roadway segments, at least initially. A potential compromise between regional transmissions, like the current NDGPS beacons, and extremely localized transmissions, like DSRC micro-beacons, might be accomplished in the 2012 time frame through digital radio data broadcasting. The expected coverage radius for these stations is 30-50 kilometers, which represents an order of magnitude increase in precision over the 300-400 kilometer range of the NDGPS beacons. Thus, the digital radio data broadcasting approach, in conjunction with multi-site corrections techniques, may provide a viable alternative for the delivery of high accuracy positioning information to moving vehicles. Current belief is that the range to a reference station for carrier phase corrections can be extended from the current 20 kilometers to perhaps 100. It is not clear if the 300-400 kilometer range is achievable, although large scale 'network effects' may make this possible.

Relevance to EDMap Applications:

Accurate vehicle position determination on a continuous basis is an inherent requirement of almost all the applications identified by EDMap. However, it appears that many of these applications are likely to be able to function fairly well with 1-meter accuracy. Applications that appear to demand centimeter-level accuracy are: lane change advisory, extended lane change advisory, intersection turn assistant, automated headway and lanekeeping. Other applications that may require centimeter-level accuracy include: lane change assistant and ranging/imaging sensor calibration. Some path for providing differential corrections to the vehicles must be available for these applications, and they increase in reliability if meter level applications also make differential corrections attractive.

Five-Year:

In the 5-year planning horizon, 1-meter positioning accuracy can be expected to be widely available from the combination of GPS / NDGPS signal reception and more processing power in receivers. This should enable many of the applications identified by EDMap, assuming that navigational databases of sufficient detail and accuracy are also available in this time frame.

Ten-Year:

Sub-meter positioning accuracy can be expected to be widely available by 2012. If centimeter-level accuracy is not able to be achieved through the combination of GPS / NDGPS signal reception and more processing power in receivers, then there is a risk that availability of centimeter-level positioning may be confined to specific roadway segments, depending upon the level of DGPS localization that is required to achieve this accuracy. From an infrastructure cost standpoint, datacasting DGPS information over local digital radio stations is expected to be preferable to low-power roadside beacons using next generation DSRC, for example. This situation may be mitigated, however, if there are many other applications (especially commercial ones) that are enabled by the next generation DSRC capabilities, since the infrastructure costs would then be able to be supported by all of these applications.

Radar

Radar systems have long been used for speed enforcement. Newer systems are being designed for vehicles to provide sensing for Adaptive Cruise Control (ACC) and other proximity detection applications. Radar encompasses a wide range of frequencies, with traffic enforcement radar commonly in the K-band (around 24 GHz), and sensors operating in the 60-80 GHz range.

Technology:

Radar technology can also be used to communicate data from a roadside beacon to vehicles. For example, the Safety Warning System™ (SWS) uses 24 GHz radar detectors as messaging units to warn of road hazards ahead (http://www.safetyradar.com/main.asp?Page=about/index.asp&Page2=true). The message conveyed in minimal, at this point, comprising 7 bits. The 7 bits are used to "trigger" one of 64 stored text messages that can be displayed on the radar detectors, or played as a verbal message. This system was implemented in 1996, and approximately 10 million radar detectors in the United States now include this capability.

It may be possible to extend this messaging capability to support a wider range of telematics applications, but there are no known development efforts underway to accomplish this and the potential remains conjecture. If this enhancement to the capabilities of such a system is possible, then it could potentially support some of the communications tasks currently planned for DSRC. The effective range for the SWS system is up to 2 kilometers, but it is one-way, so it has characteristics that may be complementary to DSRC characteristics.

In addition, the successful operation of the SWS messaging system implies that other radar systems (e.g., ACC sensors) may also be able to support messaging capabilities. With the extremely short wavelengths of signals in the 10's of GHz range, directionality of the transmissions can be highly constrained through the antenna design. Directionality down to roadway single-lane is likely to be practical in the 50-100 meter range, with wider coverage expected as the range increases.

Internationally, a joint ETSI ERM RP08/CEN 278 WG9 Task Group has been assigned the task (among others) of studying "the requirements and compatibility issues related to further spectrum for RTTT applications in the context of the goal to achieve a global system, e.g. 5.9 GHz and *63-64 GHz*" (emphasis added) (http://www.etsi.org/ERM/ERMRP08_ToR.htm).

Expected Developments:

The basic capabilities of this technology are available now, with 64 "canned" messages already in place. Over the longer term, it is possible that the technology can be enhanced to support variable messages, greatly improving the flexibility of the system.

Even the current system could provide a very useful wireless communications component if it could be integrated with on-board telematics systems.

Likely Deployments:

With around 10 million SWS compatible radar detectors already in the field, the installed base is compelling, even if the existing system capabilities are quite limited. There are currently SWS transmitters installed in 32 States, primarily by DOTs. The transmitters are currently being used to broadcast warnings for school zones, school buses, police and fire, work zones, toll booths and hospital zones.

Work zone warning has been the most widely deployed use of the system. This has been effective, since non-SWS compatible radar detectors operating in the 24 GHz range are also activated by an SWS transmitter, essentially creating a “drone” radar, which has proven effective at reducing traffic speeds at work zones. By triggering radar detectors, even without specific messaging, in a percentage of the vehicles proceeding through a work zone, the overall traffic flow is slowed as the radar-equipped vehicles initiate a braking response to the radar indication and non-equipped vehicles respond to the braking of the equipped vehicles. In the near term, State DOTs in the United States are likely to continue with their deployment of SWS transmitters to enhance work zone safety. The transmitters are small enough to be mounted on mobile signage that announces the work zone, for example, providing for great flexibility in deployment.

It remains to be seen whether or not effective use will be made of the other messaging capabilities of the SWS system in the United States. One significant issue is that radar detectors are illegal in a number of areas. Another issue is that radar messaging transmitters (currently in the $5000 price range) typically must be purchased and installed by public sector organizations. It appears to be difficult to justify spending for such enhanced services when only a small portion of vehicles are equipped to receive the messages. Although much more expensive than SWS transmitters, variable message signs can often be justified for purchase and installation by public sector organizations precisely because the drivers of ALL vehicles can see these messages.

In other countries, deployment of SWS systems are proceeding. Some of the innovative installations are making use of mobile transmitters to inform of emergency vehicles active in the area, for example.

Relevance to Vehicle Communications Environment:

The SWS technology has demonstrated the potential usefulness of messaging applications over radar frequencies. With a high likelihood of at least forward-looking radar capabilities on future vehicles (in conjunction with ACC), a standards-based method of providing messaging capabilities for these systems could extend the vehicle’s capabilities for deriving useful information from the roadside. These capabilities may be very complementary to DSRC capabilities, although some overlap is likely.

One of the big questions about this technology concerns 2-way communications capabilities. The expense of transmitters operating in these frequency ranges is the most likely limiting factor regarding 2-way capabilities.

Five-Year:

In the 5-year time frame, a much greater percentage of the installed base of radar detectors can be expected to have the SWS capabilities. This means that on some routes, a significant proportion of vehicles will have this capability, even if it is provided through an isolated, stand-alone device in each vehicle.

Ten-Year:

By 2012, this technology (if such developments prove feasible and economical) could be enhanced to meet a large number of the short range wireless communications needs of telematics applications.

Relevance to EDMap Applications:

With enhancements to support variable message reception (receive only operation), radar communications could be used to support a number of the applications activities identified by EDMap. These could readily include such activities as construction zone information, road blockage, traffic speed, traffic density, guidance instruction, special instruction, traffic signal status, rail crossing information, and road condition. Additional activities that might also be supported include in-vehicle display of regulation signs, information signs, warning signs and other informational inputs. As well, assuming that transmitters become much less expensive over time, grade and road curvature, road surface type, friction coefficient, intersection location, speed limit and other immediate road infrastructure related information could also be conveyed to vehicles in this manner.

Five-Year:

Still using stand-alone receiver devices, primarily with the existing “canned messages”, in the 5-year horizon, this communications channel could still support a significant number of the wireless communications activities envisioned by EDMap. The following list of messages is taken from the SWS web site at (http://www.safetyradar.com/main.asp?Page=about/index.asp&Page2=true) and selecting the “list of SWS text messages”:

{PRIVATE**}Highway Construction / Maintenance**

- Work Zone Ahead
- Road Closed Ahead/Follow Detour
- Bridge Closed Ahead/Follow Detour
- Highway Work Crews Ahead
- Utility Work Crews Ahead
- All Traffic Follow Detour Ahead
- All Trucks Follow Detour Ahead
- Right Lane Closed Ahead
- Center Lane Closed Ahead
- Left Lane closed Ahead
- Stationary Police Vehicle Ahead
- Reserved for future use

Highway Hazard Zone Advisory

- Train Approaching/At Crossing

- Low Overpass Ahead
- Drawbridge Up
- Observe Bridge Weight Limit
- Rock Slide Area Ahead
- School Zone Ahead
- Road Narrows Ahead
- Sharp Curve Ahead
- Pedestrian Crossing Ahead
- Deer/Moose Crossing
- Blind/Deaf Child Area
- Steep Grade Ahead/Trucks Use Low Gear
- Accident Ahead
- Poor Road Surface Ahead
- School Bus Loading/Unloading
- No Passing Zone
- Dangerous Intersection Ahead
- Stationary Emergency Vehicle Ahead
- Reserved for future use

{PRIVATE**}Travel Information/Convenience**

- Rest Area Ahead
- Rest Area With Service Ahead
- 24 Hour Fuel Service Ahead
- Inspection Station Open
- Inspection Station Closed
- Reduced Speed Area Ahead
- Speed Limit Enforced
- Hazardous Materials Exit Ahead
- Congestion Ahead/Expect Delay
- Expect 10 Minute Delay
- Expect 20 Minute Delay
- Expect 30 Minute Delay
- Expect 1 Hour Delay
- Traffic Alert/Tune AM Radio
- Pay Toll Ahead
- Trucks Exit Right
- Trucks Exit Left
- Reserved for future use

Fast/Slow Moving Vehicles

- Emergency Vehicle In Transit
- Police In Pursuit
- Oversize Vehicle In Transit
- Slow Moving Vehicle

Weather Related Hazards

- High Wind Ahead
- Severe Weather Ahead
- Heavy Fog Ahead
- High Water/Flooding Ahead
- Ice On Bridge Ahead
- Ice On Road Ahead
- Blowing Dust Ahead
- Blowing Sand Ahead
- Blowing Snow White Out Ahead

- Reserved for future use

Ten-Year:

In the 10-year time frame, radar message reception could include variable short messages, and be integrated into vehicle telematics systems, thus providing support for a large number of wireless communications requirements to the vehicle from the immediate road infrastructure. The SWS system illustrates the potential of radar-based technology to support at least short message delivery to the vehicle from the road infrastructure.

Remote Keyless Entry (RKE)

This technological category refers to the wireless communications systems used to support pushing a button on a keyfob and having vehicle doors automatically lock/unlock, trunk automatically open, alarm automatically activate/deactivate, etc..

Technology:

Remote Keyless Entry systems have been used for a number of years. These systems are proprietary to each vehicle manufacturer, but typically use narrow, designated spectrum at 318, 418 and 433 MHz. (http://www.scsfrigette.com/html/products/security.htm) The keyfob portions of the system are simple, transmit-only devices, designed to be small and inexpensive, and to draw very little current from the small batteries in these devices. The receive portion of the system in the vehicle is designed to be inexpensive and to operate in an "always listening" mode that draws very little power from the vehicle battery. This is especially important for times when the vehicle is left parked for extended periods.

Expected Developments:

There appear to be market demands for increasing the number of vehicle functions that can be accessed from remote keyfob transmitters. For example, remote engine starting and engine disabling are features being promoted by aftermarket vendors. The balancing trend is that increasing the complexity of the keyfob transmitters increases the cost, size and complexity of the user interface. In addition, further complexity for the keyfob transmitters is likely to increase the current drawn from their batteries, increasing the required size of the batteries, or decreasing the life of the batteries.

At the protocol level, the RKE systems have been designed with very simple, proprietary systems to recognize only the coded signals arriving from the "matching" transmitter units. If more complex applications were to be designed into these systems, more capable protocol layers would need to be developed at the software level. In addition, more processing power would be required to support the more complex software.

Existing RKE systems are inherently one-way wireless channels. The keyfob units are transmitters, and the in-vehicle units are receivers. It is not expected that existing systems will be expanded to include two-way capabilities. Rather, it is more likely that other two-way systems will be used to support any wireless two-way capability requirements for RKE applications.

One interesting development is hands-free RKE. In this case, a radio-responsive identification device is carried by a person (could be embedded in a card, keyfob, etc.). When the person carrying one of these devices approaches the matching vehicle within a short distance (around 5 feet), the vehicle recognizes the identifications device, and automatically unlocks the doors without a button needing to be pushed. (http://www.visteon.com/technology/automotive/SaftySecurity_hnd_free_entry.html).

If Bluetooth gateways (integrated with the control bus systems) become common on vehicles, and Bluetooth remote modules become very inexpensive, there may be a movement to move the RKE functions onto Bluetooth technology. Since Bluetooth is

already a *de facto* international standard, this approach could generate economies of scale in the near term future, as well as providing a standard protocol stack for applications development.

Likely Deployments:

Although the frequencies of operation have been designated, there are no obvious efforts underway to create an industry-wide standard for RKE systems. These systems are therefore most likely to continue to be proprietary to each vehicle manufacturer.

Relevance to Vehicle Communications Environment:

The current RKE wireless systems are designed to be low-cost to manufacture, but reliable over time. The wireless linkage is not reliable from a communications standpoint, but if the first door unlock message does not get through, the user can just press the button again. The communications channels being used are fairly narrow, limiting the amount of data that could be effectively transmitted.

Five-Year:

In the five-year horizon, it is expected that RKE systems will remain basically the same as they are at the present time. They are currently very inexpensive and do their specific job very well, so major changes are unlikely. New features can be supported by the current wireless technologies.

Ten-Year:

In the ten-year perspective, it is likely that wireless technologies, other than the current proprietary RKE ones, will be used to support more advanced RKE-type applications. This replacement may include incorporation of the RKE-type functions into advanced mobile phones, or other mobile wireless devices normally worn, or carried, on the person.

Relevance to EDMap Applications:

Safety applications, like those being studied by the EDMap project, generally require reliable wireless communications channels. As well, these safety applications generally require interoperability between the vehicles of different manufacturers, and between these vehicles and the road infrastructure. RKE systems, as they are currently designed, could not effectively support either of these requirements.

Five-Year:

Since they are “always on”, it might be possible to redesign RKE receivers to receive map database downloads while the vehicle is parked in the garage. This would also require development of garage-based transmitters and interfaces to home computer network systems. Unless an industry-wide standard was developed, separate systems would have to be designed and marketed by each individual automobile manufacturer. It seems much more likely that other wireless systems that are already becoming available, or are under development, will be less expensive and more efficient for the data downloading task.

In the five-year horizon, it is expected that RKE systems will remain basically the same as they are at the present time, thus not of much relevance for EDMap applications.

Ten-Year:

If new wireless systems are deployed that support RKE-type applications, among other applications, then these systems may be useful for EDMap applications. However, the new wireless systems that may be able to “absorb” RKE functionality are most likely to be standardized wireless systems that are discussed under other research topic areas, such as 3G, Bluetooth and DSRC.

Satellite Digital Audio Radio Systems (SDARS)

Satellite Digital Audio Radio Systems (SDARS), namely XM Satellite Radio and Sirius Satellite Radio, have only very recently begun service in the US (4Q 2001 – XM, 1Q 2002 (planned) - Sirius). These systems are mainly targeted toward mobile users – people in automobiles. They both offer 50+ channels of near-CD quality digital audio programming, with nationwide coverage, and both use satellite delivery augmented by terrestrial repeaters. At this time, the technology of each system is proprietary, and XM receivers will not receive Sirius transmissions (and vice versa).

Technology:

These services operate at S-Band (2.310 – 2.360 GHz) frequencies for the downlink to vehicles. These frequencies have only been allocated by the WRC for SDARS in the US. Systems proposed for other parts of the world are expected to use other frequencies. Both the US systems contain digital bit streams sent to the vehicles. The digital bit streams could support any form of digital data – voice, graphics, control messages or file downloads, for example.

Receivers to convert the satellite audio into a form that existing automotive radios can utilize are the first to come to market. Automobile manufacturers are expected to have dealer options for the installation of embedded satellite radio receivers in many models of new vehicles beginning almost immediately.

Each of the digital “channels” available on these systems supports data transmissions in the range of 64 Kbps. This technology is inherently point-to-multipoint, so the 64 Kbps data channel would be available simultaneously on a nationwide basis. For audio services, the 64 Kbps is just used to provide compressed stereophonic streaming audio. The compression algorithms being used effectively provide near-CD quality audio over 64 Kbps digital “channels”.

Expected Developments:

The most likely future developments are in the area of receivers. It is expected that more companies will begin to manufacture SDARS receivers, and that features will improve while prices decrease.

Another critical receiver development is that the next generation receivers will be able to receive either XM or Sirius transmissions.

Some financial analysts have predicted that the US market for SDARS is only big enough to support one such player. If this is true, then some future consolidation of these two systems might be expected.

The subscription-based radio concept has yet to be proven in the market, so this, too, presents a significant economic risk for the long-term viability of these systems.

Likely Deployments:

Over the next several years, automobile manufacturers are likely to offer more factory options for satellite radio. This willingness of the automotive OEMs to promote satellite radio is due to the superior audio performance of satellite-based digital radio, and the enhanced selection of music and audio programming content. As well, automotive OEMs have become large equity participants in both XM Satellite Radio and Sirius Satellite Radio, so can be expected to facilitate the deployment of these systems.

Relevance to Vehicle Communications Environment:

The initial marketing focus for SDARS operators is to consider themselves “collections of national radio stations”, focusing on audio services. However, any digital data that would fit within the available SDARS bit stream could also be sent nationwide using these systems. Conceivably, a single data message sent through one of these systems could simultaneously reach every automobile (that has one of the satellite receivers) in the US. For vehicle communications that could effectively use a relatively inexpensive nationwide data channel, these systems may prove to be the most economical wireless communications method.

Five-Year:

Since the satellite infrastructure is already in place for both XM Satellite Radio and Sirius Satellite Radio, commercial service has been initiated, and receivers are already commercially available to receive the audio programming, SDARS data broadcasting to vehicles can be expected to be implemented within the five-year time frame.

It is expected that automotive OEMs, as equity participants in these SDARS systems, will be among the first users of data broadcasting over SDARS. Some suggested uses are upgrading in-vehicle software in embedded devices, and sending messages to categories of automotive customers.

Ten-Year:

If these systems prove to be economically viable in the longer-term, data broadcasting could become a more important component of the transmissions. This is based upon the expectation that data storage capacities will be greatly increased, and prices will greatly decrease in this time frame. This means that any information that does not have a near-real-time requirement (songs, non-breaking news stories, magazine articles, audio books, etc.) could be pre-stored in a vehicle on a daily basis (for example, through intelligent agents in a home-based network, and wireless downloads to the vehicle in the garage overnight). This would free up SDARS “airtime” for information download that was time-sensitive, down to the minutes, basis.

Relevance to EDMap Applications:

Many EDMap safety applications depend upon a very accurate, on-board location database in the vehicle. Updates to such an in-vehicle database that are time sensitive

from the “daily” range to the “up to the minutes” range might be effectively accomplished using SDARS data broadcasting. Even information more static than the “daily” range might be included, just because these receivers are already being put into vehicles to support the initial audio entertainment and information services. Since the major automotive OEMs are equity participants in the SDARS operators, they could strongly lobby for at least one 64 Kbps channel to support their data broadcasting interests. Some of these interests would be the EDMap-type safety applications that depend upon in-vehicle, detailed, up-to-date location databases.

One argument against this scenario is that the SDARS broadcasts are nationwide, and detailed location database updates are more pertinent on a local/regional basis. This follows from the realizations that much irrelevant location database information would potentially be received and stored on vehicles through a nationwide database update data broadcast. The system-wide economics would be the most likely deciding factor in such decisions.

Five-Year:

In the five-year time frame, data broadcasts could be readily implemented on SDARS systems to support location database updates enabling EDMap applications. The SDARS systems are already in place and operational. Receivers are being installed in new vehicles.

The two things that would be required to begin using these systems for providing database updates are:

1) designation of one SDARS “channel” for data broadcasting; and

2) design of on-board systems to extraction the relevant data from the SDARS transmissions and integrate the new data with the existing location database on the vehicle.

Ten-Year:

Although there are lingering questions concerning the long-term economic viability of SDARS systems, if these systems do prove to be viable, they could be very important for EDMap safety applications. If satellite radio receivers become an integral, factory-installed part of every new vehicle, then SDARS has the potential to become an important, pre-existing communications channel into vehicles on a mass, point-to-multipoint basis. The possibilities discussed in the five-year time frame could therefore become virtually ubiquitous in the ten-year time frame.

Terrestrial Digital Radio

The radio broadcasting industry is one of the last communications media to convert from analog to digital technologies. The reasons for digital conversion are compelling – nearly five times the information carrying capability for digital technologies, compared to analog technologies using the same spectrum. At the same time, radio broadcasters in the United States receive their spectrum in exchange for "public service", rather than having to bid for the spectrum at FCC auctions. These broadcasters have developed a strong lobbying voice in the National Association of Broadcasters.

Over the years, the radio broadcasting industry in the United States has achieved a carefully balanced relationship among competitors in each market, with special emphasis on population coverage (which relates directly to advertising revenues). This means that there is a strong vested interest in maintaining the status quo within the industry. However, Satellite Digital Audio Radio Services (SDARS) threaten to disturb this industry equilibrium in the near future. In the United States, XM Satellite Radio has already launched their service, and Sirius Satellite Radio intends to roll out its service in the near future (please see SDARS section for more information). The terrestrial broadcasters therefore have gained a strong desire to convert to digital technology to have the same audio quality as the satellite radio services. They are hoping to accomplish this within their current spectrum assignments through the In-Band, On-Channel (IBOC) approach, while maintaining their current population coverage and competitive equilibrium within markets.

At the same time, most of the rest of the world has decided to convert by assigning digital radio to new frequency bands. The Eureka 147 digital radio standard was recommended as a world wide standard by the ITU-R in recommendation BS.774 (http://www.itu.int/rec/recommendation.asp?type=folders&lang=e&parent=R-REC-BS.774) in 1995. This standard provides for very high quality audio transmission, as well as datacasting capabilities, but requires the allocation of new spectrum, with different propagation and coverage characteristics.

While two-way wireless systems will likely be most efficient for point-to-point communications, higher speed data capabilities on 3G systems will be expensive, for example, in terms of airtime charges. This situation is expected because of the cost of the required spectrum for 3G systems – in European auctions, the wireless carriers paid so much at the 3G spectrum auctions that they are having problems raising the necessary capital to actually build the 3G networks. All of these costs need to be recovered through airtime charges to end-users.

There are a significant number of telematics-type applications that could potentially use terrestrial digital radio datacasting to most efficiently and effectively communicate with vehicles. These types of applications are generally point-to-multipoint in nature, where the same information is sent to all the vehicles at the same time.

This situation indicates that vehicle communications systems will need to include multiple channels of wireless communications capabilities in order to minimize the communications expenses and still meet the necessary performance characteristics required for various telematics applications.

Technology:

In industry practice, the basic analog technologies for radio broadcasting have changed very little over time. Amplitude Modulation (AM) and Frequency Modulation (FM) transmission systems have been the standard approaches for radio broadcasting. These technologies have worked very well throughout the years, and there is a vast installed base of AM/FM receivers. The main problem with analog AM and FM systems is spectral efficiency. Digital systems are capable of broadcasting roughly five times the information content of analog systems within the same spectrum. Spectrum has become an increasingly scarce and valuable commodity as wireless communications systems have proliferated. Radio broadcasting is one of the last wireless services to convert to digital technology. Various "hybrid" systems have been deployed to combine digital data content with analog modulation systems. Some of these systems are described in the following section. The IBOC approach warrants its own section, even though the initial implementation of this system would actually be a hybrid system. The Eureka 147 technology is also described in its own section.

Hybrid:

In this section, the hybrid systems that place digital signals along with the current FM and AM analog signals (within the presently licensed spectral mask) are described. Although the transitional state for the IBOC system is hybrid, it is discussed in the next section.

FM subcarrier systems have been used for quite some time. In these systems, digital data is sent on subcarriers contained within the allowable spectral envelope of the FM station. These data signals are then received by special-purpose receivers that can extract the data from the main FM transmission. The normal FM audio receivers are not affected by this extra data. These types of systems have been used to provide paging, messaging and data broadcasting services, for example, as well as to provide telemetry control signals for energy management of household appliances (for example, see http://www.cue.net).

Most of the installed systems have a data throughput of around 1 Kbps, but newer subcarrier technologies have become available that support data rates of 16 Kbps, or more. The existing subcarrier systems, especially those with higher data throughputs, may not be fully compatible with IBOC systems, so the transitional period to digital radio is likely to create some uncertainty for the long-term availability of these wireless channels.

In the AM hybrid area, new technology has recently become available to embed digital data within the existing AM transmissions, without disturbing the analog audio signal. Mikros Systems Corporation, for example, has demonstrated a prototype system that can reliably provide 3 – 6 Kbps (and possibly as much as 16 Kbps) to mobile users at highway speeds (http://www.mikrossystems.com). This system is likely to be incompatible with IBOC hybrid AM mode, so implementation of this system is likely an interim step for the 5-10 year horizon.

In-Band, On-Channel (IBOC):

IBOC developments received a major boost in 2000, when Lucent Digital Radio and United States Advanced Digital Radio (who had been promoting competing IBOC technologies) merged to form iBiquity. iBiquity's IBOC system is currently under testing by the National Radio Systems Committee (NRSC), a joint committee of the National Association of Broadcasters (NAB) and the Consumer Electronics Association (CEA)

(http://www.nab.org/SciTech/nrsc.asp). iBiquity's stated timetable (http://www.ibiquity.com/navframe.html?02content.html) for IBOC development is to gain the approval and endorsement of the NRSC by the end of 2001, have the FCC make IBOC the standard technology for terrestrial digital radio in the United States in 2002, and have IBOC receivers in consumer market channels in 2003.

The IBOC technology will initially be deployed as a hybrid system, since the existing analog radio transmission will continue as before, but digital signals will be added to carry a high quality digital audio transmission, as well as some digital data. This will be the intended operational mode through a 10-15 year transition period. After this transition period, the analog transmissions will be eliminated, and the resulting all-digital system will provide much more data-carrying capabilities.

The test results for the FM IBOC system have been provided to the NRSC's Evaluation Working Group (EWG), through the NRSC DAB (digital audio broadcasting) Subcommittee. This group thoroughly evaluated the FM test results, and decided that the technology warrants endorsement. In the test report, the data-carrying capabilities of the FM technology are described ("Report to the National Radio Systems Committee: FM IBOC DAB Laboratory and Field Testing", August 2001, iBiquity Digital Corporation, pp 35-36). For the hybrid FM system, if the audio signal occupies the full 96 Kbps available for high quality audio, then only 1 Kbps will be available for data broadcasting. If, however, a station chooses to use only 64 Kbps for its audio signal, then 33 Kbps would be available for datacasting.

After the expected 10-15 year transition period to digital radio, then most of the portion of the transmission that has been used for analog audio can be recovered for datacasting. This all-digital mode could potentially offer over 200 Kbps of data capacity, depending upon the digital audio quality being used in the system ("Report to the National Radio Systems Committee: FM IBOC DAB Laboratory and Field Testing", August 2001, iBiquity Digital Corporation, pp 35-36).

The reported acquisition latency of this system is on the order of 135 milliseconds ("Report to the National Radio Systems Committee: FM IBOC DAB Laboratory and Field Testing", August 2001, iBiquity Digital Corporation, pp 35), but it is still unclear if the system is able to acquire the digital data channel within this time.

Test results and more information about the AM IBOC system are expected in the near future. Since there is less spectrum available in the AM license allocation, the digital capabilities of the AM system are expected to be less that those of the FM system.

Eureka 147:

Development of the Eureka 147 Digital Audio Broadcast (DAB) standard began in 1988 (http://www.eurekadab.org/frame.htm), and, in 1995, Eureka 147 was recommended as a world wide standard by the ITU-R in recommendation BS.774 (http://www.itu.int/rec/recommendation.asp?type=folders&lang=e&parent=R-REC-BS.774). Eureka 147 transmitters and demonstration receivers became available for implementation in the same time frame. Since that time, this system has been rolling out in many countries throughout the world. Eureka 147 receivers became generally available in 1998, and are now provided by over 16 manufacturers. At the present time, over 230 million people are within range of digital transmissions based on Eureka 147 implementations (http://www.worlddab.org/wdab/aboutwdab_frame.htm).

The Eureka 147 system provides flexibility to support audio signals at discreet intervals between 8 Kbps and 384 Kbps, and offers the opportunity to support data transmissions up to several hundred Kbps along with the audio transmission (ETSI EN 300 401 v1.3.3 (2001-05) "Radio Broadcasting Systems; Digital Audio Broadcasting (DAB) to mobile, portable and fixed receivers", pp 24-26). Another interesting characteristic of Eureka 147 is that the receivers are designed to operate with both terrestrial or satellite Eureka 147 signals, using a small, stub antenna.

Eureka 147 uses Orthogonal Frequency Division Multiplex (OFDM), a modulation technique that has proven to be extremely well-suited for mobile operations. This system is not compatible with existing AM and FM stations operating in the same frequency bands, and therefore new spectrum must be allocated for this service. For Eureka 147, these new frequencies have been assigned either at the Very High Frequency (VHF) range of 216 – 240 MHz, or at L-band frequencies in the 1.45 GHz range. In the United States, the L-band is not available due to military aeronautical telemetry uses, and the VHF range is also not available.

Expected Developments:

It is not a foregone conclusion that the current IBOC technology will be widely adopted in the United States. Although the NRSC DAB Subcommittee has recommended the adoption of IBOC, there remains a possibility that the improvement in audio quality and limited datacasting capabilities will not warrant the broadcasters' expenses for converting to this technology. If this proves to be the case, digital conversion may still occur by designating another band for digital radio.

With the IBOC technology now endorsed by the NRSC DAB Subcommittee (as of November 2001), a public process will soon be initiated at the FCC. While it is possible that this process will be completed in 2002, there are real possibilities that it could take longer. Another part of the IBOC plan that could take longer than expected is the availability of receivers. Receivers that iBiquity expects to be widely available in 2003 may take longer to reach market, as is common for such new technologies (the launches of both SDARS services were delayed by over a year from their initial plans, mainly be delays in receiver availability).

Before IBOC can move to all-digital transmission from its hybrid mode, all stations on the band must convert to IBOC. The all-digital signals would create too much interference with analog stations to co-exist on the same band. The anticipated length of the transition period, during which hybrid IBOC and analog stations co-exist on the same band, can be gauged from the transitional period planned for the conversion to digital television (DTV) in the United States. The DTV transition officially began in 1996, and is scheduled to be completed in 2006. A similar 10-year period is likely for the digital radio transition. Since the 10-year transition period would not start until after FCC proceedings, 2002 is the earliest possible start date. This means that all-digital IBOC is unlikely to be available until after 2012.

In spite of the cautionary notes above, some form of terrestrial digital radio is likely to be gaining momentum in the United States by 2007. In the rest of the world, terrestrial digital radio is expected to be well-established and widely deployed in this time frame. By 2012, wide deployment is also likely in the United States, even though this will still be hybrid mode if the IBOC plan is followed. If a different frequency band is allocated for digital radio, however, all-digital transmissions are likely to be available sooner in the United States.

Likely Deployments:

Deployment of new systems that are meant to replace legacy systems face the "chicken and egg" syndrome. For example, more end users would buy receivers if they were less expensive and there were more digital programs available, while more digital programs could be made available and the receivers could be less expensive, if more receivers were being sold. This means that conversion of radio stations to IBOC and the number of IBOC receivers that are sold are both likely to ramp up slowly in the initial stages of deployment. This projection compares with the adoption rate for DTV, which has been slower than expected, even though television broadcasters have taken the initiative to broadcast DTV in many of the major markets.

Digital radio deployment, in any case, is very likely to follow the major market pattern, since one can cover the majority of the United States population by deploying systems in the 50 major markets.

Datacasting applications on the digital radio systems may take longer to be deployed, since not too much data carrying capacity will be available during the IBOC hybrid transition period. This situation may force applications that could most effectively and efficiently use terrestrial radio datacasting to adopt alternative technologies, like 3G, that, although less efficient, become available sooner than digital radio datacasting.

Relevance to Vehicle Communications Environment:

Datacasting over terrestrial digital radio appears to offer the long-term potential to send the same information to a large number of vehicles simultaneously. This implies very economical airtime costs on a per vehicle basis. This type of capability could be used to provide near real time updates to on-board map databases, or, possibly, to carry differential GPS correction information on a more local basis than the regional beacons of the NDGPS system.

Five-Year:

In the 5-year time frame, the hybrid terrestrial radio systems are most likely to predominate in terms of relevance for vehicle communications in the United States. On a global basis, digital radio will likely be a significant factor in Europe and elsewhere outside the United States. Either of these systems will support useful telematics services in this time period. For example, Cue's near real time traffic information service, provided over FM subcarrier, makes much more efficient use of available spectrum than similar information services that depend upon point-to-point wireless communications (http://www.cue.net).

Ten-Year:

In the 10-year time frame, digital radio is likely to be extensively used on a global basis to support many telematics applications. In the United States, this is likely to happen more slowly, since digital radio will be deployed more slowly, and the hybrid systems will support only limited data rates in comparison to all-digital systems. The digital radio communications capabilities will be complementary to other wireless communications channels, and the applications supported by digital datacasting will be chosen to maximize efficiency and effectiveness, thereby reducing costs.

Terrestrial digital radio will most likely be used to support local or regionally-based information flow through datacasting. Datacasting over satellite based digital radio (also see SDARS chapter) will most likely be used to support nationwide information flows.

Relevance to EDMap Applications:

Datacasting through digital radio (or hybrid systems) is likely to be vitally important for a number of applications identified by EDMap. For example, near real time traffic information, both in terms of incidents and road segment speeds, can be effectively and efficiently datacast to all vehicles in a region over terrestrial digital radio (or hybrid) systems. The intelligent systems in the vehicles can then use or display only the information of specific relevance to their location and intended route. System delays of 30 – 60 seconds can be expected for these datacasting systems, which limits their use for applications that demand immediate real time characteristics.

Another very effective use of datacasting over terrestrial radio systems is near real time, continuous updates of on-board geographical databases. Beside obvious commercial applications, variable information like work zone locations, lane closures, detours, malfunctioning traffic signals and time-of-day restrictions, for example, might best be conveyed to the vehicle databases through such point-to-multipoint systems.

Another useful application that could enhance the “parking spot locator” is the wider-area parking availability information, which could be supported by datacasting over terrestrial radio channels. In this case, the wider-area system would provide information about what parking lots have available parking, and short range systems would likely be used to provide the information about which specific spots are available once the vehicle reaches the desired parking lot. This illustrates how different communications channels are likely to complement each other in supporting useful applications.

Five-Year:

In the 5-year time frame, hybrid systems are likely to be the only ubiquitous terrestrial radio datacasting systems available in the United States. Digital radio systems have a good chance of being widely enough deployed in Europe and elsewhere to effectively support telematics applications. Construction zone information, traffic speed, traffic density, traffic conditions, weather information, parking availability are some of the specific application activities identified by EDMap that are likely to be able to be supported by terrestrial radio datacasting systems (either all-digital or hybrid).

Ten-Year:

The widespread availability of all-digital terrestrial radio datacasting systems (outside the United States) will reliably support the continuous updating of on-board navigational databases to a very dense level of detail. This will allow database density to be dynamically increased for all suitably-equipped vehicles within a local or regional area, for example. This level of detail and the dynamic update capabilities will drastically increase the accuracy and relevance of on-board databases, enabling other innovative new applications besides the applications identified by EDMap.

Two-way Satellite

Two-way satellite systems have both a forward and a return communications path. This allows for data request, responses and acknowledgements to be supported in the low-speed data realm. Two-way characteristics also support voice telephony at higher speeds and interactive multimedia at broadband data rates.

Technology:

Besides the two-way designation that defines the systems described in this section, there are other ways to classify these systems that relate to their design and operation. One of the most common methods of classifying satellite systems is to group them into different categories according to the nature of their orbits, with altitude being the main determinant of orbital considerations.

Each type of satellite orbits is better suited for specific applications. Satellites at great distance from earth are not well-suited to handle voice or other isochronous traffic, because of their inherent latency. The satellite orbits that are closest to the earth have lower latency, and are much better suited to handle mobile voice services. However, these lower orbiting satellites move quickly in relation to the earth;s surface, so rapid mobility must be supported by the space segment radio links. As well, because they are closer to earth, many more satellites in total are required to cover the earth.

Geostationary Earth Orbit (GEO)

GEO satellite systems rely upon achieving an orbit around the earth's equator that takes exactly as long as the rotation of the earth (i.e., 24 hours) to remain "motionless" with respect to a particular point on the earth's surface. The "magic" altitude, first identified by science fiction writer Arthur C. Clarke, is around 22,500 miles above the earth. This altitude in much higher than the other satellite systems. Due to the higher altitude, each GEO satellite is able to transmit to a larger coverage area on the earth. GEO systems typically need only three to eight satellites to cover most latitudes for the entire earth.

GEO satellite systems have proven well-suited for one-way, point-to-multipoint media distribution. These systems, however, are less-than-optimal for voice communication and other two-way communications applications that are sensitive to latency. A one-way trip from the earth's surface, through a satellite, and back to the ground is called a "single-hop". Since radio waves travel at the speed of light, the inherent delay for a single hop through a GEO satellite is around a quarter of a second due to the distance that must be traveled to reach the high orbital location and return. If more than a single hop is used, the latency problems are further compounded.

Some of the GEO systems are now being used for two-way data applications, like truck and trailer tracking and interactive telemetry, that are not sensitive to the inherent latency of these systems. The two-way uses have been enabled by newer satellite technologies, and especially by major improvements in antenna designs. (http://www.vistar.ca/vistar_datacom/index2.html)

Of the different categories of satellites, GEOs are generally the biggest and heaviest, making them the most expensive to build. Because of the height of the orbits and the large

size and weight of GEO satellites, they are also the most difficult and expensive satellites to launch into orbit. On the plus side for GEO satellite systems, however, the satellites themselves typically last 10-15 years, which is regarded as a long service life for satellites.

Low Earth Orbit (LEO), MEO, HEO

LEO satellite systems use orbital altitudes of 1200 miles and lower. This is much lower that GEO satellite systems, and this difference brings advantages and disadvantages for LEO systems. For example, from a fixed point on the earth, each individual LEO satellite will only be within transmission range for about 15 minutes. After this time, communications must be switched to another LEO satellite as it comes into communications range. These transfer procedures add a significant cost component to the terrestrial gateways of LEO satellite systems. Another effect of the limited time communications window with each satellite is that LEO satellite systems typically must consist of large numbers of satellites to provide consistent coverage to particular portions of the earth's surface.

On the positive side, however, LEO satellites are much smaller and less expensive that GEO satellites. The higher cost of the larger GEO satellites is a result of both their more complex construction and the fact that satellite launches for bigger, heavier satellites are much more expensive. Other advantages of LEO satellite systems are:

- much better link margins (allowing the ability to support handheld terminals, for example); and

- much lower latency (allowing two-way voice communications, for example).

The typical operation life for a LEO satellite is approximately 5-7 years (about half that of a GEO satellite). This shorter life span is the result of high lateral speeds (around 17,000 mph), and the presence of significant amounts of "space junk" at the LEO orbital altitudes of 1200 miles or less. One advantage of the low altitudes for the LEO satellites, however, is that they remain below both Van Allen radiation belts. Radiation damage and the resultant material degradation are serious design constraints for satellite systems that must traverse the radiation belts in their orbital paths.

There are already several LEO satellite systems in operation. OrbComm, for example, was the first to successfully operate a commercial LEO satellite system. The OrbComm systems consists of a constellation of 35 LEO satellites orbiting approximately 500 miles above the Earth. This system is used to offer low-speed packet data service to fixed and mobile devices worldwide. (http://www.orbital.com/SatelliteCommunications/index.html)

The OrbComm satellites are "orbiting packet routers" that transmit and receive small data packets to/from sensors in vehicles, containers, vessels or remote fixed sites, and relay them through a tracking Earth station. Volvo, for example, uses OrbComm packet data service to provide automotive "mayday" service outside the range of cellular coverage.

According to a recent press release: "ORBCOMM provides two-way monitoring, tracking and messaging services through the world's first commercial low-Earth orbit (LEO) satellite-based data communication system. ORBCOMM applications include tracking mobile assets such as trailers, containers, locomotives, rail cars, heavy equipment, fishing vessels, barges and government assets; monitoring fixed assets such as electric utility meters, oil and gas storage tanks, wells and pipelines and environmental projects; and

messaging services for consumers and commercial and government entities." (http://www.orbcomm.com/press.htm)

Medium Earth Orbit (MEO)

MEO satellite systems represent a compromise between GEO and LEO characteristics, including cost, performance, number of satellites required and latency. Orbits for MEO satellites are typically at altitudes of about 6000 miles, which is positioned between the two Van Allen radiation belts.

As opposed to the 15-minute "window" for LEO satellites, MEO satellites are generally within the communications range of a single terrestrial location for two-to-four hours. This means that many fewer transfers between satellites must be coordinated by the terrestrial gateway systems.

Highly Elliptical Orbit (HEO)

A significant advantage of HEO satellite systems is their ability to provide much better coverage of extreme northern and southern latitudes, using polar orbital paths. HEO satellites are somewhat unique, in that they do not a consistent altitude in their orbit, but rather follow an elliptical orbit that includes both low and high altitudes. Using an elliptical orbit allows HEO satellites to travel more slowly when they are at the high altitude portion of their orbit. This slower movement at higher altitudes allows for extended coverage during those periods. At the higher portions of their orbits, HEO satellites reach altitudes comparable to GEO satellites. While the HEO satellites are at their peak altitudes, their performance closely resembles that of GEO satellites. Generally HEO systems use three satellites in the same elliptical polar orbit path to provide continuous coverage of the intended geographical areas on the earth. One significant disadvantage of the HEO satellite system approach is that the satellites must cross through both Van Allen radiation belts on each orbit, resulting in a decreased life expectancy for the satellites. (http://www.networkcomputing.com/905/905f2side4.html#you)

Expected Developments:

A number of the newer satellite systems have encountered financial difficulties. Iridium declared bankrupcy, and the satellite system was sold for cents-on-the-dollar. OrbComm is just emerging from Chapter 11 with new ownership. The dominant question that arises is: can markets for these systems be established quickly enough to support the costs of deploying and operating the systems?

The markets can be expected to develop over time, and it seems likely that at least some of the two-way satellite systems will achieve profitability (and therefore remain in operation). This will allow system improvements to be gradually implemented, as the satellites are replaced upon reaching the ends of their operational lives, and network systems as well as mobile transceivers are improved through technological development.

Likely Deployments:

The deployment of new two-way satellite systems will most likely be based upon a "wait and see" observation of the existing systems. If there are systems that demonstrate profitability, then additional systems will likely be deployed to compete in this market.

At some point, the technologies will be available to support broadband, two-way satellite systems, so the deciding factor will most likely be economics. If terrestrial wireless communications systems provide broadband Internet access for mobile users over a wide enough geographical area, then satellite systems would need to evaluate whether or not they could be cost competitive with the terrestrial wireless services. This is similar to the situation that has played out for satellite-based voice services, like Iridium, that were much more expensive than available terrestrial wireless voice services.

Relevance to Vehicle Communications Environment:

Two-way wireless data communications, with ubiquitous coverage over the continental US (as well as extended global coverage), provides a strong argument to consider two-way satellite services for wireless connectivity on vehicles. So far, the data services that are available and affordable have rather limited data capacity. For example, OrbComm packet data service typically supports text messages of less than 500 characters maximum.

One of the most significant considerations for using satellite-based communications is that generally a clear path must exist from the antenna on the vehicle to the relevant satellite. This requirement means that this communications channel will most likely be unavailable in garages, urban canyons, under dense foliage or in vehicle rollover situations, for example.

Five-Year:

The Volvo use of OrbComm packet data service to serve as a backup to cellular mayday capabilities illustrates the value of the ubiquitous geographical coverage of satellite systems. Another application that could potentially use such ubiquitous coverage capabilities to good advantage in the five-year time frame is the stolen/lost vehicle location service.

There are a fairly wide range of other telematics-type applications that could be supported using a short message data structure, such as that currently available from OrbComm. These include applications that relate to:

- telemetry of vehicles (for example, monitoring engine operating parameters to proactively suggest repairs before breakdowns occur);
- automotive manufacturers sending messages to vehicle owners (for recall notifications, or service reminders, for example); and
- control messages sent to vehicles (for example, remote unlocking of doors, honking the horn, flashing the lights, etc.).

Ten-Year:

When (and if) two-way broadband capabilities become available over satellite systems, many applications using wireless communications to support multimedia entertainment in vehicles will become possible. These capabilities could also be used to support infotainment, and other information services related to multimedia entertainment. The

most relevant consideration at this point will likely be cost of the airtime, as well as satellite transceiver costs.

Relevance to EDMap Applications:

Most of the EDMap applications with a wireless communications component have requirements that do not seem particularly well-suited for two-way satellite systems. Some of the potential applications that could be supported by two-way satellite systems are described below in the relevant planning time frames. It is interesting to note that the probe vehicle application discussed in the five-year time frame, could potentially be supported using the current OrbComm two-way satellite packet data system.

Five-Year:

There would be an opportunity to use low bandwidth packet data services over satellite to support vehicle telemetry applications, such as very basic probe vehicle monitoring. Since the two-way satellite services are designed to operate as point-to-point communications channels, these systems are unlikely to be useful for the distribution of location database updates, due to slow data speeds and expected airtime costs. Most other EDMap applications either have latency requirements preventing use of satellite systems, or require specific place-based communications channels.

Ten-Year:

If two-way broadband satellite systems are deployed, they should be reaching operational status in the ten-year planning horizon. The availability of high-bandwidth connectivity could allow location database downloads over two-way satellite systems. The major consideration would be communications costs relating to satellite airtime and satellite transceiver equipment costs. If the cost differential is significantly in favor of terrestrial wireless systems at this time, only applications that require ubiquitous geographical coverage are likely to be implemented using two-way satellite systems.

Ultrawideband (UWB)

From the glossary maintained by the National Telecommunications and Information Administration (NTIA): **Ultrawideband (UWB):** "**1.** Referring to any radio or wireless device where the occupied bandwidth is greater than 25% of the center frequency or greater than 1.5 GHz. **2.** A radio or wireless system that uses narrow pulses (on the order of 1 to 10 nanoseconds), also called carrierless or impulse systems, for communications and sensing (short-range radar). **3.** A radio or wireless system that uses time-domain modulation methods (*e.g.,* pulse-position modulation) for communications applications, or time-domain processing for sensing applications." (http://www.its.bldrdoc.gov/projects/t1glossary2000/)

Ultrawideband is therefore a radio technique consisting of sending a large number of low power pulses spread over a wide frequency range to provide remote sensing (like radar) or communications capabilities, for example. This technology has been in use for military applications for over a decade, but has only recently begun to be commercialized. The FCC, through proceedings in ET Docket 98-153, is presently considering what rules are necessary to allow this new technology to be deployed without creating interference to existing applications within assigned spectrum. The FCC has issued a Notice of Proposed Rule Making (May 11, 2000) in this proceeding, and has been accepting and evaluating technical reports and comments relating to these considerations. http://gullfoss2.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6511356101

The NTIA and other groups have conducted extensive testing (for example, http://www.its.bldrdoc.gov/pub/ntia-rpt/01-384/) to determine the potential for interference to GPS reception and other low-level reception situations. For example, a report submitted to the FCC on March 5, 2001 contains the results of UWB laboratory testing conducted by Qualcomm. These results demonstrate that UWB transmitters in close proximity to PCS CDMA handsets create sufficient interference to render the handsets unuseable under marginal reception conditions. Qualcomm therefore expresses "considerable concerns for the integrity of existing and licensed communications and navigation systems in cases where Ultra Wideband devices are allowed to co-exist." http://gullfoss2.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6512561396

Various other groups with diverse interests in spectrum, including radio astronomers, the Air Transport Association of America, the US GPS industry council, amateur radio operators and many others, have also filed (and continue to file – November 2001) comments to the FCC in this proceeding, expressing concern that the proposed rulemaking by the FCC must include sufficient testing to ensure protection from interference in spectrum that has been assigned for specific services or users.

With a sponsorship by Time Domain (a UWB proponent), Johns Hopkins University Applied Physics Laboratory analyzed data collected by the Applied Research Laboratories at the University of Texas. In a 279 page report, this analysis is presented in great technical detail. With UWB devices operating at power levels compatible with FCC Part 15 (unlicensed) regulations, there was consistently severe degradation in GPS receivers within 3 meters of the UWB device. Similar interference was also noted for existing devices operating under Part 15 regulations. This seems to offer a rationale for keeping the UWB devices (and other unlicensed devices) away from the frequencies used for GPS. At further separation distances between transmitters and receivers, the UWB devices could be modulated in a manner that

approximates “white noise”, both individually and in aggregate. Various implications can be drawn (and have been drawn) from this research report, so no clear-cut conclusion regarding allowable UWB spectrum-sharing has been possible.
http://gullfoss2.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6512561625

Although these test results are available, the conclusions still need to be interpreted into rational public policy by the FCC. Comments continue to be filed with the FCC in regard to this proceeding (ET Docket 98-153), with over 700 comments already on file (including over 20 in November 2001). At this point, it is not clear when the FCC may make a decision on this proposed rule making, nor what that decision is likely to be.

Technology:

UWB systems can be considered to be a unique form of spread spectrum communications. Typical UWB systems use extremely short duration pulses, in the range of 1 or 2 nanoseconds with power levels of only a few microwatts. Military uses have typically been in the areas of ground penetrating radar, electronic warfare, and stealth communications. The implementation of UWB in these applications has demonstrated all-digital design, resulting in relatively low cost and small size.

The engineering and operations of UWB technologies has been characterized as “highly complex” in the Johns Hopkins report. Apparently, the pulse shaping and modulation techniques employed in a UWB system have a very large impact on the potential for interference to other systems.
http://gullfoss2.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6512561625

The FCC’s Notice of Proposed Rule Making describes the UWB pulses in a footnote as: “Typical pulse widths currently are on the order of 2-0.1 nanoseconds, or less, in width. The emission spectrum appears as a fundamental lobe with adjacent side lobes that can decrease slowly in amplitude. Annex J of Chapter 5 of the National Telecommunications and Information Administration’s Manual of Regulations and Procedures for Federal Frequency Management contains a procedure to calculate the 20 dB bandwidth of a non-FM pulsed radar using the equation $B = 1.79/\sqrt{(\tau_r \tau)}$ or $6.36/\tau$, whichever is less, where B is the bandwidth in megahertz, τ is the emitted pulse duration, in microseconds, at the 50% amplitude (voltage) points and τ_r is the emitted pulse rise time in microseconds from the 10% to the 90% amplitude points on the leading edge. As an example, for a pulse with X = 1.0 nS, ignoring the rise time, the 20 dB bandwidth of the emission is calculated to be 6.36 GHz. The spectrum produced by a pulsed emission consists of a line spectrum with the spectral lines separated by 1/T, where T is the time, in seconds, of the pulse spacing.”
http://gullfoss2.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6511356101

The effective utilization of these techniques in practical applications has only recently become possible due to rapid progress in digital technologies. Much more progress in this area can be expected, and such progress in digital technologies may produce a substantial cost advantage for UWB-type systems.

Expected Developments:

The most likely scenario at this time is for the FCC to eventually allow UWB operations under Part 15 regulations, but restrict such operations to specific frequency ranges, such as those well above 6 GHz, that are well-removed from critical frequencies (like those used for GPS and potentially DSRC).

The commercial development of this technology has been focused upon very low-power applications for sensing and communications. The communications characteristics for local area wireless data networks are very impressive – with very high bandwidths being supported, and very good performance throughout the interiors of buildings.

Once the FCC decides how to make appropriate rules for UWB to be deployed, commercial development will be able to proceed very quickly toward providing innovative new products using this technology.

Likely Deployments:

One company is already advertising wireless LAN products utilizing UWB. (http://www.fantasma.net/). The company claims that UWB has the advantages of "reliability, high throughput, ease of use and affordability". Fantasma claims to be able to reliably transmit 60 Mbps.

One of the first promoters of UWB for commercial applications is Time Domain (http://www.time-domain.com/), which holds a number of patents in this area. Time Domain claims that its chipsets offer "high-speed and high performance for communications, radar, and precise positioning/tracking." They also claim to be able to "fuse wireless communications, positioning and radar in a single chipset". Time Domain further claims that their technology "does not interfere with existing spectrum users".

If the FCC establishes rules that allow UWB technology to operate over sufficiently wide spectrum, a proliferation of commercial applications can be expected. The applications included in most of the projections for commercialization are very short range, extremely low-power deployments. The main concern for the FCC is if the cumulative effect of many low-power USB devices operating "on top of" existing spectrum license holders will create interference to existing services, particularly by raising the noise floor within the existing spectral allocations.

At some point in the future, longer-range commercial applications, like cellular telephony, may be proposed for UWB. If such applications are implemented, and are competitive with existing applications for which the operator paid for finite spectrum, then many public policy issues will need to be resolved to deal with the paradigm shift to time domain regulation.

Relevance to Vehicle Communications Environment:

The largest limitation of UWB for vehicle communications is the limited range expected with the initial systems that are likely to become available. One of the positive aspects of UWB for vehicles is the all-digital implementation, which allows low cost, light weight and small size to be realized. As well, UWB appears to be almost immune to multipath

interference, a significant benefit for moving vehicles. Since cost, weight, size and mobile performance are very important considerations for automotive sensors and communications equipment, the development of the UWB technology warrants the continuing attention of automotive manufacturers.

Besides communications, vehicle applications that may be supported by UWB include “invisible security domes and fences”, as well as collision avoidance sensors. Pulse-based radar has been in military use for over a decade, and offers potential advantages for vehicle sensor applications.

Five-Year:

Depending upon the FCC rulemaking, short-range UWB transceivers could be expected to be available for vehicle applications in the five-year time frame. Initial uses are likely to be sensor-type applications, but communications capabilities may also be utilized for short-range applications.

Ten-Year:

In the ten-year time frame, there may be longer-range communications capabilities through UWB. In addition, there would seem to be an opportunity to implement short-range vehicle-to-vehicle communications using UWB. This would require early agreement on standard protocols for vehicle-to-vehicle communications.

Relevance to EDMap Applications:

The low-cost, small size characteristic of UWB devices, coupled with their potential use as an integrated communications, positioning and radar solution, makes UWB a reasonable candidate to monitor for further developments facilitating its use for EDMap applications. Since this technology is so new on the commercial scene, it may be some time before real relevance for EDMap applications can be confirmed.

Five-Year:

With UWB sensor-type applications and short-range communications expected to be realizable in the five-year time frame, there are a number of EDMap applications that might potentially be able to use UWB. Any of the applications with radar-type sensor requirements (like lane changing, forward collision, ACC, etc.) might be able to consider UWB as an alternative. If the expected cost/size advantages are realizable in production units, then UWB might provide a very desirable technology choice.

Ten-Year:

If short-range vehicle-to-vehicle communications become viable using UWB, it is most likely to be in the ten-year time frame. Assuming that an early agreement on standard protocols for vehicle-to-vehicle communications could be achieved within the industry, then this capability might be able to be effectively implemented in vehicles in the ten-year planning horizon. As well, if standards and implementations of UWB for other vehicle applications proceed, then vehicle-to/from-roadside communications may be another area to consider for UWB integration.

Longer-range communications is another area in which UWB may represent opportunities for vehicle communications in the ten year time period. This longer-range development has a lower-probability expectation due to potential interference and spectrum regulation problems. High bandwidth, longer-range communications capabilities have already been developed for military applications, so there are at least real technological possibilities for longer-range commercial applications.

Chapter 4

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Integrated Wireless Environment For Vehicles

This section describes likely wireless capability scenarios representing the integrated wireless environments for vehicles in the five- and ten-year time frames. This integrated view includes the capabilities of the most likely deployments from the wireless technology areas discussed in Section 3.

Wireless Technology Environment

The wireless technology environments expected in the five- and ten-year time frames are derived from technology discussions in the previous section. The most likely deployments of the various technologies expected in the five- and ten-year time frames are summarized in Tables 4.1 a, b and c, shown on the following three pages.

Table 4.1 a

	Wireless Environment for Vehicles (a)	
Wireless Technologies	**Five-Year (2007)**	**Ten-Year (2012)**
2.5-3G PCS and Digital Cellular	2.5G cellular systems are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas. 3G systems are likely to begin to be installed in major markets in the United States.	High-bandwidth 3G systems, including “always on” packet data connectivity, are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas.
Bluetooth	Widespread adoption of Bluetooth is expected, if prices targets can be met. Automotive Bluetooth gateways may provide a flexible connection between handheld devices and vehicle systems. Inexpensive, low power, short-range communications within “pico-nets” could be assumed for Bluetooth within the vehicle environment.	Bluetooth could become ubiquitous after having time to meet cost targets. Assuming that Bluetooth is able to meet its cost targets and become widely deployed, its relevance to vehicle communications is likely to remain in the connection of mobile devices to the vehicle network systems.
Dedicated (Digital) Short Range Communications (DSRC)	If automotive manufacturers are able to ensure the development of cost effective DSRC systems that fully support the desired automotive safety-related and telematics applications, then significant deployment of these systems is likely. There are likely to be extensive deployments within certain geographical areas, particularly where desirable commercial applications have been effectively deployed and marketed.	The United States is likely to experience fairly widespread deployment of enhanced DSRC, assuming that automotive manufacturers are able to provide effective input into the standards and systems development process.
Digital Television (DTV)	In the US, the ATSC system will be just reaching market penetration in the five-year time frame. Since this system is not useful for mobile applications, no relevance for vehicle applications is expected in this time frame.	There is a potential for new technologies to be developed that might replace the ATSC system, or allow that system to be used for mobile applications. If these events occur, then DTV may be able to provide high bandwidth, one-way, data broadcasting channels to vehicles.

Table 4.1 b

	Wireless Environment for Vehicles (b)	
Wireless Technologies	**Five-Year (2007)**	**Ten-Year (2012)**
High Altitude Platforms	The most likely scenario is for significant roll-out to be delayed beyond this time, while the airborne transceivers and matching ground-based, end-user equipment for the 28-48 GHz “main application” of wireless broadband access is developed and commercialized.	Since the stratospheric platform approach represents very new technology, there is a real risk that the entire concept may not prove to feasible. However, if this is a feasible approach, then the ten-year time frame should allow enough time for these platforms to be deployed for most major metropolitan areas in the United States.
IEEE 802.11 Wireless LAN	The 802.11b systems are likely to become fairly ubiquitous in homes and small offices. Public “wireless islands” are likely to become very common, including some specifically targeted toward vehicles in slow, or parked, operation. If 802.11a R/A systems are able to be rapidly developed and implemented for vehicle applications, then these systems are likely to be achieving significant market penetration.	Radical innovations beyond 802.11a, that primarily provide greatly increased bandwidth, are expected to have had time to develop into agreed standards, have chips and equipment manufactured, and be building market presence.
Nationwide Differential Global Positioning System (NDGPS)	NDGPS deployment can be expected to reach the point of dual-station coverage for the majority of the United States. One-meter positioning accuracy can be expected to be widely available from the combination of GPS / NDGPS signal reception and more processing power in receivers.	Sub-meter positioning accuracy can be expected to be widely available. If centimeter-level accuracy is not able to be achieved through the combination of GPS / NDGPS signal reception and more processing power in receivers, then availability of centimeter-level positioning may be confined to specific roadway segments, depending upon the level of DGPS localization that is required to achieve this accuracy.

Table 4.1 c

	Wireless Environment for Vehicles (c)	
Wireless Technologies	**Five-Year (2007)**	**Ten-Year (2012)**
Radar	A much greater percentage of the installed base of radar detectors can be expected to have the SWS capabilities.	Radar message reception may include variable short messages, and be integrated into vehicle telematics systems, thus providing support for a large number of wireless communications requirements to the vehicle from the immediate road infrastructure.
Remote Keyless Entry (RKE)	RKE systems are likely to retain basically the same technology that they are currently using.	It is likely that wireless technologies, other than the current proprietary RKE ones, will be used to support more advanced RKE-type applications. This replacement may include incorporation of the RKE-type functions into advanced mobile phones, or other mobile wireless devices normally worn, or carried, on the person.
Satellite Digital Audio Radio Systems (SDARS)	SDARS data broadcasting to vehicles is expected to be implemented.	If satellite radio receivers become an integral, factory-installed part of every new vehicle, then SDARS has the potential to become an important, pre-existing communications channel into vehicles on a mass, point-to-multipoint basis.
Terrestrial Digital Radio	Hybrid terrestrial radio systems are likely to predominate in the United States. Outside the United States, digital radio will likely be a significant factor.	Digital radio is likely to be extensively used on a global basis to support many telematics applications. In the United States, digital radio will be deployed more slowly, and the interim hybrid systems will support only limited data rates in comparison to all-digital systems.
Two-way Satellite	Low-speed packet data service continues to be available with ubiquitous geographical coverage.	When (and if) two-way broadband capabilities become available over satellite systems, high-bandwidth data services become possible.
Ultrawideband (UWB)	Short-range UWB transceivers, primarily used for sensor applications, may become available for vehicle applications, depending upon FCC rulemaking.	Short-range vehicle-to-vehicle communications using UWB may be deployed, if the technology proves feasible. Although unlikely, there may also be longer-range communications capabilities through UWB.

Five-Year Time Frame

Within a five-year window culminating approximately in the year 2007, a fair amount of development and deployment can be expected for technologies that have already been designed, and especially that have already been standardized. The relative economics of the various technologies are also expected to provide significant incentives or disincentives for their deployment. The economic considerations include not only vehicle-based equipment, but also infrastructure and airtime costs.

The integrated wireless environment for vehicles in the five-year time frame is described in terms of the geographical coverage ranges of the wireless technologies expected to be deployed in this time frame.

Nationwide

In the five-year time frame, nationwide coverage for the United States pretty well means satellite-based services, although hybrid terrestrial radio systems are expected to provide one-way coverage to vehicles over 85-90% of the geographical area of the United States. These hybrid systems are expected to offer point-to-multipoint datacasting with data rate capabilities of 5-10 Kbps. The satellite systems are expected to provide various capabilities, depending upon each particular satellite system.

The SDARS systems are expected to offer simultaneous one-way, point-to-multipoint coverage of the entire United States. If one of the roughly 100 channels on these systems is able to be dedicated to datacasting, then this would represent a continuous 64 Kbps data stream. It is also possible that data may be “interspersed” within the “holes” in audio channels. This may be able to provide a datacasting capability with varying data carriage capacity that would not require the dedication of a particular channel.

For two-way satellite systems, the low speed capabilities (in the 10 Kbps range), and tight link margins, are most likely to continue to limit two-way data communications to small packets (less than ~500 bytes) where the high cost of the satellite airtime is justified by the value of the application.

Although, each transmitter station will be regional in scope, the NDGPS system in total can be expected to include dual-station coverage on a nearly nationwide basis by 2007. In conjunction with increased processing power in GPS receivers, this combination of GPS and NDGPS can be expected to provide positioning accuracy for moving vehicles in the range of one meter.

Major Metropolitan Areas

Packet data enhancements to cellular and PCS systems, operating under 2.5G wireless network technologies, are expected to be fairly ubiquitous in virtually all major metropolitan centers and surrounding areas in the United States. These systems are expected to provide two-way data communications in the 144 Kbps range. Current airtime rates for wireless voice service (requires ~12 Kbps) may be expected to fall to half (~$0.10 / minute) in this time range. Using a per-bit pricing basis, this implies 144 Kbps data airtime costs of ~ $1/minute in the five-year time frame.

By 2007, 3G systems are expected to begin to be deployed in major metropolitan centers. These systems will likely be capable of 384+ Kbps two-way data communications. Since the necessary spectrum for real 3G operation is expected to be auctioned in the United States, the spectrum costs are likely to be very high (similar to the 3G spectrum auction costs in Europe). This, plus the need for major network infrastructure overhauls, is likely to slow the rollout of 3G services, especially to areas outside major metropolitan centers. As well, these costs must be amortized over time through the airtime revenues of the systems. This is likely to keep airtime rates very high, especially for high-speed data connections at 384 Kbps, which require 30 times the bandwidth of voice connections.

Outside major metropolitan areas and interstate highways, 2.5G wireless coverage is expected to be spotty, at best, in the five-year horizon. The situation is likely to be analogous to the present situation with digital PCS coverage – most places that are not in cities or along interstate highways are not currently covered. The rural areas that have wireless coverage, generally have analog systems at the present time, since these systems do not experience the traffic loading that cost-justifies digital systems in more congested areas. Unless a significant, concentrated demand for wireless data services develops in rural areas, which is unlikely, these capabilities are not likely to be deployed there.

Hybrid terrestrial radio systems are expected to be readily available in this time frame to provide one-way, point-to-multipoint data broadcasting capabilities in the 5-10 Kbps range on a regional basis that might economically include areas around smaller population centers within the range of radio broadcasts.

Specific Roadways

The enhanced 5.9 GHz DSRC systems are likely to begin to displace some of the 900 MHz DSRC systems along specific toll roads, and in regions where extensive toll roads and bridges enable electronic toll collection to become widely accepted. The high data communications rates of these enhanced systems may be used to support enhanced commercial applications, like entertainment and infotainment, along these specific roadway segments. Since the airtime costs appear at this point to be very low for these systems, multimedia downloads may be much more economical through these systems than 3G, for example. Any more than “spot” coverage of roadways, such as the toll plaza areas, would require very extensive infrastructure deployment at the roadside, however, so “spot” coverage is the expected mode of operation for these specific roadway segments in this time frame.

Radar messaging may be able to effectively provide limited one-way, short message delivery to vehicles from the roadway. This capability has already been deployed in approximately 10 million radar detectors, but has not been integrated into vehicle-based human-machine interfaces. As well, the number of message transmitters has been very limited, so far. One significant problem limiting the wide usage of these systems is that radar detectors are illegal in many areas. With the strong likelihood that 5.9 DSRC developments will proceed rapidly, and will allow variable messages and much larger messages, it seems unlikely that radar messaging will achieve a dominant role. The current capability with 64 “canned messages” is likely to continue to be used to good effect, however, in specific areas where radar detectors are widely used.

In and Immediately Around Vehicles

Basic RKE systems are likely to retain essentially the same proprietary, simple wireless technologies that they currently use. However, in the five-year time frame, Bluetooth technology is fairly likely to become widely deployed in cellphones, PDAs and other mobile devices, assuming cost targets can be met. If this is the case, the RKE functionality may be taken on by such Bluetooth-equipped devices and Bluetooth gateways in upscale vehicles. This evolution would enable more complex RKE-type features to be readily implemented in vehicles, and also allow customized user profiles to be implemented in individual vehicles and devices, to very precisely control the features and preferences.

Bluetooth gateways in vehicles are expected to allow cellphones, laptops, PDAs and other mobile devices to become functionally integrated with the vehicle systems. This capability is expected to be used primarily within the vehicle, but could also be extended to the 10 meter Bluetooth range around the vehicle. This might allow vehicle-based systems, for example, to complete electronic payments at gas bars, parking lots, "drive-thru" restaurants and similar locations. In addition, the 1 Mbps data capacity of Bluetooth could be used to download fairly large data files while refueling, buying hamburgers or possibly, even when parked in the garage.

In the five-year time frame, 802.11b wireless LANs are expected to be fairly ubiquitous in homes and small offices. 802.11b is unlikely to be able to support mobile operations, however, so will most likely be limited to static-type situations, such as where the vehicle is parked. Within such limitations, though, 802.11b transceivers might be effectively integrated into vehicles to allow communication, like entertainment and infotainment file download, between home LANs and vehicles while the vehicle is garaged.

If 5.9 GHz DSRC is able to be effectively developed to meet automotive manufacturers' needs, in terms of costs and capabilities, then these systems might begin to be used in and around the vehicle in this time frame. DSRC may be able to effectively support vehicle-to-vehicle communications, as well as immediate vehicle to/from infrastructure communications, but widespread deployment will require the development of a substantial "community of interest" of DSRC-equipped vehicles – rather like the classic "chicken and egg" syndrome. If Bluetooth, with a significant deployment headstart over DSRC, becomes widely used in vehicles for commercial applications, like electronic payments, then DSRC will likely have less impetus for rapid, widespread deployment. If such commercial applications are widely deployed using mobile devices, as currently seems likely, then DSRC is likely to remain fairly limited to specifically vehicle-based applications.

Ten-Year Time Frame

Analogous to the organization of the five-year time frame section, the integrated wireless environment for vehicles in the ten-year time frame is described in terms of the geographical coverage ranges of the wireless technologies likely to be available in an approximately 2012 time frame.

In this longer time frame, much more uncertainty is to be expected. With wireless technologies achieving significant innovations every few years, and major technological breakthroughs occurring several times over the past decade, surprises are likely to be encountered in the ten-year environment. The relevant technology trends, however,

indicate that such surprises can realistically be expected to move in the direction of increased performance and reduced cost. Since wireless marketing campaigns have been mainly focused within the five-year, or shorter, horizon, fewer potentially unrealistic expectations have yet been created for the ten-year wireless environment.

As the efficiencies and resulting economics of various wireless technologies are matched to appropriate applications over time, it is most likely that multiple communications technologies will be used in each vehicle. Applications, like entertainment, traffic information, or database updates, that can effectively use less expensive point-to-multipoint wireless communications technologies are likely to adopt this approach for cost reasons. Multiple wireless communications channels are expected to be integrated into the vehicle in this time frame, in order to provide the most efficient and effective wireless channel for each safety-related and telematics application, based upon the specific communications needs of each individual application, and taking into account the respective hardware and airtime costs for each communications channel. The intelligence in the vehicle will be expected to transparently integrate data received through multiple communications channels into a cohesive set of information to present to the driver (and/or passengers).

Nationwide

With nationwide agreement on standards for 5.9 GHz DSRC that are acceptable for public-sector needs, automobile manufacturers' needs, and for commercial service providers, it is reasonable to expect that nationwide deployment may be well underway in the United States in the ten-year time frame. Even though the standards are likely to ensure nationwide interoperability, the deployment of these systems is likely to proceed on a location-by-location basis, under the discretion of the decision-making authority for each roadway segment location, reflecting the localized nature of the wireless coverage of each DSRC transceiver, unless there is a significant initiative at the federal level to support the rapid, uniform rollout of these systems.

At this time, there are lingering questions concerning the long-term economic viability of SDARS systems. However, if these systems prove to be viable and satellite radio receivers become an integral, factory-installed part of every new vehicle in the ten-year time frame, then SDARS has the potential to become an important, pre-existing, point-to-multipoint communications channel into vehicles on a mass market basis. On this basis, SDARS datacasting could support concurrent downloading of time-sensitive information (down to the minute) to virtually all vehicles in the United States.

If business cases for two-way broadband satellite systems provide the necessary investment rationale within the next three-to-five years, they should be reaching operational status in the ten-year planning horizon. If such two-way broadband capabilities become available over satellite systems, it is therefore likely to occur around 2012. Many applications using wireless communications to support infotainment and other information services related to multimedia entertainment in vehicles will become possible if this happens. The availability of high-bandwidth connectivity might also allow location database downloads over two-way satellite systems.

The most relevant consideration determining whether or not these systems are actually deployed is likely to be the cost of the airtime (reflecting satellite system costs), as well as the cost of automotive satellite transceivers. If the cost differential is significantly in favor of terrestrial wireless systems at the time of satellite system deployment, then only applications that require ubiquitous geographical coverage are likely to be implemented using two-way satellite systems.

In the ten-year time frame, the NDGPS system is likely to cover the entire geographical area of the United States with overlapping regional transmissions. If the development of the high accuracy NDGPS (20 centimeter accuracy range) proves successful and practical, then deployment of the high accuracy enhancements could be expected to be well-underway, or even completed, by 2012. This rapid deployment would seem to be achievable, since the enhancements are expected to use the same beacon antennas as the "regular" NDGPS system. Even if the 20 centimeter accuracy proves not to be practical, at least sub-meter positioning accuracy using the NDGPS system can be expected to be widely available by 2012. If the accuracy possible using the combination of GPS / NDGPS signal reception and more processing power in receivers is not sufficient for the positioning requirements of major automotive applications, then additional localized correction information will need to be provided on a metropolitan area, or even specific roadway, basis.

Major Metropolitan Areas

High-bandwidth 3G systems are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas in the ten-year time frame. "Always on" packet data connectivity over these systems is likely to allow vehicles, by this time, to become as "connected" to the Internet as the typical small office, home office is today with DSL or cable modem connection. This connectivity will come at a price, however, since the very high expenses of auctioned spectrum and new network equipment will need to be repaid through compensatory airtime charges.

Rural areas are expected to lag many years behind in the deployment of new network technology, so "networked vehicle" connectivity is unlikely to be ubiquitous in the US within the foreseeable future. Additionally, there are still likely to be a number of competing technologies being deployed in the US, so region-by-region (and carrier-by-carrier) differences in wireless technologies are likely to be prevalent. Any critical wireless applications in vehicles that use primarily cellular communications will need to have alternative wireless communications channels to use whenever they are out of range of their main systems.

The "always on" packet data capabilities of the 2.5-3G cellular technologies will virtually eliminate the call set-up delays of data connections over current cellular systems. However, end-to-end latency is likely to remain in the range of at least several seconds, due to the server processing required in the mobile location registers, and the multiple packet forwarding necessary to deliver data to/from dynamically changing cellular sites.

Since the stratospheric platform approach represents very new technology, there is a real risk that the entire concept may not prove to be feasible. However, if this is a feasible approach, then the ten-year time frame should allow enough time for these platforms to be deployed for most major metropolitan areas in the United States. The stratospheric platform approach toward wireless deployment offers the opportunity for multiple wireless communications technologies to be simultaneously supported on a single platform. The main limitations on the number of different technologies supported are likely to be antenna spacing, interference between different technologies, and power and weight considerations.

If 3G wireless technology is deployed on stratospheric platforms, this could represent early deployment of high-bandwidth mobile communications capabilities for vehicles. Another

significant consideration is the potential for data broadcasting (one-way, point-to-multipoint) from stratospheric platforms. This capability could be especially appealing for sending regional information, like traffic, weather, and road work zones to vehicles.

In the 10-year time frame, digital radio is likely to be extensively used on a global basis to support many telematics applications. Terrestrial digital radio will most likely be used to support local, or regionally-based information, through near-real-time datacasting. In the United States, this is likely to happen more slowly, since terrestrial digital radio is expected to be deployed much more slowly in this country. The hybrid terrestrial digital radio systems being planned for the 10 – 15 year time frame in the United States will support only limited data rates in comparison to the all-digital systems being deployed elsewhere.

A potential need has been identified for the reception of supplementary DGPS information on a more localized basis than that provided by the NDGPS system. Potential candidate communications technologies for transmitting this additional positioning information are radio datacasting (both hybrid and terrestrial digital), or using high-altitude platforms, and "micro beacons" using next generation DSRC (most likely), or possibly UWB. From an infrastructure cost standpoint, datacasting DGPS information over local digital radio stations, for example, is expected to be preferable to low-power roadside beacons using next generation DSRC. This situation may be mitigated, however, if there are many other applications (especially commercial ones) that are enabled by the next generation DSRC capabilities, since the infrastructure costs would then be able to be supported by all of these applications.

Specific Roadways

If centimeter-level accuracy is not able to be achieved through the combination of GPS / NDGPS signal reception and more processing power in receivers, then the availability of centimeter-level positioning may be confined to specific roadway segments, depending upon the level of DGPS localization that is required to achieve this accuracy. The use of short-range wireless technologies, like 5.9 GHz DSRC, would seem to be one of the most likely methods to transmit the necessary DGPS corrections information to vehicles on a localized basis along particular roadway segments.

Assuming that automotive manufacturers are able to provide effective inputs to the DSRC standards development process to ensure cost effective systems, then widespread use of high bit-rate, 5.9 GHz DSRC systems seems very likely in the ten-year horizon. This type of system will likely be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles, as well as between vehicles in close proximity. The short-range communications capabilities represented by 5.9GHz DSRC are viewed as extremely necessary to support many of the location-specific telematics services being planned for commercial service. The expected wide availability of such systems in this time frame is likely to enable many safety-related automotive applications to be effectively implemented. The earlier success of such applications in Europe and Japan, if these regions continue with their current plans, is very likely to provide solid motivation for rolling out these applications in the United States.

Considering the rapid changes in wireless LAN technologies since 1997, represented by the rapidly evolving IEEE 802.11 standards, radical technological innovation can be expected in this area over the next ten years. In this time frame, some of these radical innovations beyond 802.11a will have had time to develop into agreed standards, have chipsets and equipment manufactured, and build market presence. Although the exact

nature of these developments is unclear, the past trends have been toward increased data throughput and higher frequencies. If the automotive OEMs and public sector organizations can establish an effective collaboration to foster 802.11a R/A deployment to support safety-related applications, particularly in conjunction with DSRC, then this technology (and further, forward and backward compatible enhancements within the spirit of the IEEE 802 Working Group) could be expected to become ubiquitous within the ten-year horizon.

By 2012, radar technology (if such developments prove feasible and economical) might be able to be enhanced to include variable message content. Although there are significant obstacles that must be overcome, it is possible that radar message reception might be able to meet a large number of the needs of telematics and safety-related applications for localized, short-range, one-way wireless communications to the vehicle. If the development of radar messaging proceeds in this direction, then this technology may become integrated into vehicle telematics and safety systems, thus providing support for a large number of applications with requirements for wireless communications from the immediate road infrastructure to the vehicle.

One of the most positive aspects of UWB for vehicles is the potential for all-digital implementation, which allows low cost, light weight and small size to be realized. As well, UWB appears to be almost immune to multipath interference, a significant benefit for moving vehicles. The effective utilization of UWB technologies in practical applications has only recently become possible due to rapid progress in digital technologies. Much more progress in this area can be expected, and such progress in digital technologies may produce a substantial cost advantage for UWB-type systems.

The largest limitation of UWB for vehicle communications is the very short range expected with the low-powered systems that are likely to become available. At this early stage in the commercial development of UWB systems, it is not yet clear whether or not the practical range will be suitable for sensor-type applications, or vehicle-to/from-roadside communications. However, if practical implementations of UWB for vehicle sensors can be effectively deployed, then vehicle-to/from-roadside communications would be a logical, additional area to consider for integration into UWB systems.

At this point in time, it is not yet clear whether or not the planned NDGPS system, even with the high accuracy capabilities currently being researched, coupled with increased receiver processing power, will be sufficient to allow centimeter-level accuracy for receivers in moving vehicles. At some point, it may become necessary to establish micro-DGPS reference stations and transmitters at close intervals near the roadways upon which critical applications requiring this level of accuracy will be implemented. This is similar to the extremely high accuracy systems being deployed in the immediate vicinity of airports to provide positioning information for automated aircraft landing. In the case of motor vehicle applications, these local transmitters could use next generation DSRC communications, for example. Another option, which may be technically and economically possible, is to establish DGPS reference stations at future digital radio stations and use the digital data channel to broadcast the differential corrections information.

In and Immediately Around Vehicles

It is likely that wireless technologies other than the current proprietary ones will be used to support more advanced RKE-type applications by 2012. This replacement may include incorporation of the RKE-type functions into advanced mobile phones, or other mobile

wireless devices normally worn, or carried, on the person. The new wireless systems that are most likely to “absorb” RKE functionality are expected to be standardized wireless systems, like 3G, Bluetooth and DSRC.

It appears feasible to expect that vehicles will have centimeter-level accuracy positioning capabilities by 2012. This is expected to require multiple (at least two) wireless communications capabilities for vehicles, and may also require very localized infrastructure development. If the DGPS is required to be extremely localized in terms of infrastructure, then vehicle applications that are dependent upon highly accurate positioning will likely be limited to major roadway segments, at least initially.

In the 10-year horizon, Bluetooth may become ubiquitous after having time to meet cost targets, but it is also possible for it to be supplanted by a new technology. Assuming that Bluetooth is able to meet its cost targets and become widely deployed, its relevance to vehicle communications is likely to remain in the connection of mobile devices to the vehicle network systems. This would allow PDAs, cell phones and laptops to effectively interface with the vehicle, providing virtual integration between carry-on devices and the vehicle.

By 2012, the United States is likely to experience fairly widespread deployment of enhanced DSRC, assuming that the standards development work progresses according to plan, and that the automotive manufacturers are able to provide effective input into the standards development process. This short-range communications channel is most likely to be integrated into the vehicle, along with other multiple wireless communications channels. DSRC is the most likely communications channel to provide the necessary support for location-specific and vehicle-to-vehicle safety-related and telematics applications.

If short-range vehicle-to-vehicle communications become viable using UWB, it is most likely to be in the ten-year time frame. The low-cost, small size characteristic of UWB devices, coupled with their potential use as an integrated communications, positioning and radar solution, makes UWB a reasonable candidate to monitor for further developments. Since this technology is so new in terms of commercial development, it may be some time before its feasibility for automotive applications can be confirmed.

Chapter 5

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Wireless Technology Summary

This section includes brief text summaries of each technology area, which describe the expected bandwidth capabilities, coverage and costs for deployed systems in each technology area in the five and ten year time frames. In addition, summary tables provide a concise view of the various technology areas in each time frame for comparison purposes. Also included in this section is a summary of the integrated wireless environment for vehicles in the five and ten year time frames.

2.5-3G PCS and Digital Cellular

The most significant, unifying concept for 2.5G technologies is the addition of data services to the existing over-the-air technologies of Global System for Mobile (GSM), TDMA and CDMA networks that are currently in use by wireless carriers in the US. These are called 2.5G to indicate that they represent a step from existing second generation wireless networks (2G) toward the 3G wireless networks defined by IMT-2000.

"True" or "real" 3G refers to technologies meeting the ITU IMT-2000 standards, even though these standards have not yet been completed at the detailed network level. The two 3G technologies that are expected to become dominant (W-CDMA and CDMA2000 3x) both use CDMA technology. Initial implementations are likely to have data capacity in the 144 Kbps range with full mobility.

W-CDMA appears to be the preferred evolution path to 3G for most GSM networks. W-CDMA will spread its transmissions over a wide, 5MHz carrier. Each of the 5 MHz channels that W-CDMA uses will support 100 simultaneous 8 Kbps voice calls, or 50 simultaneous packet data users at up to 384 Kbps of "bursty" data each.

CDMA2000 3x uses three 1.25 MHz carriers to support high-speed data capabilities. CDMA2000 3x is backward compatible with cdmaOne, allowing legacy handsets to be supported, but it requires new baseband and radio frequency hardware throughout the network, as well as new software.

There are expected to be significant network implementations of 3G in Japan and Europe within the next year or two. In the US, new spectrum for 3G has not yet been made available by the FCC. Without a clear view of when spectrum may become available for 3G in the US, wireless carriers are concentrating on improving the performance of their systems within their existing spectrum allocations. This is basically the 2.5G approach.

Many automotive applications planners have assumed that cellular technologies will provide the only wireless communications channel for telematics and other automotive applications. While it seems obvious that many telematics applications will use cellular communications, there are limits to the applicability of this technology. In the US, cellular systems (as described above) are in the midst of constant change. One common standard has not been applied for these systems – an approach that encourages innovation, but hinders interoperability. The average lifecycle of a wireless handset is around two years, in contrast to the much longer average lifecycle of an automobile. The limited geographic coverage of cellular systems remains a significant issue for automotive applications.

In the five-year planning horizon, 2.5G cellular systems will be widely deployed in virtually all major metropolitan centers and surrounding areas. Also at this time, 3G systems will begin to be installed in major markets in the US. High-bandwidth 3G systems are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas in the ten-year time frame.

The “always on” packet data capabilities of the 2.5-3G cellular technologies will virtually eliminate the call set-up delays of data connections over current cellular systems. However, end-to-end latency is likely to remain in the range of at least several seconds, due to the server processing required in the mobile location registers, and the multiple packet forwarding necessary to deliver data to/from dynamically changing cellular sites. As well, data communications over these networks tend to be lower priority than voice communications, so data packets can be expected to encounter buffer-based latency if the networks are busy with voice traffic. These latency limitations will likely preclude the use of cellular communications for the majority of the EDMap applications’ wireless requirements.

For EDMap applications, the transition from 2.5G to 3G cellular technologies in the ten-year time frame is likely to be fairly inconsequential. Data rate expansion will be the main benefit of this transition in technologies, and EDMap applications do not seem to require high bandwidth communications. The network latency is unlikely to improve through this transition to 3G, so the relevance for EDMap applications is likely to be virtually the same as in the five-year perspective – that is, potentially downloading location database updates, and marginally support for the two applications described in the previous section.

Bluetooth

Bluetooth is an emerging industry group *de facto* standard that has the support of major telecommunications equipment manufacturers. This specification is designed to facilitate small-form factor, low-cost, short-range radio links between mobile PCs, mobile phones and other portable devices. Intended applications include wireless links between miniature headsets and cell phones, connections between PDAs and cell phones, laptops to printers, and generally replacement of cables interconnecting electronics devices. The main developments required at this time are reductions in costs for Bluetooth modules. The Bluetooth standard is complete enough to allow standardized manufacturing to proceed, however, so prices should be able to be reduced as manufactured quantities increase.

Bluetooth technology represents a "multiple piconet structure" for unlicensed radio frequency communications in the 2.45 GHz industrial, scientific and medical (ISM) band at data rates up to 1 Mbps. Bluetooth offers both point-to-point and point-to-multipoint communications at a range of up to ten meters, but its range can be extended to more than 100 meters by increasing the transmit power.

Due to the LAN-like technology characteristics of Bluetooth, it is viewed primarily as a way to connect mobile devices together. In the vehicle environment, this could take the likely form of a Bluetooth "gateway" to/from embedded vehicle networks. Such a gateway would allow PDAs, cell phones and laptops to effectively interface with the vehicle. Potentially, information available on the vehicle bus could be utilized in applications running on PDAs and cell phones, to provide virtual integration between carry-on devices and the vehicle.

Bluetooth might also serve as a vehicle to/from infrastructure communications channel for stationary vehicles in close proximity to the desired communications point. The limitations of this connection would not prevent it from supporting electronic payments at fast food drive-thrus, for example, or communications between a garaged vehicle and the house.

In the 10-year horizon, Bluetooth could become ubiquitous after having time to meet cost targets. In another future scenario, however, Bluetooth could be outflanked by 802.11 developments, or supplanted by a new technology. Assuming that Bluetooth is able to meet its cost targets and become widely deployed, its relevance to vehicle communications is likely to remain in the connection of mobile devices to the vehicle network systems.

Although the operational parameters of Bluetooth limit its role in supporting most of the EDMap identified applications, it could be used to update navigational databases while the vehicle is parked in the garage, for example, or to download turn-by-turn directions for a driving destination.

Dedicated (Digital) Short Range Communications (DSRC)

This communications systems category – DSRC – includes current deployments around 900 MHz that are mainly used for Electronic Toll Collection (ETC) and various commercial vehicle identification applications. Technology has recently progressed to the point where much-higher frequencies have become commercially-viable for these systems, allowing planning and standards development to proceed for next-generation systems in the 5.8-5.9 GHz range. Even the basic 900 MHz DSRC systems (that are likely to continue to represent the bulk of DSRC systems deployed in the United States in five years), however, may be able to be effectively used as vehicle probes, for example.

A number of standards development activities relating to DSRC were listed as "critical standards" for ITS by the U.S.DOT in 1999. Also in 1999, as a result of efforts by ITS America, the FCC allocated 75 MHz of spectrum (5.850 – 5.925 GHz) for ITS applications, with ITS as a co-primary user. The intended uses for the 75 MHz of spectrum in the 5.9 GHz range allocated by the FCC in 1999, in terms of applications, as well as the band plan and other technical standards, are presently under intensive development. The short-range communications capabilities represented by 5.9 GHz DSRC are viewed as extremely necessary to support many of the location-specific telematics services being planned. This type of system has the bandwidth and, potentially, other beneficial performance characteristics, to be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles, as well as between vehicles in close proximity, if the correct technological choices are made for the standards to be used in this spectrum.

In August, 2001, the DSRC 5.9 GHz Standards Writing Group, a sub-group of ASTM E17.51, selected the IEEE 802.11a R/A (roadside applications) as the standard physical layer to be used for 5.9 GHz DSRC. The ASTM E17.51 subcommittee has developed an action plan to complete the necessary standards for DSRC, ready for balloting in the various standards development organizations, in the next six-to-nine months. The

committee plans to meet at least monthly, support a number of concurrent task forces, and work in close cooperation with the IEEE and other, related standards development organizations to coordinate all aspects of DSRC standards in this aggressive time frame. There is therefore likely to be agreement in the United States on the major components of a 5.9 GHz set of standards for DSRC by the summer of 2002.

The International Telecommunications Union – Radio Sector (ITU-R) has recommended DSRC standards at 5.8 GHz. These standards were basically developed by the European Telecommunications Standards Institute (ETSI) in 1999, and basically represent testing procedures for type-approval of DSRC devices. Japan DSRC standards also use the 5.8 GHz ISM band, and have been included in the ITU-R recommendations. As well, there has been an effort for the 5.9 GHz DSRC standards development group in the United States to communicate with the DSRC standards groups elsewhere in the world, in the hopes of fostering international harmonization.

The short-range communications capabilities represented by DSRC are viewed as extremely necessary to support many of the location-specific telematics services being planned. This type of system will likely be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles, as well as between vehicles in close proximity. As well, most of the applications identified by EDMap that require wireless communications are likely to require the enhanced capabilities of the 5.9 GHz DSRC systems.

The band plan being proposed in the United States for the 75 MHz of spectrum in the 5.9 GHz range has been under development for some time. The DSRC standards group has included a number of obviously safety-related applications in their deliberations, but their deployment assumptions may or may not prove to be valid for mass-produced automotive applications. Automotive implementation cost considerations have not been a priority for the DSRC standards being developed, with the result that, for example, three separate DSRC transceivers may be required on each vehicle to provide vehicle-to-vehicle communications, intersection collision avoidance and emergency vehicle notification. As well, new safety-related applications with wireless communications requirements may be precluded from using 5.9 GHz DSRC communications, just because the DSRC standards are being developed without specific, detailed knowledge of these potential applications. This may slow, or even prevent, the timely introduction of valuable, new safety-related applications. In general, automotive manufacturers have not been actively involved in the detailed development of the 5.9 GHz band plan, or other aspects of DSRC standards, in spite of the fact that they will be the ones mainly responsible for implementing the safety-related applications.

The next two years will likely prove critical for the development of the full range of 5.9 GHz DSRC standards, with the next six-to-nine months representing the most intensely critical period. Although the basic structure for the DSRC standard will likely be determined by the third quarter of 2002, there is a great deal of detailed standards work to be completed for the higher layers of DSRC and related issues (like security). The detailed portions of the DSRC standards are likely to take at least an additional year beyond the determination of of the lower layer structure. These DSRC standards have the potential to provide support for many automotive safety-related applications, but if detailed standards are not optimized for automotive applications, safety-related applications may be too costly, or too inefficiently supported, to become widely available at the earliest possible time. This situation could result in the unnecessary loss of life through accidents that are preventable by the earliest possible deployment of automotive safety-related applications. For this reason it has become an urgent priority for automotive manufacturers, on a pre-competitive basis, and in close cooperation with the public sector, to actively participate in

the development and testing of DSRC standards and technologies, especially within the next six-to-nine months.

If the automotive manufacturers are able to provide effective input into the DSRC standards development process to ensure cost effective DSRC systems that fully support the desired automotive safety-related and telematics applications, then the likelihood of significant deployment of these systems by 2007 increases dramatically, and the widespread use of high bit-rate, 5.9 GHz DSRC systems seems very likely in the ten-year horizon. With development and selection of the correct, detailed DSRC standards over the next two years, DSRC should be able to support simultaneous usage of multiple applications among many vehicles in the same location. Current calculations are being based upon supporting 100 vehicles within the range of a single DSRC unit.

DSRC, or a similar short range system, is a necessary component of many of the applications areas identified by EDMap. For example, although the first five functions in "Enhanced Route Planning and Guidance" could be provided through a 3G communications channel, it is likely to be much more efficient and effective (and economical) to support these through DSRC channels. In other cases, like "traffic signal status", only immediate, real time systems, like DSRC, could provide this information effectively. For the "Cooperative Collision Warning/Avoidance" application, the "communication with infrastructure" and "communications between vehicles" functions demand an immediate, real time communications system. DSRC is likely to be about the only wireless communications system that can reasonably support such functions. Thus, deployment of enhanced DSRC systems is likely to be one of the largest pacing items on the critical path for implementation of EDMap-envisioned applications in the United States. If the United States DSRC standards prove to be successful, then it is likely that they will form the basis for international DSRC standards subsequently.

Digital Television (DTV)

Digital Television (DTV) is the general term used to describe all digital television broadcasts and formats, including High Definition Television (HDTV), Standard Definition Television (SDTV) and the use of digital data broadcasting. DTV transmissions carry a high-speed bit stream, which can include packets of encoded video, audio, data and system information. As part of the ten-year conversion to DTV in the US, DTV is transmitted within the same frequency bands used for analog television, but broadcasters have each been given an additional channel to simulcast in analog and digital throughout the conversion period. By 2006, DTV is planned to totally replace analog television in the US.

The Advanced Television Systems Committee (ATSC) Digital Television Standard (A/53), was adopted by the FCC in 1996 as the DTV standard for the US. This standard utilizes the 8-Level Vestigial Side-band (8-VSB) modulation method as the basis for digital transmissions. Other areas in the world are deploying a DTV standard based upon the Coded Orthogonal Frequency Division Multiplex (COFDM) modulation method. The vestigial sideband approach adopted for the ATSC DTV standard is not readily applicable for mobile applications. Without major technological breakthroughs in antennas and receivers, the vestigial sideband DTV system will not be at all relevant to the vehicle communications environment.

In the ten-year time frame, there is a potential for new technologies to be developed that might replace the ATSC system, or allow that system to be used for mobile applications. If these events occur, then DTV could provide high bandwidth, one-way data broadcasting channels to vehicles. This development would probably be most applicable for multimedia-

type, entertainment applications in the vehicle, rather than the types of applications identified by EDMap.

High Altitude Platforms

There are presently several concepts under development to place a communications payload in the stratosphere over major population centers. High altitude platforms (HAPS) refers to systems currently being developed to place large, stationary, lighter-than-air platforms at stratospheric altitudes (around 70,000 feet) over major metropolitan areas for the purpose of providing wireless communications services. These large, remotely/automatically piloted platforms would be put into station-keeping flight for extended periods (years at a time). The current plans call for solar powered platforms over 500 feet long. Another approach proposes to use multiple shifts of piloted aircraft flown over major metropolitan areas at altitudes between 50,000 and 60,000 feet.

Although the companies developing these approaches have been focused upon wireless broadband communications in the 28 or 47-48 GHz range, the high altitude platforms also offer the potential to support rapid deployment of other wireless communications technologies at lower frequencies, for example, initial 3G cellular deployments. The advantages of having a “cell tower” at 70,000 feet over a major metropolitan area are obvious. For vehicular applications that require high-bandwidth, two-way communications capabilities, 3G communications using stratospheric platforms may be able to provide a fairly rapid deployment path in major metropolitan areas.

It is estimated that 250 stratospheric platforms could provide global coverage (presumably of population, since all major population centers would be included). Unlike satellite systems, deployment can proceed on a city-by-city basis. Some of the most significant advantages of stratospheric communications in comparison to satellite services are the low latency (less than 0.5 millisecond compared to about 250 milliseconds for GEO-based services) and none of the hand-off problems that LEO-based technologies encounter.

One significant strength of the stratospheric platform approach is that multiple wireless communications technologies could be simultaneously supported on a single platform. The main limitations would be antenna spacing/interference between different technologies, and power and weight considerations. The anticipated payload capacity of each platform is in the 1700-2200 pound range. Besides two-way communications, therefore, there is the potential to support one-way data broadcasting (point-to-multipoint) from stratospheric platforms. This capability could be especially appealing for sending regional information to vehicles. Such local/regional information as traffic, weather, road work zones, as well as commercially-significant location-based information, could potentially be very well-supported by wireless datacasting from stratospheric platforms.

The potential for data broadcasting (point-to-multipoint) from stratospheric platforms has particular relevance for EDMap applications. In-vehicle map databases could be continuously updated in this way, providing support for EDMap applications that require high accuracy database support with more dynamic information elements at the local/regional level. As location databases become more accurate, they also necessarily become more detailed. As the level of detail increases, the dynamic component of the database information increases significantly. Thus, increasing the accuracy of location databases requires more frequent, detailed updates to the database.

Since the stratospheric platform approach represents very new technology, there is a real risk that the entire concept may not prove to feasible. However, if this is a feasible approach, then the ten-year time frame should allow enough time for these platforms to be deployed for most major metropolitan areas in the US, at the least. If many of the EDMap

applications being deployed in this time frame require high accuracy location database support, then there may be good synergy with the stratospheric platform deployment.

IEEE 802.11 Wireless LAN

The Institute of Electrical and Electronic Engineers (IEEE) Project 802 is targeted toward providing standards for Local Area Networks (LANs) and Metropolitan Area Networks (MANs). The 802.11 Working Group is focused strictly on wireless LANs, thus the 802.11 series of standards were developed by the IEEE specifically to support wireless LANs. These standards are focused toward the first two layers of the Open Systems Interconnection (OSI) Basic Reference Model (7 layer protocol model) – the PHY layer and the MAC layer.

In 1999, 802.11 was updated, and the 802.11b standard for higher data rate PHY at 2.4 GHz was included. This new PHY extension uses high rate direct sequence spread spectrum to boost the maximum data throughput to 11 Mbps from the maximum of 2 Mbps in the original 802.11 standard. Further work is underway to add standards to support more security features, access points and other features that will improve 802.11b. Since 1999, this standard has been widely adopted for home and office wireless LAN equipment. Internal modems for desktop computers and PC Card modems for laptop computers are now widely available to consumers. Using these modems in conjunction with a base unit provides a multi-user wireless LAN within an indoor range of approximately 30 meters. The range is much further (over 1000 meters) for line-of-sight communications outside.

This technology is based upon a mature standard, and there are receivers available from Lucent, Apple, Cisco and others in the $100-200 range. The 802.11b wireless gateways are priced in the $200-1000 range. The units operate in the unlicensed 2.4 GHz band (the same as Bluetooth and HomeRF systems). It is commercially-available wireless broadband, operating in a part of the spectrum that, unlike third-generation, or 3G, mobile telephony, requires no license. This is the wireless technology that is currently being installed in Starbuck's coffee shops to support customers' wireless email and web browsing.

In the 5-year time frame, 802.11b systems are likely to become nearly ubiquitous for home LANs. This will offer the opportunity for 802.11b-equipped vehicles to upload and download data through the home LAN while the vehicles are parked in the garage, assuming that the on-board systems can be powered at this time. Just using the first minute after startup, however, nearly an entire CD of data can be downloaded to the vehicle at 11 Mbps.

Task Group a (TGa) has developed a new 802.11 PHY for high-speed operation in the newly available unlicensed national information infrastructure (U-NII) bands in the 5 GHz range. An orthogonal frequency division multiplexing (OFDM) system was chosen, and this PHY was agreed and added to the 802.11 standard as a supplement in 2000 (IEEE Std 802.11a-1999). 802.11a R/A (roadside applications) represents a variation of 802.11a that is optimized for highly mobile wireless communications, such as vehicle-from/to-infrastructure at highway speeds. Preliminary testing of 802.11a R/A indicates that the further development of this standard will be able to provide a viable option for DSRC communications for vehicles at highway speeds. This version of 802.11a recently achieved high visibility (August 2001) when the DSRC 5.9 GHz Standards Writing Group (a sub-group of ASTM E17.51) selected IEEE 802.11a R/A as the preferred technology to provide national interoperability for DSRC Public Safety-based applications.

Since 802.11a R/A has been chosen as the wireless communications standard to support 5.9 GHz DSRC, detailed development of this standard is expected to proceed fairly rapidly. Major portions of this standard are expected to be completed in the 6-9 month time frame, with completion of the detailed portions of the relevant standards likely over the subsequent 12-18 months. The use of the 802.11 framework allows portability of applications that have been written for other 802.11 wireless LAN standards, as well as the use of existing development tools and libraries.

Both 802.11a and 802.11b (depending upon data rates required) could support the inclusion of vehicles in wireless home LANs. Such home systems could provide extensive data downloads to garaged vehicles, as well as allowing the vehicles to download non-time-critical information to wider area networks. If 802.11a R/A capabilities become commonly installed in vehicles, then this communications mode is likely to also be employed for garaged vehicle communications with home network systems.

If 802.11a R/A systems are able to be rapidly developed and implemented for vehicle applications, then these systems are likely to be achieving significant market penetration in the five-year time frame. As other technologies in the 5 GHz range reach technical maturity, the prices are likely to continue to fall. With the rapid changes in wireless LAN technologies, as evidenced in the rapidly evolving IEEE 802.11 standards since 1997, more radical changes can be expected. In the 10-year time frame, some of these radical innovations beyond 802.11a will have had time to develop into agreed standards, have chips and equipment manufactured, and build market presence. Although the exact nature of these developments is unclear, the past trends have been toward increased data throughput and higher frequencies. These trends probably provide clues toward the future directions of wireless LAN technological progress.

The expected rapid development of 802.11a R/A, in conjunction with the 5.9 GHz DSRC standards development activities in the United States, may provide a very effective short range wireless capability for the vehicle-to-vehicle and vehicle-to/from-infrastructure communications requirements of a number of the safety –related applications identified by the EDMap project. In order to ensure that these wireless capabilities meet the communications requirements of the EDMap and many other safety-related applications, effective collaboration will be required over the next several years among the automotive OEMs, standards development organizations (SDOs) and public sector organizations.

If 802.11a R/A systems are developed and implemented as rapidly as possible for vehicle safety applications, there should be significant availability of the technology components in the five-year time frame. Although commercial applications may help drive the market penetration of 802.11a R/A technologies, it will require a concerted, long-term effort from automotive OEMs and public sector organizations to enable the type of mass deployment necessary to achieve the kinds of safety benefits identified by the EDMap project.

Nationwide Differential Global Positioning System (NDGPS)

The Global Positioning System (GPS) is a worldwide, satellite-based radio-navigation system developed and operated by the United States Department of Defense. GPS was developed to support military applications, but the government then made the system available for limited accuracy civilian use. In May 2000 the intentional degradation of the GPS signals that limited accuracy for civilian users was removed. GPS is a worldwide system that is available 24/7 in any weather conditions. The GPS system uses 24 satellites that broadcast their identification and very accurate time information. This “raw” GPS data is able to provide around 20 meter accuracy, since “selective availability” (intentional degradation of the GPS signals to non-U.S. military users) was removed in

May 2000. The rapid adoption of GPS technology for commercial uses demonstrates the inherent usefulness of accurate positional information. System enhancements are likely to continue to be developed which may enable inexpensive receivers to achieve sub-centimeter accuracy over the longer term.

The U.S. Coast Guard Navigation Center (NAVCEN) operates the maritime and nationwide differential GPS system (NDGPS), which provides additional data to GPS receivers to improve the accuracy beyond what is possible with satellite-based GPS data alone. When fully deployed, the NDGPS system will use differential GPS reference station transmitter systems located throughout the country to broadcast additional information that can be used by GPS receivers to generate more accurate location estimates. These DGPS transmitters broadcast in the 300 KHz frequency range. Using NDGPS to augment the GPS system currently provides accuracy in the one-meter range for “good quality” receivers that are moving (such as those located in vehicles). With many public sector users having a vested interest in accurate DGPS, and the U.S. DOT having a leading role in the NDGPS rollout, rapid progress is expected in deployment of this system.

At this point in time, it is not yet clear whether or not the planned NDGPS system, even with the high accuracy capabilities currently being researched, coupled with increased receiver processing power, will be sufficient to allow centimeter-level accuracy for receivers in moving vehicles. At some point, it may become necessary to establish micro-DGPS reference stations and transmitters at close intervals near the roadways upon which critical applications requiring this level of accuracy will be implemented. This is similar to the extremely high accuracy systems being deployed in the immediate vicinity of airports to provide positioning information for automated aircraft landing. In the case of motor vehicle applications, these local transmitters could use next generation DSRC communications, for example. Another option, which may be technically and economically possible, is to establish DGPS reference stations at future digital radio stations and use the digital data channel to broadcast the differential corrections information.

Assuming adequate funding is dedicated to this program, NDGPS deployment can be expected to reach the point of dual-station coverage for the majority of the United States by 2007. In this time frame, it will become apparent whether or not the NDGPS transmissions and improved on-board receivers are capable of providing sufficiently accurate positioning for moving vehicles. However, this may be too late to begin planning for the implementation of supplementary DGPS systems, if necessary. Focused research, supported by increased funding, would seem to be required to determine this need at an earlier time, so that any necessary planning could be completed in a timely manner.

In the 5-year planning horizon, 1-meter positioning accuracy can be expected to be widely available from the combination of GPS / NDGPS signal reception and more processing power in receivers. This should enable many of the applications identified by EDMap, assuming that navigational databases of sufficient detail and accuracy are also available in this time frame.

It appears feasible to expect that vehicles will have sub-meter accuracy positioning capabilities by 2012. This is expected to require multiple (at least two) wireless communications capabilities for vehicles, and may also require very localized infrastructure development. If the DGPS is required to be extremely localized in terms of infrastructure, then vehicle applications that are dependent upon highly accurate positioning will likely be limited to major roadway segments, at least initially. Digital radio data broadcasting represents a potential compromise between regional transmissions and extremely localized transmissions. The digital radio data broadcasting approach, in

conjunction with multi-site corrections techniques, therefore may provide a viable alternative for the delivery of high accuracy positioning information to moving vehicles.

Radar

Radar systems have long been used for speed enforcement. Newer systems are being designed for vehicles to provide sensing for Adaptive Cruise Control (ACC) and other proximity detection applications. Radar encompasses a wide range of frequencies, with traffic enforcement radar commonly in the K-band (around 24 GHz), and sensors operating in the 60-80 GHz range. Besides sensor applications, radar technology can also be used to communicate data from a roadside beacon to vehicles. For example, the Safety Warning System™ (SWS) uses 24 GHz radar detectors as messaging units to warn of road hazards ahead. The message conveyed is minimal, at this point, comprising 7 data bits. The 7 bits are used to "trigger" one of 64 stored text messages that can be displayed on the radar detectors, or played as a verbal message. This system was implemented in 1996, and approximately 10 million radar detectors in the United States now include this capability.

Even the current system could provide a very useful wireless communications component if it could be integrated with on-board telematics systems. There are currently SWS transmitters installed in 32 States, primarily by DOTs. The transmitters are currently being used to broadcast warnings for school zones, school buses, police and fire, work zones, toll booths and hospital zones. Work zone warning has been the most widely deployed use of the system. This has been effective, since non-SWS compatible radar detectors operating in the 24 GHz range are also activated by an SWS transmitter, essentially creating a "drone" radar, which has proven effective at reducing traffic speeds at work zones. By triggering radar detectors, even without specific messaging, in a percentage of the vehicles proceeding through a work zone, the overall traffic flow is slowed as the radar-equipped vehicles initiate a braking response to the radar indication and non-equipped vehicles respond to the braking of the equipped vehicles.

One significant issue is that radar detectors are illegal in a number of areas. Another issue is that radar messaging transmitters must typically be purchased and installed by public sector organizations. It appears to be difficult to justify spending for such enhanced services when only a small portion of vehicles are equipped to receive the messages. Although much more expensive than SWS transmitters, variable message signs can often be justified for purchase and installation by public sector organizations precisely because the drivers of ALL vehicles can see these messages.

The effective range for the SWS system is up to 2 kilometers, so it has characteristics that may be complementary to DSRC characteristics. In addition, the successful operation of the SWS messaging system implies that other radar systems (e.g., ACC sensors) may also be able to support messaging capabilities. With the extremely short wavelengths of signals in the 10's of GHz range, directionality of the transmissions can be highly constrained through the antenna design. Directionality down to roadway single-lane is likely to be practical in the 50-100 meter range, with wider coverage expected as the range increases.

One of the big questions about this technology concerns 2-way communications capabilities. The expense of transmitters operating in these frequency ranges is the most likely limiting factor regarding 2-way capabilities. However, even with receive-only capabilities, the SWS technology has demonstrated the potential usefulness of messaging applications over radar frequencies. With a high likelihood of at least forward-looking radar capabilities on future vehicles (in conjunction with ACC), a standards-based method of

providing messaging capabilities for these systems could extend the vehicle's capabilities for deriving useful information from the roadside. These capabilities may be very complementary to DSRC capabilities, although some overlap is likely.

By 2012, this technology (if such developments prove feasible and economical) could likely be enhanced to meet a large number of the short range wireless communications needs of telematics applications. With enhancements to support variable message reception (receive only operation), radar communications could be used to support a number of the applications identified by EDMap. Within this time frame, radar message reception could be integrated into vehicle telematics systems, thus providing support for a large number of wireless communications requirements to the vehicle from the immediate road infrastructure.

Remote Keyless Entry (RKE)

This technological category refers to the wireless communications systems used to support pushing a button on a keyfob and having vehicle doors automatically lock/unlock, trunk automatically open, alarm automatically activate/deactivate, and related features. RKE systems have been used for a number of years. These systems are proprietary to each vehicle manufacturer, but typically use narrow, designated spectrum in the 300-400 MHz range. The keyfob portions of the system are simple, transmit-only devices, designed to be small and inexpensive, and to draw very little current from the small batteries in these devices. The receive portion of the system in the vehicle is also designed to be inexpensive and to operate in an "always listening" mode that draws very little power from the vehicle battery. This is especially important for times when the vehicle is left parked for extended periods.

Increasing the complexity of the keyfob transmitters would increase the cost, size and complexity of the user interface, as well as increasing the current drawn from their batteries, increasing the required size of the batteries, or decreasing the life of the batteries. At the protocol level, the RKE systems have been designed with very simple, proprietary systems to recognize only the coded signals arriving from the "matching" transmitter units. If more complex applications were to be designed into these systems, more capable protocol layers would need to be developed at the software level. In addition, more processing power would be required to support the more complex software.

Existing RKE systems are inherently one-way wireless channels. The keyfob units are transmitters, and the in-vehicle units are receivers. It is not expected that existing systems will be expanded to include two-way capabilities. Rather, it is more likely that other two-way systems will be used to support any wireless two-way capability requirements for RKE applications. If Bluetooth gateways (integrated with the control bus systems) become common on vehicles, and Bluetooth remote modules become very inexpensive, there may be a movement to move the RKE functions onto Bluetooth technology. Since Bluetooth is already a *de facto* international standard, this approach could generate economies of scale in the near term future, as well as providing a standard protocol stack for applications development.

The current RKE wireless systems are designed to be low-cost to manufacture, but reliable over time. The wireless linkage is not reliable from a communications standpoint, but if the first door unlock message does not get through, the user can just press the button again. The communications channels being used are fairly narrow, limiting the amount of data that could be effectively transmitted. Although the frequencies of operation have been designated, there are no obvious efforts underway to create an industry-wide

standard for RKE systems. These systems are therefore most likely to continue to be proprietary to each vehicle manufacturer.

In the five-year horizon, it is expected that RKE systems will remain basically the same as they are at the present time. They are currently very inexpensive and do their specific job very well, so major changes are unlikely. New features can be supported by the current wireless technologies. In the ten-year perspective, it is likely that wireless technologies, other than the current proprietary RKE ones, will be used to support more advanced RKE-type applications. This replacement may include incorporation of the RKE-type functions into advanced mobile phones, or other mobile wireless devices normally worn, or carried, on the person.

Safety applications, like those being studied by the EDMap project, generally require reliable wireless communications channels. As well, these safety applications generally require interoperability between the vehicles of different manufacturers, and between these vehicles and the road infrastructure. RKE systems, as they are currently designed, could not effectively support either of these requirements. If new wireless systems are deployed that support RKE-type applications, among other applications, then these systems may be useful for EDMap applications. However, the new wireless systems that may be able to "absorb" RKE functionality are most likely to be standardized wireless systems that are discussed under other research topic areas, such as 3G, Bluetooth and DSRC.

Satellite Digital Audio Radio Systems (SDARS)

Satellite Digital Audio Radio Systems (SDARS), namely XM Satellite Radio and Sirius Satellite Radio are in the early stages of launching service in the US (4Q 2001 for XM, and forecasted 1Q 2002 for Sirius). At this time, the technology of each system is proprietary, and XM receivers will not receive Sirius transmissions (and vice versa), however, the next generation receivers will be able to receive both XM and/or Sirius transmissions. The SDARS services operate at S-Band (2.310 – 2.360 GHz) frequencies for the downlink to vehicles. These frequencies have only been allocated by the WRC for SDARS in the US. Systems proposed for other parts of the world are expected to use other frequencies.

Both the US systems contain digital bit streams sent to the vehicles. The digital bit streams could support any form of digital data – voice, graphics, control messages or file downloads, for example. Each of the approximately 100 digital "channels" available on these systems supports data transmissions in the range of 64 Kbps. This technology is inherently point-to-multipoint, so the 64 Kbps data channel would be available simultaneously on a nationwide basis. Therefore, any digital data that would fit within the available SDARS bit stream could be sent nationwide using these systems. Conceivably, a single data message sent through one of these systems could simultaneously reach every satellite-equipped automobile in the US. For vehicle communications that could effectively use a relatively inexpensive nationwide data channel, these systems may prove to be the most economical wireless communications method.

Since the satellite infrastructure is already in place for both XM Satellite Radio and Sirius Satellite Radio, commercial service has been (or will soon be) initiated, and receivers are already commercially available to receive the audio programming, SDARS data broadcasting to vehicles can be expected to be implemented within the five-year time frame. It is expected that automotive OEMs, as equity participants in these SDARS systems, will be among the first users of data broadcasting over SDARS. Some

suggested uses are upgrading in-vehicle software in embedded devices, and sending messages to categories of automotive customers.

Many EDMap safety applications depend upon a very accurate, on-board location database in the vehicle. Updates to such an in-vehicle database that are time sensitive from the “daily” range to the “up to the minutes” range might be effectively accomplished using SDARS data broadcasting. In the five-year time frame, data broadcasts could be readily implemented on SDARS systems to support location database updates enabling EDMap applications. One argument against this scenario is that the SDARS broadcasts are nationwide, and detailed location database updates are more pertinent on a local/regional basis. This follows from the realizations that much irrelevant location database information would potentially be received and stored on vehicles through a nationwide database update data broadcast. The system-wide economics would be the most likely deciding factor in such decisions.

Although there are lingering questions concerning the long-term economic viability of SDARS systems, if these systems do prove to be viable, they could be very important for EDMap safety applications. If satellite radio receivers become an integral, factory-installed part of every new vehicle, then SDARS has the potential to become an important, pre-existing communications channel into vehicles on a mass, point-to-multipoint basis.

Terrestrial Digital Radio

The radio broadcasting industry is one of the last communications media to convert from analog to digital technologies. The basic analog technologies for radio broadcasting - Amplitude Modulation (AM) and Frequency Modulation (FM) transmission systems - have changed very little over time. These technologies have worked very well throughout the years, and there is a vast installed base of AM/FM receivers. The main problem with analog AM and FM systems is spectral efficiency. Digital systems are capable of broadcasting roughly five times the information content of analog systems within the same spectrum. Spectrum has become an increasingly scarce and valuable commodity as wireless communications systems have proliferated.

Various “hybrid” systems have been deployed to combine digital data content with analog modulation systems. These hybrid systems place digital signals along with the current FM and AM analog signals (within the presently licensed spectral mask). FM subcarrier systems have been used for quite some time. In these systems, digital data is sent on subcarriers contained within the allowable spectral envelope of the FM station. These data signals are then received by special-purpose receivers that can extract the data from the main FM transmission. Most of the installed systems have a data throughput of around 1 Kbps, but newer subcarrier technologies have become available that support data rates of 16 Kbps, or more. In the AM hybrid area, new technology has recently become available to embed digital data within the existing AM transmissions, without disturbing the analog audio signal. System delays of 30 – 60 seconds can be expected for these datacasting systems, which limits their use for applications that demand immediate real time characteristics.

The FM portion of In-Band, On-Channel (IBOC) technology is being recommended by the National Radio Systems Committee (NRSC) for adoption by the United States broadcasting industry. If approved by the FCC, IBOC will initially be deployed as a hybrid system, since the existing analog radio transmission will continue as before, but digital signals will be added to carry a high quality digital audio transmission, as well as some digital data. This will be the intended operational mode through a 10-15 year transition

period. After this transition period, the analog transmissions will be eliminated, and the resulting all-digital system will provide much more data-carrying capabilities. For the hybrid FM system, if the audio signal occupies the full 96 Kbps available for high quality audio, then only 1 Kbps will be available for data broadcasting. If, however, a station chooses to use only 64 Kbps for its audio signal, then 33 Kbps would be available for datacasting. After the expected 10-15 year transition period to digital radio, then most of the portion of the transmission that has been used for analog audio can be recovered for datacasting. This all-digital mode could potentially offer over 200 Kbps of data capacity, depending upon the digital audio quality being used in the system.

Test results and more information about the AM IBOC system are expected in the near future. Since there is less spectrum available in the AM license allocation, the digital capabilities of the AM system are expected to be less that those of the FM system.

In 1995, Eureka 147 was recommended as a world wide standard for digital radio by the ITU-R. The Eureka 147 system provides flexibility to support audio signals at discreet intervals between 8 Kbps and 384 Kbps, and offers the opportunity to support data transmissions up to several hundred Kbps along with the audio transmission. Since that time, this system has been rolling out in many countries throughout the world. Eureka 147 receivers became generally available in 1998, and are now provided by over 16 manufacturers. Eureka 147 uses Orthogonal Frequency Division Multiplex (OFDM), a modulation technique that has proven to be extremely well-suited for mobile operations. This system is not compatible with existing AM and FM stations operating in the same frequency bands, and therefore new spectrum must be allocated for this service. For Eureka 147, these new frequencies have been assigned either at the Very High Frequency (VHF) range of 216 – 240 MHz, or at L-band frequencies in the 1.45 GHz range. In the United States, the L-band is not available due to military aeronautical telemetry uses, and the VHF range is also not available.

Some form of terrestrial digital radio is likely to be gaining momentum in the United States by 2007. In the rest of the world, terrestrial digital radio is expected to be well-established and widely deployed in this time frame. By 2012, wide deployment is also likely in the United States, even though this will still be hybrid mode if the IBOC plan is followed. If a different frequency band is allocated for digital radio, however, all-digital transmissions are likely to be available sooner in the United States. Datacasting applications on the digital radio systems may take longer to be deployed, since not too much data carrying capacity will be available during the IBOC hybrid transition period. This situation may force applications that could most effectively and efficiently use terrestrial radio datacasting to adopt alternative technologies, like 3G, that, although less efficient, become available sooner than digital radio datacasting.

There are a significant number of telematics-type applications that could potentially use terrestrial digital radio datacasting to most efficiently and effectively communicate with vehicles. These types of applications are generally point-to-multipoint in nature, where the same information is sent to all the vehicles at the same time. In the 5-year time frame, the hybrid terrestrial radio systems are most likely to predominate in terms of relevance for vehicle communications in the United States. On a global basis, digital radio will likely be a significant factor in Europe and elsewhere outside the United States. Both of these systems are likely to be able to support useful telematics services in this time period. A very effective potential use of datacasting over terrestrial radio systems is near real time, continuous updates of on-board geographical databases. Low-bandwidth, variable information, like work zone locations, lane closures, detours, malfunctioning traffic signals and time-of-day restrictions, for example, might best be conveyed to the vehicle databases through such point-to-multipoint systems.

In the 10-year time frame, digital radio is likely to be extensively used on a global basis to support many telematics applications. In the United States, this is likely to happen more slowly, since digital radio will be deployed more slowly, and the hybrid systems will support only limited data rates in comparison to all-digital systems. The digital radio communications capabilities will be complementary to other wireless communications channels, and the applications supported by digital datacasting will be chosen to maximize efficiency and effectiveness, thereby reducing costs. In this time frame, the widespread availability of all-digital terrestrial radio datacasting systems (outside the United States) will reliably support the continuous updating of on-board navigational databases to a very dense level of detail. This will allow database density to be dynamically increased for all suitably-equipped vehicles within a local or regional area, for example. This level of detail and the dynamic update capabilities are likely to drastically increase the accuracy and relevance of on-board databases, enabling other innovative new applications besides the applications identified by EDMap.

Two-way Satellite

Two-way satellite systems have both a forward and a return communications path. This allows for data request, responses and acknowledgements to be supported in the low-speed data realm. Two-way characteristics also support voice telephony at higher speeds and interactive multimedia at broadband data rates. One of the most common methods of classifying satellite systems is to group them into different categories according to the nature of their orbits, with altitude being the main determinant of orbital considerations.

Each type of satellite orbit is better suited for specific applications. Satellites at great distance from earth – like Geostationary Earth Orbit (GEO) satellites - are not well-suited to handle voice or other isochronous traffic, because of their inherent latency. The satellite orbits that are closest to the earth – called Low Earth Orbit (LEO) satellites - have lower latency, and are much better suited to handle mobile voice services. However, these lower orbiting satellites move quickly in relation to the earth;s surface, so rapid mobility must be supported by the space segment radio links. As well, because they are closer to earth, many more satellites in total are required to cover the earth.

Access to two-way wireless data communications, with ubiquitous coverage over the continental US (as well as extended global coverage), provides a strong argument to consider two-way satellite services for wireless connectivity on vehicles. So far, however, the data services that are available and affordable have rather limited data capacity. For example, OrbComm packet data service typically supports text messages of less than 500 characters maximum. Within the next five years, there are a fairly wide range of telematics-type applications that could be supported using a short message data structure. These include applications that relate to:

- telemetry of vehicles (for example, monitoring engine operating parameters to proactively suggest repairs before breakdowns occur);
- automotive manufacturers sending messages to vehicle owners (for recall notifications, or service reminders, for example); and
- control messages sent to vehicles (for example, remote unlocking of doors, honking the horn, flashing the lights, etc.).

There would be an opportunity to use low bandwidth packet data services over satellite to support vehicle telemetry applications, such as probe vehicle monitoring. Since the two-way satellite services are designed to operate as point-to-point communications channels,

these systems are unlikely to be useful for the distribution of location database updates, due to slow data speeds and expected airtime costs. Most other EDMap applications either have latency requirements preventing use of satellite systems, or require specific place-based communications channels.

If two-way broadband satellite systems are deployed, they should be reaching operational status in the ten-year planning horizon. Many applications using wireless communications to support multimedia entertainment in vehicles will become possible. These capabilities could also be used to support infotainment, and other information services related to multimedia entertainment. The availability of such high-bandwidth connectivity could also allow location database downloads over two-way satellite systems. The major consideration would then be communications costs relating to satellite airtime and satellite transceiver equipment costs. If the cost differential is significantly in favor of terrestrial wireless systems at this time, only applications that require ubiquitous geographical coverage are likely to be implemented using two-way satellite systems.

Ultrawideband (UWB)

Ultrawideband is a radio technique consisting of sending a large number of low power pulses spread over a wide frequency range to provide remote sensing (like radar) or communications capabilities, for example. This technology has been in use for military applications for over a decade, but has only recently begun to be commercialized. Typical UWB systems use extremely short duration pulses, in the range of 1 or 2 nanoseconds with power levels of only a few microwatts. Military uses have typically been in the areas of ground penetrating radar, electronic warfare, and stealth communications. The implementation of UWB in these applications has demonstrated all-digital design, resulting in relatively low cost and small size. The FCC is presently considering what rules are necessary to allow this new technology to be deployed without creating interference to existing applications within assigned spectrum.

The NTIA and other groups have conducted extensive testing to determine the potential for interference to GPS reception and other low-level reception situations. In general, the testing has found that UWB devices can interfere with other devices operating within assigned frequency spectrum, under various power levels and modulation techniques. This testing has not yet produced any definitive conclusion regarding allowable UWB spectrum-sharing, however, due to the varying conditions that cause such interference. Although the various reports of test results are available, the conclusions still need to be interpreted into rational public policy by the FCC. Comments continue to be filed with the FCC in regard to this proceeding (ET Docket 98-153), with over 700 comments already on file (including over 20 in November 2001). At this point, it is not clear when the FCC may make a decision on this proposed rule making, nor what that decision is likely to be.

Once the FCC decides how to make appropriate rules for UWB to be deployed, commercial development will be able to proceed very quickly toward providing innovative new products using this technology. The commercial development of this technology has been focused upon very low-power applications for sensing and communications. The communications characteristics for local area wireless data networks are very impressive – with very high bandwidths being supported, and very good performance throughout the interiors of buildings. In my opinion, the most likely scenario at this time is for the FCC to eventually allow UWB operations under Part 15 regulations, but restrict such operations to specific frequency ranges, such as those above 6 GHz, that are well-removed from critical frequencies (like those used for GPS).

If the FCC establishes rules that allow UWB technology to operate over sufficiently wide spectrum, a proliferation of commercial applications can be expected. The applications

included in most of the projections for commercialization are very short range, extremely low-power deployments. The main concern for the FCC is if the cumulative effect of many low-power USB devices operating “on top of” existing spectrum license holders will create interference to existing services, particularly by raising the noise floor within the existing spectral allocations.

The largest limitation of UWB for vehicle communications is the limited range expected with the initial systems that are likely to become available. One of the positive aspects of USB for vehicles is the all-digital implementation, which allows low cost, light weight and small size to be realized. As well, UWB appears to be almost immune to multipath interference, a significant benefit for moving vehicles. Besides communications, vehicle applications that may be supported by UWB include “invisible security domes and fences”, as well as collision avoidance sensors. Pulse-based radar has been in military use for over a decade, and offers potential advantages for vehicle sensor applications. Since cost, weight, size and mobile performance are very important considerations for automotive sensors and communications equipment, the development of the UWB technology warrants the continuing attention of automotive manufacturers.

The low-cost, small size characteristic of UWB devices, coupled with their potential use as an integrated communications, positioning and radar solution, makes UWB a reasonable candidate to monitor for further developments facilitating its use for EDMap applications. Since this technology is so new on the commercial scene, it may be some time before real relevance for EDMap applications can be confirmed.

If short-range vehicle-to-vehicle communications become viable using UWB, it is most likely to be in the ten-year time frame. Assuming that an early agreement on standard protocols for vehicle-to-vehicle communications could be achieved within the industry, then this capability might be able to be effectively implemented in vehicles in the ten-year planning horizon. As well, if standards and implementations of UWB for other vehicle applications proceed, then vehicle-to/from-roadside communications may be another area to consider for UWB integration.

Longer-range communications is another area in which UWB may represent opportunities for vehicle communications in the ten year time period. This longer-range development has a lower-probability expectation due to potential interference and spectrum regulation problems. High bandwidth, longer-range communications capabilities have already been developed for military applications, however, so there are at least real technological possibilities for longer-range commercial applications.

Summary Tables – Estimated Wireless Technology Capabilities and Costs

The wireless technology capabilities and costs summary tables that are presented below show capabilities and costs in relevant subcategories for each technology areas summarized above. These tables provide a concise view of the various technology areas in each time frame for comparison purposes. It should be noted that there are high degrees of uncertainty surrounding most of the estimates portrayed in these tables, especially in the area of costs. This uncertainty is particularly severe in the ten-year time frame. The figures given therefore represent “best guess” estimates of the relevant capabilities and costs, based upon current trends and points of reference.

Table 5.1 – Five-Year Estimated Wireless Technology Capabilities and Costs

Capabilities >>>>	Range	Coverage	Directionality			Directivity		Maximum Bit Rate		System	Cost		
Wireless Technology Areas:			One-way to vehicle	One-way from vehicle	Two-way	Point-to-point	Point-to-multipoint	Stationary	Mobile	Latency [note 1]	Infrastructure [note 2]	On-Board Equipment (OBE)	Airtime
2.5-3G PCS and Digital Cellular	~4-6 km	2.5G major metros			X	X		384 Kbps	144 Kbps	1.5-3.5 sec	$7-10K	$80-100 [note 3]	~$1.50-2.50 /Mb?
Bluetooth	10 m	[note 4]			X	X		1 Mbps	1 Mbps	3-4 sec	$8	$8	0
Dedicated (Digital) Short Range Communications (DSRC) w/ 802.11a R/A	15-400 m	select roadways			X	X		27 Mbps	27 Mbps	200 micro sec	$40-100	$20-30	0
Digital Television (DTV)	~40 km	major metros	X				X	19 Mbps	NA	10-30 sec	$250-500K	$40-50	$0.0015 /Kb?
High Altitude Platforms	120 km	?	?	?	?	?	?	1 Mbps	?	?	?	?	?
IEEE 802.11a Wireless LAN	500 m	[note 4]			X	X		54 Mbps	[note 5]	3-5 sec	$40-150	$20-30	0
IEEE 802.11b Wireless LAN	1000 m	[note 4]			X	X		11 Mbps	[note 5]	3-5 sec	$20-75	$10-15	0
Nationwide Differential Global Positioning System (NDGPS)	300-400 km	most of US 48 states	X				X	200 bps	200 bps	NA	?	$20-30	0
Radar	2 km	[note 4]	X	X			X	<100 bps	<100 bps	NA	~$5K	$25-40	0
Remote Keyless Entry (RKE)	30 m	NA	X			X		<100 bps	<100 bps	NA	NA	~$5	0
Satellite Digital Audio Radio Systems (SDARS)	US 48 states	US 48 states	X				X	64 Kbps / channel	64 Kbps / channel	10-20 sec	?	~$50 [note 7]	$0.03 /Kb?
Terrestrial Digital Radio	30-50 km	limited metros	X				X	33 Kbps	33 Kbps	10-20 sec	$100-250K	~$50 [note 7]	$0.003 /Kb?
Two-way Satellite	NA	global			X	X		<20 Kbps	<20 Kbps	60+ sec	$1-2M	~$70?	~$0.08 /Kb
Ultrawideband (UWB) [note 6]	15-30 m ?	[note 4]		?			?	multi Mbps	multi Mbps	?	?	?	0

[note 1] System / Latency - represents the time to establish communications, log in to the network and exchange content.
[note 2] Transceiver / transmitter cost per base station, not including automated control, backhaul communications, physical structure or power supply.
[note 3] 2.5-3G PCS & digital cellular transceiver costs are difficult to estimate, due to subsidization of retail prices by wireless carriers.
[note 4] The coverage in these cases will be limited to areas within the range of the individual transceiver / transmitter locations.
[note 5] For mobile use, the way that these systems log-on and establish network communications would need to be eliminated or modified, since they were designed for stationary LANs.
[note 6] UWB assumes very low-powered transmissions in multi-gigahertz frequency range.
[note 7] Cost is for data-only portion of digital radio receiver and antenna.

Table 5.2 – Ten-Year Estimated Wireless Technology Capabilities and Costs

Capabilities >>>>	Range	Coverage	Directionality			Directivity		Maximum Bit Rate		System	Cost		
Wireless Technology Areas:			One-way to vehicle	One-way from vehicle	Two-way	Point-to-point	Point-to-multipoint	Stationary	Mobile	Latency [note 1]	Infrastructure [note 2]	On-Board Equipment (OBE)	Airtime
2.5-3G PCS and Digital Cellular	~4 km	3G major metros			X	X	?	2 Mbps	384 Kbps	1-2 sec	$10-20K	$70-80 [note 3]	~$0.15-0.25 /Mb
Bluetooth	10-100 m	[note 4]			X	X		1 Mbps	1 Mbps	2-3 sec	$5-20	$5	0
Dedicated (Digital) Short Range Communications (DSRC) w/ 802.11a R/A	15m-1 km	major roadways +			X	X		27 Mbps	27 Mbps	200 micro sec	$20-50	$10-15	0
Digital Television (DTV)	~40 km	all TV xmtrs	X				X	19 Mbps	?	10-30 sec	$200-400K	$20-25	$0.0015 /Kb?
High Altitude Platforms	120 km	major metros	?	?	?	?	?	1 Mbps	?	?	?	?	?
IEEE 802.11a Wireless LAN	500 m	[note 4]			X	X		54 Mbps	[note 5]	2-3 sec	$20-75	$10-15	0
IEEE 802.11b Wireless LAN	1000 m	[note 4]			X	X		20 Mbps	[note 5]	2-3 sec	$10-50	$5-10	0
Nationwide Differential Global Positioning System (NDGPS)	300-400 km	entire US	X				X	?	?	NA	?	$10-15	0
Radar	2 km	[note 4]	X	X			X	?	?	NA	~$3K	$15-20	0
Remote Keyless Entry (RKE)	2 m	NA	X			X		<100 bps	<100 bps	NA	NA	<$5	0
Satellite Digital Audio Radio Systems (SDARS)	US 48 states	US 48 states	X				X	64 Kbps / channel	64 Kbps / channel	5-10 sec	?	~$30 [note 7]	$0.03 /Kb?
Terrestrial Digital Radio	30-50 km	major metros	X				X	~200 Kbps	~200 Kbps	5-10 sec	$100-250K	~$30 [note 7]	$0.003 /Kb?
Two-way Satellite	NA	global			X	X		~1 Mbps	~1 Mbps	5-10 sec	$1-2M	~$100?	~$1.50-2.50 /Mb?
Ultrawideband (UWB) [note 6]	15-30 m ?	[note 4]	?	?	?	?	?	multi Mbps	multi Mbps	?	?	?	0

[note 1] System / Latency - represents the time to establish communications, log in to the network and exchange content.
[note 2] Transceiver / transmitter cost per base station, not including automated control, backhaul communications, physical structure or power supply.
[note 3] 2.5-3G PCS & digital cellular transceiver costs are difficult to estimate, due to subsidization of retail prices by wireless carriers.
[note 4] The coverage in these cases will be limited to areas within the range of the individual transceiver / transmitter locations.
[note 5] For mobile use, the way that these systems log-on and establish network communications would need to be eliminated or modified, since they were designed for stationary LANs.
[note 6] UWB assumes very low-powered transmissions in multi-gigahertz frequency range, but with the possibility of higher power options in this time frame.
[note 7] Cost is for data-only portion of digital radio receiver and antenna.

Summary Tables – Wireless Technologies Relevance to EDMap Applications

The following summary tables present the EDMap applications versus the thirteen wireless technologies. A scale of 1 – 5 (1 = least likely, 5 = most likely) has been used to rate the likelihood of a particular technology, including capabilities and cost, being used to support a particular EDMap application. The technologies are non-exclusive, meaning that if there are two equally likely wireless technology options for a particular application, both technologies will have the same rating. Of course, if one technology is deployed first, it may become the technology of choice for that application, to the practical exclusion of the other technology.

Table 5.3 presents the summary of the five-year wireless technology environment of relevance to EDMap applications. Table 5.4 presents the summary of the ten-year wireless technology environment. Table 5.5 provides the wireless implementation assumptions for the EDMap applications, as well as comments related to potential future wireless requirements for EDMap applications which do not yet have wireless communications requirements.

Because it is being developed specifically for DSRC, 802.11a R/A is implicitly included in the DSRC columns in Tables 5.3 and 5.4. The 802.11 columns therefore include 802.11a and 802.11b technologies.

Since it is not identified as a specific EDMap application, map database updates are considered a significant component for wireless requirements for all EDMap applications. Map database updates can be continuous, and near-real-time for dynamic database elements, like variable one-way streets and work zone locations, for example. Map database updates may also include new street names, new traffic signals, etc., on a less-frequent, but continuous basis. Point-to-multipoint data broadcasting technologies seem to be the best-suited wireless technologies to support these ongoing map database updates on an efficient and economical basis.

Tables 5.3 and 5.4 show that two technologies, DSRC and high-accuracy NDGPS (and to a lesser extent, Terrestrial Digital Radio) predominate in being likely to support EDMap applications. If these three technologies were widely deployed, then most EDMap wireless communications needs would be met, with the exception of an ubiquitous low data rate signal from vehicles to infrastructure, which might use digital cellular, or even DSRC if it was widely enough deployed to approximate ubiquitous coverage in the necessary locations.

Table 5.3 – Five-Year Wireless Environment

Application	Wireless Technology												
	2.5-3G PCS and Digital Cellular	Bluetooth	Dedicated (Digital) Short Range Communications (DSRC)	Digital Television (DTV)	High Altitude Platforms	IEEE 802.11 Wireless LAN	Nationwide Differential Global Positioning System (NDGPS)	Radar	Remote Keyless Entry (RKE)	Satellite Digital Audio Radio Systems (SDARS)	Terrestrial Digital Radio	Two-way Satellite	Ultrawideband (UWB)
Approaching Emergency Vehicle Assistant	1	2	5	1	1	1	3	2	1	1	2	1	2
Cooperative Vehicle System - Platoon	1	2	5	1	1	1	5	2	1	1	1	1	2
Cooperative Collision Warning	1	2	5	1	1	1	5	2	1	1	1	1	2
Enhanced Route Planning and Guidance	3	3	3	1	1	3	3	1	1	2	5	2	1
Extended Lane Change Advisory	1	2	5	1	1	1	5	2	1	1	1	1	2
Forward Collision Warning/Avoidance	1	2	5	1	1	1	5	2	1	1	1	1	2
Infrastructure Based Traffic Management - Probes	2	2	3	1	1	1	3	1	1	1	5	2	1
Infrastructure Based Traffic Management - Road Sensors	2	2	4	1	1	1	3	1	1	2	5	2	1
Intersection Collision Warning/Avoidance	1	2	5	1	1	1	4	2	1	1	1	1	2
Optimal Speed Advisory	2	2	4	1	1	1	3	1	1	2	5	2	1
Parking Spot Locator	3	4	5	1	1	3	3	1	1	1	4	1	2
Railroad Collision Avoidance	1	2	5	1	1	1	4	2	1	1	1	1	2
Road Maintenance Aid	3	3	4	1	1	3	4	1	1	1	1	1	1
Selective Disable for ACC	1	2	5	1	1	1	3	2	1	1	2	1	2
Stop Light Assistant - Infrastructure	1	2	5	1	1	1	4	2	1	1	1	1	2

Key: 1 = least likely, 5 = most likely

Table 5.4 – Ten-Year Wireless Environment

Application	Wireless Technology												
	2.5-3G PCS and Digital Cellular	Bluetooth	Dedicated (Digital) Short Range Communications (DSRC)	Digital Television (DTV)	High Altitude Platforms	IEEE 802.11 Wireless LAN	Nationwide Differential Global Positioning System (NDGPS)	Radar	Remote Keyless Entry (RKE)	Satellite Digital Audio Radio Systems (SDARS)	Terrestrial Digital Radio	Two-way Satellite	Ultrawideband (UWB)
Approaching Emergency Vehicle Assistant	1	2	5	1	2	1	4	3	1	1	3	1	3
Cooperative Vehicle System - Platoon	1	2	5	1	1	1	5	2	1	1	1	1	3
Cooperative Collision Warning	1	2	5	1	1	1	5	2	1	1	1	1	3
Enhanced Route Planning and Guidance	3	4	3	1	3	3	4	1	1	3	5	3	2
Extended Lane Change Advisory	1	2	5	1	1	1	5	2	1	1	1	1	3
Forward Collision Warning/Avoidance	1	2	5	1	1	1	5	3	1	1	1	1	3
Infrastructure Based Traffic Management - Probes	2	2	3	1	3	1	4	1	1	1	5	2	2
Infrastructure Based Traffic Management - Road Sensors	2	2	4	1	3	1	4	1	1	2	5	2	2
Intersection Collision Warning/Avoidance	1	2	5	1	1	1	5	3	1	1	1	1	3
Optimal Speed Advisory	2	2	4	1	3	1	4	2	1	2	5	2	2
Parking Spot Locator	3	5	5	1	3	3	4	1	1	1	5	1	3
Railroad Collision Avoidance	1	2	5	1	1	1	5	3	1	1	1	1	3
Road Maintenance Aid	3	4	4	1	1	3	5	1	1	1	1	1	2
Selective Disable for ACC	1	2	5	1	2	1	4	3	1	1	4	1	3
Stop Light Assistant - Infrastructure	1	2	5	1	1	1	5	3	1	1	1	1	3

Key: 1 = least likely, 5 = most likely

Table 5.5 – Applications Comments

Application	Wireless Communication Comment
Adaptive Drivetrain Management	longer term - might benefit from having real time road conditions information
Adaptive Headlight Aiming	na
Adaptive Transmission Management	na
Approaching Emergency Vehicle Assistant	assume vehicle-to-vehicle or infrastructure-based communications
Lateral & Longitudinal Control	na
Cooperative Vehicle System - Platoon	assume vehicle-to-vehicle communications
Cooperative Collision Warning	assume vehicle-to-vehicle communications
Curve Speed Assist	longer term - might benefit from having real time road conditions information
Enhanced Route Planning and Guidance	assume communications of real time traffic, road construction, road conditions
Extended Lane Change Advisory	assume vehicle-to-vehicle communications w/ merging traffic
Forward Collision Warning/Avoidance	assume vehicle-to-vehicle communications w/ followed vehicle
Improved ABS	longer term - might benefit from having real time road conditions information
Improved Stability Control	longer term - might benefit from having real time road conditions information
Improved Traction Control	longer term - might benefit from having real time road conditions information
Infrastructure Based Traffic Management - Probes	assume communication of real time traffic information to/from vehicle, plus dynamic traffic light timing information to vehicle
Infrastructure Based Traffic Management - Road Sensors	assume communication of real time traffic information to vehicle, plus dynamic traffic light timing information to vehicle
Intersection Collision Warning/Avoidance	assume vehicle to/from infrastructure and/or vehicle-to-vehicle communications w/ very low latency
Intersection Turn Assistant	na

Table 5.5 (cont) – Applications Comments (cont)

Application	Wireless Communication Comment
Lane Change Assistant	longer term - might benefit from vehicle-to-vehicle communications with relevant vehicles in immediate vicinity
Lane Following Assistant	na
Merging Traffic Assistant	no communications in description, but longer term - might benefit from vehicle-to-vehicle communications with relevant vehicles in immediate vicinity
Optimal Speed Advisory	assume communication of real time traffic information to vehicle, plus dynamic traffic light timing information to vehicle
Parking Assistant	na
Parking Spot Locator	assume real time communication of vacant parking spot information
Passing Assistant	longer term - might benefit from vehicle-to-vehicle communications with relevant vehicles in immediate vicinity
Railroad Collision Avoidance	assume infrastructure-to-vehicle communications w/ low latency
Ranging/Imaging Sensor Calibration	na
Road Maintenance Aid	assume non-time-critical vehicle-to-infrastructure communications
Selective Disable for ACC	assume vehicle-to-vehicle communications w/ followed vehicle, infrastructure-to-vehicle communications for emergency vehicle notifications, possibly road conditions longer term
Speed Limit Assistant	longer term - might benefit from having real time road conditions information, also possible variable speed limits
Stop Light Assistant - Infrastructure	assume infrastructure-to-vehicle communications w/ very low latency
Stop Light Assistant - Vision	na
Stop Sign Assistant	na

Summary of Integrated Wireless Environment for Vehicles in the Five and Ten Year Time Frames

Summary of the Integrated Wireless Environment for Vehicles in the Five-Year Time Frame

The integrated wireless environment for vehicles in the five-year time frame is expected to include mainly technologies that have already been designed and standardized. On a nationwide basis, most wireless coverage will be provided by satellite systems. The SDARS systems are expected to offer simultaneous one-way, point-to-multipoint coverage of the entire United States. Two-way satellite systems are most likely to continue to small packet-based data communications with nationwide coverage. Hybrid terrestrial radio systems are expected to provide one-way, point-to-multipoint datacasting coverage to vehicles over 85-90% of the geographical area of the United States. The NDGPS system can be expected to include dual-station coverage on a nearly nationwide basis by 2007, providing positioning accuracy for moving vehicles in the range of one meter.

In major metropolitan areas, packet data enhancements to cellular and PCS systems, operating under 2.5G wireless network technologies, are expected to become fairly by 2007. Also in this time frame, 3G systems are expected to begin to be deployed in major metropolitan centers. Hybrid terrestrial radio systems are expected to be readily available in this time frame to provide one-way, point-to-multipoint data broadcasting capabilities that might also economically include areas around smaller population centers within the range of radio broadcasts.

In the five-year environment, the enhanced 5.9 GHz DSRC systems are likely to begin to displace some of the 900 MHz DSRC systems along specific toll roads, and in regions where extensive toll roads and bridges enable electronic toll collection to become widely accepted. With the strong likelihood that 5.9 DSRC developments will proceed rapidly, and will allow variable messages and much larger messages, it seems unlikely that radar messaging will achieve a dominant wireless communications role along specific roadway segments.

In and immediately around vehicles, Bluetooth technology is fairly likely to become widely deployed in cellphones, PDAs and other mobile devices. If this is the case, then RKE functionality may be taken on by such Bluetooth-equipped devices and Bluetooth gateways in upscale vehicles. In the five-year time frame, 802.11b wireless LANs are expected to be fairly ubiquitous in homes and small offices. Although unable to support mobile operations, 802.11b transceivers might be effectively integrated into vehicles to allow communication, like entertainment and infotainment file download, between home LANs and vehicles while the vehicle is garaged. If 5.9 GHz DSRC is able to be effectively developed to meet automotive manufacturers' needs, in terms of costs and capabilities, then these systems might begin to be used in and around the vehicle in this time frame. DSRC may be able to effectively support vehicle-to-vehicle communications, as well as immediate vehicle to/from infrastructure communications, but widespread deployment will require the development of a substantial "community of interest" of DSRC-equipped vehicles.

Summary of the Integrated Wireless Environment for Vehicles in the Ten-Year Time Frame

Predicting the integrated wireless environment for vehicles in the ten-year time frame encompasses a great deal of uncertainty. The relevant technology trends, however, indicate that wireless technologies can realistically be expected to move in the direction of increased performance and reduced cost. Multiple wireless communications channels are expected to be integrated into the vehicle in this time frame, in order to provide the most efficient and effective wireless channel for each safety-related and telematics application. The intelligence in the vehicle will be expected to transparently integrate data received through multiple communications channels into a cohesive set of information, and present this information through an integrated human-machine interface.

Assuming nationwide agreement on standards for 5.9 GHz DSRC that are acceptable for public-sector needs, automobile manufacturers' needs, and for commercial service providers, it is reasonable to expect that nationwide deployment may be well underway in the United States in the ten-year time frame. If satellite radio receivers become an integral, factory-installed part of every new vehicle in the ten-year time frame, then SDARS has the potential to become an important, pre-existing, point-to-multipoint communications channel into vehicles on a nationwide basis. If two-way broadband capabilities become available over satellite systems, it is likely to occur around 2012. In this time frame, the NDGPS system is likely to cover the entire geographical area of the United States with overlapping regional transmissions. If the development of high accuracy NDGPS (20 centimeter accuracy range) proves successful and practical, then deployment of the high accuracy enhancements could be expected to be well-underway, or even completed, by 2012. Even if the 20 centimeter accuracy proves not to be practical, at least sub-meter positioning accuracy using the NDGPS system can be expected to be widely available by 2012.

High-bandwidth 3G systems are likely to be widely deployed in virtually all major metropolitan centers and surrounding areas in the ten-year time frame. The 3G connectivity will likely come at a high price, however, since the very high expenses of auctioned spectrum and new network equipment will need to be repaid through compensatory airtime charges. If the stratospheric platform approach proves to be feasible, then the ten-year time frame should allow enough time for these platforms to be deployed for most major metropolitan areas in the United States. Terrestrial digital radio will most likely be used to support local, or regionally-based information, through near-real-time datacasting. The hybrid terrestrial digital radio systems being planned for the 10 – 15 year time frame in the United States are likely to support only limited data rates in comparison to the all-digital systems being deployed elsewhere.

If centimeter-level accuracy is not able to be achieved through the combination of GPS / NDGPS signal reception and more processing power in receivers, then there is a risk that the availability of centimeter-level positioning may be confined to specific roadway segments. Assuming that automotive manufacturers are able to provide effective inputs to the DSRC standards development process to ensure cost effective systems, then widespread use of high bit-rate, 5.9 GHz DSRC systems along specific roadways seems very likely in the ten-year horizon. This type of system will likely be the most reliable, effective and efficient way to support the communication of very localized information from the roadside to vehicles, as well as between vehicles in close proximity. If practical implementations of UWB for vehicle sensors can be effectively deployed, then vehicle-to/from-roadside communications may also be able to be integrated into UWB systems in the ten-year time frame.

It is likely that wireless technologies other than the current proprietary ones will be used to support more advanced RKE-type applications in and immediately around vehicles by 2012. The new wireless systems that are most likely to “absorb” RKE functionality are expected to be standardized wireless systems, like 3G, Bluetooth and DSRC. If Bluetooth is able to meet its cost objectives, it is likely to become ubiquitous by 2012, providing virtual integration between carry-on devices and the vehicle.

Multiple wireless communications capabilities for vehicles are likely to be required to support positioning-related communications. It appears feasible to expect that vehicles will have some form of centimeter-level accuracy positioning capabilities by 2012, supported by the various wireless communications systems. It is not yet clear if the planned NDGPS system, even with the high accuracy capabilities currently being researched, will be sufficient to allow centimeter-level accuracy for receivers in moving vehicles.

DSRC is the most likely communications channel to provide the necessary support for location-specific and vehicle-to-vehicle safety-related and telematics applications, potentially including very specific DGPS data reception. The low-cost, small size characteristic of UWB devices makes UWB potentially very appealing for possible use as an integrated automotive communications, positioning and radar solution, but this very new technology may or may not prove to be feasible for automotive applications.

Chapter 6

The Wireless Communications Environment for EDMap Applications in 5 and 10 Years

FINAL REPORT

Conclusions

Conclusions related to specific areas of the wireless research are presented in the following subsections. A number of promising wireless technologies are being implemented, or planned for implementation, within the EDMap project planning horizon. The wireless communications research has uncovered no fundamental wireless technological impediments to the deployment of the types of automotive safety applications being proposed. There are, however, significant opportunities to exert positive influences on the development of specific wireless technologies that are likely to be the most critical components for support of the automotive safety applications identified by the EDMap project. Current opportunities exist to exert positive, timely influence on the development of public policies and technological standards for DSRC and terrestrial digital radio. As well, there appears to be an immediate opportunity to encourage and facilitate the acceleration of research and development of high accuracy NDGPS, and potentially accelerate the deployment of this technology if the proposed level of accuracy proves to be achievable in practice.

DSRC:

DSRC is likely to be the preferred wireless technology to support the communications requirements of many of the safety applications identified by the EDMap project, not only because its technical capabilities are likely to be specifically fine-tuned for these applications, but also because of the co-primariy designation of the 5.9 GHz spectrum by the FCC. In the United States, the potential future system capabilities have rapidly expanded with this 75 MHz of spectrum being designated by the FCC for DSRC. Standards are very important to ensure interoperability, and various standards development organizations are currently working on this new system, with ASTM E17.51 taking the main coordination role. With its recent selection as the physical layer to be used in the new US 5.9 GHz DSRC standards, IEEE 802.11a is proposed to be adapted by IEEE 802.11 Task Group a (TGa) into the R/A (roadside applications) version for mobile use at highway speeds. A very recent proposal has been made for another task group within IEEE to develop the appropriate lower layer standards under a “fast track” approach. If this approach is followed to accelerate the standards development, there is a risk that compatibility with 802.11 may be compromised. The present, intensive standards development activities represent a significant opportunity to influence the future capabilities of DSRC systems.

The next two years will likely prove critical for the development of the full range of 5.9 GHz DSRC standards, with the next six-to-nine months representing the most intensely critical period. These DSRC standards have the potential to provide support for many automotive safety-related applications, but if detailed standards are not optimized for automotive applications, safety-related applications may be too costly, or too inefficiently supported, to become widely available at the earliest possible time. This situation could result in the unnecessary loss of life through accidents that are preventable by the earliest possible deployment of automotive safety-related applications. For this reason it has become an urgent priority for automotive manufacturers, on a pre-competitive basis, and in close cooperation with the public sector, to actively participate in the development and testing of DSRC standards and technologies, especially within the next six-to-nine months.

Deployment of DSRC based safety applications can be enabled and accelerated by increased involvement of automotive OEMs with the standards process, specifically by further defining the specific communications requirements of EDMap applications, and then effectively conveying these requirements for inclusion in the standards development process.

NDGPS:

Very accurate positioning is a critical component for future vehicle systems, and especially for many of the safety-related applications identified by the EDMap project. GPS satellite receivers can be expected to be a core component of the future vehicle communications requirement, but more critical positional applications are likely to require at least NDGPS reception in addition. It is not yet clear if the planned NDGPS system, even with the high accuracy capabilities currently being researched, will be sufficient to allow centimeter-level accuracy for receivers in moving vehicles, but it is clear that this level of positional accuracy will be required for the EDMap safety applications. At the present time, and over the near term, broadcast NDGPS over the regional beacons seems to be the only viable alternative for reasonable cost, integrity and reliability. If necessary in the ten year time frame, the NDGPS data may be able to be rebroadcast over digital radio, for example. Including phase measurements should greatly increase the value of this system to many users and should be enthusiastically endorsed.

It appears that current funding levels are insufficient to rapidly determine if high accuracy NDGPS using regional beacons will be capable of providing a practical system to support positional accuracy of 20, 10 or 5 centimeters in moving vehicles. The development of high accuracy corrections algorithms using multi-reference-site approachs will require additional research. Only upon the culmination of this research will the practical accuracy limits become apparent for differential corrections provided over a 300-400 kilometer radius (the distance range for current NDGPS beacons). However, this may be too late to begin planning for the implementation of supplementary DGPS systems, if necessary. Focused research would seem to be required to determine this need at an earlier time, so that any necessary planning could be completed in a timely manner. It appears that acceleration of the high accuracy NDGPS research could be achieved with increased visibility and increased funding priority. There is therefore an immediate opportunity and need to encourage and facilitate the acceleration of research and development of high accuracy NDGPS, in order to determine the level of accuracy that is practically achievable. If the proposed level of accuracy proves to be achievable in practice, accelerating the deployment of this technology might enable the earlier implementation of many automotive safety applications.

Digital Radio:

Datacasting through digital radio (or hybrid systems) is likely to be vitally important for a number of applications identified by EDMap. Although system delays of 30 – 60 seconds can be expected for these datacasting systems, there are many wireless communications requirements for near-real-time characteristics that can be met by digital radio systems. Near-real-time, point-to-multipoint datacasting over terrestrial radio systems can provide very effective and efficient continuous updates of on-board geographical databases, including variable information like traffic flow, work zone locations, lane closures, detours, malfunctioning traffic signals and time-of-day restrictions. Less dynamic map database updates could also be efficiently supported using terrestrial digital radio datacasting. If NDGPS is not able to achieve the desired level of accuracy using its regional transmitter approach, then it may be technically and economically feasible and desirable to establish NDGPS reference stations at future digital radio stations and use the digital data channel to broadcast the differential corrections information.

Radio broadcasting is the last major wireless service in the US to convert from analog to digital operation. The Digital Audio Broadcasting (DAB) Subcommittee of the National Radio Systems Committee (NRSC) has recommended that the In-band, On-channel (IBOC) technology developed by iBiquity become the United States digital radio standard. With a recommendation by the NRSC, the FCC is likely to be considering IBOC technology in 2002, as the potential choice for the conversion of radio broadcasting (AM & FM) in the United States to digital. Therefore, over the next year there will be a significant opportunity to influence digital radio license terms, especially for the longer-term, through the FCC rulemaking public process. Some of the emerging information needs of automotive safety-related applications may be deemed essential enough to the public good that carriage of this data might be able to be included in the FCC's license terms for all-digital radio stations, with the proper level of support from automotive manufacturers and the Department of Transportation, for example.

Emerging Technologies:

These emerging technologies may, or may not, prove feasible to deploy. If they are deployed, they might play a significant role in wireless communications for vehicles. Thus, the development of these technologies should be actively monitored as they emerge toward deployment, or attempt to overcome potential roadblocks.

UWB: Ultra-wideband is a very new technology that has so far been mainly used for military applications (like ground-penetrating radar and devices that can "see through" walls). Unlike TV "channels" or radio station frequency assignments (like 89.1 MHz), this technology defies channelization, because it is virtually on all frequencies within a range. Low-power, short-range uses seem to be the most likely potential non-military deployments for this technology in the foreseeable future. Potential interference with other wireless services - especially GPS - is currently being studied and debated for proposed rulemaking by the FCC. Because it readily lends itself to all-digital hardware implementation, non-military deployment of this technology is likely in the longer-term, if the spectrum issues can be resolved effectively.

High-Altitude Platforms: This also represents a very new technology that has significant potential for wireless communications. Large wireless communications platforms are proposed to be placed in semi-stationary locations at stratospheric altitudes (~70,000 feet) near major metropolitan centers. Due to the much lower altitude than satellites, the latency for these systems could be potentially much lower than that of satellite systems. Global coverage for such a system is estimated at one-tenth the system cost of equivalent global

satellite coverage (250 such platforms could cover roughly 95% of the world's population), so there may be significant economic incentives for deployment of this technology. Many applications that require specific metropolitan/regional coverage could benefit from the natural coverage characteristics of these systems. Datacasting of in-vehicle positional database updates, is one potential example of relevance to the EDMap project. Another potential example is very early initial deployment of metropolitan area 3G coverage.

Multiple Wireless Technologies:

Throughout the course of the wireless communications research conducted for the EDMap project, it has become increasingly obvious that there is unlikely to be a single wireless technology that meets the requirements of all EDMap applications. Instead, as the efficiencies and resulting economics of various wireless technologies are matched to appropriate applications over time, it is most likely that multiple communications technologies will be used in each vehicle.

Applications with two-way, very low latency communications requirements, like intersection collision warning, are most likely to use short-range wireless technologies, like DSRC. Applications with wider-area, two-way wireless requirements, like Mayday service, are likely to "piggy-back" on wireless voice networks. Applications, like entertainment, traffic information, or database updates, that can effectively use less expensive point-to-multipoint wireless communications technologies are likely to adopt this approach for cost reasons. The GPS and NDGPS systems can both be considered to "contain" point-to-multipoint wireless communications systems, satellite datacasting in the case of GPS, and terrestrial radio frequency beacon transmitters in the case of NDGPS. The intelligence in the vehicle will be expected to transparently integrate data received through multiple communications channels into a cohesive set of information to support the relevant applications.

The best way to ensure the widespread availability and affordability of diverse wireless communications systems that can support the needs of EDMap applications seems to be to foster and facilitate commercially-viable services that would be able to use (and subsidize) these same wireless systems. For example, the capabilities of the enhanced DSRC systems to support profitable commercial services might be leveraged to generate the economic justification for the installation of DSRC systems that can also be used to support safety-type applications. This objective may be able to be effectively accomplished through public-private partnerships, or through large-corporate direct involvement in facilitating innovative new telematics service providers.

Appendix A - GLOSSARY

The following information has been assembled as a high level overview of the various topics. Most of the related technical explanations have been developed with the assistance (and often selected partial text) of technical definitions contained in the Federal Standard 1037C (http://glossary.its.bldrdoc.gov/fs-1037/), except as otherwise noted for specific references and general industry knowledge (GIK).

3G – third generation wireless systems (analog cellular was the first generation, current digital cellular is second generation technology) (GIK).

802.11 – a set of standards developed by the IEEE to support wireless LANs [http://grouper.ieee.org/groups/802/11/index.html].

802.11a - IEEE wireless LAN standard for transmissions on unlicensed frequencies in the 5.9 GHz range [http://grouper.ieee.org/groups/802/11/index.html].

802.11a R/A (roadside applications) – proposed IEEE wireless LAN standard for transmissions on dedicated DSRC frequencies in the 5.9 GHz range, optimized for vehicle applications (mobile at highway speeds) (GIK).

802.11b – IEEE wireless LAN standard for transmissions on unlicensed frequencies in the 2.4 GHz range [http://grouper.ieee.org/groups/802/11/index.html].

ACC - Adaptive Cruise Control – a vehicle based system that includes sensory inputs to dynamically reduce the cruise control speed to match that of a vehicle ahead in the same lane (GIK).

AM - Amplitude Modulation – a modulation scheme in which the amplitude of a carrier wave is varied in accordance with some characteristic of the modulating signal.

API – Application Programming Interface – the set of commands, messages and protocols that are supported by an application and are available to external programs (GIK).

Asynchronous communications – a form of communications in which operations are executed out of time coincidence with any event.

Bluetooth - an emerging industry group *de facto* standard for a particular 2.4 GHz, short-range, low-powered, inexpensive wireless communications technology that has the support of major telecommunications equipment manufacturers (GIK).

Category 5 wiring – cabling that is typically used for wired Ethernet LAN connections (GIK).

CEN – European Committee for Standardization [http://www.cenorm.be/].

CEA - Consumer Electronics Association [http://www.ce.org/].

DAB - Digital Audio Broadcast – a generic term applied to the various technologies that have been proposed and/or deployed to support the transition of radio broadcasting from analog to digital (GIK).

dBm – decibel milliwatt - dBm is used in communication work as a measure of absolute power values. Zero dBm equals one milliwatt.

DGPS - differential GPS systems – enhanced systems which provide additional data over terrestrial wireless links to GPS receivers to improve the accuracy beyond what is possible with satellite-based GPS data alone (GIK).

DOT – (US or State) Department of Transportation

DSRC - Dedicated Short Range Communications (also sometimes called Digital Short Range Communications) – "a communications approach allowing short range communications between vehicles and the roadside for a variety of purposes, such as intersection collision avoidance, transit or emergency vehicle signal priority, electronic parking payments, and commercial vehicle clearance and safety inspections." [http://www.its.dot.gov/tcomm/specqa.htm]

DSSS - Direct Sequence Spread Spectrum - a system for generating spread-spectrum transmissions by phase-modulating a sine wave pseudorandomly with a continuous string of pseudonoise code symbols.

DTV - digital television - a new technology for transmitting and receiving broadcast television signals. DTV provides clearer resolution and improved sound quality than analog systems (GIK).

Ethernet 10baseT – a common technology, based upon a standard protocol (IEEE 802.3), for wired LANs operating at 10 Mbps (GIK).

ETSI - European Telecommunications Standards Institute [http://www.etsi.org/aboutetsi/home.htm].
Eureka 147 – international standard for digital radio using frequencies other than existing AM and FM bands (GIK).

EWG – the NRSC Digital Audio Broadcasting Subcommittee' s Evaluation Working Group – currently evaluating IBOC technology for recommendation to the FCC as the preferred digital radio technology in the United States [http://www.nab.org/SciTech/Dab/dabsub.asp].

FCC – Federal Communications Commission

FHSS - Frequency Hopping Spread Spectrum - a signal structuring technique employing automatic switching of the transmitted frequency. Selection of the frequency to be transmitted is typically made in a pseudo-random manner from a set of frequencies covering a band wider than the information bandwidth.

FM - Frequency Modulation - signaling method that varies the carrier frequency in proportion to the amplitude of the modulating signal.

FM subcarrier systems – analog or digital systems used to broadcast additional information over commercial FM radio stations, without interfering with the main audio transmission (GIK).

GHz – Giga Hertz - a unit of frequency representing 1,000,000,000 cycles per second.

GPS - Global Positioning System - a worldwide, satellite-based radio-navigation system developed and operated by the United States Department of Defense.

Hz – Hertz - the SI unit of frequency, equal to one cycle per second.

IBOC - In-Band, On-Channel – technology developed by iBiquity Corporation and proposed as the preferred technological approach for digital radio in the United States [http://www.nab.org/SciTech/Dab/dabsub.asp].

IEEE - Institute of Electrical and Electronic Engineers

IR – infrared - the region of the electromagnetic spectrum bounded by the long-wavelength extreme of the visible spectrum (approximately 0.7 m) and the shortest microwaves (approximately 0.1 mm).

ISM - industrial, scientific and medical applications - operation of equipment or appliances designed to generate and use locally radio-frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of telecommunications.

ISO - International Organization for Standardization

Isochronous - pertaining to data transmission in which corresponding significant instants of two or more sequential signals have a constant phase relationship. Such a relationship is particularly significant in supporting "streaming" digital audio or video.

ITU-R – International Telecommunications Union / Radiocommunications Sector - which is responsible for studying technical issues related to radiocommunications, and also has some regulatory powers.

Kbps – kilo (1000) bits per second (GIK).

LAN – Local Area Network - a data communications system that (a) lies within a limited spatial area, (b) has a specific user group, (c) has a specific topology, and (d) is not a public switched telecommunications network, but may be connected to one.

L-band – refers to frequencies in the 1.45 GHz range

LMSC - LAN / MAN Standards Committee - this portion of the IEEE standards effort comprises around 600 technical representatives who meet every four months to further the standards-setting developments.

MAC - Medium Access Control sublayer - the MAC layer represents a portion of OSI layer 2 functionality. In particular, the MAC represents the part of the data link layer (OSI layer 2) that supports topology-dependent functions and uses the services of the physical layer to provide services to the logical link control sublayer.

MAN - Metropolitan Area Network - a data communications network that (a) covers an area larger than a campus area network and smaller than a wide area network (WAN), (b) interconnects two or more LANs, and (c) usually covers an entire metropolitan area, such as a large city and its suburbs.

Mbps - Mega (1,000,000) bits per second (GIK).

NAB - National Association of Broadcasters [http://www.nab.org/].

NAVCEN - U.S. Coast Guard Navigation Center – the organizational entity that operates the maritime and nationwide differential GPS systems [http://www.navcen.uscg.gov/dgps/].

NDGPS - Nationwide Differential GPS – described as the "world's largest ground-based GPS augmentation service", this system "will provide double DGPS coverage across the continental United States" [http://www.navcen.uscg.gov/dgps/ndgps/Enhancements0106.htm].

NRSC - National Radio Systems Committee – "Its purpose is to study and make recommendations for technical standards that relate to radio broadcasting and the reception of radio broadcast signals." [http://www.nab.org/SciTech/nrsc.asp]

OBE – On-Board Equipment – a term being applied to the (especially DSRC) equipment that is mounted in a vehicle

OFDM - Orthogonal Frequency Division Multiplexing – "The basic idea is that each bit occupies a frequency-time window which ensures little or no distortion of the waveform. In practice it means that bits are transmitted in parallel over a number of frequency nonselective channels. This technique is for instance used in digital audio broadcasting (DAB)." [http://diva.eecs.berkeley.edu/~linnartz/MCCDMA.html]

OSI - Open Systems Interconnection - pertaining to the logical structure for communications networks standardized by ISO. The OSI Basic Reference Model is a standard 7 layer protocol structure that is widely used to organize protocol stacks and ensure interoperability.

PDA – Personal Digital Assistant – the PALM organizer represents the prototypical PDA (GIK).

PHY – the physical protocol layer which represents OSI layer 1 functionality – "Layer 1 is the lowest of seven hierarchical layers in the OSI Reference Model. The Physical layer performs services requested by the Data Link Layer (Layer 2). The major functions and services performed by the physical layer are: (a) establishment and termination of a connection to a communications medium; (b) participation in the process whereby the communication resources are effectively shared among multiple users, e.g., contention resolution and flow control; and, (c) conversion between the representation of digital data in user equipment and the corresponding signals transmitted over a communications channel."

Piconet – a wireless *ad hoc* micro network (within about a 10 meter radius in current considerations) comprised of multiple devices. Bluetooth is the main technology being promoted to support piconets at this time (GIK).

Point-to-multipoint – refers to transmissions that are sent from a single transmitter location and received simultaneously by multiple receivers in various locations. Radio broadcasting represents a good example of point-to-multipoint communications (GIK).

Point-to-point – refers to a wireless communications approach where a specific transmitter/transceiver communicates with only one other specific receiver/transceiver at a time. Cellular telephony using current technology represents a good example of point-to-point communications (GIK).

RKE – Remote Keyless Entry systems using small keyfob transmitters with buttons to lock/unlock the car, etc.

RTTT - Road Transport and Traffic Telematics – a primarily European vision of using information technologies and telecommunications to improve the safety and efficiency of road transportation (extensively discussed in document CEN/TC 278) [http://www.cenorm.be/].

SDARS - Satellite Digital Audio Radio Services – represented by Sirius Satellite Radio and XM Satellite Radio in the United States (GIK).

SIG - Special Interest Group – often a technical group that forms around a particular technology or technology concept to promote further technology development and/or relevant standards development (GIK).

SWS - Safety Warning System™ – this system uses radar detectors and "employs special microwave transmitters to generate messages in receivers that alert drivers to the presence of dozens and dozens of specific hazards and special traffic conditions" [http://www.safetyradar.com/main.asp?Page=about/index.asp&Page2=true].

TCP/IP - Transmission Control Protocol/Internet Protocol - two interrelated protocols that are part of the Internet protocol suite.

TGa - Task Group a (under IEEE 802.11) – the standards group that was tasked to develop a new 802.11 PHY for high speed operation in the 5.8 GHz U-NII [http://grouper.ieee.org/groups/802/11/index.html].

TGg - Task Group g (under IEEE 802.11) – the standards group that has been tasked to develop a higher speed(s) PHY extension to the 802.11b standard, and published the first draft in November 2001 which supports data rates up to 54 Mbps [http://grouper.ieee.org/groups/802/11/index.html].

U-NII - Unlicensed National Information Infrastructure – in 1997, the FCC amended Part 15 rules to allow operation of unlicensed devices on 300 MHz of spectrum from 5.15 – 5.35 GHz and 5.725 – 5.825 GHz [http://www.fcc.gov/learnnet/].

UWB – Ultra Wide Band is a new technological concept that uses time domain, rather than frequency domain characteristics for sensing and communications.

VHF - Very High Frequency - the part of the radio spectrum from 30 to 300 megahertz, which includes TV Channels 2-13, the FM broadcast band and some marine, aviation and land mobile services.

WAAS - Wide Area Augmentation System – "a geographically expansive augmentation to the basic GPS service. The WAAS improves the accuracy, integrity, and availability of the basic GPS signals. This system will allow GPS to be used as a primary means of aircraft navigation for enroute travel and some kinds of landing approaches in the United States". [http://gps.faa.gov/Programs/WAAS/waas.htm]

1 Task 8B – External Deployment Factors

This appendix contains the Task 8B Report, published April 23, 2004. It discusses the potential development of an automobile positioning system with a nationwide infrastructure using GPS and inertial techniques that could reliably determine where in a land a vehicle is driving.

The Appendix consists of the following sections:

- Executive Summary
- Introduction
- Policy, Institutional, and Technology Developments
- GNSS Positioning Systems, Capabilities, and Timeline
- User, Vehicular, and Infrastructure, Developments
- Communications and Wireless Technology for EDMap

Vehicular Positioning and Communications Deployment Study

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Vehicular Navigation and Positioning Deployment Study

Executive Summary

This report is a contribution to the Enhanced Digital Mapping (EDMap) Project. It follows that Project's earlier Task 8A Interim Report of 31 January 2002. The Task 8A Report investigated the potential for industry to develop an automobile positioning system with a nationwide infrastructure using GPS and inertial techniques that could reliably determine where in a lane a vehicle is driving.

Objectives

In light of the generally positive findings, conclusions and recommendations of the 2002 Task 8A Report, this new study undertakes Task 8B. For Task 8B, this report provides an overview of advances since the Task A Report for in-vehicle equipment and for supporting infrastructure capabilities whose safety-focused applications may use enhanced digital map databases. Beyond this overview, it seeks to clarify current and future issues that arise out of institutional, technological, and policy concerns relevant to the Enhanced Digital Mapping Project.

Rationale

This study is needed because the field of vehicular navigation and its associated disciplines is moving ahead rapidly, powered by new satellite deployments, important technological improvements, and growing consumer interest. Industry analysts predict a remarkable growth in the business area of GPS technology over the next decade. The project that sponsors this report is evidence of the strong interest of the US Department of Transportation, other government agencies and major automobile manufacturers in the potential benefits that could result from equipping future vehicles with a positioning capability.

In addition to user navigation services (already widely available on newer autos), the principal purposes for such capabilities involve safety and security, which are of central importance to both individual drivers and the general public. These capabilities include collision avoidance, stolen vehicle tracking, emergency and roadside assistance, vehicle accident notification, and remote monitoring. To these one can add a wide range of such related services as traffic information, communication and entertainment. This study will be justified if its information and analysis help ensure that positioning technology moves rapidly forward to fulfill its promise and potential.

Methodology

This study has five chapters. To provide the context for this study, a brief introductory chapter reviews the Enhanced Digital Mapping Project's Task 8A Interim Report of January 31, 2002. An outline and survey of the topics treated in the remaining four chapters of this Task 8B Report follows. The second chapter, "Policy, Institutional and Technology Developments," is intended to be accessible to readers whose technical knowledge of these matters is at the interested layman's level. Chapters 3 and 4, on the other hand, offer more detailed answers to the principal questions

concerning the current status and future of positioning systems' capabilities, applications, and deployment for vehicular navigation. Chapter 5 addresses the communications and wireless technology aspects relating to vehicular applications. In all of these chapters, the approach to these topics describes and assesses what exists today, what developments are under way, and what results can be expected at various points in the near- to mid-term future.

This study's principal investigator, Keith D. McDonald, FRIN, has engaged several independent consultants from the US, Canada and Germany whose contributions to this work reflect their special expertise. (These consultants are noted in the "Acknowledgements" section.)

Results

The study's findings fall into the following six principal categories, each of which is summarized below:

A. Institutional and Policy Developments
B. GPS and Galileo Capabilities
C. In-Vehicle Positioning Systems
D. Infrastructure and Anticipated Changes
E. Future Positioning Capabilities
F. Communications and Wireless Technology

The first category's summary (A), "Institutional and Policy Developments," is based on Chapter 2, while the next four summaries (B, C, D and E) are based on the treatment of these topics in Chapters 3 and 4. The final category (F) "Communications and Wireless Technology" is addressed in Chapter 5 (as noted in the Acknowledgements below) and follows Mr. Thomas Schaffnit's "EDMap Project: Task 8B Communications Research Report," which stands on its own.

A. Institutional and Policy Developments: The US defense and civil communities' on-going commitment to GPS promises a strong, vigorous long-term program. The US military services' capabilities increasingly depend on GPS services. The tremendous growth of GPS devices, systems and applications in the civil sector indicate an economic "goliath" that no one is seriously interested in stopping or slowing. The economic benefits to the US government are enormous. The tax revenue created by the GPS industry and its work force are estimated to pay for the system's ten-year cost nearly every year. GPS may be the only Department of Defense program in history to produce such an excellent return on investment. It is not surprising that the European Community, Russia and several Asian states are interested in having similar systems serve their citizens, businesses and governments.

Chapter 2 summarizes policy developments that have assisted GPS growth and success, and that are now poised to help develop and implement the projected European Galileo system. The US government's early decision to go forward with GPS and to provide its civil capabilities to the world free of charge has had a strong impact on GPS acceptance and use. The European Union (EU) and its member states also have a strong economic and technology development commitment to deploy their own navigation satellite system (Galileo). The Galileo program plans to have an "open service" that will be free to all users as well as a fee-based services for special capabilities. To justify their cost, the fee-based services are being configured to provide additional benefits.

Using both systems, the GPS and Galileo systems will provide impressive capabilities and services that will have significant impact on their use with automobiles and other vehicles. These capabilities will increase greatly in the next five to ten years as GPS is modernized and Galileo

deployed. At this time there appear to be no policy or institutional concerns that would tend to impede the use of GPS and Galileo for vehicular applications.

B. GPS and Galileo Capabilities: GPS provides the primary positioning technology for almost all current in-vehicle positioning systems. It has a clear edge over cellular technology location techniques, which for this purpose are still in the research and development stage. Salient GPS advantages include high accuracy, global coverage unlimited by boundaries, and the means to improve accuracy by minimizing error sources. GPS limitations, notably weak or deflected (multipath) signals, have effective solutions that employ both receiver enhancement and system augmentation technologies.

The new European Galileo system, which should become operational by 2008-2010, will be interoperable with GPS and share similar characteristics. Galileo's additional satellites will expand availability, increase accuracy to the sub-meter level, and significantly improve reliability. The two systems together will substantially improve, in both timeliness and coverage, the ability to resolve any position ambiguities and to operate generally in a much more capable manner.

C. In-Vehicle Positioning Systems: The principal GPS limitations for vehicular positioning systems are "urban canyon" conditions (where tall buildings block signals), tree cover in residential neighborhoods, multipath effects, and weak signals. A variety of enhancements offer solutions, including Assisted GPS, High Sensitivity GPS (HSGPS), HSGPS with filtering, and map constraint GPS positioning. Augmenting GPS with other sensors provides even better systems; these augmentations include inertial navigation systems, odometry, digital compass, barometric altitude and enhanced digital map matching.

D. Infrastructure and Anticipated Changes: Infrastructure concerns mainly relate to the ability to provide vehicular positioning systems with up to date or up to the minute data. Navigation and positioning capabilities in equipment and related services using GPS, and certain augmentations to GPS, now appear to be somewhat ahead of the vehicular community's current ability to use these services. Communications and data links for the transfer of timely and useful data to vehicular systems are not now as capable as needed.

For future precision services employing GPS, improvements in vehicular GPS equipment and systems need to support positioning accuracy in the 10-40 cm range. There are a number of data link developments that may provide this accuracy, including a new type of differential corrections for the Nationwide Differential GPS service. Other requirements relate to providing updates on a regular or as needed basis to the enhanced digital maps that vehicles use to make judgments concerning routes, accident regions, road closures, travel times and a variety of other matters. The report covers both the position and communications areas, giving priority attention to the navigation and positioning field.

E. Future Positioning Capabilities: GPS currently provides excellent capabilities for many users worldwide at a reasonable cost for the basic GPS positioning system "engine." For practical, reliable operation in vehicles, however, the GPS receiver needs to be integrated with such other devices as an odometer, electronic compass, a sensor providing course direction, and an enhanced digital map database with software. The cost for such a group of devices can be substantial.

A large number of future vehicular applications will clearly need improved performance capabilities. This is true for positioning and communications as well as for such related equipment as human interface devices and an interactive infrastructure that can provide vehicular safety, route guidance and driver convenience data. While the current GPS civil standard positioning service (SPS) capabilities of 5-10 meters already meet many of these needs, improved precision position data would allow additional features and capabilities to be implemented.

Fortunately, both GPS and Galileo plan to provide substantially improved performance in the future. This performance will reflect improvements in:

- **Accuracy** of position, velocity, acceleration and time determination
- **Availability** of the navigation service
- **Coverage** of all regions of user interest
- **Continuity** of the service when needed
- **Integrity**, acceptable service assurance without hazardous or misleading information

These improved capabilities are obtained through a combination of:

- **Additional signals and frequencies** already planned for GPS and Galileo civil users
- **Improvements in the signal structure** to provide better performance (accuracy, etc.)
- **Greater power levels** for GPS and Galileo signals (compared to current GPS)
- **Ground control segment improvements** more accurately to determine and predict satellite location and orbits, time, etc.
- **More extensive augmentations** of GPS to improve real time accuracy, integrity, availability and coverage. These include improved differential corrections.
- **Improved signal processing and receiver technologies** to provide sub-meter to centimeter level positioning precisions

The report describes more fully the principal techniques to achieve these improvements.

F. Communications and Wireless Technology for EDMap: The technical feasibility of probe vehicle data collection for map data base enhancement appears very likely, using any of a number of currently-available wireless technologies, including existing cellular systems. Another result of the communications research is the conclusion that individual vehicles with navigation systems could potentially be provided with wireless map database updates using DSRC/IEEE 802.11a as soon as model year 2008, whereas there are serious bandwidth constraints with attempting to use SDARS to deliver map database downloads.

EDMap type vehicle safety applications could potentially use the same equipment and systems for little or no marginal cost, if a significant number of other vehicle safety applications are deployed in the future using DSRC technology in the infrastructure and in the vehicles. For several of the other vehicle safety applications, the specific preferred deployment sites in the infrastructure also appear to be ideal for deployment of EDMap type applications.

The communications research identified serious bandwidth constraints with the use of many of the available wireless technologies for map database downloading. Cellular data, SDARS, IBOC and Bluetooth systems were shown to be ineffective for delivering map data downloads with the current sizes of such data files. Even standard WiFi (802.11b) would take over an hour and a half to download the current size nationwide map database. Further constraints were identified in terms of deployment time frames, geographic coverage and cost considerations.

Acknowledgments

This study's principal investigator is Mr. Keith D. McDonald of Navtech Consulting, Alexandria, Virginia. A number of other contributors, however, should be recognized. Chief among these are: Professor Dr. Guenter Hein, Director, Laboratory for Navigation and Geodesy, University of the Federal Armed Forces, Munich, Germany; and Dr. Gerard Lachapelle, Professor of Geomatics, University of Calgary, Alberta, Canada. Professor Lachapelle was assisted by Dr. Mark Petovello and Dr. Chaminda Basnayake of the Geomatics Department's Research Engineering staff. These consultants provided admirable support during the investigation and contributed excellent material for the study.

We owe special thanks to Mr. Tom Schaffnit of Schaffnit Consulting, Inc., whose ″EDMap Project: Task 8B Communications Research, Topics 1–6 Reports," we have incorporated in our study with only minor changes. We have added his Topic 1 Report to Chapter 4 and his Topics 2–6 Reports now form our work's fifth and final chapter. We have done this with Mr. Schaffnit's permission and at the suggestion of our study's project director.

We are also grateful for the very helpful overall direction of Dr. Tom Pilutti of the Ford Scientific Research Laboratory, who as project director offered both clear guidance and valuable insights. Mr. Chris Wilson, Vice President of Daimler-Chrysler Research and Technology, North America, also provided invaluable support and perspective for the project.

The study benefited from the editing skills of consultants Dr. J. Kenneth McDonald and Mr. Howard Fisher. These individual and the assistance of Ms. Carolyn P. McDonald, who edited drafts and managed certain business aspects of the work, greatly strengthened the effort. These combined efforts have helped produce a focused, more readable and interesting study.

Any errors in the report are, of course, the sole responsibility of Mr. McDonald. We welcome comment on this work, which can be given to Mr. McDonald at his phone (703.256.8900), Email (kmcdonald@navtechgps.com), or fax number (703.256.8988).

Vehicular Navigation and Positioning Deployment Study

Chapter 1 Introduction

1.1 Background of CAMP Task 8 and Review of Prior Task 8A Report

This report is a contribution to the Enhanced Digital Mapping (EDMap) Project. Focusing on vehicular navigation and positioning deployment, this report follows the Project's earlier CAMP Task 8A Interim Report of 31 January 2002 [Ref. 1.1-1]. Basic information concerning CAMP Task 8 can be found in the January 2002 Task 8A Interim Report just noted and in the Task Statement for the Task 8B study [Ref. 1.1-2]. The earlier Task 8A Report investigated the potential for industry to develop an automobile positioning system with a nationwide infrastructure using GPS and inertial techniques that could reliably determine where in a lane a vehicle is driving.

The U.S. Department of Transportation, Federal Highway Administration and National Highway Traffic and Safety Administration in Washington, DC have supported work on Task 8. The project as a whole is under the supervision and management of a consortium known as the Crash Avoidance Metrics Partnership (CAMP), which includes:

- Daimler Chrysler Research and Technology, North America, Inc.
- Ford Scientific Research Laboratory of the Ford Motor Company
- General Motors Company
- Toyota Motor Company
- Navigation Technology Corporation (Navteq)

Task 8's goal is to provide an overview of in-vehicle and infrastructure-related equipment and capabilities for enhanced digital map (EDMap) safety-focused applications. Task 8 studies are divided into two major parts, Task 8A, completed in January 2002, and Task 8B, of which the report at hand is part. Although Task 8 is not part of the EDMap Program, it is closely related and provides critically needed inputs for the development of EDMap technology.

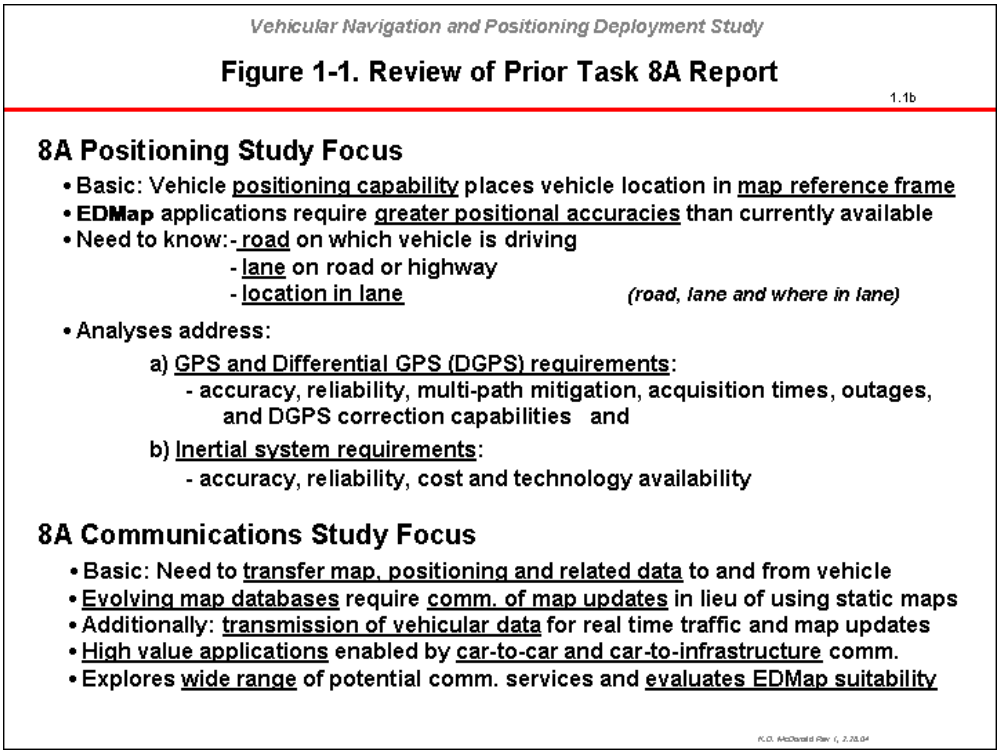
The EDMap Project concentrates on the EDMap databases and their specification, formation and maintainability. A number of other factors, such as vehicle positioning technology and communications capabilities are also important in the EDMap Project.

Task 8 is also intended to provide a reality check for the vehicular positioning and communications technology community in order to assure their confidence in and support for the EDMap applications. The Task 8 components include both the completed Task 8A investigation and this present Task 8B investigation. The Task 8A Report at the beginning of the EDMap Project provided a substantial amount of useful information and helpful reference point for both

the US Department of Transportation (DoT) and the vehicular safety application interests of original equipment manufacturers (OEM).

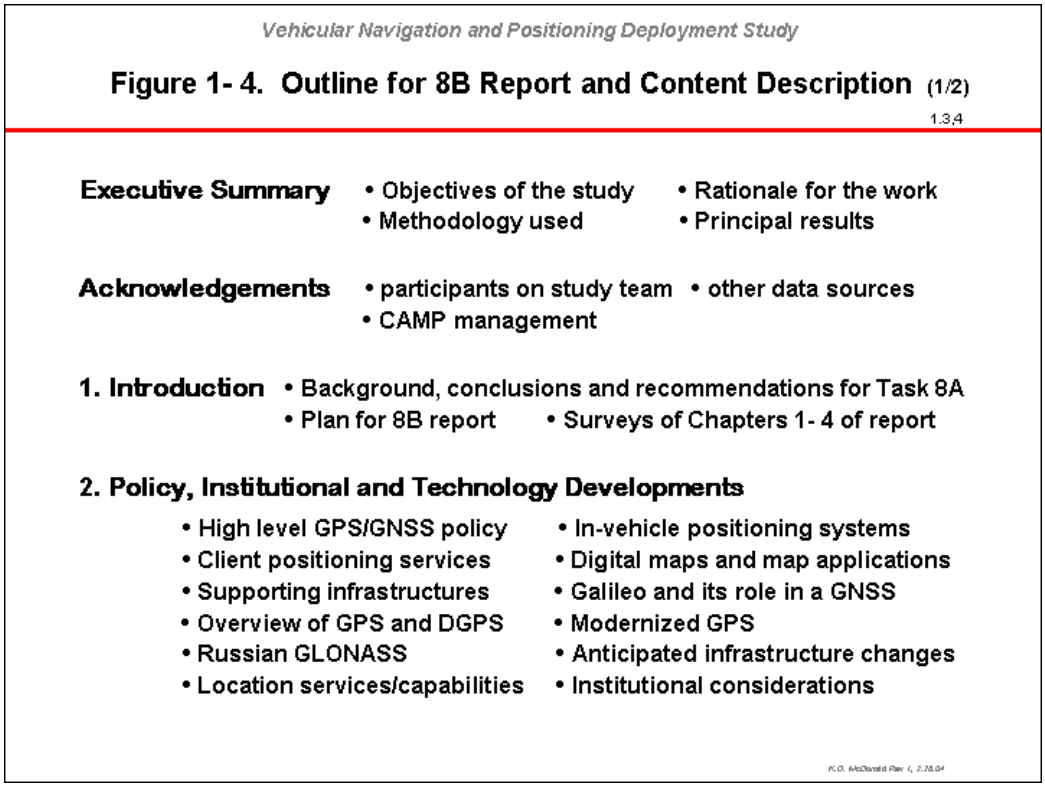
The current Task 8B report has been prepared near the end of the project to address the advances in the two years since the completion of the Task 8A report. This new Task 8B report attempts to clarify current and future policy, institutional concerns, and technology developments and projections.

Figure 1-1, entitled "Review of Prior Task 8A Report," addresses that report's positioning and communications studies, which found that many EDMap applications require greater positional accuracy than is currently available. Although positioning systems can now achieve position determinations at the meter and sub meter level, map resolution is considerably less accurate. It is therefore desirable (and in some cases essential) substantially to improve map databases. It also appears important in the future to provide the vehicle with information on map data changes and road conditions. This will require the transmission of larger quantities of digital data in real time than current vehicular communications can now handle. New capabilities are needed.



1.2 Task 8B Report Outline and Content Description: Chapter 1 Survey: Introduction

Figures 1-4 and 1-5 outline the content of the Task 8B Report. Its Executive Summary, which explains this report's objectives, rationale, methodology, and principal results, is followed by a brief acknowledgment of the study's

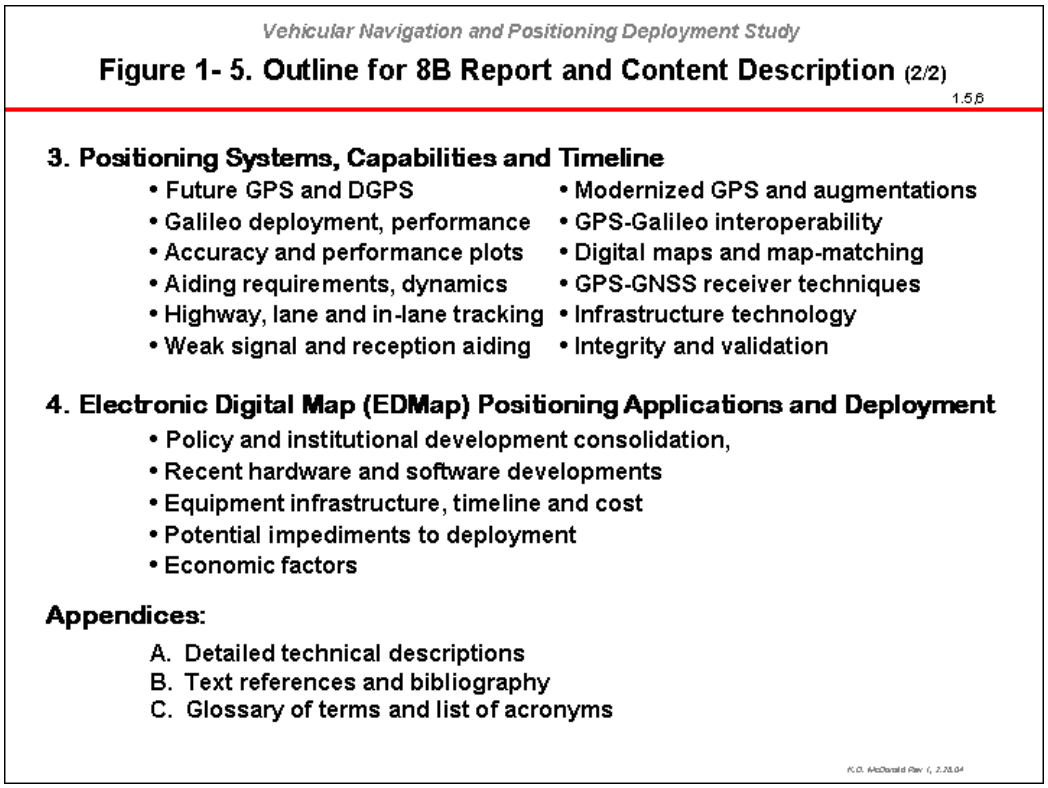


In the report's main body, Chapter 1 provides an introduction to each of the report's chapters. The remaining Chapters 2, 3, 4 and 5, examine the supporting infrastructure and costs associated with vehicular positioning systems and their relation to digital maps and the presentation of information to the user. In particular, Chapter 1 addresses the potential benefits, costs, and growth of the technology involved in vehicular positioning as well as some of the policy and other factors that will influence its growth.

1.3 Chapter 2 Survey: Policy, Institutional and Technology Developments

This chapter is written in a general manner for readers who desire a description of the study results with a minimum of possibly unfamiliar technical terms.

Chapter 2 first addresses high level policy issues relevant to the Global Positioning System (GPS) and the Global Navigation Satellite System (GNSS). The GNSS is assumed to include the GPS and its augmentations (including the differential correction and integrity providers), the forthcoming European Galileo system and its augmentations, as well as the Russian GLONASS and other evolving satellite-based systems that provide positioning services around the world.



Chapter 2 also covers the principal elements of in-vehicle positioning systems, including digital maps, client positioning services and supporting infrastructures. Finally, it offers overviews of GPS, Differential GPS (DGPS), Galileo, DGalileo and GLONASS, and discusses modernization activities for GPS and related upgrade plans for other systems.

1.4 Chapter 3 Survey: GNSS Positioning Systems, Capabilities and Timeline

In moderate technical detail, Chapter 3 addresses the principal space-based systems and capabilities available to develop and implement vehicular positioning and related systems. Where appropriate, this chapter provides in-depth information relating to the systems and services that are available in this field. GPS and Galileo developments are discussed in some detail including the schedule and operations of both systems as well as the impact on GPS of the forthcoming Galileo developments. The augmentations that are operational or planned for both systems are covered, as are the inter-operability aspects for the systems.

1.5 Chapter 4 Survey: User, Vehicular and Infrastructure Developments

One of the principal areas addressed is the future of GPS and DGPS receiver systems in the context of the developing European Galileo navigation satellite system. Within the next decade, extremely capable GPS and Galileo systems can be expected to provide performance to combined GPS-Galileo receivers allowing significantly improved, highly reliable and accurate position, velocity and time services. The deployment and use of both systems will provide about sixty orbiting satellites as well as robust ground control capabilities. This will result in outstanding

system coverage, user availability, accuracy, unprecedented continuity of service and many other performance benefits.

A discussion of recent hardware and software developments and the evolving equipment infrastructure necessary for their operation is presented. The chapter provides a timeline for many of the developments expected and discusses some of the relevant cost factors.

Since the applications of these and related techniques are of great importance for highway, lane, and in-lane tracking of vehicles, Chapter 4 examines these techniques. This examination focuses on infrastructure characteristics and navigation satellite receiver technologies as well as their costs and performance capabilities.

1.6 Chapter 5 Survey: Communications and Wireless Technology for EDMap

This chapter addresses a variety of data collection approaches, the potential systems to deliver the detailed map database updates and the potential synergies with other vehicle safety applications. The first section describes the results of research on probe vehicle approaches for map database data accumulation. It also identifies and discusses potential communications constraints for the probe vehicle approaches.

The second section discusses the potential of DSRC systems to deliver detailed map database updates. It addresses communications requirements for map database updates using DSRC technology, as well as scenarios for deployment and economic considerations. The final section identifies the implications of current research results for the deployment of communications capabilities to support EDMap type applications. It discusses potential synergies with other vehicle safety applications and with consumer applications. It also notes possibilities for building/cost sharing with consumer telematics type applications and specifically considers place-based commerce applications.

1.7 Appendices

The report concludes with five appendices:

Appendix A, "References," lists source and other references included in the brackets within the report.

Appendix B, "Bibliography," contains a selected list of publications and studies relevant to this study.

Appendix C, "Technical Information," provides more extended and detailed technical descriptions of some of the vehicular positioning systems and related technologies only briefly described in Chapter 3.

Appendix D, "Glossary," defines terms used in this study.

Appendix E, "Acronyms," explains the acronyms, including both those peculiar to the vehicular positioning field and those generally used in the navigation, navigation satellite and communications areas.

Chapter 2 Policy, Institutional and Technology Developments

2.1 High Level GNSS Policy

Probably the most important single policy directive concerning GPS in the last decade is the Presidential Decision Directive (PDD) of March 29, 1996 [Ref. 2.1-1]. This directive recognizes the dual-use nature of GPS, its potential to enhance the effectiveness of both US and allied forces, and its promise for rapid improvements in civil and commercial GPS markets. Led by the Department of Defense (DoD), the US Government has taken an active role in funding, coordinating, and promoting the GPS system. There are various agency and interagency responsibilities for this, principally as designated in the DoD, the Department of Transportation (DoT), and the Department of State (DoS).

The 1996 PDD provided guidelines for the operation and management of GPS. It also encouraged the acceptance of GPS for peaceful civil, scientific and commercial applications. The directive also required the system to promote safety and efficiency in transportation and to encourage private investment in the manufacture and applications of GPS equipment. The system's primary purpose, however, remained as it had been from the outset, to maintain and strengthen national security. The PDD also stated that GPS would have an important role in promoting international cooperation, which its use peaceful purposes would strengthen. Although primarily addressed to GPS, the PDD also recognized that GPS was an important component of an international Global Navigation Satellite System (GNSS).

2.1.1 Institutional Concerns, Funding, and Planning

There has been substantial delay in upgrading GPS characteristics, especially in its modernization capabilities. This, surprisingly, can be considered a problem of success, since the delay results from spacecraft lifetimes much longer than expected. While such longevity is generally desirable, it nevertheless considerably slows the system's replenishment schedule. Spacecraft replenishment offers the only reasonable opportunity for upgrading the system or for adding new features. Although the planned and contracted lifetime of the GPS II and IIA satellites was nominally 7.5 years, they are typically lasting about nine to 12 years. Since satellites are not ordinarily launched until they are needed (launch on need) in the constellation, this delay has had some deleterious effects on schedules for replenishing and upgrading the system.

Presidential Decision Directive (PDD) of 1996

The 1996 PDD also described new arrangements for the management, funding and operations of GPS. In particular, the directive changed the overall management of GPS, formerly a DoD program, to be jointly led by the designated representatives of the Secretary of Defense and the Secretary of Transportation.

The directive also stated that by September 30, 2006 the intentional degradation of the GPS signal, called Selective Availability (SA), would be turned to zero. Further, it indicated that beginning in the year 2000 there would be an annual review under White House supervision of the Selective Availability retention policy. Many believed that an objective appraisal of SA would result in its removal. On May 1, 2000, SA was set to zero with an announced policy of not returning it to operation.

Galileo Development

The European Community has become interested in fielding a navigation satellite system named Galileo for their own technology development, applications and use. Galileo has been investigated for a number of years by the European Space Agency (ESA) and their European Space Technology Engineering Center (ESTEC) in Noordwijk, the Netherlands. The Galileo program received a go-ahead from the European Union (EU) in 2002, with a substantial 1.3 billion euro funding following in 2003 [Ref. 2.1–2]. The program, which is moving rapidly forward, plans to have an operational system deployed by 2008. This date is probably somewhat optimistic and even those involved in the program believe that a more reasonable estimate would be 2010.

Although the Galileo system's capabilities are excellent and competitive with GPS in many ways, there are also a number of differences between the two systems. Galileo plans to have both an open service and a commercial service. In the latter, users will pay a fee to use Galileo services. GPS, on the other hand, will remain a free service indefinitely. This makes the situation a bit difficult for Galileo, whose commercial service will need to offer additional value and features beyond those available free from GPS. It is not yet clear what these services or fees will be.

The Galileo system plans a number of capabilities that will provide performance superior to current GPS capabilities. Galileo will have several (at least three, and possibly four or five) signal frequencies available in their satellites The GPS system will have one new frequency at L5, at 1176.45 MHz, for a total of three signal frequencies available for use.

In a sense, both of these systems are competitive. Most observers believe, however, that Galileo's principal benefit to the US will be its use in combination with GPS. The combined Galileo and GPS systems will provide a satellite constellation of over 60 spacecraft capable of correcting almost all of the visibility, coverage, integrity, and other concerns that currently exist for GPS alone.

The additional capabilities that are available from multiple frequency operations are substantial and important. Chapters 2, 3 and 4 address these operations in some detail. These capabilities will be available from Galileo in 2008 to 2010 (realistically, probably nearer 2010). Although similar GPS capabilities are planned and scheduled for deployment, fully operational multi-frequency civil GPS capabilities probably will not be available on spacecraft until between 2015 and 2018. This provides an initial 5-8 year Galileo lead in precision capabilities that appear appropriate for some vehicular applications.

2.1.2 International Implications

Although the coordination of GPS with Galileo has been progressing well recently, it is a difficult enterprise because of its sensitive political, civil, defense, economic and national autonomy issues. The US, in its initial negotiations with the EU and the European Commission, was not altogether friendly or supportive of the Galileo initiative. The US Department of Defense (DoD), working closely with the US Department of State (DOS) in these negotiations, had serious objections to the deployment of a European navigation satellite system such as Galileo. Chief among the DoD concerns was the question of how the US could deny Galileo's capabilities to a US military adversary in the event of hostilities. To protect US forces, the DoD would need to develop and deploy substantial jamming and related equipment.

Initial estimates of the cost of the research, development, manning and maintenance for the necessary jamming equipment were over one billion dollars. For this reason, the US did not initially support Galileo and questioned the need for its development. Since 2003 that position has changed. The US Departments of Defense and State no longer oppose the implementation of Galileo, although they have requested agreements on a number of points concerning its relationship with GPS. These issues are not contentious and appear to be amenable to amicable resolution.

2.2 GPS, Differential GPS and Modernized GPS Overview

2.2.1 GPS Overview

The Global Positioning System (GPS) was developed under Department of Defense (DoD) auspices in the early 1970's. The initial concept development work was done by the DoD Navigation Satellite Executive Steering Group between 1970 and 1973. After program approval by the Defense Systems Acquisition Review Committee (DSARC), the US Air Force (USAF) was designated as the Executive Agent for the implementation of the system. The GPS Joint Program Office (JPO) was established by the USAF in 1974 at their Space and Missile Systems Organization in El Segundo, CA in the Los Angeles area. The GPS JPO was charged with a) the detailed design and full development of the system based upon the preliminary work that had been done by the Steering Group, b) the testing and implementation of the system, and c) the transition of the completed elements of the program to operational status with the military departments as appropriate.

The system became fully operational in December, of 1995 and has been in continuous operation ever since. The baseline space segment configuration was established as a 24 satellite constellation but GPS has had 27 or 28 spacecraft operational for the past several years. As of March, 2004, GPS has 29 spacecraft operational.

We will review the various operating modes and performance capabilities of GPS and briefly discuss certain of the modernization initiatives that have been planned for implementation. Then we will take a brief look at the estimated performance improvements and capabilities available from the system between the years 2004 and 2015, and beyond. A brief mention of the international considerations and current activities in this area also will be provided.

Figure 2.2-1 illustrates the general configuration of GPS showing the constellation of 24 spacecraft in medium altitude orbit above the earth in six orbit planes. It also shows the manner in which the GPS spacecraft are maintained in good performance by the use of a set of monitor stations that receive the GPS signals from the spacecraft, determine their acceptability and general performance and then relay this information to the Master Control Station (MCS). The MCS is located at Shriever Air Force Base in Colorado Springs, CO.

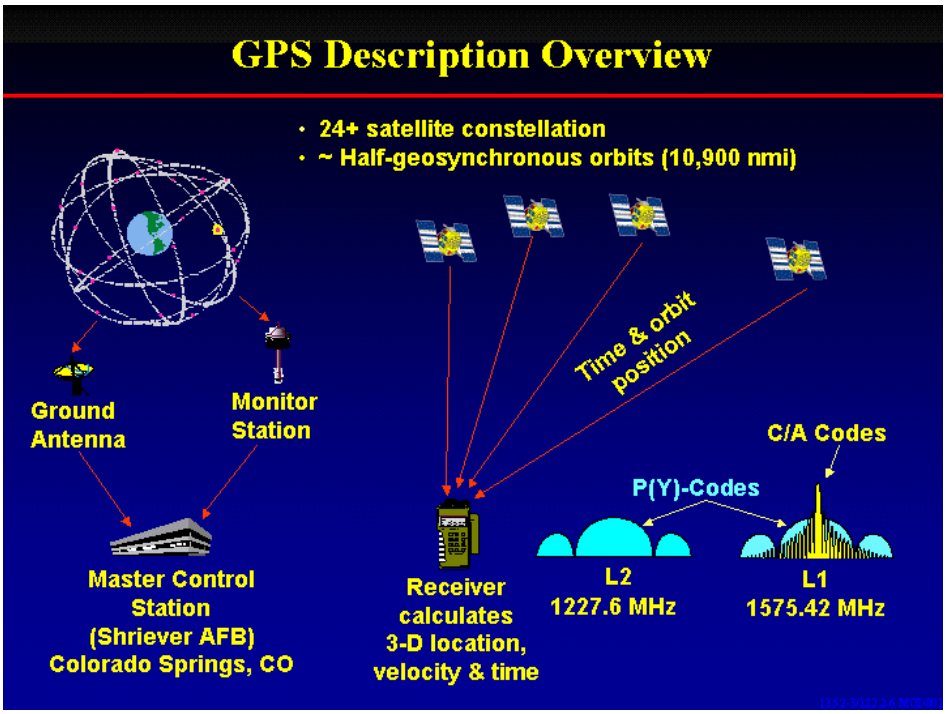


Figure 2.2-1

Changes in the spacecraft transmissions are uploaded to the S/C as they come into view. Figure 2.2-2 shows the principal GPS spacecraft generations, or production "Blocks."

The operating modes for the user equipment are as follows:

1. **Stand-alone** receiver operation
2. **Differential code** system operation
3. **Carrier phase measurement** receivers
4. **Attitude measurement** receivers

The conventional stand-alone receivers that typically use the civil (C/A) codes on the L1 frequency (at 1575.42 MHz) provide an accuracy of between 5-10 meters worldwide. The military users have two frequencies available and by using these, obtain about 2-4 meters of accuracy (on a 95% confidence basis in the horizontal).

Many of the military receivers, however, have been designed to have only the capability for operating at one frequency (L1). These receivers include the Precise Lightweight GPS Receiver (the PLGR) that the military has acquired in large quantities (approximately 150,000 units are in service). These receivers use the military P(Y)-codes that have a bit rate ten times that of the C/A-codes and are therefore somewhat more precise.

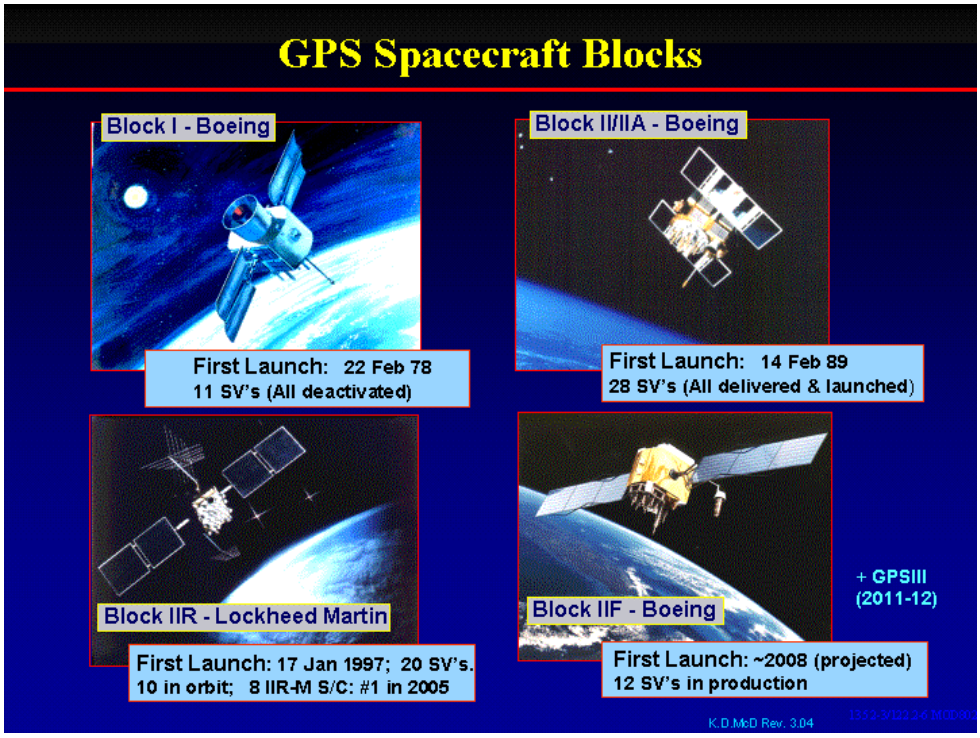


Figure 2.2-2

Addressing the various capabilities in GPS, refer to Figures 2.2-3 and 2.2-4.

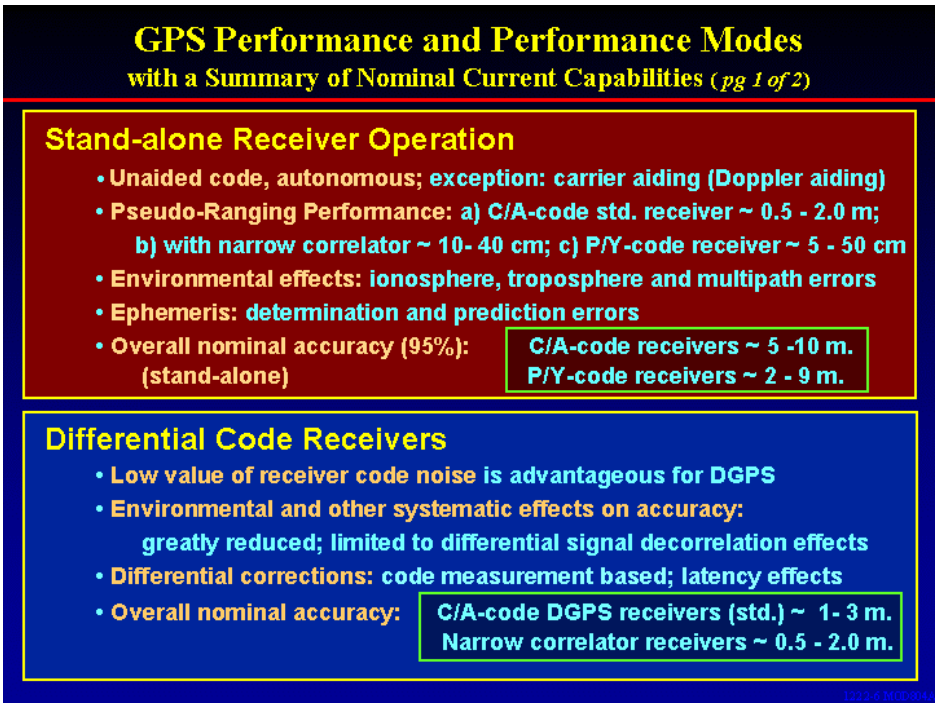


Figure 2.2-3

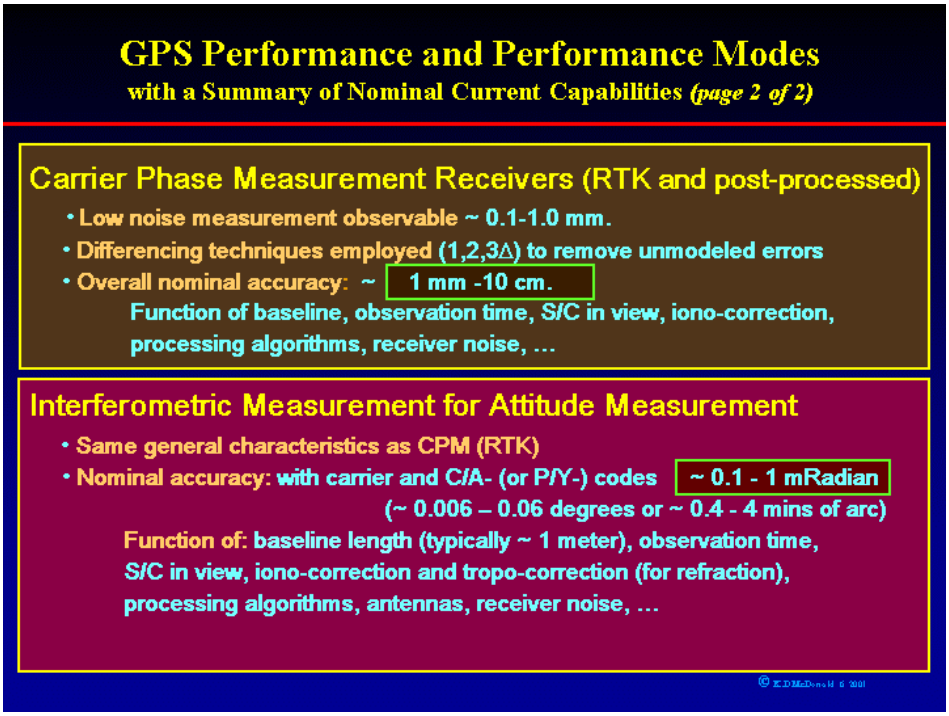


Figure 2.2-4

Differential code receivers

The differential GPS (DGPS) receivers employ data link corrections that are determined and transmitted to the receiver by differential monitor, or base, stations. These corrections allow the receivers to cancel out most of the error components that are common to both the reference and the remote, or rover, receiver. Fortunately, most of the errors in normal GPS reception are common to both which typically allows very good corrected accuracy from differential systems. Typical operation for a GPS code receiver, as indicated in the figure, is in the order of 1 to 3 meters. This can be improved by the use of a special receiver type, known as the narrow correlator receiver. These receivers can improve the accuracy of the position to a level of 50 cm., or about 20 inches (depending on the qualityof differential corrections).

Carrier phase receivers, static operation

The carrier phase measurement (CPM) receivers use the relative phase difference between the spacecraft signal received by two separated antennas. This provides a highly precise measurement that can be used to accurately determine the separation distance, or "baseline." Similar techniques have been used in radio astronomy and in other areas. The methods typically involve a considerable amount of analysis and processing, but the techniques are extremely accurate.

Conventional GPS survey receivers that post-process the measurement data with software programs are described as operating in a static mode. These equipments can obtain relative position accuracies over an observation period of 5-15 minutes in the order of a millimeter (1/25") to ten centimeters (4"). The performance varies somewhat with separation distance. The values cited are for separation distances of a few hundreds of meters to several hundred kilometers.

RTK receivers

Another carrier phase measurement technique obtains measurements on a real time basis and rapidly processes them which allows for the accurate determination of position for vehicles in motion. This commonly called real time kinematic (RTK) operation and provides position accuracies of about 10-30 cm.

Attitude measurement techniques

The final GPS mode of operation to be discussed is the use of the interferometric technique for attitude measurement, as indicated in Figure 2.2-4. Since the measurement of the carrier phase can be extremely precise, it is possible to determine the orientation in space, or the attitude, of a vehicle or other object equipped with appropriate GPS antennas. This can be done by the use of small antennas separated by only a meter or so. Since data on the location of the spacecraft (the ephemeris data) are accurately known, the signals that are received by the antennas are compared in phase resulting in attitude accuracy measured to the milliradian level or better. This is in the order of a few minutes of arc, or in hundredths of a degree.

GPS modernization

For the past 5-8 years, there has been a good deal of interest and effort placed into the modernization of GPS. The civil community has been very interested in obtaining a second frequency signal that would provide a correction for the principal error that degrades civil performance, namely the ionospheric delay error. This error can be well corrected by the use of signals on two separated frequencies, as the military capabilities provide.

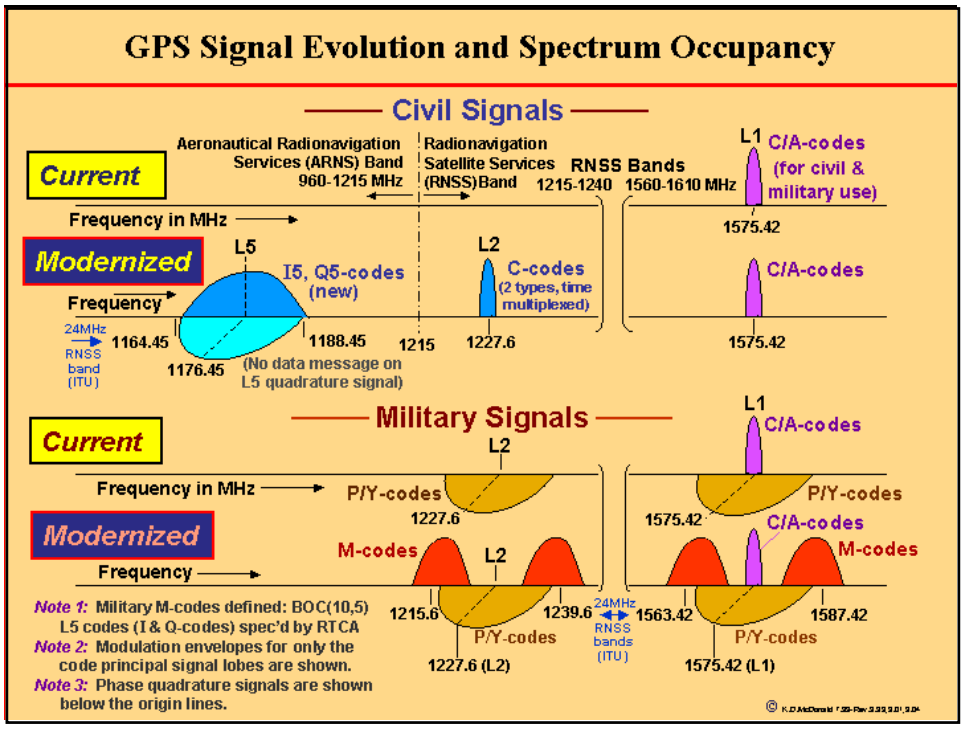


Figure 2.2-5

The current capabilities for GPS civil and military community use are shown in Figure 2.2-5. The civil community is basically limited in access to the L1 C/A-codes. The military signals include the C/A-codes on L1 as well as the precise/encrypted, or P(Y)-codes, on L1 and L2. All of these codes will be retained for an extended period of time to allow for an evolutionary transition between them. The military is adding a set of Military-codes (or M-codes) to the signals at L1 and

L2. As the figure shows, these new signals are "split spectrum" signals that separate most of their energy from the band's center region to its edges. This allows for excellent isolation of the military signals from the civil signals on L1, and in the future on L2.

The civil community will also receive new capabilities in a new set of coded signals on L2 that are somewhat similar to the C/A-codes on L1. Known as C-coded signals, these are a set of two different codes providing very good performance characteristics for future GPS users.

Unfortunately, the L2 band is not protected for safety of life applications by the International Telecommunications Union rules. The L2 band, under ITU rules is designated as co-primary with radio determination satellite system (RDSS) signals which makes L2 not acceptable to the US Federal Aviation Administration (FAA) for use in aviation applications. A new GPS signal band called L5 has been established for SoL applications at a frequency about 50 MHz below L2 at 1176.45 MHz. This signal is somewhat similar in its spectral appearance to the P(Y)-codes of the military on L1 and L2, as shown in the figure. These two additional signals on L5 provide some excellent improvements in performance as well as providing an additional band for aviation (and other) safety of life operations.

Planning Activities

Figure 2.2-6 illustrates the results of some of the principal planning activities and commitments that have occurred in the past few years that will influence GPS operations in the next decade or two. GPS modernization has caused the addition of new civil signals at L2 and L5 as well as new military signals, the M-code signals, at L1 and L2.

Figure 2.2-6

Removal of selective availability

The previous intentional degradation on the civil signals, called selective availability (SA) was set to zero by the system operators on May 1,2000. The stand-alone horizontal accuracy for the system immediately improved to the 5-10 meter level worldwide.

Also, throughout the last 10-15 year period, a number of systematic error sources related to the satellite uncertainties and receiver processing have been significantly reduced. Most of these errors are becoming very small and much less of a concern than the propagation media errors. Greatly improved signal availability has occurred with the full deployment of the GPS constellation. The more recently deployed satellites transmit at increased power levels and plans for the future are to continue this trend.

Timeline on system improvements

Although there have been significant accomplishments in the deployment and improvement of GPS, there have been many delays as well. Although there is a commitment to the modernized capabilities, there has been considerable slippage in the schedule for actually achieving these capabilities. For example, the full operational capability for the new civil C-code implementation on L2 was originally to occur by about 2010. It now appears that this FOC capability will occur in about 2014, or possibly later. Similarly, the FOC for the L5 signals were to occur in about 2014; these now appear to be closer to 2018, or later. The GPS III initial launches were to occur by 2009 but have been deferred to 2011-2012, and may be later. Possibly budget concerns related to the anti-terrorism expenditures, the recent large tax rebates and the substantial current operating deficits of the Federal government have had an unfortunate impact on GPS funding. In any case, there appears to have been nearly a delay of about one year per year in the planned future GPS capabilities for the past four to five years.

Formation of Interagency GPS Executive Board

New arrangements have been formed for the top-level management of GPS. Prior to the Presidential Decision Directive (PDD) of 1996, GPS was clearly a Defense Department (DoD) managed and implemented system. The Interagency GPS Executive Board (IGEB) was established by the PDD as shown in Figure 2.2-7. This document specifies that the GPS management will involve many other agencies and is to be co-chaired by representatives of the Secretaries of Defense and Transportation.

International Implications

The Galileo system of the European Union has been approved and is going forward with development and deployment on a rapid basis. Coordination of GPS with Galileo has been actively progressing for several years and it appears to be well coordinated. This is not a simple task since European Union countries, as well as the US have concerns about their national autonomy as well as the political and economic issues that go with the development and operation of a navigation satellite system.

Plans are for Galileo to be operational with civil, multi-frequency capabilities by 2008. This generally is felt to be a bit optimistic, and 2010 seems to most observers to be more viable.

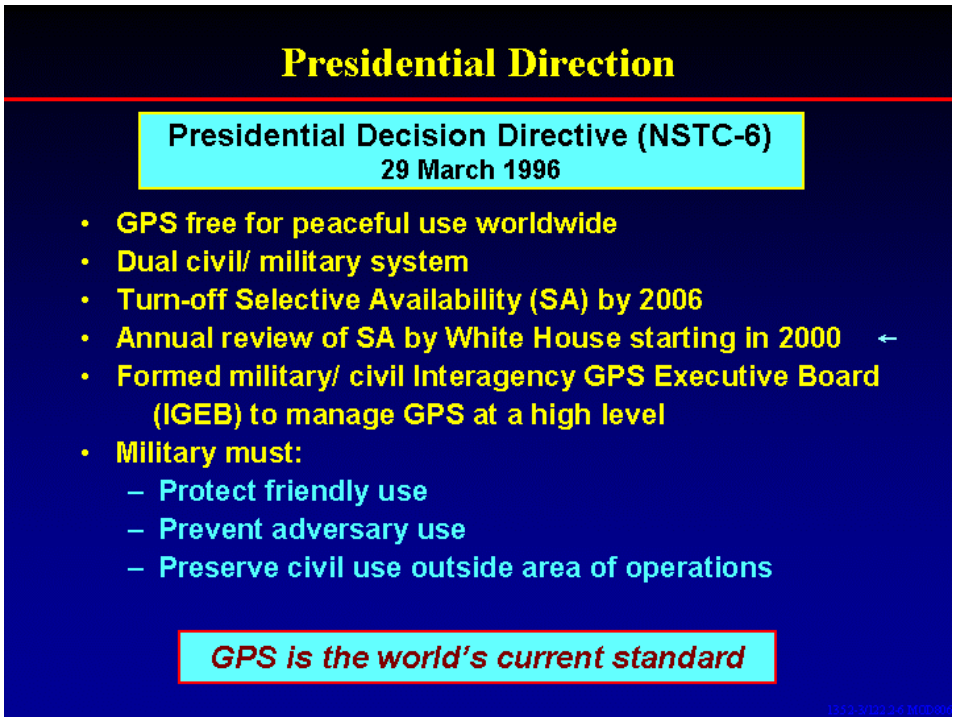


Figure 2.2-7

The modernization of GPS has been scheduled to be operational with civil multi frequency capabilities by 2012 to 2014. Many believe this is optimistic and a date of 2017-18 is more realistic.

2.2.2 Overview of Differential GPS (DGPS)

The availability of differential GPS (DGPS) depends on two things: first, the user receiver's ability to track enough satellite signals to compute a position; and second, the system's ability to provide the user receiver with differential corrections. Since GPS is a reasonably robust worldwide system, the ability to track satellites is not a concern, save for environments with high signal masking or in regions of signal loss or interference. This section will rather focus on the character and availability of differential corrections and the services that provide them.

Three characteristics are important for differential and related services. First, what is the coverage area? Larger coverage areas can support more users and require fewer transitions between service providers. Second, how reliable is the service? Safety of life applications, for example, require a very high confidence level for reliability. Third, does the service include integrity information? Although not explicitly a differential service, integrity relates to the service's ability to inform the user of any serious problem (often termed hazardously misleading information, or HMI) that may cause the user to have an erroneous position possibly affecting safety. This may include informing the receiver that a particular satellite appears to be malfunctioning and should not be used.

There are two main types of correction services: ground-based and space-based. Both operate using the same basic principles. Space-based correction services, however, use dedicated geosynchronous satellites to broadcast information to users, while ground-based correction services will typically use a local or regional communication link.

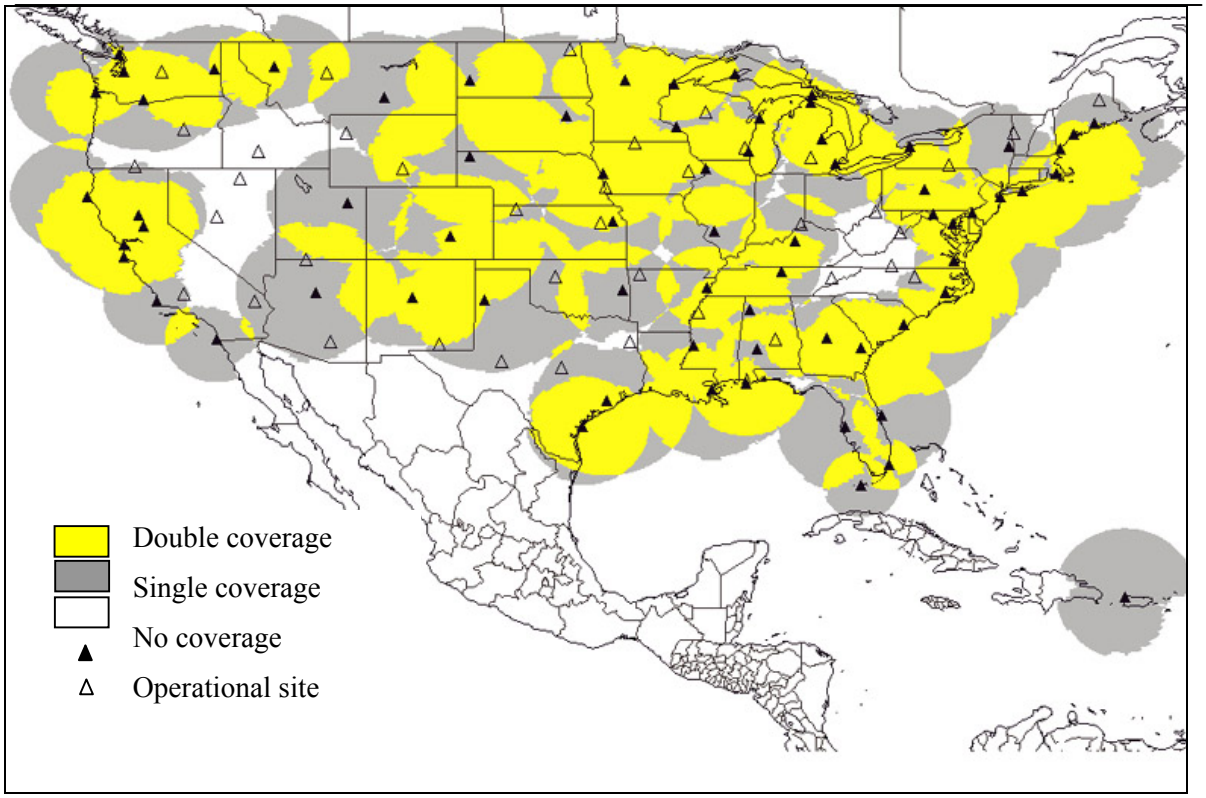


Figure 2.2–8 Current US Coast Guard Nationwide Differential GPS (NDGPS) Coverage Plot

Current and Planned Systems

The United States Coast Guard (USCG) with its Nationwide DGPS network of receivers provides one of the few large-scale ground-based correction services. This network provides correction coverage over most of the continental US (CONUS) as shown in Figure 2.2–8. Although there are some coverage "holes" (which are being addressed), most of CONUS has coverage from at least one and frequently two reference stations.

Currently, each reference station operates independently of the others. Although these stations may not use data to its full potential, the system specifications guarantee 10 m (2drms, or 95% confidence) accuracy [Ref. 2.2-1]. In practice, position accuracy is better, in the order of one to three meters. The service will also provide integrity alarms within 10 seconds for out of tolerance conditions. All reference stations are fully redundant, so the system's reliability is extremely high.

Since most other ground-based systems are local or regional in nature, they are typically not well suited for large-area systems required for vehicular navigation. For this reason, space-based systems are often employed to provide correction services to a large geographic area. Several space-based systems provide nationwide or worldwide GPS differential correction services, as follows:

OmniSTAR: This subscription-based service provides virtually worldwide coverage over land. Two levels of service are available:

1. "OmniSTAR VRS" allows users to obtain "sub-meter" accuracy [Ref. 2.2-2]

2. “OmniSTAR HP” (High Performance) provides decimeter level accuracy.

The system’s subscription fees and lack of integrity monitoring make it somewhat less attractive than some other systems. Moreover, having only a single satellite transmitter for a large region limits system reliability, since the satellite’s failure would result in a loss of service.

WAAS **(Wide Area Augmentation System):** Originally designed to meet Federal Aviation Administration (FAA) in-flight and precision navigation requirements down to Category/approach performance, WAAS has a distribution of ground stations that monitor the GPS signals and provide data to central processing centers that derive correction information.

Uplink transmission sites send the processed data to geosynchronous satellites that transmit corrections and integrity information to users. Although coverage is large, it is limited mostly to CONUS, as shown in Figure 2.2–9.

Commissioned in July 2003, WAAS is specified to provide 7.6 m of accuracy, although an accuracy of 1-3 m is typically available [Ref. 2.2-3].

In contrast to OmniSTAR, WAAS is free of charge and provides integrity monitoring that may be significant for some vehicle-based applications. The signal that broadcasts the corrections and integrity data to users is at the L1 frequency, as the standard GPS civil signal. This signal also provides ranging capabilities.

WAAS satellites not only provide correction and integrity information but also augment GPS with additional pseudorange measurements that improve positioning accuracy. The WAAS deployment is considered to be a Satellite-Based Augmentation System (SBAS).

EGNOS **European Geostationary Navigation Overlay System:** EGNOS is another SBAS system, which is operated by the European Space Agency. It is similar to WAAS but its coverage area is focused on Europe. EGNOS is expected to be declared operational in the spring or summer of 2004 and will be interoperable with WAAS. This interoperability will allow for seamless transitions between North America and Europe with a single WAAS equipped receiver.

MTSAT/MSAS **Multi-functional Transport Satellite Space-Based Augmentation System:** This is another SBAS, developed by Japan. The system will be fully interoperable with WAAS and EGNOS. Because of a launch failure of the program’s initial spacecraft in 1999, however, no MTSAT satellites are currently in orbit. The replacement launch has been postponed to the end of 2004 or possibly 2005. [Ref. 2.2-3]

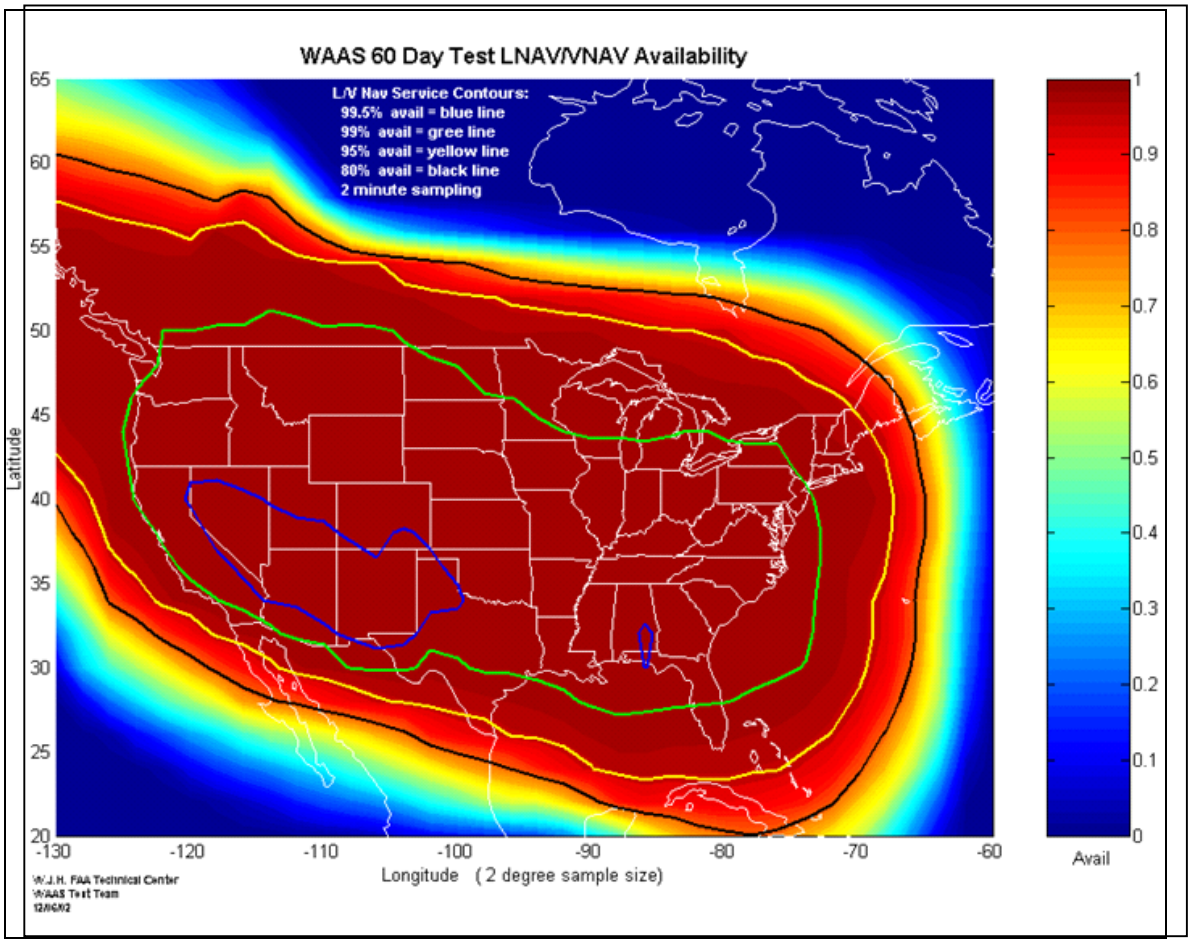


Figure 2.2–9 WAAS Availability during a 60-Day Test [Ref 2.2-4]

Coverage areas for WAAS, EGNOS and MTSAT/MSAS are shown in Figure 2.2–10.

Near Future Systems

The systems will probably be modified to accommodate new civil signals that are planned from GPS and Galileo. It is noteworthy that three of these systems use multiple base stations to generate corrections for the user. Since the geographic density of these stations is quite low, the stations can obtain only limited spatial information about GPS errors. These systems focus mainly on meter-level accuracy.

RTK System Implementation

Currently, the USCG is investigating ways to improve system accuracy by having their base stations work interactively and in a synchronized manner. The relatively high density of stations in the NDGPS network should translate into user position accuracy at the 1-2 m level. No decision has been made, however, on how or when such a change may occur or how it might affect the system specifications and operation.

To achieve even better position accuracies, different approaches will need to be implemented. To this end, network-based real-time kinematic (RTK) approaches appear to be a viable way to obtain 5–20 centimeter accuracy over a large geographic area. In contrast to traditional

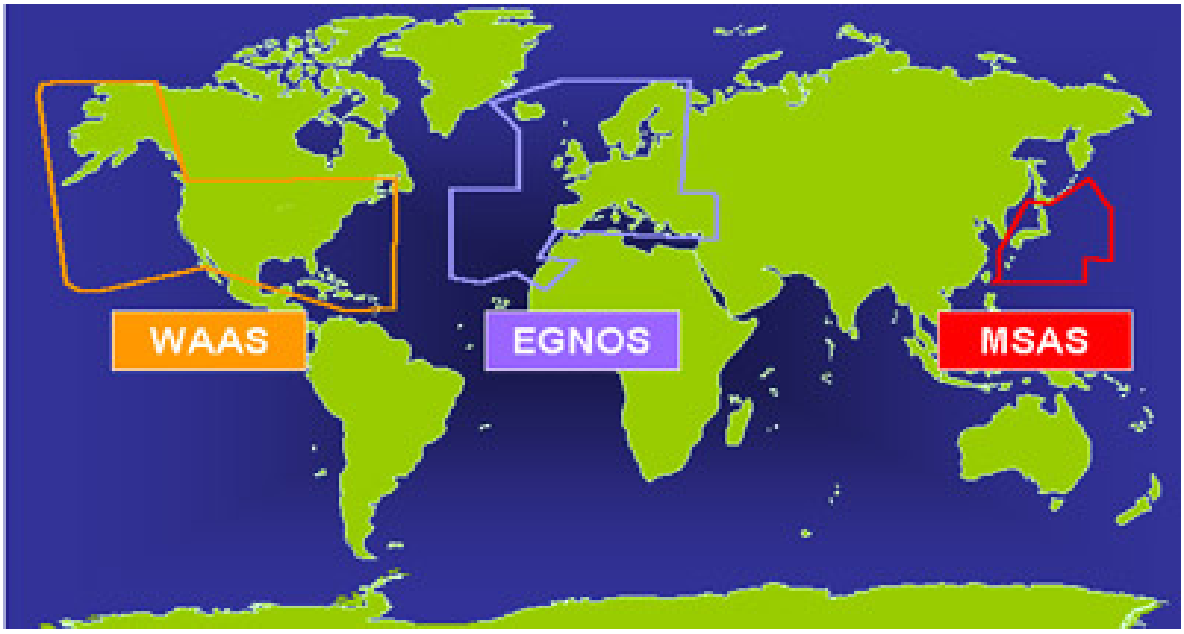


Figure 2.2–10 Coverage Areas for WAAS, EGNOS and MTSAT/MSAS

RTK systems that use a single base (reference) station, network-based approaches use multiple base stations to model the GPS errors over a region. This has several benefits, including:

- **Higher accuracy** positions for the user
- **Reduced capital expenditures**, since fewer base stations can cover a given region
- **Increased reliability**; the system can continue service even if one base station fails.

The current disadvantages of using a network for high-accuracy positioning are two-fold. First, the various base stations must communicate all of their data to one or more central processing stations. To achieve a higher level of positioning accuracy for the system, the amount of data to communicate may be larger than that required for meter-level accuracy. This could create the need for higher bandwidth communication links. Furthermore, the relatively large distances between base stations will often require specialized or dedicated communication lines. Once corrections are obtained, they must be sent to the user or users by yet another communication link. The techniques for transmitting this information to the vehicle (RF, cellular, DSRC, etc.) are discussed in Chapter 4.

Second, the data processing requirements at a central processing station are considerable. This, in turn, may restrict the number of stations in a network and the number of processors the central processing sites requires, and may affect the latency of the system. Research may need to focus on optimal processing to mitigate these problems while still achieving the benefits of the multiple base station approach.

Currently, network-based approaches use one or two central processing station(s) to perform the necessary computations to generate corrections and integrity data for the user. Recent research, however, has attempted to find a way to perform all of the necessary computations inside the user receiver itself. Although such an approach is only now becoming feasible, increased processing power in the future will inevitably facilitate such processing in the receiver. Research is also needed to investigate algorithm efficiency, especially for low-cost implementations.

RTK Interoperability

With respect to network infrastructure, many countries, including the United States, Japan, South Korea, Sweden, Turkey and Italy, already have networks of GPS stations that could possibly be used in a network structured RTK system. One of the largest concerns for European states, however, will be on maintaining interoperability. Some of these networks may have to be densified to obtain a desired level of performance. Various existing networks could potentially be used in parallel to achieve this densification with minimal capital expenditures. This may require better cooperation between government agencies, depending on the operational (or national) management of the various networks.

As a final note, the introduction of Galileo and GPS civil signals should dramatically improve DGPS system capabilities, especially in accuracy. Both code and carrier phase operations will benefit from this improved accuracy. The additional satellite coverage and availability, coupled with additional signal codes and carrier frequencies will facilitate receiver operation at substantially improved accuracy (50-80 cm). The use of multiple carrier phase measurement techniques can improve the accuracy further (10-30 cm).

2.3 Galileo and Its Impact on GPS and Related Systems

2.3.1 Availability

Galileo will provide a significant improvement to satellite-based navigation systems such as GPS. Availability refers to the number of satellite signals in view of, or being received by, a receiver as well as the capability of the receiver to track and compute position, velocity and time (PVT) solutions at a given location and time. The introduction of Galileo will provide about 30 to 33 more space vehicles which can be operationally combined in user equipment with the 27 to 30 SVs of GPS. This combined GPS-Galileo constellation will have excellent geometric properties for positioning (low dilution of precision, or DOP, capabilities) and a significant increase in the average number of space vehicles continuously in view (i.e., from 8 to about 16 SVs in normal conditions).

If one adopts a specialized aspect of availability, namely the ability to track sufficient satellite signals to provide receiver autonomous integrity monitoring (RAIM) capabilities, then the combination of GPS and Galileo will play a very significant role. For example, signals from four spacecraft in good geometry are required to obtain a position determination from GPS or Galileo. If there is a faulty SV, or erroneous information being provided by one spacecraft, it is not possible to detect this with just four SVs. With five SVs in good geometry, it is possible to determine that there is a problem but it is not in general possible to establish which SV is causing the fault. Therefore, six or more SVs in good geometry are necessary to determine signal integrity for the case of one possible SV fault. With normal visibility conditions, there are many instances when six or more SVs are not available with even a 28 SV GPS constellation, and integrity warning is not feasible. With the addition of Galileo, however, the number of SVs in view is

doubled and in these circumstances the autonomous determination of integrity is feasible in essentially all cases.

GPS or Galileo alone cannot always guarantee a certain desired accuracy level, even under excellent visibility conditions. The additional satellites of the combined system essentially double the number of satellites available to a given user. This will both improve the satellite constellation geometry and strengthen the position solution. In many cases, this may be the improvement needed to make an occasionally unacceptable GPS-only solution meet operational requirements. Figure 2.3–1 reveals how the addition of Galileo provides a combined system with substantial improvements in accuracy on a global scale.

The most significant improvement in availability will occur in high signal masking conditions. In urban canyons, for example, GPS-only or Galileo-only satellite geometry may be so poor that the resulting position accuracy can be as much as several tens of meters. In some cases, the use of the combined GPS-Galileo system will reduce this uncertainty several-fold.

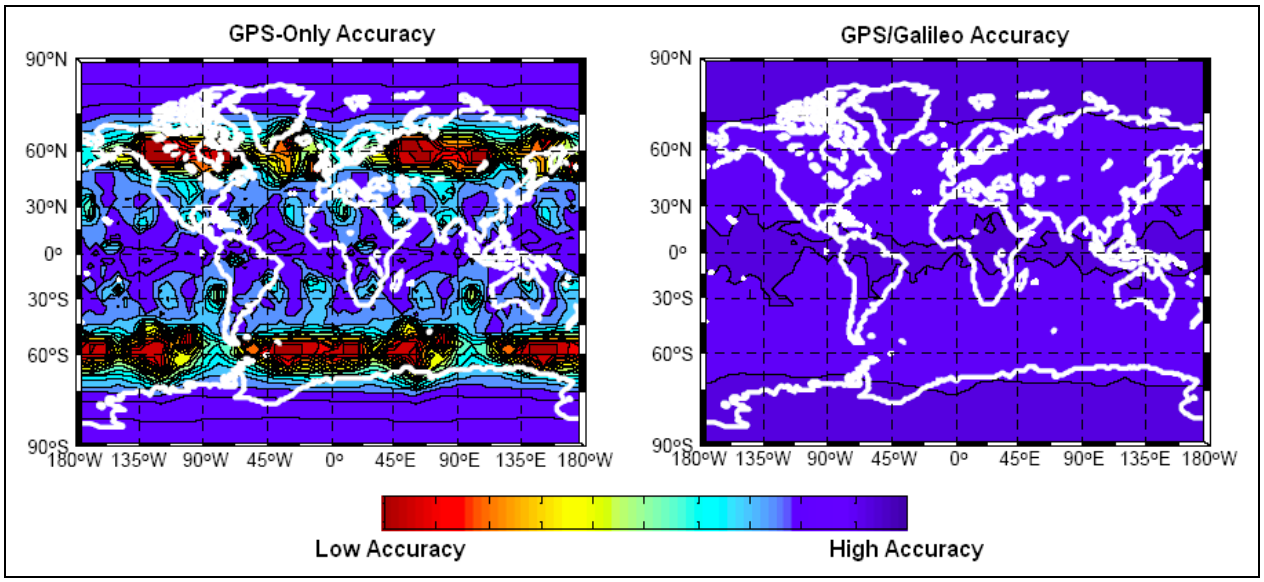


Figure 2.3–1 Global GPS-Only and GPS/Galileo Positioning Accuracy (modified from Ref. 2.3-1)

Reliability and integrity are related to a system's ability to identify and reject erroneous measurements before they contaminate the position solution. For safety of life applications, for example, reliability and integrity are critical. Reliability is closely related to the continuity of service provided by the system. On a global scale, the combination of GPS and Galileo substantially improves the system's reliability [Ref.: 2.3–1]. This improvement may allow the implementation of a variety of applications that would not be possible without the use of a combined GPS-Galileo system.

The additional measurements and the improved geometry of the combined GPS-Galileo system translates into more accurate position determination. For conventional DGPS applications, this improvement may be sufficient to provide sub-meter accuracy instead of the 1-2 meters now typically available.

2.4 GLONASS Navigation Satellite System Overview

The Soviet Union developed the Global Orbiting Navigation Satellite System, known as GLONASS, at about the same time or shortly after, GPS. The first GLONASS spacecraft were launched in 1982, following the publication of an ITU International Frequency Review Board (IFRB) Notice. The Soviet Union planned to deploy spacecraft using the frequencies previously authorized for their navigation satellite system.

2.4.1 Early Development of GLONASS

Development work on GLONASS apparently started in the early to mid-1970's. The Soviet Ministry of Defense initially supported this work to satisfy naval requirements, which were later expanded to include those of all military services. In 1992, the former Soviet Union, now the Russian Federation, founded the Internavigation Interdepartmental Commission and expanded the system to support civil users as well. In January 1996, GLONASS reached its full constellation of 24 operational satellites on orbit.

2.4.2 The GLONASS Constellation

Since 1996, the economic situation in the Russian Federation has made it difficult to maintain the GLONASS constellation. At present the system has only ten operational satellites, less than half of those planned.

Figure 2.4–1 is an artist's view of a first generation GLONASS spacecraft. The constellation deployment for GLONASS is in many respects similar to that for GPS. It is a medium altitude orbital constellation of spacecraft operating at 19,100 km above the mean sea level of the earth, which places the system about 1100 km lower than GPS spacecraft. The orbital period for this altitude is 11 hours and 15 minutes. Figure 2.4–2 shows a recent GLONASS deployment, which reveals that GLONASS has three orbit planes as opposed to GPS's six, and has eight satellites in each orbit plane as its baseline configuration. The reader can see that only ten spacecraft are currently active in the GLONASS constellation, leaving one of its orbit planes (Plane B) vacant. The inclination of the GLONASS system is at 64.8° to the equatorial plane.2.4.3 Ground Control Segment

Figure 2.4–3 shows that the GLONASS Ground Control Segment is located entirely in Russian territory, with the Control Segment headquarters in Moscow. As shown on the GLONASS spacecraft figure, the earth-facing part of the satellite contains a number of retro-reflectors for tracking the spacecraft as well as 12 helical antennas for transmitting signals to the earth. These retro-reflectors permit the Russian sites indicated in the Ground Control Segment to track the spacecraft accurately. The Russians use optical and laser sensors with competence, and apparently determine the orbit for the GLONASS spacecraft primarily from these measurements.

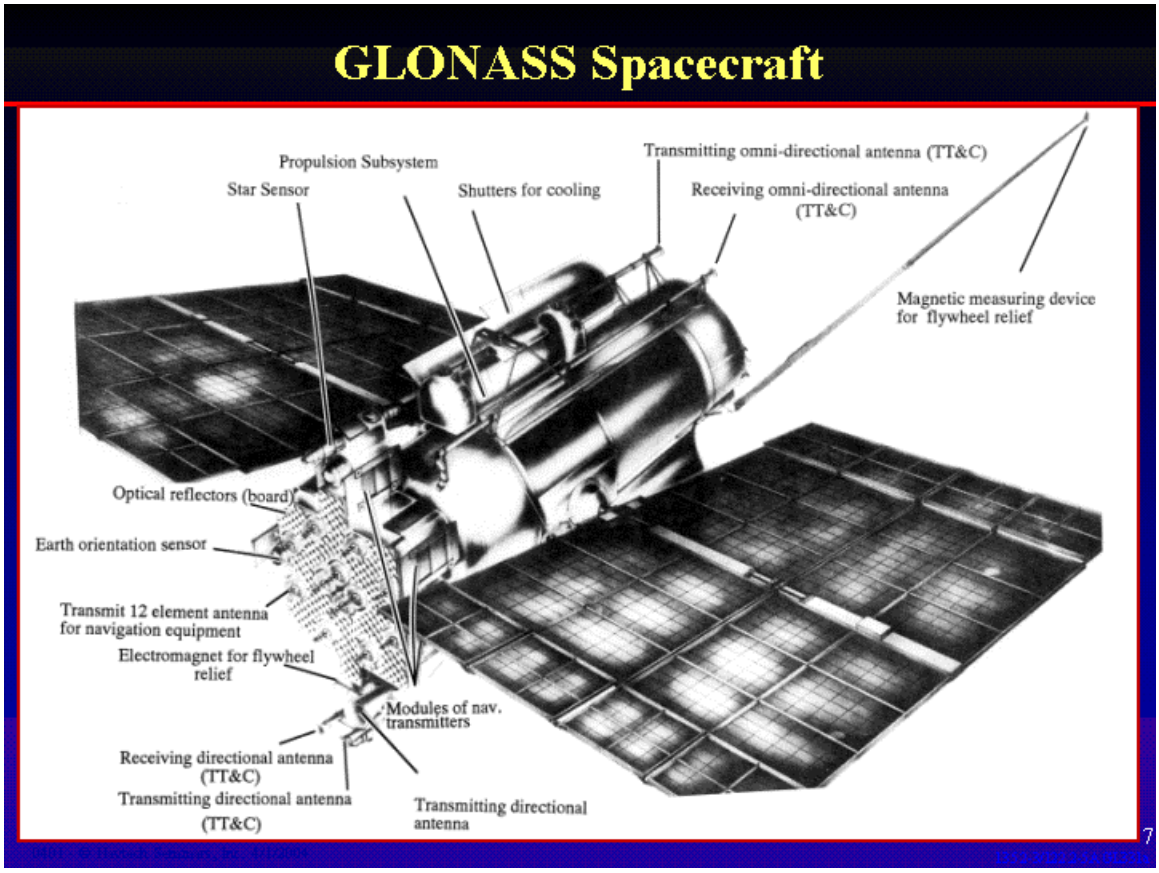


Figure 2.4–1 GLONASS Spacecraft

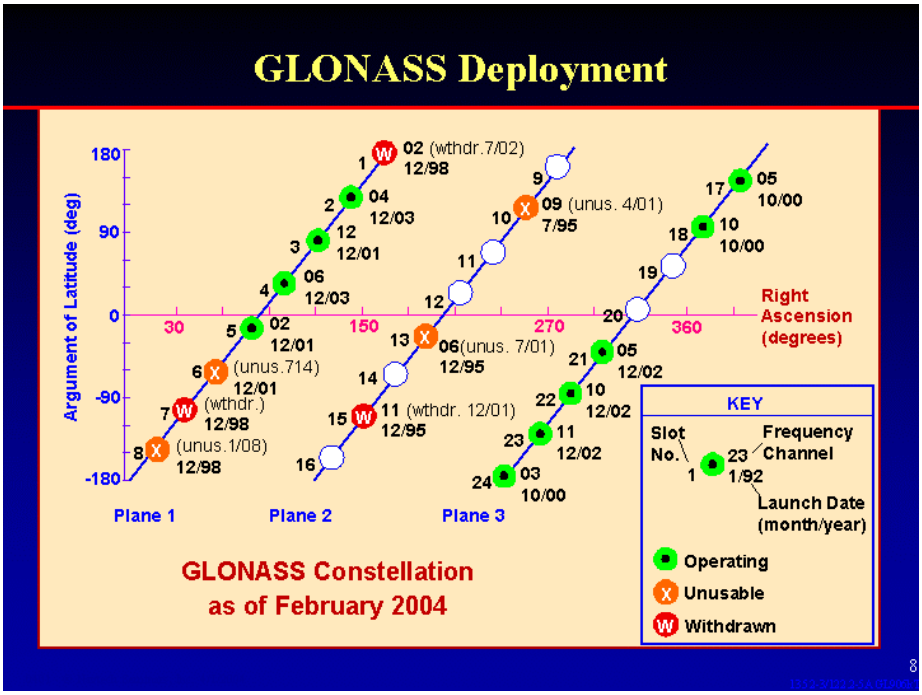


Figure 2.4–2 Recent GLONASS Deployment

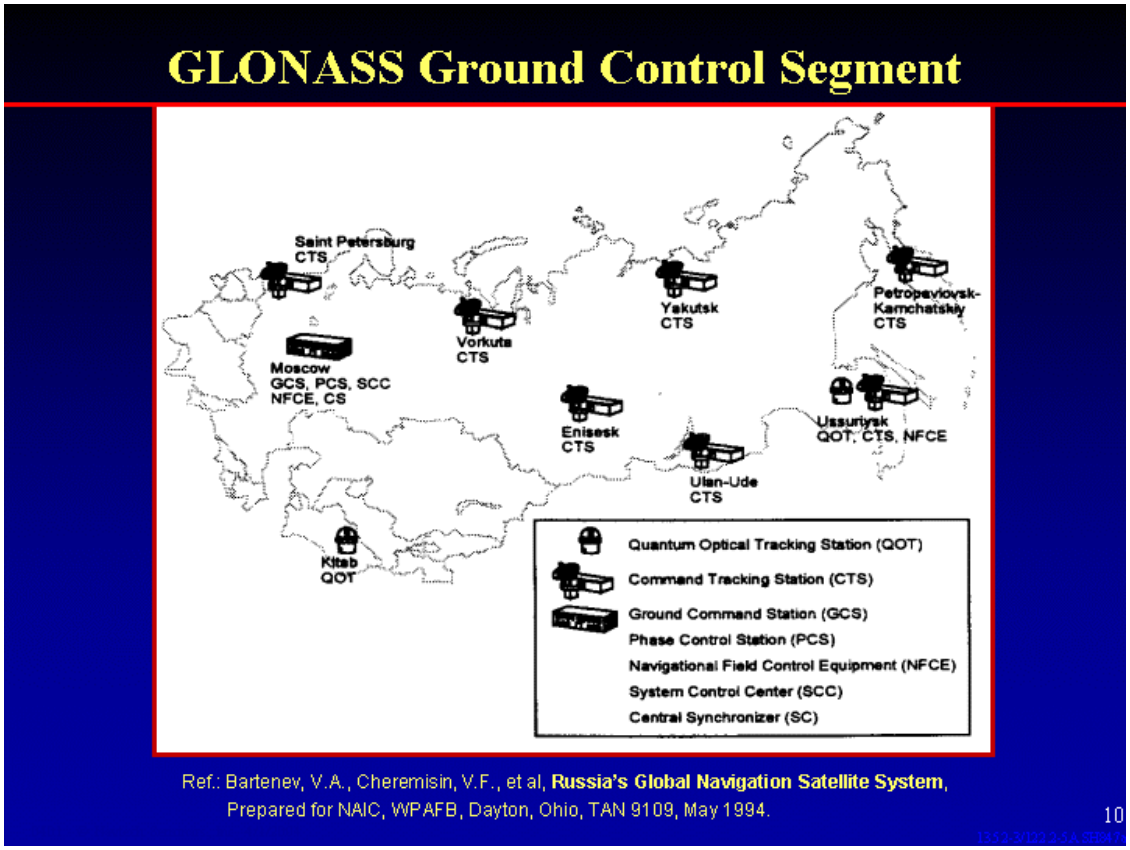


Figure 2.4–3 GLONASS Ground Control Segment

2.4.4 GLONASS User Equipment

GLONASS receivers have been built at a number of locations within the Russian Federation and also by investigators in the United States and Europe. The Russian government's claimed accuracy for the system is somewhat pessimistic, since it is not nearly as good as that of US and European built GLONASS receivers.

In the most recent period when was GLONASS was in worldwide operational status, nominal accuracy was about 25 m in the horizontal and 44 m in the vertical for the Russian units as reported by Russian officials. US-built GLONASS receivers do considerably better. For precise applications, some US-built GLONASS receivers have also been configured to provide carrier phase measurements. Figure 2.4–4 shows an Ashtech GG-24 receiver that incorporates 12 channels for GLONASS reception and 12 channels for GPS.

2.4.5 Signals, Similarities and Differences

GLONASS differs from GPS in a number of ways. First, it is a frequency division multiple access (FDMA) system, since every satellite transmits on its own frequency. The system uses pseudorandom noise (PRN) codes from the satellites, similar to GPS. All GLONASS satellites use the same PRN code, however, an arrangement that is the reverse of that employed by GPS.

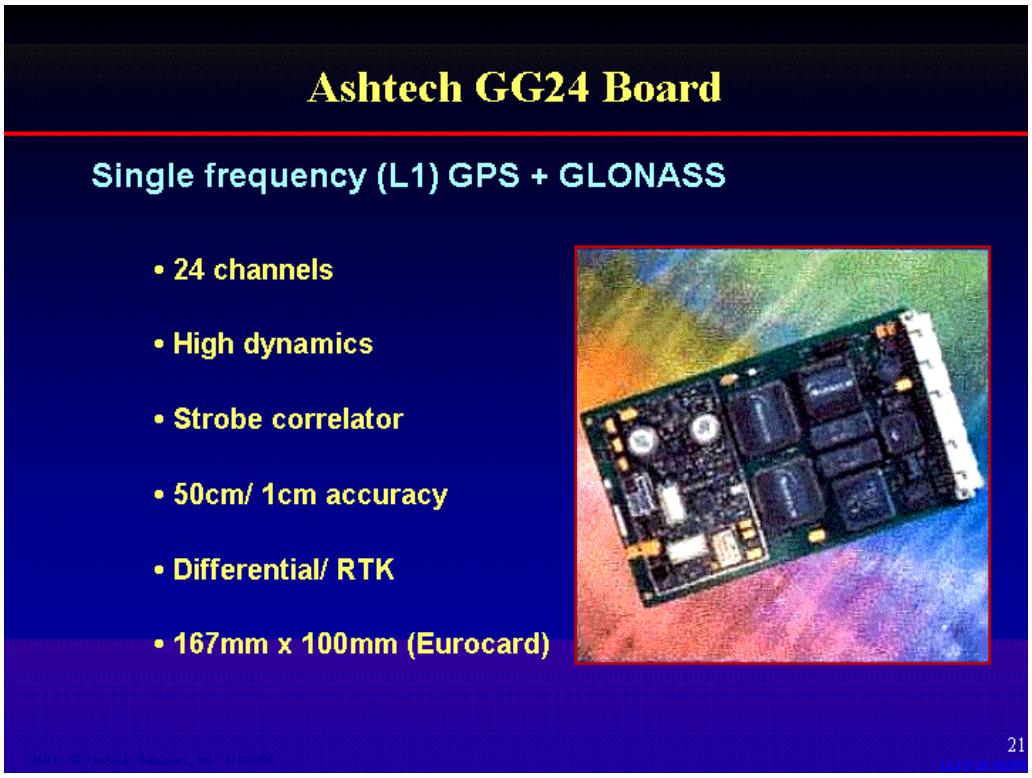


Figure 2.4–4 Ashtech GG-24 GPS-GLONASS Receiver Board

GLONASS transmits a coarse/acquisition (C/A) code somewhat similar to that of GPS. The code length for this code is about half that of the GPS C/A-code sequence but its duration of ,one millisecond is the same as for GPS. Figure 2.4–5 illustrates the frequency plan and spectrum utilization for GLONASS showing the L1 and L2 band configurations for both GLONASS and GPS. The C/A-code is only carried on L1, as is the case currently with GPS. The GLONASS precise-code (P-code) has a bit rate that is ten times that of its C/A-code. The C/A- codes consist of a 511 bit (or "chip") length sequence that occurs in one millisecond. The P-code has a bit, or chipping, rate of 5.11 Mcps.

Table 2.4–1 is a comparison of GPS and GLONASS characteristics. Both systems are spread spectrum systems, that is, they both use PRN codes. GPS is a code division multiple access system while GLONASS is a frequency division system. Both systems have a baseline configuration of 24 satellites with the differences indicated. The L1 carrier frequencies for GLONASS span the range from 1598 to 1609 MHz, a range that will drop back to 1597 to 1605 MHz in the year 2005. This change will minimize possible interference with the Mobile Satellite Service (MSS) band that occupies 1610 to 1626.5 MHz.

The GLONASS L2 band is centered at 1250 MHz and covers 10 MHz on either side. L2 carriers are from 1243 MHz to 1251 MHz and will be constrained to 1243-1248 MHz. in 2005. GLONASS neither has nor has plans for Selective Availability or other intentional degradation of its signal. While GLONASS also has no anti-spoof (A-S) encryption, there are indications that this could be placed on the signal in the future. There is a modest difference in the way that GLONASSS provides orbital information, the ephemeris data, to the receivers.

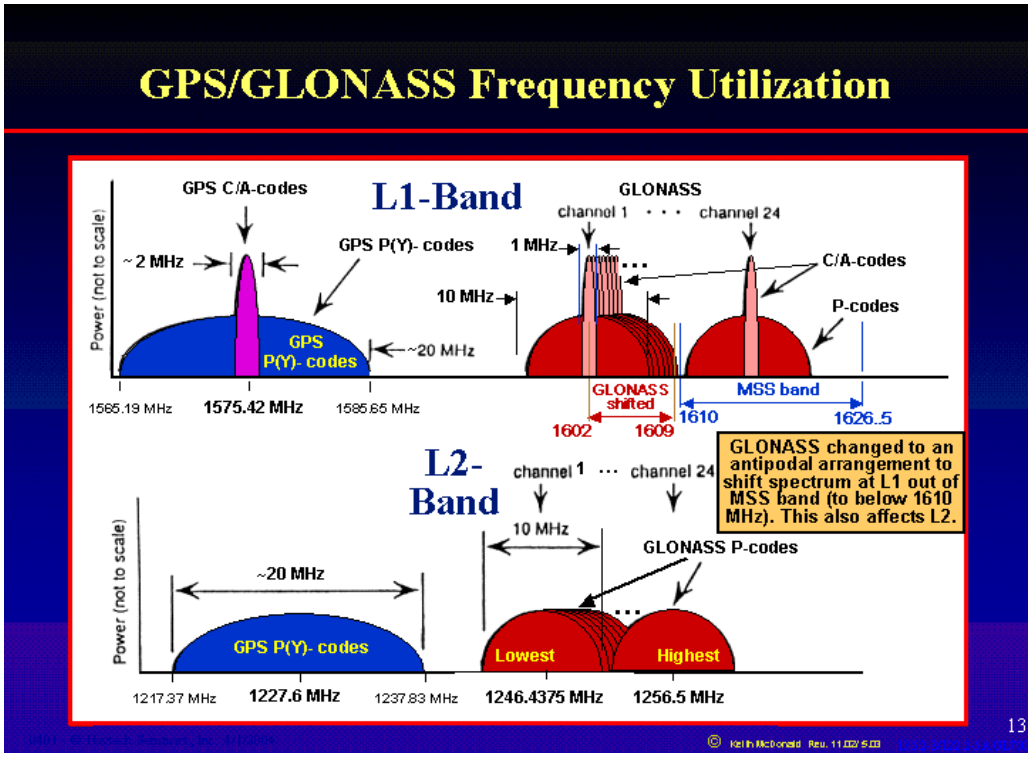
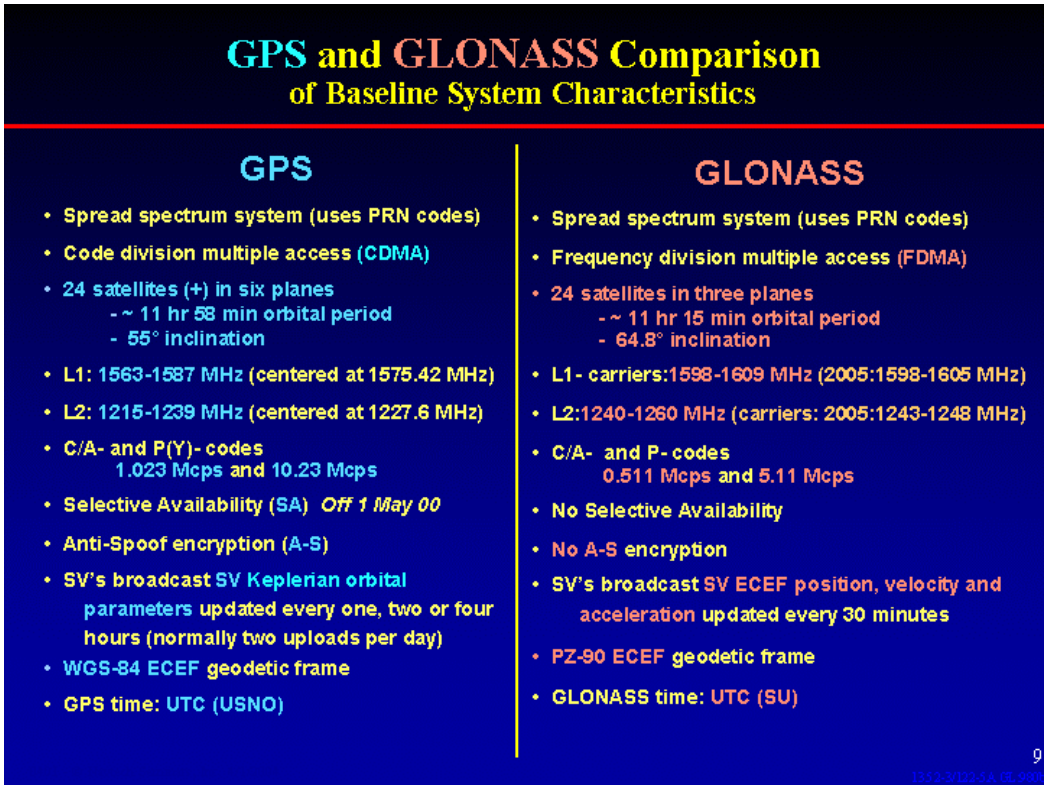


Figure 2.4–5 GPS and GLONASS Frequency Utilization

Table 2.4-1 GPS and GLONASS Comparison of Characteristics



2.4.6 GLONASS Geodetic Reference and Time Scale

GLONASS uses a somewhat different geodetic reference frame than GPS. It uses the PZ-90 Earth-Centered Earth-Fixed (ECEF) Geodetic Frame, sometimes called PE-90 (for "Parameters of the Earth, 1990"). Another significant difference is that the GLONASS time-scale is Universal Coordinated Time (UTC) as established by the Russian Government. This is referred to as UTC (SU). GLONASS officials have considered a plan to coordinate their timescale with that of GPS and to transmit the offset (difference) between the timescales in their data message on a frequent basis.

2.4.7 Comments and Concerns on the Near Term Use of GLONASS

It is not clear when GLONASS will return to operational status. In December 2003, the Russian Federation launched three more satellites into a sparse constellation. Many of their spacecraft are several years old, however, and have minimal lifetimes remaining. GLONASS thus does not appear to be viable for automotive navigation purposes for some time. For purposes of the current investigation, GLONASS is not seriously considered as a viable alternative. However, this could change in the next five or six years which could mean that a fully operational GLONASS as well as an operational Galileo may become available at about the same time. The advantages of GLONASS at that time are desirable but may be somewhat marginal with both GPS and Galileo available and providing services.

2.5 Enhanced Digital Maps Overview

This section is a brief overview of digital maps. It focuses on the geographic information that an integrated car navigation system can use as an additional sensor or data source. We assume a digital map of well-defined precision that can provide additional information to the position location system of a land vehicle. The basic location information provided to a digital map is the point where the vehicle is located on a straight or a curved line.

This determination can be treated as an additional observation along with the information obtained from other sensors in the system. The location accuracy depends on the quality or resolution of the digital map, which is never entirely free from error.

Some basic questions concern this approach:

- What is the **basic role of the digital map** in an integrated car navigation system?
- What is the **quality of the geometric and geographic information** available from digital maps?
- **How accurate does the digital map data have to be** for navigation systems of different positioning accuracy capabilities?
- **How accurate does the digital map data have to be** for a variety of safety and assistance systems?

A stand-alone digital map does not determine the location coordinates of the vehicle [e.g., latitude (North/South) and longitude (East/West)]. For example, in an integrated location system that provides position accuracy at the meter level, the map resolution has to be accurate to a comparable level. If the map accuracy is poorer than the accuracy of the position determination, the map will not indicate accurately the position and track of the vehicle. On the other hand, if the

map accuracy is better than the position location measurement, it will offer no benefit for vehicle location accuracy.

A precise digital map is helpful when GNSS determinations are not available, e.g. under bad satellite visibility or coverage conditions. In these cases, the information available from the map will significantly reduce the location error of the vehicle by the position sensor combining process.

The principal role of the digital map in a very precise car navigation system is to serve as a back-up system for situations where the primary position sensor (such as GNSS) has availability problems. In such situations, the map matching system will assure the availability and integrity of navigation information. Some of the basic factors associated with digital mapping systems are presented in Figure 2.5-2.

2.6 In-Vehicle Positioning Systems Overview

Providing positioning capability on a vehicle platform is becoming essential. Indeed, all existing vehicle telematics systems incorporate a positioning capability. With respect to consumer interest, navigation and positioning capability rank third after safety and security applications. In-vehicle positioning is an integral requirement for many other essential functions such as Automatic Crash Notification (ACN) Automatic Accident Notification (AAN), emergency and roadside assistance, stolen vehicle tracking and remote monitoring.

2.6.1 GPS Technology Advantages

GPS technology has become a significant positioning technology for many of the in-vehicle positioning systems that are currently available. All major providers of vehicle telematics services [OnStar (GM) and ATX Technologies] rely on conventional GPS technology for positioning their client vehicles. The US Federal Communications Commission (FCC) has established requirements for enhanced 911 (E911) services to cell phone providers and for location equipage in all cell phones. Since cell phones are typically used in vehicles, this requirement has provided a common technique for linking voice and data services to vehicles.

Although vehicle positioning that uses cellular signals has been identified as a potential competitor for GPS, this aspect of cellular system technology is still at the research and development level [Ref. 2.6-1, see developer websites for details]. Much of this research has its origins in applications that address large populations of vehicles for traffic monitoring purposes [Ref. 2.6-2].

Use of a Precise Digital Map in an Integrated Car Navigation System:

- **A digital map defines a reference or framework for the location of a vehicle**
- **It is treated as a sensor with a given accuracy when combined with other location devices. It acts as a dead-reckoning device**
- **A standalone digital map cannot determine vehicle coordinates**
- **A digital map's principal role is to provide both a context in which the position information is meaningful for the driver and a set of constraints that help limit the positioning error**
- **A digital map enhances the navigation system's capability in situations of bad satellite coverage or signal loss**
- **A digital map's accuracy must be consistent with the navigation system's accuracy**
- **A digital map makes no contribution to accuracy—but can degrade accuracy—if its accuracy is worse than that of the navigation system**
- **Efforts to develop digital maps with approximately decimeter accuracy should be pursued**
- **The digital map's use as a back-up system enhances the availability, integrity and continuity of the positions provided by an integrated navigation system**

Figure 2.6–2 Precise Digital Map Summary

Although there may still be some who believe that cellular-based positioning can provide access to a larger population of vehicles than GPS, the availability of low cost and high performance GPS technology gives GPS/GNSS positioning a clear edge over cellular-based positioning. The following technological advantages can be expected to ensure that GNSS-based positioning maintains its lead:

Accuracy: Cellular-based positioning has yet to provide convincing position determination accuracy comparable to GNSS-based positioning. Cellular technique developments have shown little real promise.

Error sources: Since both systems share some of the basic principles of signal propagation, they both encounter multipath and signal degradation phenomena. In GNSS, however, these issues are relatively well identified and methods exist to minimize their impact, while little has been done for cellular-based positioning.

Cross boundary operation: In-vehicle positioning systems have to function across local and state borders, between service providers, among differing mobile communications technologies, and even over national boundaries. While such cross boundary operations have no impact on GNSS, cellular-based positioning will need to address and resolve these issues.

System coverage: Most cellular networks are concentrated on population centers and corridors connecting such centers. The requirement for in-vehicle positioning capability is not limited to these areas. This is especially critical for services such as emergency assistance

2.6.2 GPS Technology Limitations, Enhancements and Augmentations

GPS technology can provide positioning accuracy of about 5-10 meters using standard single frequency receivers. With additional capabilities such as multi-frequency capability or differential GPS (DGPS), this could be further improved to the decimeter level at the high accuracy end. GPS suffers from a number of performance concerns, however, in urban and related environments such as the following:

1. **Urban canyon conditions:** GPS is a line-of-sight system (receiver to satellite signal) and estimates the receiver position by measuring the ranges to the satellites in view. Buildings can block the signals from GPS satellites, making position estimation less accurate or at times impossible

2. **Multipath:** GPS signals can be reflected by surfaces and objects, creating multiple signals at the receiver. This results in range measurement errors and position errors.

3. **Weak signals:** GPS signals can degrade after passing through tree canopies or other obstacles, resulting in less accurate position estimation.

A comprehensive discussion on GPS error sources and their mitigation is given in several publications [Ref. 2.6-3]. Much research has focused on minimizing the impact of these error sources. With varying levels of success, almost all of these effects can be reduced. Although augmentation with other sensors provides the most promising solution for all-weather and all-operating environment positioning capability, several GPS enhancement technologies have emerged that offer considerable performance gains over conventional GPS.

GPS Enhancement Technologies

Assisted GPS (A-GPS): In A-GPS technology, commonly used with cell phones, some of the GPS related positioning and timing information is transmitted to the GPS receiver through means such as cellular links. This enables the receiver to determine its position more quickly, even with intermittent GPS signal losses. Moreover, this minimizes reacquisition times after signal losses, which improves availability and accuracy. A-GPS technology is commercially available through several developers including QualComm's SnapTrack [Ref. 2.6-4].

1. **High Sensitivity GPS (HSGPS):** HSGPS employs a special processing technique that uses long GPS signal integration times to provide higher sensitivity to weaker GPS signals [Ref. 2.6-5]. This markedly improves GPS position availability over conventional processing techniques. Higher sensitivity, however, also results in tracking multipath signals that can compromise accuracy under some conditions. Augmentations with other sensors and techniques such as map matching can successfully deal with these issues [Ref. 2.6-6]. HSGPS receivers are commercially available from several developers such as SiRF Technologies [Ref. 2.6–7].

2. **HSGPS and filtering:** Research on HSGPS receivers with built-in proprietary filtering algorithms has proven that filtering can minimize some of the error sources unique to HSGPS. Using HSGPS measurements of both position and velocity, these filtering techniques combine both measurements by modeling vehicle dynamics. SiRF Technologies has commercially available solutions with HSGPS and internal filtering capabilities [Ref. 2.6-7].

3. **Map constraint GPS positioning:** Map constraint techniques with GPS have emerged as a solution for vehicle positioning when satellite visibility is restricted [Ref. 2.6-8].

Although GPS enhancement provides considerable improvement for in-vehicle positioning over conventional GPS, augmentation with other sensors provide the best available in-vehicle positioning solutions. The following augmentation techniques and sensors are currently used with GPS with a high degree of success:

1. **Inertial Navigation Systems (INS):** INS has proved to be a highly complementary sensor for augmenting GPS. In GPS/INS integrated systems, GPS is used to initialize the INS when good GPS availability and position data exists. The INS is used to bridge positioning gaps created by obstructions of the GPS signal or outages of the GPS receiver. Many integration techniques exist and more details are given in Ref. 2.6-9 as well as in the CAMP 8A investigation. Note, however, that INS's characteristic biases and bias accumulation over time limit its stand-alone application in commercial systems. Figure C–4 in Appendix C illustrates the general status of inertial devices that may be appropriate for vehicular applications.

2. **Odometry:** As a standard feature of almost all automobiles, odometry is used as an integrating navigation sensor with a relatively low cost. Although odometry does not offer good capability as a standalone sensor, it provides rather accurate distance measuring capability and, in a differential mode, can be an acceptable vehicle heading angle change indicator [Ref. 2.6-10].

3. **Map Matching:** Nearly all vehicle-based telematics systems use digital maps as their user interface, and show the vehicle position on a digital map. Map matching with GPS has shown excellent vehicle positioning capability. (for more information, see Ref. 2.6-11). Although map matching is usually implemented with GPS, and other sensors measure vehicle position and velocities, map constrained position and velocity estimation is also a viable technique [Ref. 2.6-12].

4. **Digital compass and barometric altitude:** These are used as auxiliary sensors for GPS or GPS/INS integrated vehicle-positioning systems. Compass data can provide accurate heading measurements that can be integrated for relatively precise heading data.

2.7 High-Level Wireless Communications Infrastructure

Providing client services requires the integration of several manufacturing and service provider groups. With the exception of the in-vehicle use of aided GPS (A-GPS), which is limited to cellular carriers and the A-GPS service provider, hardware manufacturers and cellular carriers integrate all other client services. This normally proceeds through the automobile Original Equipment Manufacturer (OEM) and telematics service provider to access the content provider. This multi-industry and multi-service collaboration is known as the telematics value chain. Since the entire telematics value chain is involved in providing services, it is important to address the infrastructure requirements of all industries and services in the chain.

Although low consumer awareness is one barrier to the mass implementation of telematics services, the cost and quality of services remain the primary barriers for mass telematics solutions [Ref.2.7-1]. The following discussion focuses on the wireless carrier and content provider sectors, where almost all quality and cost issues are found. The discussion also addresses existing supporting infrastructure and related issues as well as those solutions currently adopted for those issues.

2.7.1 Wireless Carriers

Telematics industry surveys have found that over 50% of the telematics communication needs are implemented through cellular networks [Ref. 2.7-1]. The infrastructure limitations of wireless carriers strongly affect the infrastructure for client service communication.

Verizon Wireless is considered the largest player in the wireless carrier service segment because of its exclusive agreement with OnStar and its non-exclusive partnerships with ATX technologies [Ref.2.7-2].

The telematics services and the larger telecommunication sector both share the same set of issues relating to wireless infrastructure, as summarized below:

1. **Limited coverage**, especially coverage of rural areas

2. **Quality of service** is not generally acceptable for delivering the high volumes of data that telematics users may require. This is generally true, although there are some exceptions such as UMTS.

3. **Lower cost rates for service** appear needed to increase the customer base. This may allow the telecommunication sector to expand their services and amortize their costs among a larger customer base

4. **Cross boundary compatibility,** such as differing cell phone standards

5. **Analog/ Digital technology compatibility** (especially as the analog network is increasingly thinned out.)

Security and safety are two major requirements for telematics users. The quality of wireless linking is typically the deciding factor in providing security and safety, yet many vehicular links frequently perform poorly. For this reason, the vehicular telematics industry may need to rely on other telecommunication sector developments to provide higher quality service. Recognizing that the wireless carrier industry alone cannot cope with all vehicular telematics needs, several special purpose wireless technologies that minimize the burden on the carriers are currently in development and use. These include:

1. **In-vehicle module-to-module communication** through Bluetooth and other locally active communication links. This has no direct relationship to the carriers' capabilities, but could provide an in-vehicle method for storing carrier data, which could then be provided to the vehicle as appropriate.

2. **Dedicated (Digital) Short Range Communications (DSRC):** automobile manufac-turers are taking part in the standards development process for DSRC. This technique would provide for the development of initial prototype application deployments. These are predicted for around 2007.

3. **Short range vehicle-to-vehicle communication** using one or more modes of the IEEE 802.11 service (a, b or g). DSRC developments in the US are the main focus for near-term adaptation of IEEE 802.11 Wireless LAN technologies for the support of short range mobile operations.

4. **Information downloading stations (InfoFueling)** with locally active data links that use IEEE 802.11, Bluetooth or Infrared technology

5. **Nationwide Differential Global Positioning System (NDGPS):** nationwide single station coverage is expected to be completed in December 2005, while nationwide double station coverage will probably require several years beyond 2005

6. **Satellite Digital Audio Radio Systems (SDARS):** since the initial launch of XM and Sirius satellite radio services in the US, XM has expanded to 1.5 million subscribers and projects 20 million by 2010, Sirius estimates one million subscribers by the end of 2004, and both services now offer around 100 channels.

7. **Terrestrial Digital Radio:** the FCC has approved In-Band On-Channel (IBOC) digital radio operation for AM and FM stations, a technology that has been licensed to almost 300 radio stations in over 100 U.S. markets. The longer term potential includes datacasting and the broadcast of map database updates. Some difficulties have arisen in the development of IBOC, however, which may take some time to resolve.

8. **Ultrawideband (UWB):** the FCC has now allowed the deployment of limited use UWB capabilities. This permits specific application areas for Vehicular Radar Systems, devices that detect the location and movement of objects near a vehicle, and for Communications and Measurement Systems, which include high-speed home and business networking devices.

These and other technologies are discussed in greater detail in Chapter 5.

2.7.2 Content Providers

Providing the user with real-time traffic, weather and similar services is a major objective for telematics Content Service Providers (CSPs). A service to provide real-time traffic information, one of the top consumer information requirements, is currently in an early stage of development. The TrafficMaster service may be a leader in the next generation of real-time traffic information providers [Ref. 2.7.3]. It is anticipated that in addition to fixed sensor technology for traffic monitoring, automobiles themselves will become information-gathering agents for traffic monitoring systems. This concept is termed Floating Car Data (FCD) collection. Although fundamental issues such as privacy must be addressed, this concept is expected to cater to the telematics consumer's information needs. In the San Francisco Bay area 511 service is now available (see: www.511.org).

Chapter 3 GNSS Positioning Systems, Capabilities and Timeline

3.1 GPS, DGPS, Modernized GPS and Augmentations

Although a reasonably complete discussion of GNSS positioning systems was provided in Chapter 2, some additional technical details of GPS, DGPS and augmentations are addressed. The signal structure for the current and planned GPS signals are given in Figure 3.1-1, showing the spectral distribution of the signal energy for the C/A-codes on L1, the C-codes on L2, the I and Q components of the L5 signal, the P(Y)-codes on L1 and L2, and the M-codes on L1 and L2. The band limits for both L1, L2 and L5 are 12 MHz either side of the band centers, in this case 1575.42 MHz for L1, 1227.6 MHz for L2 and 1176.45 MHz for L5.

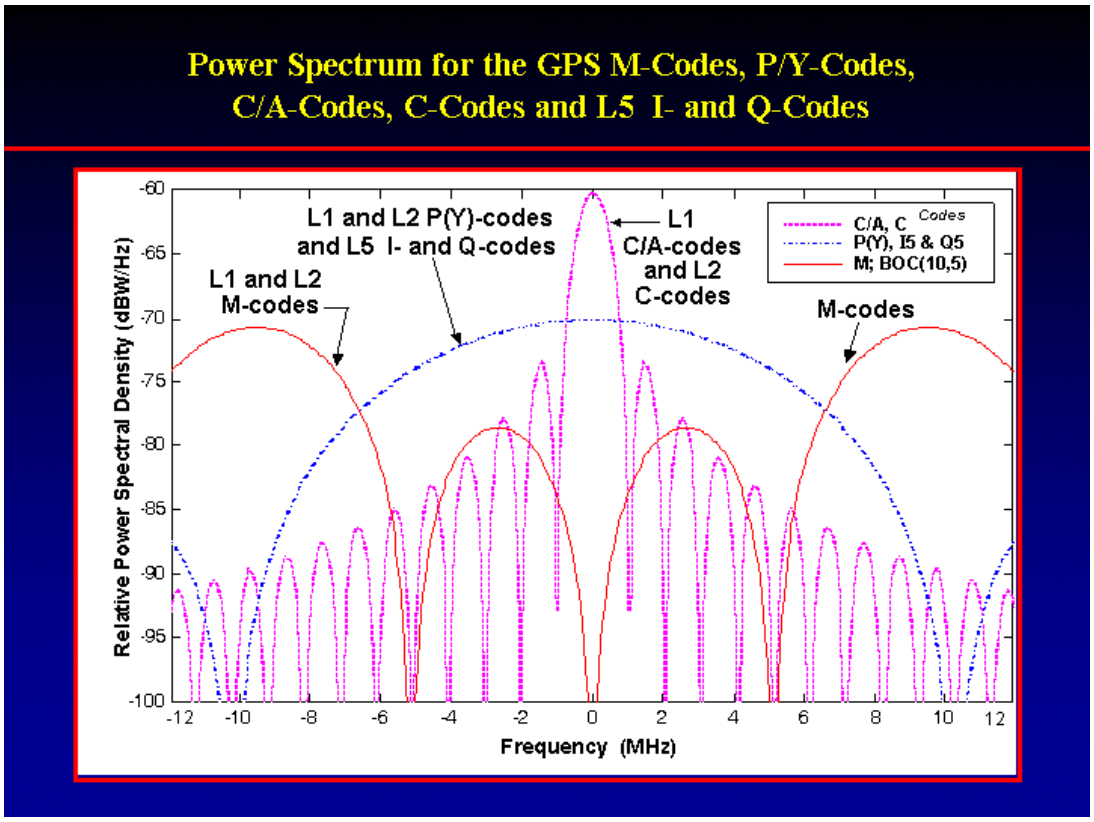


Figure 3.1-1 Power Spectrum for the GPS M-Codes, P(Y)-Codes, C/A-Codes, C-Codes and L5 I and Q-Codes

The L5 signals at 1176.45 MHz have the same chipping rate of 10.23 Mbps as the P(Y)-codes and the same spectral distribution as the L1 and L2 P(Y)- codes. Although the M-code power distribution exceeds the ITU assigned 24 MHz band at L1 and L2, the levels of the out of band signal energy are apparently believed to be low enough so as to be at an acceptable level.

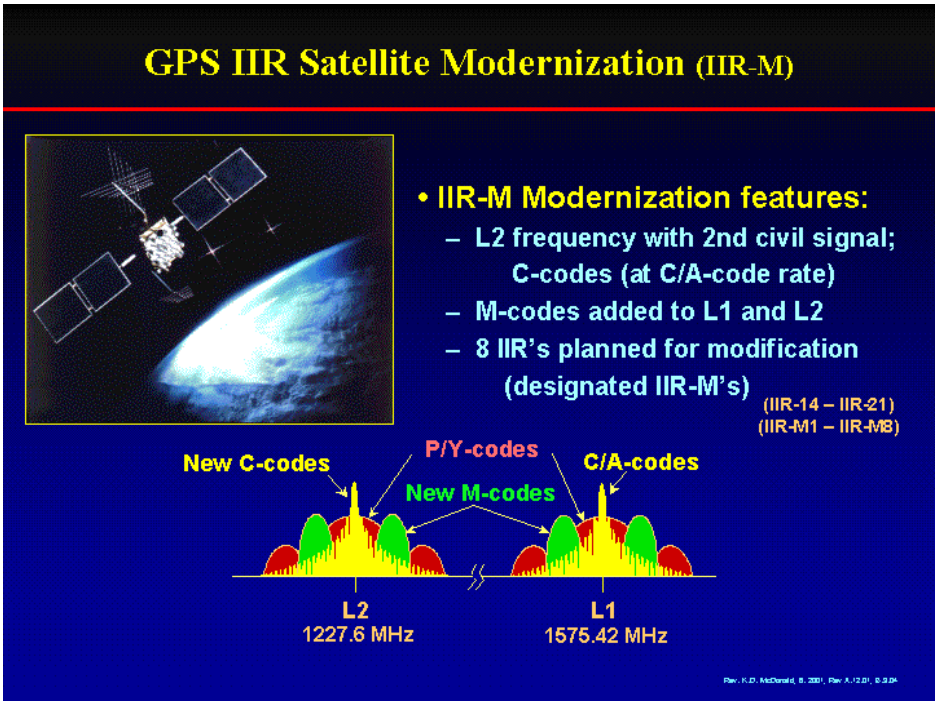


Figure 3.1-2 GPS IIR-M Satellite Modernization Signals

Figure 3.1-2 illustrates the signals planned for each of the last eight GPS IIR-M spacecraft that are being modified. GPS IIR No. 11, launched in mid March, 2004 indicates two more IIR spacecraft for launch and the eight IIR-M spacecraft. Figure 3.1-3 shows the IIF S/C and the additional L5 signal at 1176.45 MHz.

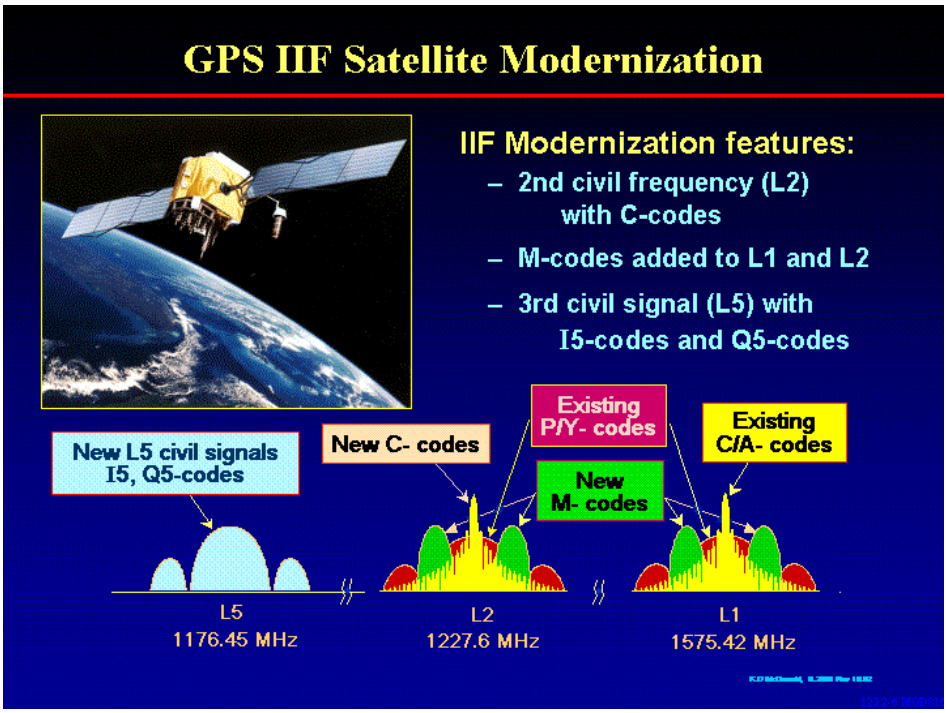


Figure 3.1-3 GPS IIF Satellite Modernization Signals

Figure 3.1-4 provides a personal perspective on the general GPS institutional and planning situation at this time. Figure 3.1-5 provides a brief list of comments and concerns relating to GPS. Both charts are believed to be self explanatory. Some of the topics of interest relate to policy changes that may be needed to obtain GPS new capabilities on a more predictable and planned basis.

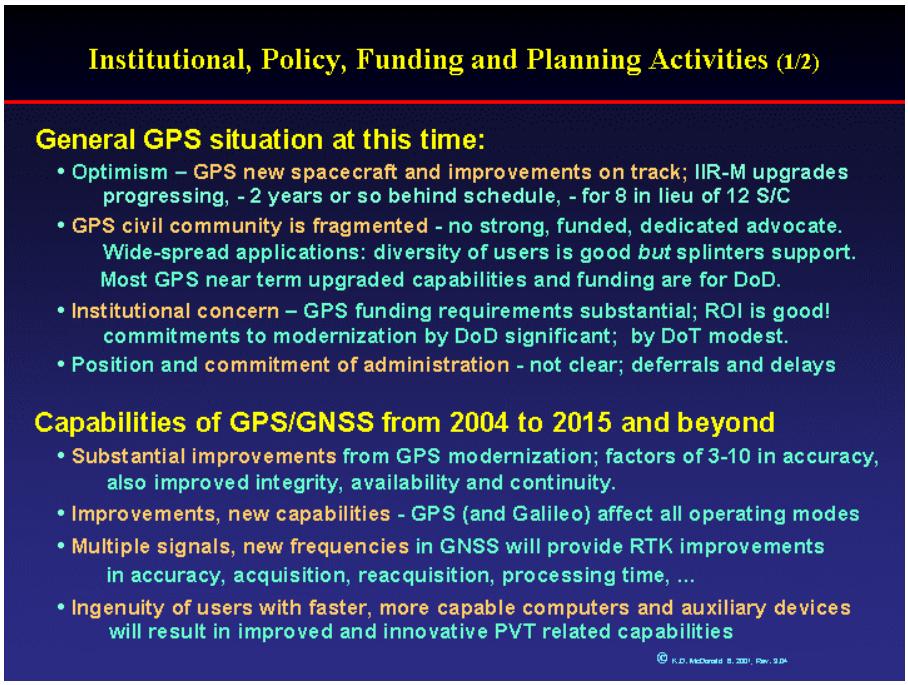


Figure 3.1-4 GPS Institutional, Policy and Planning Activities

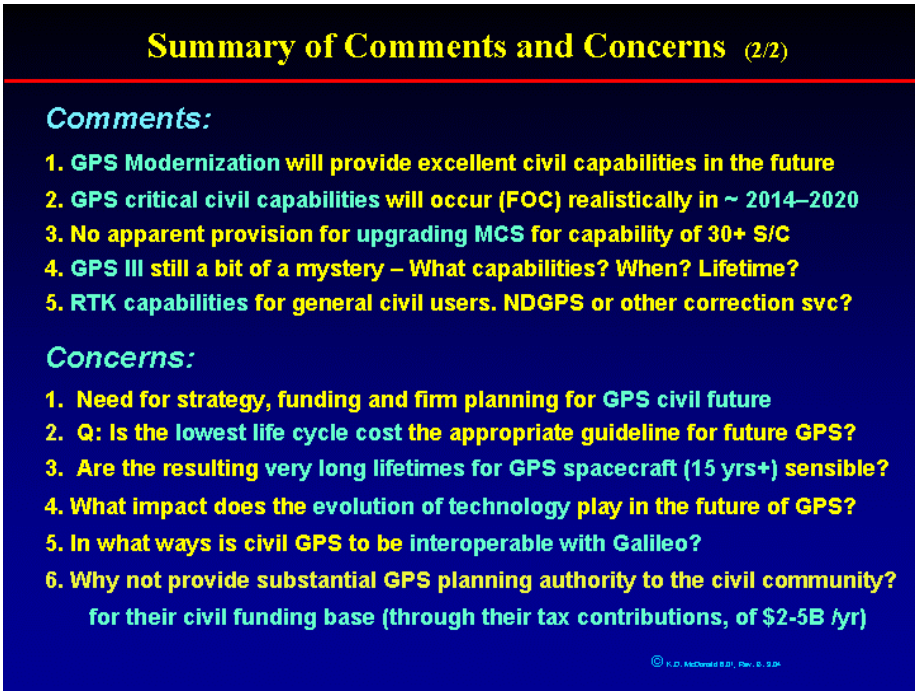


Figure 3.1-5 Summary of Comments and Concerns Relating to GPS

3.2 Galileo Development, Status, Schedule and Operations

3.2.1 Galileo Joint Undertaking (GJU)

In July 2003, the Galileo Joint Undertaking (GJU) began to function as the agency in charge of the overall Galileo project. GJU's main shareholders are the European Commission (EC) and the European Space Agency (ESA). The latter is responsible for the development of Galileo. In mid-2003 GJU had just released the first Invitation to Tender (ITT) for the Galileo Concession Company (GCC). The GCC, not yet formed, will comprise one or more of the companies that are bidding for inclusion.

Once selected (at the end of 2004), the GCC will take over the management and funding of the Galileo project. At that time, the Public Private Partnership (PPP) for Galileo should be resolved. The GCC is expected to provide approximately half of the development cost and to manage operations and maintenance on its own. GJU will also manage some Galileo projects (at a cost of approximately 100 million euros) over the next two or three years within the EC 6th Framework Program, the research program of the European Union. Those projects cover mainly administrative and Galileo service activities. GJU will exist only for about four years, until the GCC starts the Deployment Phase.

3.2.2 Galileo Schedule

Galileo is currently (March, 2004) in the Definition and Validation Phase. Phase B2, including a B2 bridging phase, was completed at the end of November 2003. In December 2003, the C0 phase, predevelopment and definition, started. The C/D phase, development and deployment, will follow in June/July 2004. See Galileo website [Ref. 3.2-1].

Concurrently, the Galileo Satellite Test Bed (GSTB) Version 1 (V1) continues, verifying algorithms and methods of satellite orbit determination and integrity, including some test cases that use GPS data. To develop the first two satellites, GSTB Version 2 (V2) was initiated in the autumn of 2003. The first satellite, a low-cost spacecraft built by a consortium organized by a UK company, is mainly intended to protect the ESA ITU filings for the assigned L-band frequencies for Galileo. Galileo Industries Inc., the company in which the major big European space companies are unified, is building the second satellite, which could be considered as the first Galileo test satellite. The GJU plans to launch the first two test satellites toward the end of 2005.

After that launch, the In-Orbit Validation (IOV) Phase, from 2005 to 2007, will begin with the launch of the first four Galileo satellites. In 2005, the Galileo Concession Company plans to issue the Invitation to Tender (ITT) for the Galileo Deployment Phase, in which the remaining 26 satellites are planned to be launched. This phase is expected to last 24 months. Although European politicians continue to cite 2008 as the date when Galileo should be operational, 2010 is a more realistic estimate.

By early 2003, GJU and ESA had already launched project activities to develop different kinds of Galileo receivers. A consortium of companies headed by Septentrio of Brussels leads this work [Ref. 3.2-2].

In early 2004, ESA awarded a contract for the C0 phase (predevelopment and definition) of the Galileo Test User Segment. In this phase the consortium will start work on the development of the first Galileo User Receivers.

Figure 3.2–1 shows a general master schedule for Galileo, which also indicates the funding commitments through deployment and initial operations.

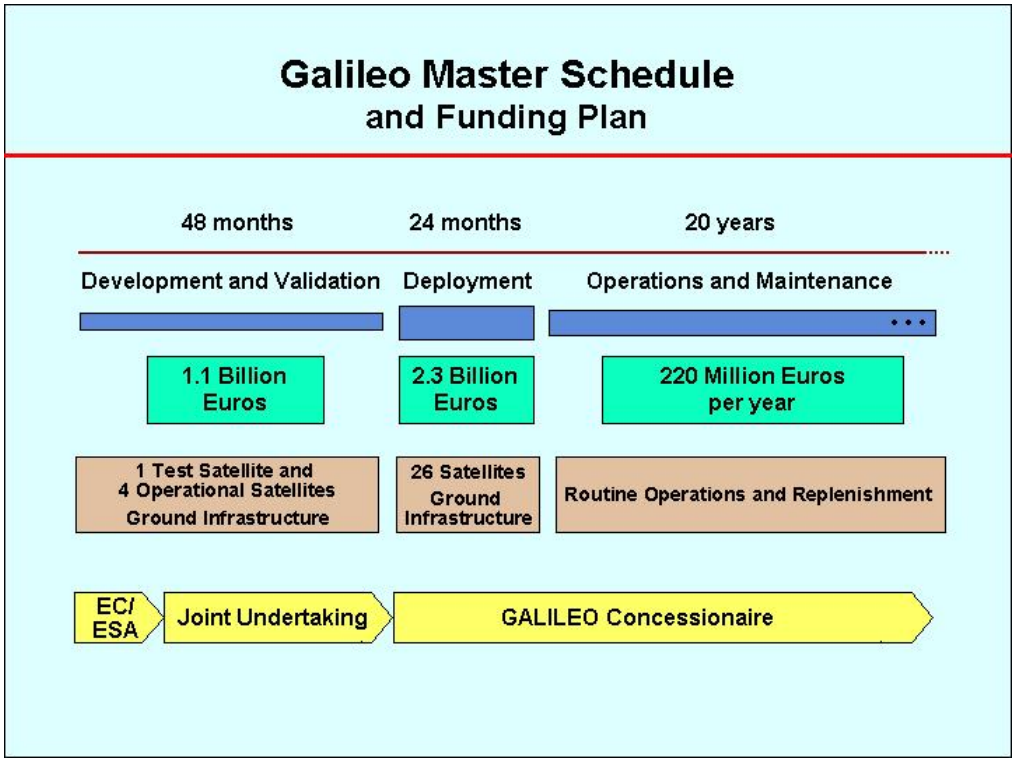


Figure 3.2–1 Galileo Master Schedule and Funding Plans

Although the ESA has widely distributed the Galileo Master Schedule shown in Figure 3.2–2, which depicts various milestones, that schedule is now somewhat outdated.

Figure 3.2–3 shows more of the management aspects in the current (Feb 2004) Galileo Master Schedule used by the EC.

Figure 3.2–4 shows the EGNOS Master Schedule. EGNOS will initially be operational in the spring of 2004. After 2010, EGNOS will be integrated into the Galileo program. Medium Earth Orbit (MEO) satellites of Galileo will then transmit integrity messages. The subject of integrity is discussed in some detail later in Chapter 3.

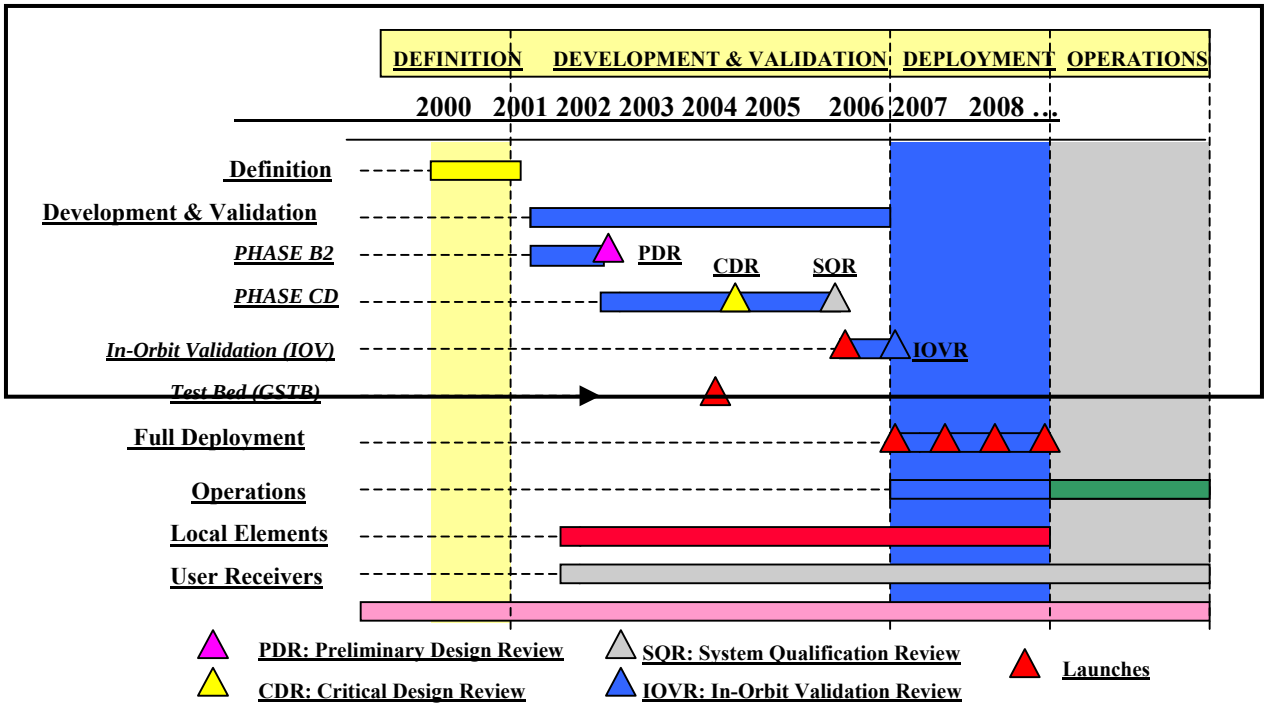


Figure 3.2–2 Galileo Earlier Master Schedule Showing Deployment Details

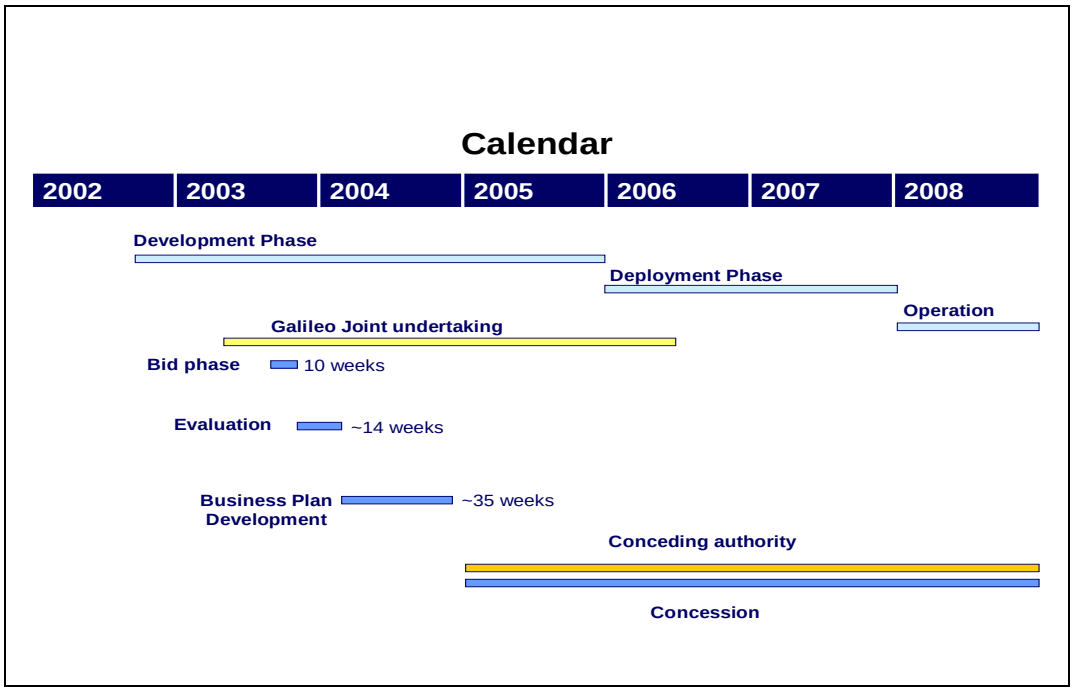


Figure 3.2–3 Galileo Master Schedule Currently Used by the EC (1/2004)

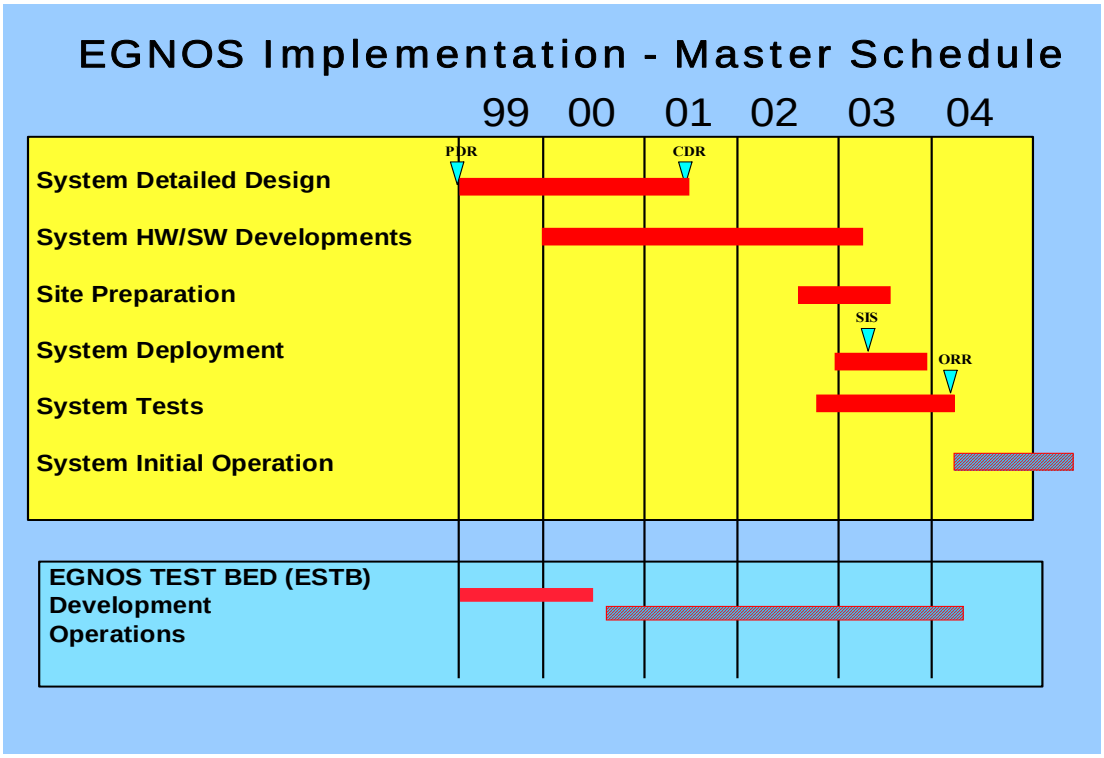


Figure 3.2-4 EGNOS Master Schedule

3.3 GNSS Augmentations

Figure 3.2-4 illustrates the European Geostationary Navigation Overlay, commonly referred to as EGNOS. The system has been in development for a number of years and is planned for initial operational deployment in the summer of 2004. Details on additional GNSS augmentations are given in Chapter 2.

3.4 Galileo-GPS Interoperability

3.4.1 Galileo-GPS Interoperability Characteristics

The following ensures Galileo and GPS interoperability:

1. **Galileo and GPS use the same center frequencies on L1 and L5** (GPS designated L5 is also Galileo E5a)

2. **Galileo and GPS are based on the use of the ITRF coordinate reference frame** (International Terrestrial Reference Frame) within a small realization accuracy (< 1-2 cm). In fact, WGS84 is only a few millimeters away from ITRF and the goal of the Galileo coordinate reference frame is to be less than 2 cm from the ITRF.

3. **Galileo and GPS use very close to the same precise time reference frame**: a real-time prediction of UTC to within 33 ns (2σ). For high precision applications, the user is able to determine the offset between the two systems, e.g., by using an additional satellite observation for this unknown. Moreover, the EC and the US have agreed that both satellite systems will monitor and periodically transmit the time offset.

These three features help assure commonality in the combined user receiver system structure and implementations.

3.4.2 Availability of Signals

Availability relates to the number of spacecraft signals in view, or being received by a user equipment. Since GPS is a worldwide system that provides good coverage characteristics on its own, with an average of about eight spacecraft in view, the addition of Galileo will make a moderate difference but not a large difference in accuracy under normal operating conditions. However, in "urban canyon" or other visibility limiting circumstances, the additional spacecraft of the Galileo constellation could make a very significant difference.

The Galileo capabilities would more than double the number of spacecraft in view to a user capable of receiving both sets of signals. This has advantages beyond the conventional availability aspect since the distribution of spacecraft provides better positioning geometry (GDOP) as well as greater flexibility to the user in nearly all conditions.

As shown in Ref. 3.4-1, the availability provided by a combined GPS III (type of spacecraft) and Galileo increases towards 99%. Figure 3.4–1 shows the simulation of the satellite visibility of GPS III at the five degree (latitude and longitude) grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

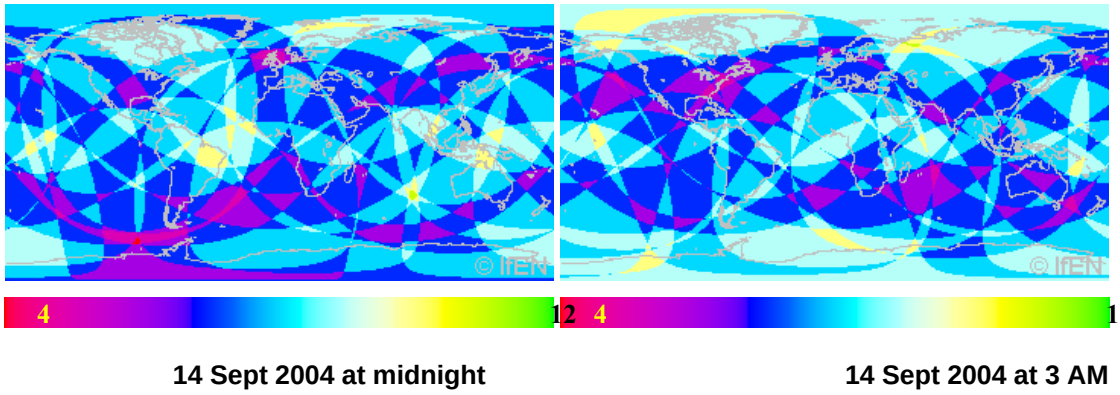


Figure 3.4-1 GPS-III Satellite Visibility Simulation, User Elevation Mask 7.5°

Figure 3.4–2 shows the satellite visibility of Galileo at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

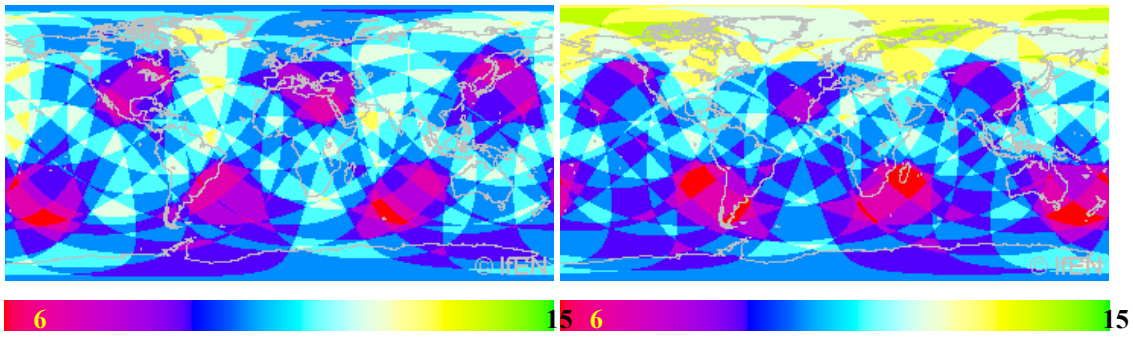


Figure 3.4-2 Galileo Satellite Visibility Simulations in Time: 7.5° User Elevation Mask

Figure 3.4–3 shows the satellite visibility of a hybrid GPS-III and Galileo system at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

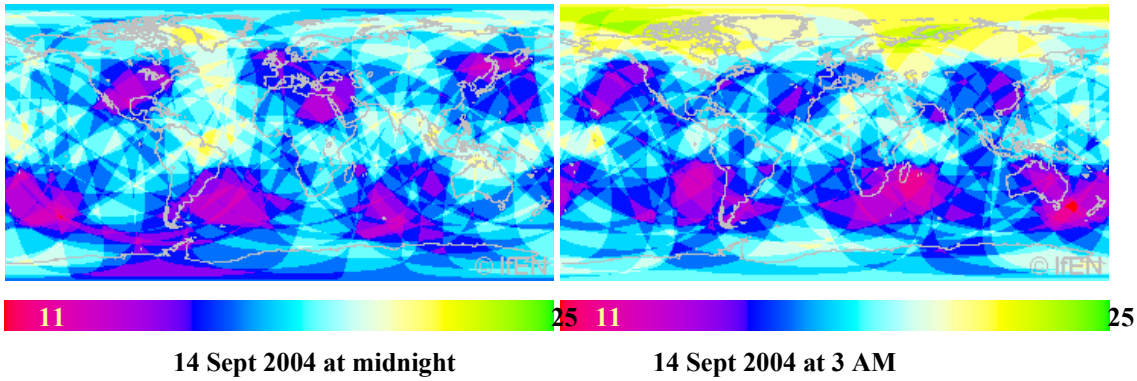


Figure 3.4–3 GPS III and Galileo Satellite Visibility Simulations: 7.5° User Elevation Mask

The figures below show that a large number of satellites are visible in a combined system (see Table 3.4-1). The large number of visible satellites and the signal redundancy enable the navigation user to check for various errors in the receiver (see RAIM availability later in this chapter).

3.4.3 Accuracy of Positions

The additional measurements from the Galileo satellites will provide improved geometry, which translates into more accurate positions. For conventional DGPS applications, this improvement may be sufficient to provide sub-meter accuracy, instead of the typical 1-2 m. For applications requiring centimeter-level accuracy, however, more significant improvements are needed such as the use of differential carrier phase measurement techniques. The ambiguity resolution process for differential carrier phase measurements will be faster with the additional Galileo spacecraft and signal frequencies. This will provide high accuracy positions in real time or near real time.

Table 3.4-1 Availability of Satellites in GPS, Galileo and Combined Navigation Satellite Systems

Receiver elevation masking angle	Number of visible Galileo satellites	Number of visible GPS satellites	Total
5º	13	12	25
10º	11	10	21
15º	9	8	17

By 2008-2010, Galileo plans to deploy capabilities that the GPS modernization program and specified GPS III performance goals wont achieve until much later. The additional multiple carrier frequencies that will be available first with Galileo and later with GPS are of great, probably underestimated, importance. Once Galileo is operational, Galileo and the combination of Galileo with GPS will provide a significant improvement in overall positioning accuracy over either system alone.

As Table 3.4-2 indicates, the Galileo signals can potentially achieve a higher accuracy in (absolute or predictable) position than present GPS C/A-code signals. Galileo's advantage in better performance may last only for about five to eight years, i.e., until the GPS modernization program is completed. This period can be considered Galileo's window of opportunity.

Table 3.4-2 GPS Operational Requirements Document for Position, Navigation & Time

System Characteristic	2000 GPS ORD		Civil PNT (Appendix F – 2000 ORD)
	Threshold	Objective	
Accuracy Horizontal	6.3m (95%) 30.0m (99.9%)	1.0m (95%) - civilian 2.1m (95%)- military 4.0m (95%)	0.01m
Vertical	13.6m (95%) 40.0m (99.9%)		0.04m
Timing	20.0 nsec (95%)	10.0 nsec (95%)	0.3 nsec (threshold) 1.0 picosec (objective)
Availability	90.0%	99.9%	100.0%
Integrity PHMI Time-to-alarm	TBD TBD	TBD TBD	$1\text{-}2\times10^{-9}$ per approach 1 sec
Continuity-of-Service	TBD	TBD	$1\text{-}10^{-4}$ per hour *and* $1\text{-}8\times10^{-6}$ per 15 sec *and* $1\text{-}6\times10^{-6}$ per 30 sec

2000 GPS ORD – 2000 GPS Operational Requirement Document; PNT – Position, Navigation, Time; PHMI – Probability of Hazardous Misleading Information
(GALILEO goals are more or less equivalent.)

Upon completion of GPS modernization in 2015-2020, the full benefits of a combined GPS and Galileo system can be realized. However, substantial benefits in operating with the combined system are clearly available well before the GPS modernization program is complete.

Table 3.4-2 shows the capability goals of GPS III, which in general are also those of Galileo [Ref. 3.4-2]. The civil stand-alone accuracy goals of 1.0 m horizontal and 3-4 m vertical indicate that after 2010 a stand-alone capability may serve much of today's differential market. Precise surveying and a number of other specialized services will continue to need precise differential techniques.

Table 3.4-3 Instantaneous Carrier Phase Ambiguity Fail Rate for Dual-Frequency GPS and Dual-Frequency Hybrid GPS and GALILEO

Baseline	GPS	GPS + Galileo
Short Term	2.4×10^{-3}	$<10^{-8}$
Medium Term	6.3×10^{-1}	6.3×10^{-2}
Long-Term	1.0	1.0

Eissfeller, 2001

The availability of a second and additional signal frequency signals for the compensation of ionospheric effects will have a substantial positive impact on civil accuracy. Although L2 will have a civil code, the band is not protected by ITU rules from possibly serious interference sources. The Safety-of-Life aspects of this part of L-band therefore have limitations. Galileo, however, will offer a SoL dual-frequency signal at L1 and E5a when it becomes operational. The new GPS L5 frequency (also the Galileo E5a frequency) signals may be at full operational capability (FOC) only after about 2015-2017.

The dual-frequency receiver of the future (after ~2015) might be an L1/L5(E5a) receiver rather than an L1/L2 receiver because of the desirability of tracking both satellite navigation systems. There has been interest in the US in encouraging the EC to also use the L2 band so that three frequency commonality would be available to users from both Galileo and GPS. Dual-frequency receivers have significant performance advantages over single frequency units. Also, three frequency receivers have substantial advantages over dual frequency units although this important feature is not widely recognized or appreciated.

Dual frequency receivers are expected to become common and inexpensive. This is because of continuing progress in semiconductor chip technology and software developments as well as associated developments in mass production cost reduction. Three frequency receivers have excellent capabilities for precision positioning (at the centimeter and decimeter level) and would probably be inexpensive if production quantities are sizable.

The feasibility of instantaneous determination of the carrier phase integer ambiguity using two and three (or more) frequencies appears practical with GPS-III or Galileo, or both together [Ref. 3.4-3]. Combining GPS and Galileo can provide a tremendous improvement in the ambiguity resolution failure rate. The operation will nevertheless still require a limited separation distance (baseline length) between reference and rover receivers. In other words: For up to about 2 miles (~3km) of separation (or baseline length), combining GPS and Galileo will make centimeter level accuracy (~5-20cm) possible with nearly 100% confidence. For the desirable longer distances, the L2 signal frequency (or other) capabilities may play an important role in real time precision civil applications.

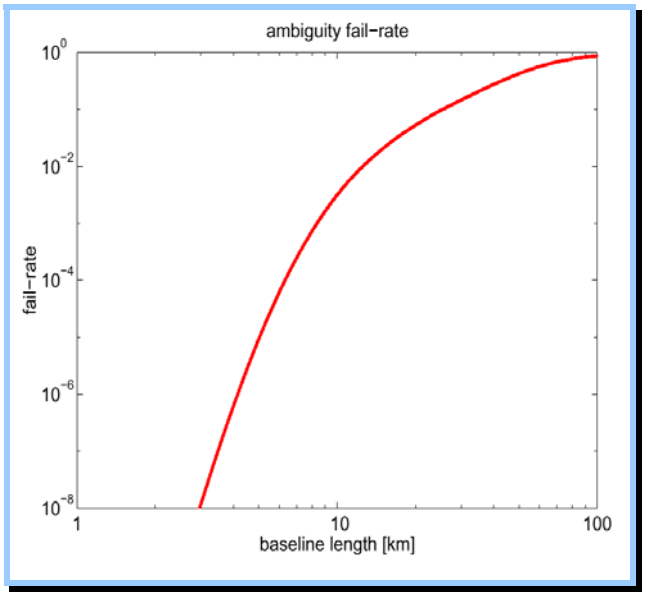


Figure 3.4–4 Instantaneous Carrier Phase Ambiguity Failure Rate for Dual-Frequency GPS and Dual-Frequency Galileo [Ref. 3.4-3]

3.4.4 Ambiguity Resolution

Ambiguity resolution is the process that allows GPS users to obtain the highest possible accuracy in the least amount of time. Unfortunately, ambiguity resolution is very sensitive to errors. Furthermore, even the smallest error in the ambiguity resolution process will produce a position error that far exceeds the expected estimation accuracy for that position. Since this creates a serious integrity risk, it is critical that ambiguity resolution processing be at the same time both robust and timely.

The addition of Galileo will have a direct positive impact on ambiguity resolution with respect to robustness, time needed to fix, and the inter-receiver distance over which the ambiguity resolution will be successful. Some supporting simulation results are shown in Figures 3.4-4. Figure 3.4-5 reveals that the use of both GPS and Galileo provides significant benefits both in the time needed to resolve ambiguities and in the percentage of the time the process was correct.

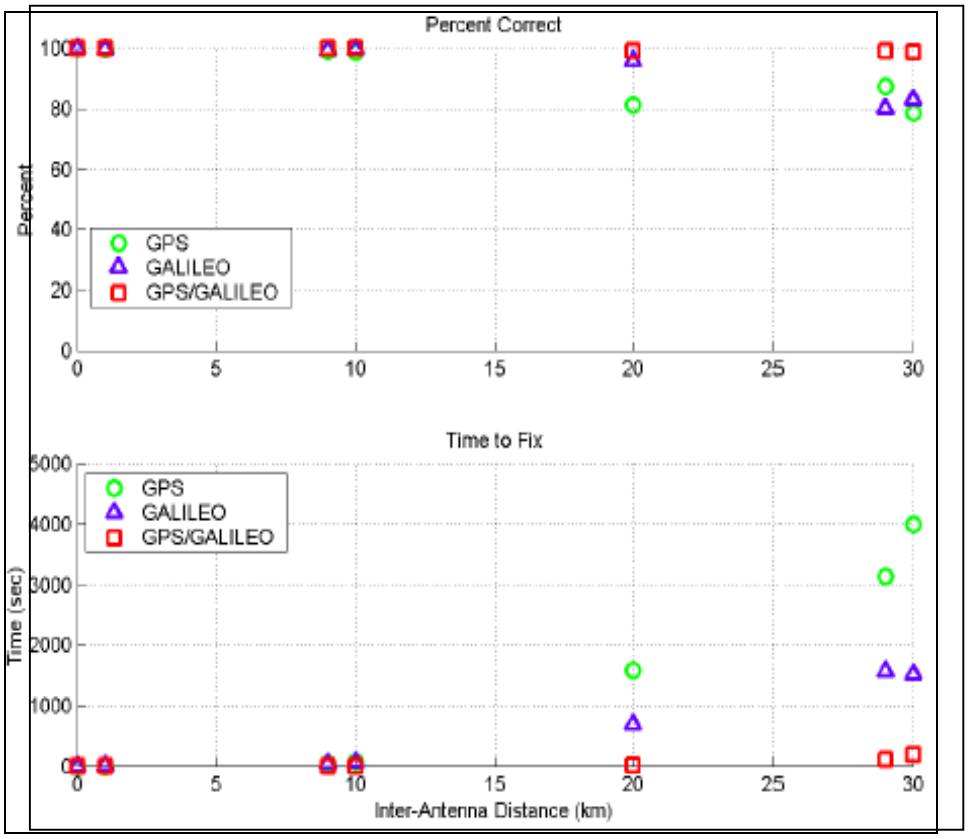


Figure 3.4–5 Percent of Time for Correct Ambiguity Resolution and Time for Ambiguity Resolution Using GPS, Galileo and Combination of GPS with Galileo [Ref. 3.4-4]

The improvement becomes more significant as the inter-receiver (antenna) separation increases. In other words, compared to current GPS (or planned Galileo) civil capabilities, the combination of Galileo with GPS will provide significantly better and more consistent ambiguity resolution over a wider geographical area. This has obvious benefits for vehicular navigation.

Furthermore, if multiple references are used in a network to model the spatial GPS errors, then an improved ambiguity resolution process will ultimately allow for even better modeling and subsequent reductions in the effects of these errors.

3.4.5 Safety Aspects

It appears realistically that the new GPS L5 signal will be fully operational only after about 2015-2017. The main benefit for GPS safety-related applications currently using L1 is that the additional use of L5 will nearly eliminate the effect of ionospheric errors, resulting in much improved accuracy. Galileo, however, will provide the same signal capabilities on L1 and L5 (or E5a) by about 2010. In the event of interference or any other disturbance on L1 or L5, integrity data can be still derived from E5b using a redundant Galileo signal. This signal reduces the vulnerability of both GPS and Galileo.

Moreover, after 2010 Galileo will offer combined tracking of E5a and E5b, represented as the E5 Binary Offset Carrier (BOC) signal. This offers a single frequency high precision signal with a total of three observables, considering the two sub-carriers on E5a and E5b. This provides a two-carrier ambiguity resolution technique that uses a wide-lane frequency reflecting the difference

frequency of the carriers. This technique has been shown with GPS (L1-L2 signals) to provide position measurement accuracies of 5-30 cm in real time.

Chapter 4 User, Vehicular and Infrastructure Developments

4.1 GNSS Capabilities, Accuracy and User Performance

4.1.1 Operational Modes of Receivers

Figure 4.1–1 provides estimates for the projected civil real-time accuracy performance trends for user receivers employing GPS, Galileo and a future combination of both. Both the stand-alone and differential modes of operation for the systems are shown. In differential operation, the receivers provide relative code ranging measurements. In the more precise applications, they employ relative carrier phase measurements.

Stand-alone operation As indicated in Figure 4.1-1, stand-alone operation of GPS or Galileo using a single frequency signal with about a 1 Mbps code rate (e.g., the GPS C/A-codes) provides an accuracy of 5-10 meters. This depends on the state of the ionosphere, and to a lesser extent the troposphere, multipath effects and receiver noise. Occasionally, with a benign ionosphere, the performance of these stand-alone receivers may reach an accuracy of 2-3 meters but this is unusual. The sharp improvement in accuracy indicated at the start of the figure (from 50-100 m. to 5-10 m.) reflects the reduction to zero on May 1, 2000 of the Selective Availability (SA) degradation that had been placed on the GPS signals by the Defense Department.

After 2010, Galileo will provide signals on several frequencies. This enables receivers to determine the ionospheric error directly and perform to an accuracy of 1-2 meters or somewhat better. With narrow correlator receivers, performance at the sub-meter level would be feasible.

Differential code operation The capabilities of single frequency (L1) GPS employing the C/A-codes operating in a code differential mode are illustrated in the figure (as 1f DGPS). The differential corrections normally transmitted to the user correct for most of the error terms listed above. Exceptions to this are the noise-like errors including multipath and the receiver noise error. Nominal accuracy values for current GPS code differential operation is about 1-2 meters with performance at times slightly below the meter level. This assumes the use of conventional, or **standard correlator receiver** implementations.

However, the use of **narrow correlator receivers** reduces the receiver code noise appreciably and simultaneously decreases the multipath errors. The figure shows an extension (downward, in red) in single frequency code accuracy to the 50-80 cm region when narrow correlator receivers are used. This capability appears to have some strong and useful implications for determining in which lane a vehicle travels.

a.

Section 4.1 and Figures 4.1-1 and 4.1-2 have been revised from the April report to carefully consider the use of special receivers, i.e., narrow correlator techniques, for obtaining robust sub-meter accuracy in the near term with high quality differential corrections. Please see Section 4.2.1 for narrow correlator definitions.

Stand-alone multiple frequency capabilities After 2010 when Galileo is planned to be available, differential capabilities from both GPS and Galileo will be in service. Galileo capabilities offer four frequencies that may be used. This provides an excellent opportunity for directly determining the group delay, or error, associated with the ionosphere. The Galileo signals also have a signal structure (split spectrum signals) that provides a better ranging precision than the C/A-codes on GPS. Possibly narrow correlator technology (and its increased cost) may not be required with certain of the Galileo signals. Also, with multiple frequencies, there will be diminished need to operate in a differential mode for certain vehicle positioning applications. Both stand-alone and differential modes are shown in Figures 4.1-1 and 4.1-2.

Two frequency (or more) ionospheric correction To obtain the benefit of determining the ionospheric group delay autonomously, signals from the same spacecraft must be measured. The propagation delay for the signals varies inversely with the signal frequency, so it is necessary to have essentially coherent signals at the starting point (the spacecraft). The receiver measures the relative delay of the code on one signal relative to the other. This provides the data needed to determine the delay characteristics of the ionosphere.

Unfortunately, two or more signals from differing spacecraft do not provide the information required to determine the ionospheric delay values.

Real time kinematic (RTK) As discussed later, the capabilities of RTK systems provide relative measurement accuracy to the 5-30 cm region. The carrier phase observable lends itself to extremely precise measurement; surveyors and others can obtain accuracy in the 1-5 mm region. However, there is a concern relating to robustness of single frequency carrier phase measurement systems. In general, single frequency systems are not robust, in that in the event of signal loss, reacquisition may take a long period, e.g., 30 seconds to several minutes. Multiple frequency systems can employ methods that overcome this single frequency deficiency. Multiple frequency systems, such as Galileo with its four frequencies, are very rapid in reacquiring the signals and the user position.

4.1.2 Space Vehicle Enhancements

The user accuracy improvements plotted for the years from 2000 to 2020 are shown in the figure. Improvements during this interval strongly depend upon planned capabilities for spacecraft deployment and use. Colored ellipses in the top part of the chart indicate evolutionary improvements in the space vehicle capabilities. This data shows that the first Galileo space vehicle launch is planned for mid-2005 and Galileo's complete 30 space vehicle (SV) constellation is planned to begin operation in 2008. This data is probably somewhat optimistic since many believe that 2010 is a more realistic date for Galileo operation.

4.1.3 Signal Enhancements

The L2 C-codes

The GPS enhancement that supports civil community needs is initially the introduction of the new C-codes on the L2 frequency (1227.6 MHz) when the first space vehicle is launched in 2005. This second civil signal for GPS will provide for the two-frequency correction of the ionosphere in a manner similar to that currently used by the military. Because other users, such as radars in some areas, share the L2 band, L2 GPS reception may be susceptible to interference and unintentional jamming. Moreover, since L2 is not a “protected” band, it is not acceptable for safety services, such as use with air carrier aircraft. For this reason, the Federal Aviation Administration and other aviation administrations do not plan to use this band. The band is nevertheless nearly always available for civil use in non-safety applications.

The L5 I- and Q-codes

In about 2007-08, the first of the Block IIF space vehicles (SVs) is planned for launch, which will provide two additional civil signals at the L5 frequency (1176.45 MHz). As GPS space vehicles are launched and placed into orbit, new enhanced signals will become more available to users. The effective use of these signals on a continuous operational basis, however, will require approximately 18-21 enhanced signal SVs operational in the constellation. The figure shows estimated dates for reaching this number of operational SVs. The GPS III space vehicles will expand the capabilities of the IIF SVs with some additional power and features.

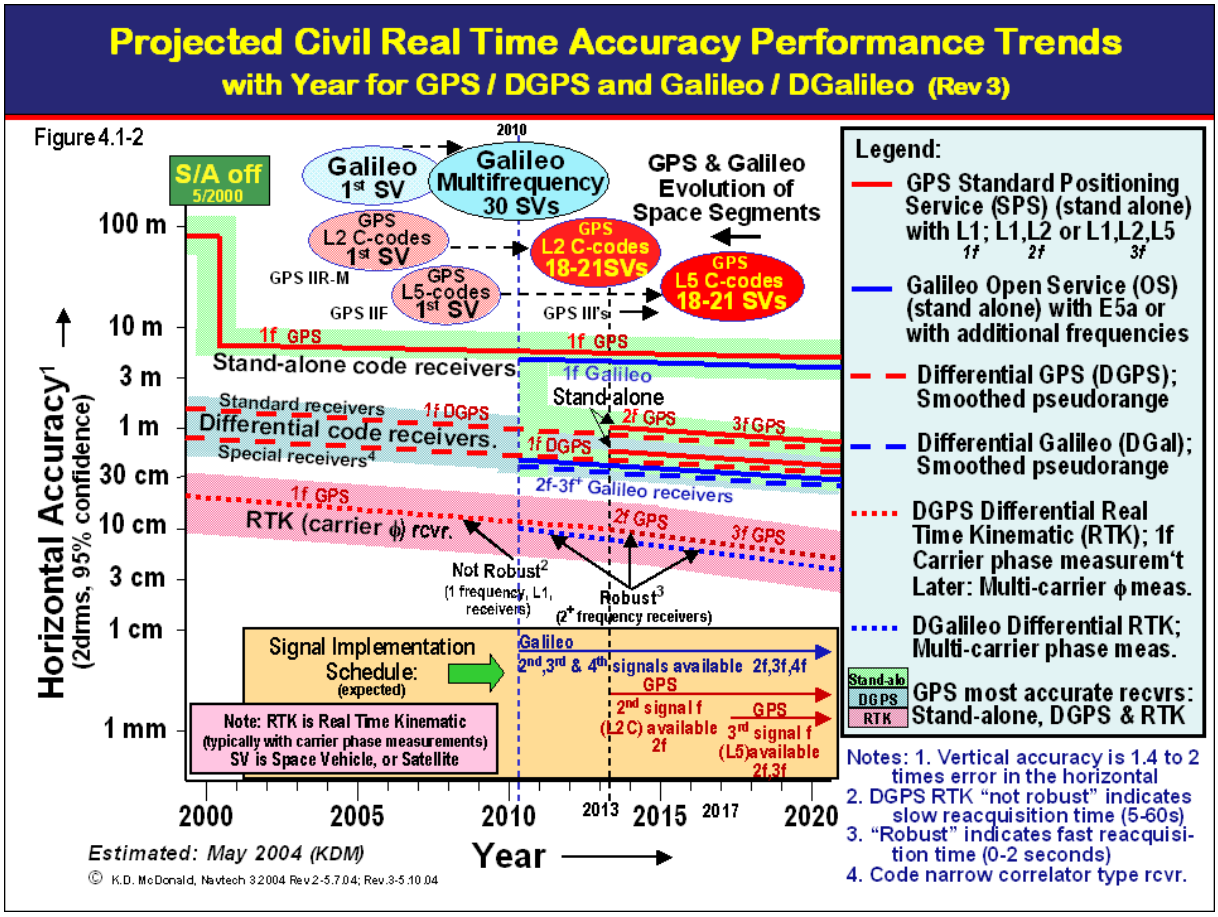


Figure 4.1–1 Projected Civil GNSS Real Time Accuracy Performance Trends

Figure 4.1-1 illustrates the projected real time performance trends for navigation and - positioning systems that are available now or are planned to be available by 2015. The chart shows the anticipated capabilities for a) stand-alone code receivers, b) differential code receivers, and c) differential carrier phase real time kinematic (RTK) receiver systems. An Annotated and updated version of these parameters is provided as Figure 4.1-2.

Removal of SA in 2000

The first substantial accuracy improvement in the Standard Positioning Service (SPS, i.e., the C/A-codes on L1 at 1575.42 MHz) occurred on May 1, 2000 (UTC) when selective availability (SA) was set to zero on the space vehicles, as indicated by the green-shaded rectangle on the chart. The DoD had placed SA on the GPS signals to degrade GPS civil accuracy for security reasons. The specification for SA was to degrade civil accuracy to about 100 meters in the

horizontal (in Latitude and Longitude) at a 95% confidence level (2drms). Once SA was no longer effective on the civil signals, the civil accuracy of GPS improved to about 5-10 meters (95%) worldwide.

As can be seen in Figures 4.1-1, 4.1-2 and 4.1-3, the performance of stand-alone (civil) GPS C/A-code equipment improved from about 50-100 meters (2drms) to 5-10 meters with the SA reduction to zero. The GPS single frequency receivers have to contend with the vagaries of

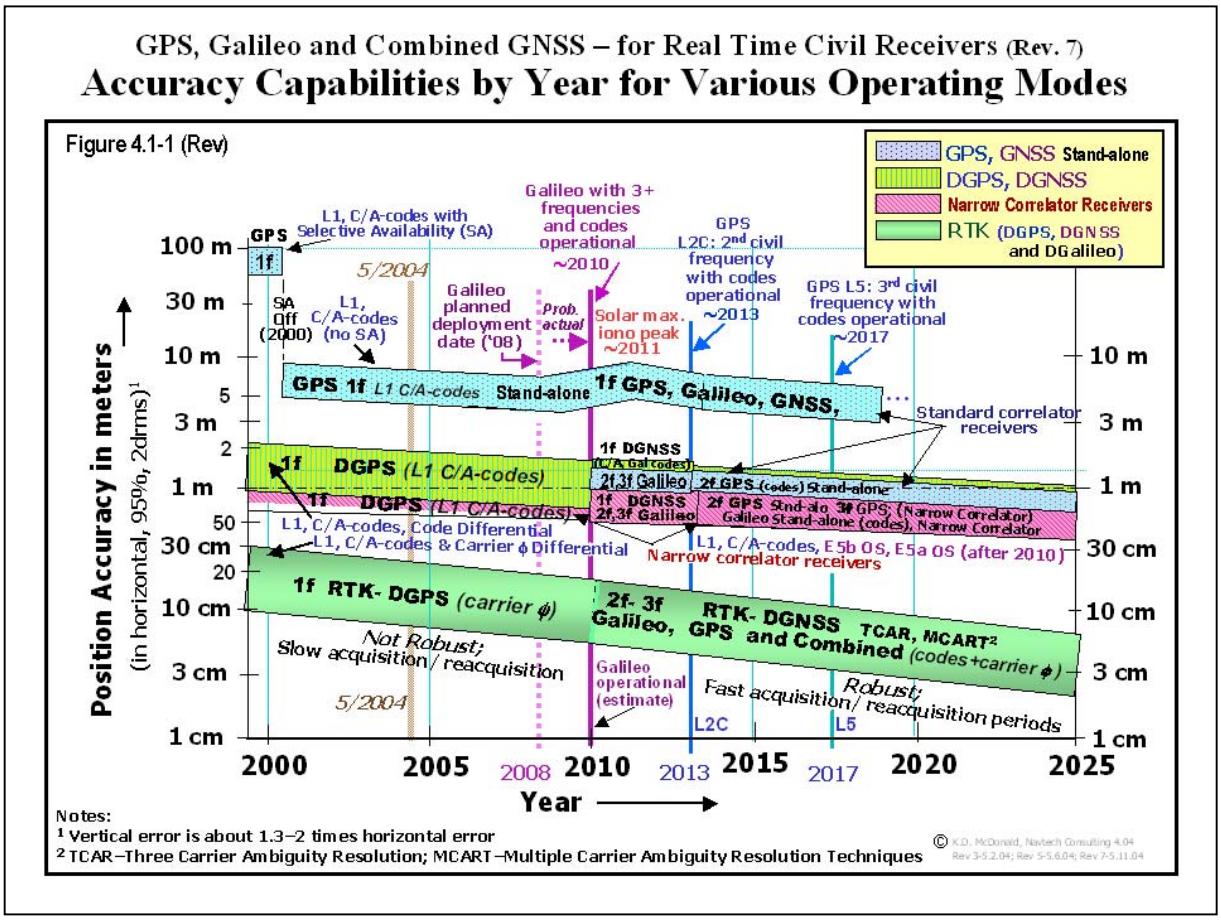


Figure 4.1-2 Accuracy Capabilities by Year for Various GPS, Galileo and Combined Operating Modes

the ionosphere and its serious, albeit cyclical, degradation effects on the signals from the GPS spacecraft. The accuracy of the stand-alone civil receiver will continue to gradually improve until about 2009. Then the ionospheric errors will again become substantial with the next solar cycle occurrence in about 2012. This is shown somewhat more graphically in Figures 4.1-2 and 4.1-3. Models of the ionospheric propagation delay effects improve the accuracy but only to a limited extent (to about 50%).

The differential GPS (DGPS) code receivers provide a good correction for the ionospheric effects as well as for many other error terms affecting both the base station and the remote receiver (the common-mode bias effects). The inherent receiver noise level limitations of the code receivers provide a lower limit on the accuracy obtainable from these receivers. This lower limit is currently at about one meter unless the narrow correlator receiver technology is employed. In this case, position errors of about 50 cm are attainable.

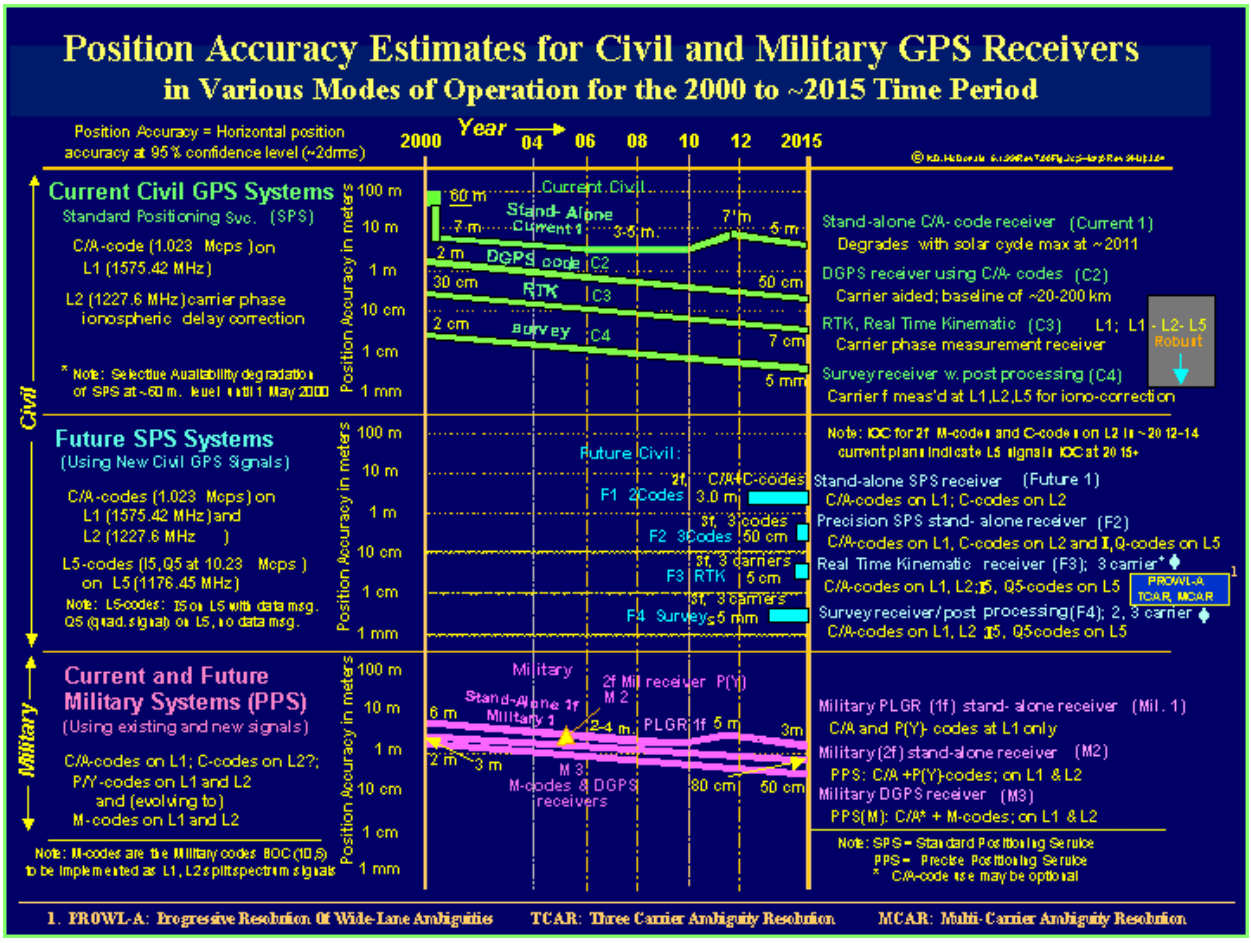


Figure 4.1–3 Position Accuracy Estimates for Civil and Military GPS Receivers

Similar performance is predicted to be obtainable from Galileo after its deployment in about 2010. In many cases the accuracy and other capabilities planned for Galileo will be better than those of GPS. However, it is unlikely that Galileo will be used as a single stand-alone system. The normal mode of operation would be for a combined. Or hybrid, GPS-Galileo system. The marginal cost of including GPS should become low quickly (GPS chip sets and boards are available now for about $30-40 in quantity) and the improved capabilities of a combined system would be both significant and of benefit to most users.

4.1.4 GNSS Receiver Capabilities

Stand-Alone receivers

The performance of the current conventional, single frequency stand-alone SPS receivers will improve only slightly as time progresses. The Sun's effect on the ionosphere will cause a variation in user accuracy with its daily and seasonal changes as well as with the 11-year solar cycle. The ionospheric delay, which is the principal error in the SPS system (as long as only a single frequency is available), can only be partially corrected. Variations in ionospheric activity,

largely caused by the solar cycle thus strongly influence the performance capabilities of such single frequency services as the current SPS.

Differential receiver system capabilities

The blue-shaded region in the figure shows the effect of providing differential corrections to SPS receivers. These corrections can reduce to a low value the common errors between the reference and remote, or "rover" receivers in a differential system, and can also provide the substantial improvements indicated. Conventional SPS receivers typically have a residual code noise error of about 0.7-1 meter, which makes it feasible for a typical differential code receiver to obtain an accuracy of 1 to 3 meters. The code noise, however, limits performance to this capability range.

Narrow Correlator Receivers

Using a narrow correlator receiver reduces the code noise by a substantial amount, (i.e. by a factor of about ten) to noise values of 10 to 30cm. This makes significantly improved performance possible from differential code receivers employing narrow correlator design.

For the narrow correlator receivers, performance accuracy in the range of 40 to 70cm is feasible with moderate separation (or baseline) distances between reference and rover receiver (i.e., to about 20 km or 12 miles). There is also a requirement for differential corrections to be derived from a base station receiver having at least the quality of the mobile narrow correlator in order to achieve stated accuracy. A footnote on the chart designates narrow-correlator receivers as "special receivers."

Multi-frequency receiver code capabilities

When satellites that provide two or more frequencies to GPS and Galileo receivers become available, differential code receivers may lose some of their current advantage. Multi-frequency (non-differential) receivers will then be able to correct for the ionosphere by using their two-frequency ionospheric correction capabilities. Furthermore, the dependency a low noise narrow-correlator receiver will likely be reduced when receivers operating with the codes planned for the L5 signal after year 2017 (at 1176.45 MHz). This is because the L5 signal codes will have a ten times faster chipping rate than L1 and L2, which provides very low code noise without requiring the use of narrow-correlator techniques.

Real time kinematic (RTK) receiver systems

The figure's red-shaded region represents the performance trend for the real-time kinematic receivers that normally employ processing of the GPS signal carrier phase on an interferometric phase measurement basis. Single frequency RTK receivers have a serious problem when undergoing dynamics since they can lose their lock on the carrier signal. They typically need an appreciable period of time to reacquire the GPS signals.

The performance of an RTK system operating on a single frequency is normally considered as **not robust**, as shown on the figure. Reacquisition times can be fairly long, that is, between about five seconds and a minute or so. With multi-carrier (frequency) signals, very rapid reacquisition and integer cycle solutions can be obtained. These future civil, multi-frequency RTK features provide a **robust,** precise, reliable receiver. The reacquisition and recovery for a multi-frequency receiver normally takes a period of less than two seconds and typically occurs on a nearly instantaneous basis.

4.2 GPS Receiver Equipment Techniques and Configurations

4.2.1 Classes of GPS Receiver Operating Techniques

This section investigates the following classes of receivers that appear to have application to vehicular positioning:

a) **Conventional low cost SPS receivers**
b) **Low noise narrow correlator receivers** and variants of this basic technique
c) **L1 carrier phase tracking and measurement receivers** (static and RTK)
d) **L1/L2 codeless carrier phase tracking and measurement receivers**
e) **Future multiple frequency, multiple code and phase measurement receivers**

Factors such as accuracy, technical complexity, acquisition and reacquisition time, cost and other performance characteristics are considered.

The term "GPS receiver" can be somewhat simplistic since most receivers implement special techniques to improve accuracy and provide other desirable characteristics. In some situations, these additional benefits can have a significant impact on system performance and it's therefore important to understand the basic operational concepts and differences. To this end, the following sections outline various techniques and their characteristics. Figure 4.2-1 illustrates several types of receiver equipment.

a) SPS Receiver

The following discussion concerns a conventional non-differential **GPS low cost receiver** that provides C/A-code measurements at L1 only, uses standard (bit width) correlator spacing, provides a position estimate once per second and uses the data available to it from the GPS data message (such as iono-model corrections). These receivers are available as "cards" or "engines" for $60 to $90 on a single or small quantity basis depending on their manufacturer and special characteristics (size, pin-outs, power drain, etc). The widespread use of GPS engines in cell phones has had a substantial impact on receiver prices. For over a year, low cost GPS receivers have been produced at a rate of over one million units a month.

b) Narrow correlator receiver

The narrow correlator technique was originally developed and patented by NovAtel, Inc. of Calgary, Alberta, Canada [Ref. 4.2-1]. In a typical GPS receiver, the signal tracking is performed with three correlators located at a relative "spacing" of 0.5 C/A chips, or a time separation of about 0.5 μs. In contrast, the narrow correlator approach spaces the correlators more closely (or narrowly) at 0.1 to 0.2 chips. This has two main benefits, reduced C/A-code noise and reduced multipath effects. The technique's main disadvantage is that the receiver requires a wider bandwidth front-end, which typically requires a higher sampling rate. These requirements are not usually a significant problem but carry an approximate 10x cost multiplier over standard receivers.

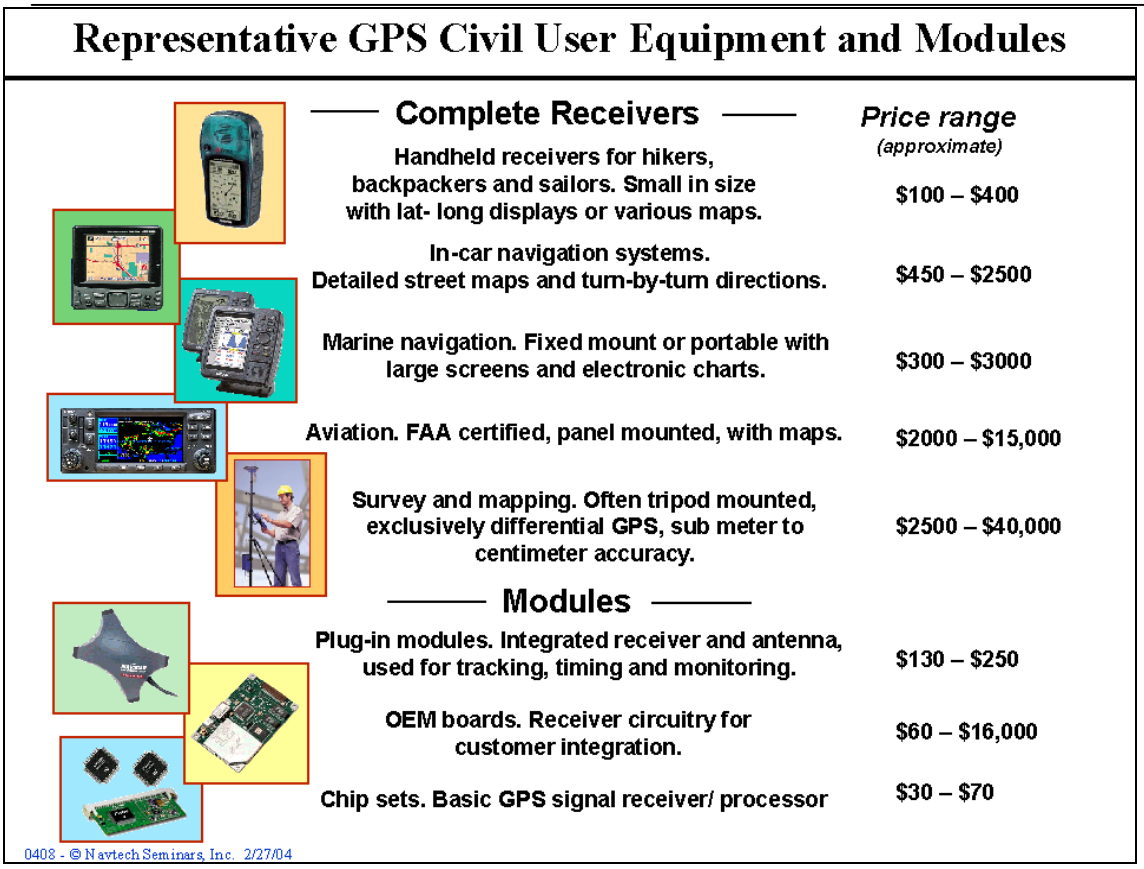


Figure 4.2–1

Narrow correlator receiver multipath mitigation

The narrow correlator technique is very effective for reducing multipath effects. This has prompted the development of several other correlator-based Multipath techniques. An early approach was Multipath Estimation Technology (MET), also by NovAtel. This measured and attempted to remove the effects of the distortion that multipath caused in the measured signal. NovAtel later developed another similar approach, the Multipath Estimating Delay-Lock Loop (MEDLL), which is still in use today. The main disadvantage of MEDLL is the large number of correlators (considerably more than the traditional three) the receiver requires and the resulting computational complexity.

In an attempt to reduce computational requirements while maintaining the benefits of the MEDLL approach, Ashtech developed the Strobe correlator technology. Other forms of receiver-based multipath mitigation techniques, similar to those discussed, are also available. Ref. 4.2–2 offers more information on multipath mitigation.

c) L1 carrier phase tracking and measurement receivers

Although all L1 GPS receivers track the L1 carrier phase to maintain signal lock, not all receivers output the carrier phase measurements. Moreover, some receivers that do output these measurements do not produce the data quality or precision normally associated with the term "carrier phase measurement." For this reason, it is important for the receiver implementation to

use a Phase Lock Loop (PLL), instead of a Frequency Lock Loop (FLL), to provide the carrier phase measurement. Using a PLL, a receiver's resulting carrier phase measurements will typically be precise to the millimeter-level. In contrast, an FLL-derived carrier phase may only be accurate to several centimeters, or worse.

The ability to provide a carrier phase measurement is extremely beneficial. First, it is the carrier phase measurements that allow GPS to obtain centimeter-level (or better) position accuracy over moderate distances. Second, even if only meter-level accuracy is desired, the carrier phase data can be used to smooth the pseudorange measurements by reducing the effect of code noise (pseudorange noise) and multipath.

d) L1/L2 Codeless and Carrier Phase Tracking

As is well known, the L2 signal currently provides only the P(Y)-codes that are encrypted by the military service provider. This enhances the signal's capabilities for the military in hostile environments, but prevents civil users from directly accessing the signal. Several techniques have been developed, however, that allow receivers to track the L2 signal and generate pseudorange and carrier phase data from the signals. These receivers are generally called "codeless" receivers, since they do not require knowledge of the encrypted code to operate. The most notable of these codeless units is the Z-tracking technique developed by Ashtech [Ref. 4.2–3].

The use of dual-frequency measurements allows receivers to exploit the dispersive nature of the ionosphere and remove the delay effects from the final pseudorange measurements. This substantially improves the position estimate. For a stand-alone GPS receiver, dual-frequency position accuracy will typically be two to three times better than that of a single-frequency receiver.

With respect to carrier phase data, access to L2 data allows users to form linear combinations (sums and differences) of the L1 and L2 measurements. This can provide solutions that are faster and more robust at resolving carrier cycle ambiguities. For example, as a first step many applications often use the wide-lane linear combination between L1 and L2 (i.e., L1-L2 = Δf of about 350 MHz for a wide-lane, or wavelength, of 86 cm), since it is easier to resolve the ambiguities of a signal that has a wavelength nearly five times longer than the basic frequencies employed.

Once the wide-lane ambiguities are resolved, the fundamental L1 signal can be used for greater precision. Other linear combinations are also available to further improve accuracy.

Unfortunately, L2 signal tracking is currently limited to high-end DGPS receivers. The least expensive L2-capable codeless receiver currently costs about $5,000. In contrast, a low-cost single frequency receiver board capable of generating carrier phase measurements may cost as little as $100, although fully functional systems with static or RTK software cost about $2000 to $5000. Dual-frequency (codeless) receivers are not widely used except for long baseline survey applications.

Since new launches of GPS IIR satellites, starting in 2005, will carry a new civil signal (the C-code signal), the use of codeless receivers may be phasing out. The new L2 signal will be in the clear (not encrypted) and much easier to receive, process and use than the current codeless approach.

e) Future Multiple Frequency and Multiple Code Receivers

As modernized GPS and Galileo satellites are deployed, GPS receiver manufacturers will undoubtedly provide products capable of making measurements on all available signal frequencies and using appropriate codes. In terms of standalone positioning accuracy, the

multiple frequencies combined with multipath resistant ranging codes should yield about a meter to sub meter level of accuracy. This is a considerable improvement over current stand-alone GPS.

This improved accuracy, combined with access to multiple sets of carrier phase data, will significantly facilitate ambiguity resolution. Perhaps more importantly, the ambiguity resolution process will become considerably more robust, a factor of central importance to safety critical applications.

4.2.2 Receiver Configurations

Over the next two decades, it can be expected that receiver configurations and capabilities will develop in the following three phases:

Phase 1—2004 to 2008

Only GPS is operational in this current phase. Beginning in mid-2004, the first GPS satellite will have a civil code on L2. The automotive industry's standard receiver will still be a single L1 frequency C/A-code receiver. Because of possible difficulties in receiving GPS differential corrections in urban areas from the WAAS geostationary satellites, most receivers will stay with the stand-alone accuracy of GPS, at about 4-8 m horizontal accuracy (95%). During this period, the position degradation effects of the ionosphere will be small and single frequency receivers will perform at their best.

At the end of this phase, trials may start with a dual-frequency (L1/L2) receiver using the C/A and C-code transmissions. Both receiver types will use limited bandwidths of a few MHz (4-6 MHz). These receivers will provide an accuracy of 2 to 4 meters and will be independent of ionospheric activity effects.

Phase 2—2008 to 2015

When Galileo goes into operation in 2008-2010, a single frequency combined GPS/Galileo L1 receiver will become interesting. This receiver, which will be simple to produce, will receive global (and perhaps regional) Galileo integrity flags as well as the SISA (Signal-in-Space Accuracy) quality parameter. The high redundancy of tracking both satellite navigation systems will then make it possible to carry out extended RAIM computations. The accuracy of this receiver configuration would be about 3-7 meters

Another option would be to do the above but include the L2 C-code measurement for the correction of ionospheric effects. This may be especially important during this period since the solar cycle peak is forecast for 2010-2011. The accuracy of this configuration would be about 1-3 meters.

The availability of more bandwidth (depending on progress in the chip industry) will result in improved multipath mitigation performance. In this phase, Galileo differential corrections will probably be available (although possibly only with a subscription fee). Higher integrity and better accuracy (to the 1m horizontal accuracy level with differential corrections) should make more safety-related applications possible.

The additional Galileo features already discussed will allow a Galileo receiver that can track L1 and E5b (and other frequencies) to possibly prevail over an L1/L2 GPS receiver. On L1, both satellite navigation systems can be tracked. With the use of additional signal frequencies, then multiple frequency processing of the carrier phases can be done and rapid ambiguity resolution is feasible. This can result in horizontal accuracy of 5-10 cm. for separation distances of a few tens of kilometers (or miles) and a few decimeters at greater distances.

Phase 3—After 2015 to 2017

Because of progress in chip development, a combined dual- or multi-frequency receiver L1/L2/L5(E5a) Galileo-GPS receiver will become the standard after the 2015-2017 period. GPS-III plans to offer integrity services so when it becomes available, the new signals and integrity similar to that provided by Galileo will be available from GPS. Reliable decimeter accuracy will be globally available.

4.2.3 Status and Future Trends of Receiver Technology

As shown in Figure 4.2–2, first generation GNSS receivers were built as analog devices until 1990, using a discrete part concept. While these receivers had full functional capabilities, their design as boxes resulted in heavy weight (~20 lbs, 10 kg), high power consumption (20 W), and linear dimensions on the order of 20 to 30 cm.

From the mid 1990s to the present has been a period of tremendous progress in semiconductor technology and digital systems. This progress has brought about the transition from analog to fully digital receivers. Printed circuit boards (PCBs) or OEM modules (cards) for GNSS receivers are both results of these developments.

Currently, highly integrated 12 channel units are produced with linear dimensions of 30 mm x 30 mm x 9 mm, power consumption below 0.4 W, and a weight of about 15 g. This progress was possible because high performance, low-power and low sized crystal oscillators have become available. Today, temperature compensated crystals (TCXO) are used for the low-end to the high-end.

All major GPS receiver manufacturers are involved in developing highly integrated dual or single chip solutions. As an intermediate step, solutions will consist of a separate RF-chip and digital signal-processing (DSP) chip. On a medium to long-term basis, the RF-chip will be integrated with the DSP on a single chip, which will make use of 0.5 to 0.3µ CMOS semiconductors.

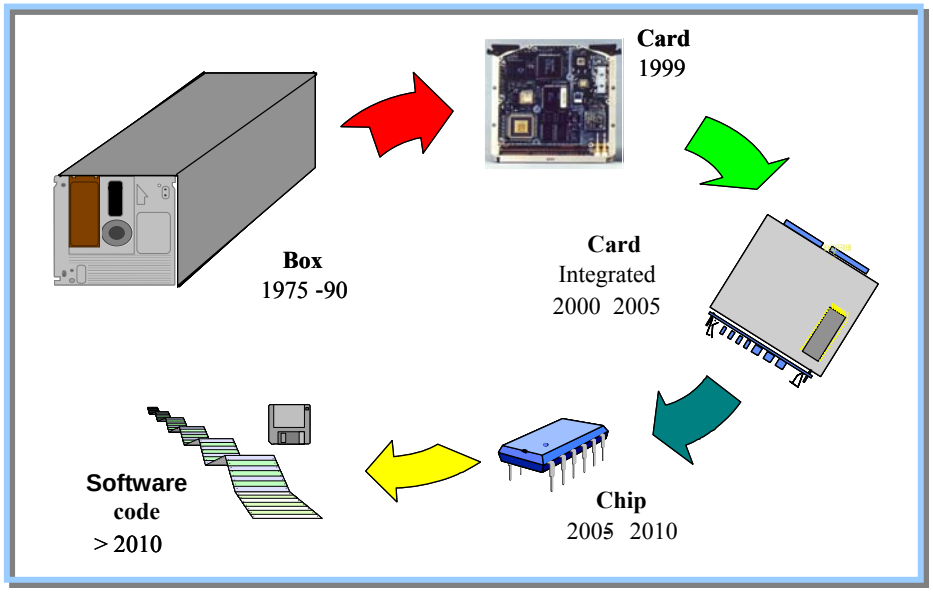


Figure 4.2–2 Development Lines of GNSS Receivers

Some believe that in the future (after 2010), the application of nano-electronics might make even higher integrations possible. The goals of nano-electronics are for flexible and affordable fabrication capabilities of fully integrated, nanometer size, ultra-dense semiconductor circuits. These capabilities may revolutionize integrated microwave, digital and optical processors. In the long-term, GNSS receivers might be part of a multi-sensor/interface digital processor consisting of software code only and receiving its data from the antenna sub-system.

In summary:

- Today, fully digital parallel channel wideband receivers are readily available
- Current integration standard is typically 12 channels (36 correlators) per ASIC
- Multipath mitigation and effective anti-jamming techniques are available
- Currently, the dual chip receiver architecture is dominant with separate RF front-end and digital chips
- Ultimately, low-cost receivers (US ~$3 per chip) will require a single chip design
- Near future: a single chip receiver on a CMOS chip will be available
- Significant efforts to implement RF front-ends in sub-micron CMOS are currently underway
- Strong trend: modular open system architectures, such as GRAM (DoD GPS receiver application module)
- Near future: ultra-fast (1Gbs) analogue-to-digital converters will be available
- Next few years: software radio concept will be realized with GPS-Galileo implications
- Continuing: development of frequency domain processing for fast acquisition

Wireless Assisted Architectures

It makes sense to augment a GNSS receiver in critical operational scenarios with accurate time, spacecraft frequency acquisition information, and other data that a wireless network can provide. The basic problems of urban canyons, inside parking garages and under trees involve satellite signal blockage and multipath interference. This frequently results in very weak signals that are difficult to acquire and track.

Wireless network assistance helps a GNSS receiver in various ways:

1. **Reduction of the size of the search space in frequency and time during acquisition**

   The network's server can predict which satellites are visible in the vicinity of a handset and transmit signals that reduce time and Doppler uncertainty to a level of ± 10 μs and ± 150 Hz; this makes the acquisition search much quicker.

2. **Increase of coherent integration time for correlation**

   If the GNSS navigation data of 50Hz (20 ms bit duration) in the case of GPS were transmitted to the handset out of the network, the handset would be able to wipe off the data bit on the received satellite signal and increase the pre-detection integration time from 20 ms to about one second. This would increase the probability of detection and lower pseudorange noise.

3. **Provision of GNSS navigation data**

   A scenario is possible in which the receiver tracks and provides noisy pseudo-range, but the signal is still too weak to provide navigation data. This problem is resolved by transmitting ephemeris data, collected by the server to the handset. This enables the handset GPS receiver to perform positioning.

4. **Network tracking can assist GNSS tracking**

   When the handset tracks the signals provided by the network in parallel to or instead of GNSS, it is generally able to measure ranges to one or several base stations. This ranging measurement can be used to augment the positioning solution. Remote positioning and autonomous positioning is possible.

Integration of Wireless Handsets and GNSS Receivers

There is commonality of structures in a handset and in GNSS architecture, and of course even more in a CDMA system like UMTS as in GSM. A combined wireless/GNSS receiver uses the following common sub-systems:

- **Local oscillator**
- **RF front-end and antenna**
- **Correlator ASIC and software**
- **Microprocessor hardware and interfaces**

The feasibility of sharing common components of, UMTS and GNSS, for example, has to be carefully analyzed. It is clear that shared use of sub-systems in the front-end is more critical for the digital signal processor and microprocessor. A benefit of close integration would be smaller size and lower power consumption.

More about the Software Radio concept

As outlined above, in most current GPS receivers the RF-signal is down-converted to an intermediate frequency with follow-on A/D conversion. In the software radio, the RF-signal is directly digitized at L-band. This approach has the advantage that pre-processing operations can be applied at a very early state in the receiver. This means that all pre-detection filtering usually done by analog filters can be implemented in digital parts, which allows higher levels of integration at lower cost at chip level.

Having the RF-signal on the digital level will make possible the implementation of adaptive digital filters to suppress interference and jamming. On the other hand, the concept is heavily dependent on the robustness of the implemented software. The current state of development is that ultra-fast (1Gbps) A/DC components are only available in military systems. Current problem areas are the high power consumption of high frequency wideband A/D converters and a very high computational load on the DSPs that must process the digital output of such a device.

Mitigation of Multipath

GNSS multipath mitigation is a key issue in all satellite applications. A variety of techniques at the signal processing level is now available. The most cost-effective approach today is the double-delta and/or strobe correlator, because it obtains P-code multipath performance by using only one additional correlator per channel. With these techniques, the sensitive path delay, i.e. the geometric path delay that can generate multipath, is restricted to 45 m. (See Ref. 4.2–2.)

4.3 Receiver Aiding Requirements for Signal Dynamics and Dropout Conditions

In the absence of GNSS signals, it may not be possible to estimate a vehicle's position without additional sensors. Several sensor options are available, including the use of gyroscopes (gyros), accelerometers, odometers, barometric altimeters, inertial measurement units (IMUs) and velocity sensors. Furthermore, vehicular applications can benefit from sensors already present in the vehicle, such as a steering angle sensor (for the steering column or wheel turning mechanism), a brake sensor, and a throttle (or acceleration) sensor. All of these sensors contribute information that is useful for estimating vehicle motion in the absence of GNSS data. These could be used to bridge the navigation capabilities during GNSS data outages.

The ability of a sensor to assist in the GNSS data outage bridging function depends on the following:

- quality of the sensor itself
- calibration state of the sensor before the outage
- data outage period of the GNSS
- position accuracy desired

For example, using a conventional moderate cost IMU (1deg/hr drift), half-meter accuracy is possible for data outages lasting up to about 20 seconds (assuming the IMU was calibrated using precise [decimeter/centimeter-level] positions prior to the data outage [Ref. 4.3-1]). Such high accuracy positions are not normally attainable. In this situation, other approaches may be required, such as those discussed in Ref. 4.3-2. In that study, position errors of about 20 m (rms) were observed during 100-second data outages using only differential odometry. Using a gyro and odometry, the error was further reduced to approximately 7 m. Integration of multiple sensors will improve results even further.

Fortunately, the cost of dead-reckoning sensors is decreasing as their accuracy improves. Over time sensors that may now be considered of medium or high quality (and cost) will probably become much less expensive, while maintaining the same (or better) level of performance. This bodes well for automobile applications that require low-cost sensors for economic viability.

Although the vehicle's dynamics during GNSS data outages affects positioning accuracy, for most vehicular applications these dynamics are relatively benign. Larger effects also often mask the effect of vehicle dynamics.

4.3.1 Primary and Secondary Sensors

Primary sensors (see Figure 4.3–1) in current and future car navigation systems may consist of one or more of the following:

- **GNSS receiver with differential and integrity data**
  (GPS, GLONASS, Galileo, WAAS, EGNOS, MSAS)
- **2D MEMS or FOG Inertial Measurement Unit (IMU)**
- **Wireless communication unit**
- **Precise digital map**
- **Hybrid positioning data handling system**

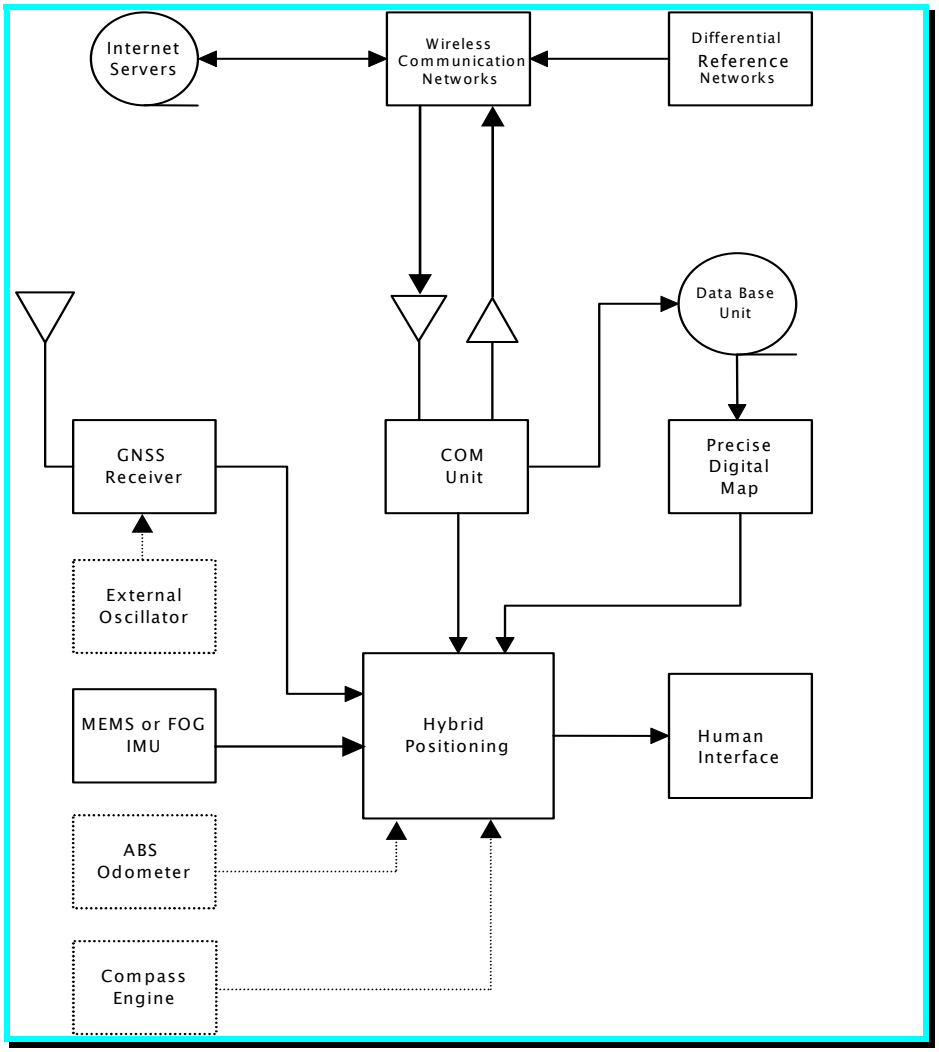


Figure 4.3-1 In-Vehicle Sensors: Primary (solid lines) and Secondary (dashed lines)

Secondary sensors may be used to augment the primary sensors to enhance accuracy, availability, integrity and continuity of the integrated car navigation system. These consist primarily of the following as received by the dotted lines in the figure:

- ABS-based odometer
- Compass engine
- Precise external oscillator

A car navigation system has to operate with various services, such as differential GNSS networks, multiple internet service providers and the capabilities of the wireless communication network.

The role of a sensor in an integrated car navigation system depends on:

- Measurement (location) function and error characteristics (stability)
- Degree of autonomy and precision
- Complementary and dissimilarity (diversity) with respect to other sensors
- Data rate and bandwidth
- State of technology (maturity, potential for high integration, physical parameters)
- Mass production potential
- Acquisition cost
- Need for external infrastructure
- Charges to be paid for external services

Providing a receiver with information on a vehicle's dynamics can substantially improve the receiver's signal tracking capabilities. For normal operational conditions (i.e. open sky, good visibility) these benefits are not significant. The aiding benefit can nevertheless be very significant when a high sensitivity GPS (HSGPS) receiver attempts to track highly attenuated signals. In this situation, the presence of additional sensors to provide information to the GPS receiver tracking loops allows for more accurate measurements with lower power signals. This ultimately improves both position accuracy and position availability.

Since research in this area continues, there are no readily available firm guidelines on the quality of sensors needed and the trade-offs involved. This type of sensor integration will nevertheless certainly play a role is future vehicular GNSS receivers.

4.3.2 Discussion of In-Vehicle Systems on a Systems Level

The following sections discuss system level concerns relevant to the main advantages and disadvantages of the in-vehicle sensors noted above. The discussion will include augmentation features and other sensors that may be useful in a vehicular integration. Table 4.3–1, entitled "Performance and Related Parameters of Integrated Car Navigation Sensors," shows a number of the important parameters in vehicular systems and provides data on their performance characteristics and cost.

4.3.3 Differential GNSS

GNSS sensors, which will probably be used in the differential mode, are expected to be primary sensors in nearly every land vehicle navigation system. Because of their ability to determine position, velocity and time in three dimensions on a worldwide basis with high precision and their excellent long-term error stability, GNSS sensors are very important primary sensors.

GNSS receivers are important sensors for the calibration of inertial and ABS sensors that do not have good long-term error stability characteristics. With the aid of GPS updates, it is possible to determine biases and scale-factor errors in these and other sensors. Optimal or other estimation filters may be used to combine the sensor data in a closed loop arrangement that corrects the sensor output.

Table 4.3–1 Performance and Related Parameters: Integrated Car Navigation Sensors

Sensor	Function	Autonomy	Precision	Error Stability	Data Rate Band-width	State of Technology	Mass Production	Cost (US$*)	External Infra-structure
DGNSS Receiver	3D PVT	No	High (long-term)	High	Low	Mature	Yes	50 (WAAS) 130 (+NDGPS)	Differential networks
MEMS IMU	2D PVA	Yes	Low (ultra short term)	Low	Very high	Development	Yes	8000	None
FOG IMU	2D PVA	Yes	Low (short term)	Low	Very high	Mature/ Development	I-FOG No R-FOG Yes	10000	None
Digital Map	1D P Condition	Yes	Medium/ high	Medium	Very low	To be improved	Yes No	100 stand-alone 150 updateable	No Yes; update concern
ABS	1D V	Yes	Medium	Medium	High	Mature	Yes	40	No
Compass Engine	1D A	Yes	Low	Medium	Medium	Mature	No	40	No
External Oscillator	1D T	Yes	High	Medium /high	High	Low-Cost TBD	Yes	500	No
Communi-cation (Wireless Assisted)	1D T & F	No	Medium	Medium	High	GSM mature UMTS TBD	Yes	70	Yes

P:Position, V:Velocity, A:Attitude, T:Time, F:Frequency, TBD:To be determined
*Estimated unit price for purchase of 1000 units

Additionally, a GNSS sensor provides excellent performance to cost characteristics. Even if the differential mode is not available or used, the GNSS receiver can generate good position solutions, although at a somewhat lower accuracy.

Because the GNSS receiver is not autonomous, there are several limitations. GNSS reception and performance in urban areas and under foliage can be degraded due to satellite visibility limitations. At least four satellites in good geometry are necessary to solve for the *four* unknowns of latitude (x), longitude (y), altitude (z) and receiver time (T) involved in the 3D positioning problem. In conditions of limited visibility, the usual 6-11 GPS spacecraft (S/C) in view may decrease to four or less. When three S/C are in view, horizontal coordinates and time (x, y and T)

can often be obtained using only three satellite observations and an assumed value for the altitude. Similarly, the three dimensions of position can be obtained with an estimate provided for the receiver time.

4.3.4 Integrity and Redundancy

In this context, one has to understand that the minimum requirement of four (or three) satellites for 3d (2d) positioning does not give any measure of integrity. *For integrity, higher redundancy is necessary:* Five satellites in good geometry are necessary to detect a malfunction within one satellite, while six satellites in good geometry are required to isolate or identify one malfunctioning satellite. Detection and identification of more malfunctioning satellites requires substantially higher redundancy.

Integrity concerns, indicating a malfunction or hazardous and misleading information (HMI), can involve elements in the space, user and control segments, as well as such local effects as multipath interference. Multipath has been identified as the main error source in urban land applications.

The implementation of Galileo with its 30 additional S/C may be very important for redundancy. Substantial improvements in both positioning and integrity performance are expected from the availability of approximately twice the number of satellites (from GPS and Galileo together), and the optimization of the Galileo constellation for high elevation angles. This should make excellent satellite signal availability and integrity feasible as well as good positioning in urban areas.

The large constellation both reduces the need for user map matching and places lower requirements on the performance of any INS aiding. The INS or the map matching would then be needed primarily for short-term navigation as, for example, in tunnels, on bridges, and in the very unlikely event of a GNSS outage.

Future instantaneous carrier phase accuracy in the centimeter range will make both very high accuracy and high integrity possible. The three estimated time periods for developing this capability are: a) from 2010 onward for a combined Galileo and GPS; b) in 2013-2015, when the civil C-code on L2 becomes fully available, for GPS alone; and c) in about 2016-2020 for the full set of spacecraft and codes at the new civil L5 frequency.

4.3.5 MEMS or FOG Inertial Measurement Units (IMU)

Although inertial measurement units (IMUs) in the general car navigation field are currently not practical because of low performance to cost relationships, future low-end systems could become candidates for integrated vehicular systems. Current and predictable technical developments in the field of MEMS technology and highly integrated FOGs (R-FOGs) and their potential for mass production indicate that costs for these IMUs will come down significantly during the next years.

A strong argument for using an IMU is its autonomy, i.e. its ability to determine position without any external sources. With such a sensor, integrity concepts can be easily implemented by making use of sensor redundancy and built-in-test-devices. In comparison to GNSS, inertial navigation systems show dissimilar error characteristics. While IMUs have good short term-error stability, gyros and accelerometers are typically biased and have additional scale factor concerns.

In order to decrease the cost of the entire system, one could consider reducing the number of sensor axes to that required for horizontal (latitude-longitude) navigation. The minimal configuration of a strap-down IMU could consist of a heading gyro and two horizontal

accelerometers. Since such a system is not Schuler tuned,* the situation with respect to error propagation is very unfavorable.

Making use of the Schuler principle would imply implementing an additional two gyros for roll and pitch. This leads to the excellent short-term stability of Schuler tuning, achieved by keeping navigational axes perpendicular to gravity. In any case, no vertical accelerometer would be necessary, because height information is available from other sources.

The most critical error component in inertial positioning is the gyro bias drift since it induces position error growth linearly with time. Accelerometer bias also shows a time behavior but the error growth is bounded by periodic functions of Schuler frequency (f_S = 1/84.4min.). The drift class above 100/hr may characterize the current state-of-the art of MEMS gyro technology. Although the reduction of drift by an order of magnitude is expected in 5 to 10 years, it is doubtful that this "high-performance" MEMS gyro will be low-cost. FOG gyro technology (I-FOG) is in the drift range of 0.05°/hr to 1°/hr because of advanced physical principles (interferometry versus elasticity) and higher maturity. Of course, a gyro performance compatible accelerometer has to be provided.

Figure 4.3-2 shows the free inertial drift on a position basis for three classes of IMUs. The accelerometer error is not considered. It is clear that a free 10°/hr IMU can be used for short time intervals (20 seconds) to bridge a gap if GNSS is not available.

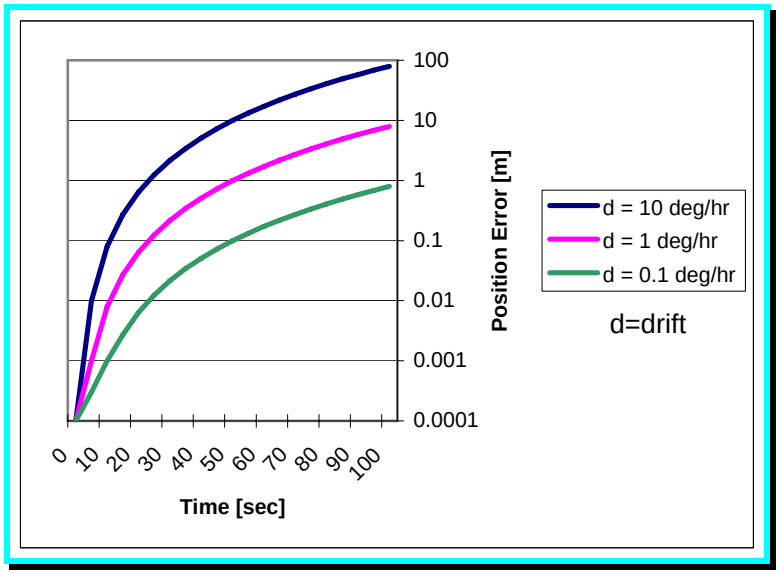


Figure 4.3–2 Free Inertial Drift of Three IMU Classes (Schuler tuned, gyro only)

In the case of a 0.1°/hr IMU, longer stand-alone performance (100 sec) is obtained. This has the advantage that the availability and continuity requirements on the GNSS sensor are not as stringent. The acquisition cost for 0.1°/hr grade IMUs will be considerably higher than for a 10°/hr version. Keeping the IMU performance at the low-end assumes that an advanced satellite navigation system, e.g. a combined GPS/Galileo/(GLONASS) system, is available.

* With Schuler tuning inertial components are adjusted to the local level (of a curved earth-surface) in such a way that they will not react on horizontal accelerations (not start to oscillate).

Another important technique for reducing the build-up of position errors of the IMU is odometer aiding.

In navigation technology, a number of developments now in place deal with methods for coupling GNSS and INS. The "deepness" of the integration between the inertial and GNSS sensors has a number of pro's and con's. Depending on the degree of integration desired, in theory ***four different coupling architectures*** are possible.

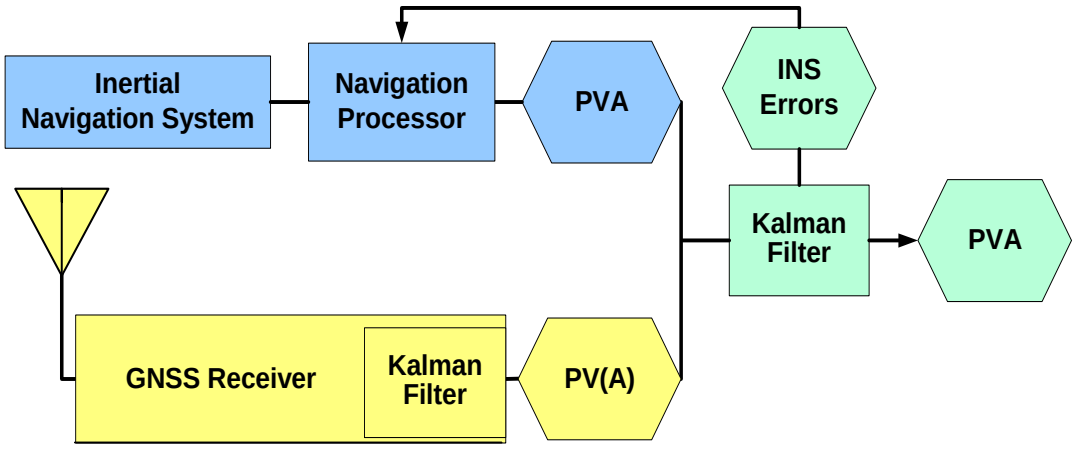


Figure 4.3-3 Loose Coupling of GNSS and INS

Loose coupling (Position aiding)—see Figure 4.3–3**.**

Loose coupling means that the IMU and the GNSS sensor are running independently and in parallel, with no significant feedback implementation. Each sub-system generates a single PVA (Position/Velocity/Attitude) solution. Fusion of the two data sources is on a position level with a final centralized Kalman filter. The advantages are good independence of GNSS and INS, leading to high integrity. The disadvantage is that the inertial data is not used to augment the GNSS function during acquisition.

Close coupling (Raw data aiding)

Close coupling is similar to loose coupling. The main difference is that no PV(A) solution is performed for the GNSS, but the centralized Kalman filter is updated with GNSS raw data, i.e. pseudoranges, Doppler and/or carrier phase data. The disadvantage is a slight loss of independence (GNSS is not generating independent PV(A)). An advantage is that it does not always require four satellites to update the Kalman filter.

Tight coupling (Tracking loop aiding)

In the tightly coupled implementation, a single centralized PVA computation with a Kalman filter is implemented and then updated by GNSS raw data. The main difference compared to loose coupling is that filtered PVA data is fed-back to the GNSS receiver. This data is provided to the Phase and Delay Lock Loops of the

signal processor. The goal is to enhance the dynamic performance of the receiver and shorten the acquisition and/or re-acquisition process.

Deep or ultra-tight coupling (GNSS signal aiding)—see Figure 4.3–4

The deepest coupling is possible in the ultra-tight coupling approach. To arrive at a very robust system, the coupling and Kalman filtering in this approach are done inside each tracking loop of the receiver. The transformed inertial data drives the tracking loops even when the GNSS signal cannot be received. There is thus no major independence of the PV(A) level present between the inertial and GNSS sensors. The advantage of this approach is a set of very stable tracking loops. The disadvantage is a large implementation and processing load in the receiver, since 24 Kalman filters must be driven in parallel for a 12-channel GNSS receiver (1 DLL & 1 PLL per channel).

4.4 Weak Signal and GNSS Enhanced Reception Aiding Techniques

4.4.1 Weak Signal Overview

GPS receivers are able to provide position estimates using a signal that is specified to be approximately 40 times weaker than the ambient noise. GPS receivers work by accumulating the incoming signal energy so that over a brief period of time the signal level becomes greater than the noise level. This accumulation is limited in duration, typically to 20 ms or less, because of the inherent GPS signal structure.

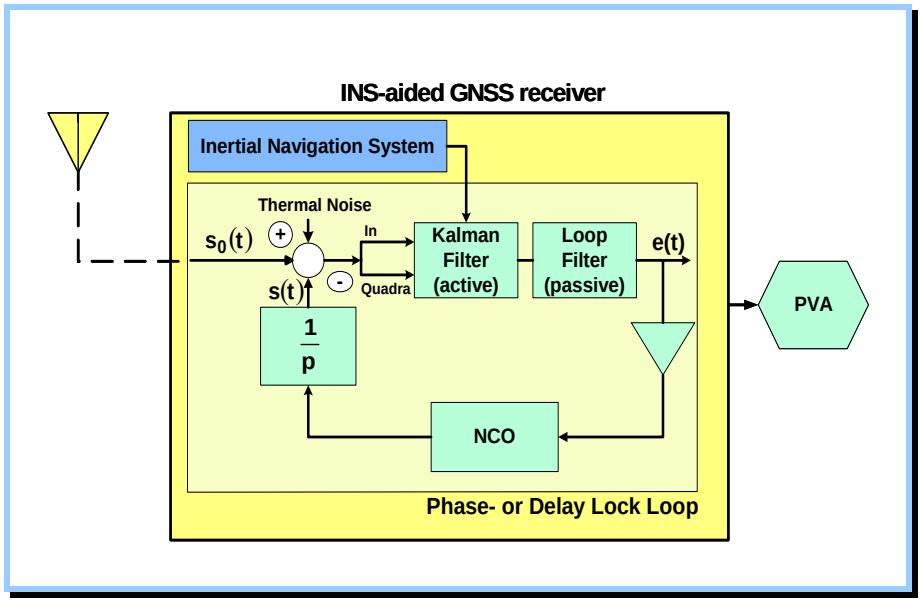


Figure 4.4-1 Deep or Ultra-Tight Coupling Between GNSS and INS

Table 4.4–1 Use of a MEMS or FOG IMU in an Integrated Car Navigation System

Use of a MEMS or FOG IMU in an Integrated Car Navigation System:
• **IMU offers autonomous determination of position, velocity and attitude vectors** • **IMU provides robustness, integrity, availability and continuity for the system** • **Error stability is only short term, because of gyro drift** • **With 10o/h IMU only 20 sec of GNSS signal loss can be bridged for 1 m accuracy** • **Currently, MEMS and FOG IMU´s are too expensive for car navigation** • **MEMS technology has the highest potential for low-cost mass production** • **Highly integrated Resonant Fiber Optic Gyro technology (R-FOG) needs analysis** • **IMU operation should be Schuler tuned** • **Loose, close, tight and deep coupling principles of GNSS/ INS are feasible** • **GNSS offers the possibility for determining bias and scale factor errors of IMUs** • **The good quality of GNSS data allows the use of low-end IMUs** • **Odometer aiding of IMU could be helpful**

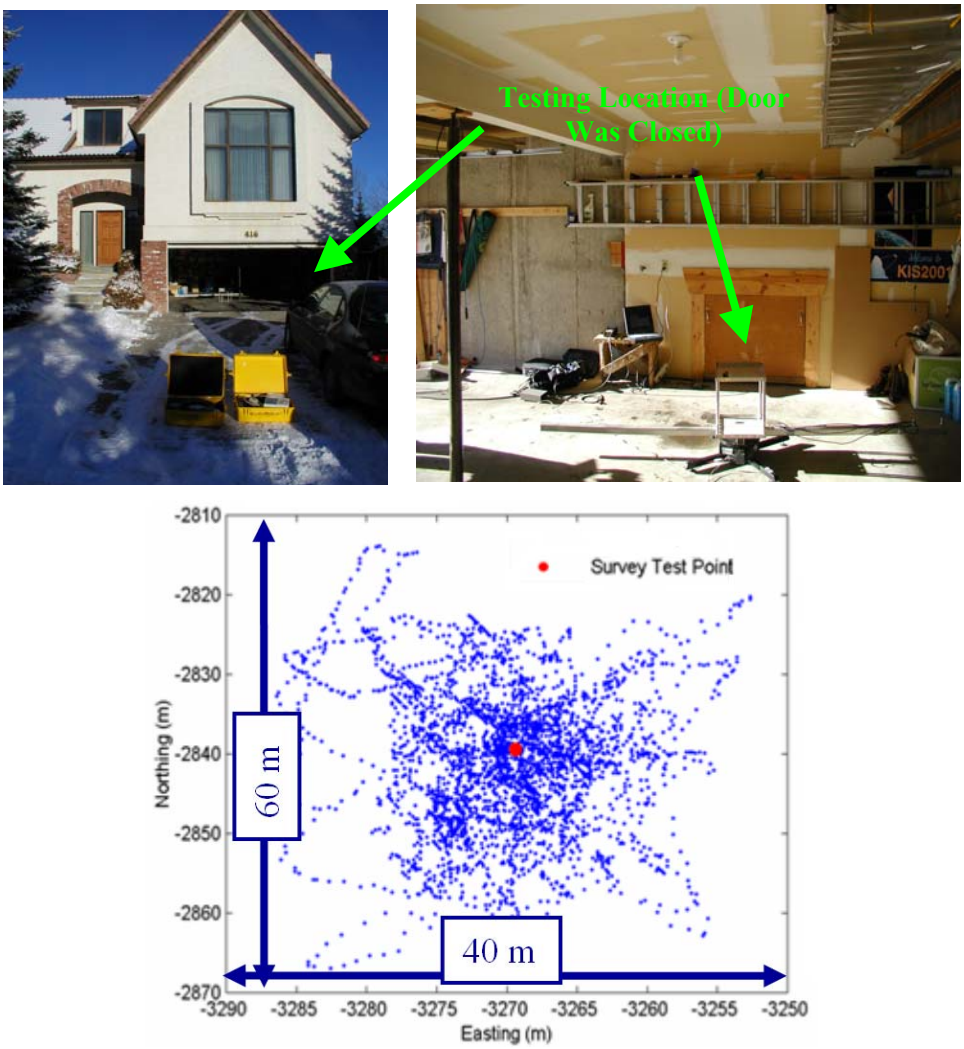
The fact that the GPS signals are so weak leads to the requirement that line of sight visibility to the satellites normally needs to be maintained. Failure to do this means that the signals received at the antenna are even weaker, and cannot be tracked reliably, if at all. This, in turn, can lead to a loss of lock. Since carrier phase measurements provide the highest attainable positioning accuracy, lost cycles (i.e. a cycle slip) require additional processing to estimate how many cycles were lost. Until this estimation process becomes reliable, the resulting position accuracy will suffer, as compared to the situation where no cycle slip occurs.

In case of a complete loss of lock on a satellite signal, no observations are available for that particular satellite and positioning accuracy will degrade. If signals from several satellites simultaneously lose lock, the problem is further compounded; in the worst-case scenario, a position estimate is unavailable.

4.4.2 High Sensitivity GPS

Convenient GPS receivers are of little use in operational environments in which only very weak signals reach the antenna. Examples of such environments include forested areas found in many suburban neighborhoods, urban areas with tall buildings, or covered parking garages. In light of these limitations, there has been a recent push towards the use of high sensitivity (HS) GPS receivers. HSGPS receivers' basic concept, originally formulated to meet FCC Figure 4.4–2 HSGPS Indoor Testing Environment and Position Results

requirements for cell phones making emergency 911 calls, is that by using special signal processing techniques inside a receiver, the "accumulation" of the signal can be performed over time intervals that far exceed the traditional 20 ms. This accumulation allows the tracking of signals that are up to 100 times more attenuated than "normal" signals.



The ultimate benefit of HSGPS receivers is an increase in the availability of position estimates. Current HSGPS receivers have been shown to yield near 100% availability in urban environments [Ref. 4.3-1]. Unfortunately, current receivers cannot reliably track the incoming carrier phase, with the result that centimeter level accuracy is not available from these receivers. In fact, HSGPS position uncertainties can be on the order of several tens of meters even under relative benign weak signal conditions. Figure 4.4–1, for example, shows the estimated position from a HSGPS receiver located inside the garage of a wood frame home (also shown). Although the accuracy is bounded by about 60 m, the position availability is near 100%.

Despite this relatively poor accuracy (compared to traditional GPS), the increased position availability is nevertheless beneficial for vehicular applications. For example, even low accuracy position information can be used to aid additional onboard sensors. Ref 4.4-2, for example, describes how a single low-cost gyro, when integrated with HSGPS, provided reasonable position accuracy in an urban canyon environment. The integration of further sensors such as inertial measurement units (IMUs), odometers and/or speed sensors should provide further benefits.

It is worth noting that HSGPS receivers are typically available in high volume and at low cost, with chip sets costing no more than a few tens of dollars at most. Such HSGPS receivers are well suited to vehicular applications, since they contribute only marginally to the overall vehicle cost.

In today's market, upwards of six manufacturers make HSGPS chipsets. This competition should drive the market forward.

4.4.3 Assisted GPS

Although HSGPS receivers have proved to be extremely useful, their signal processing techniques require that several pieces of information be available. These include the receiver's approximate position, the current time, and specific information regarding the GPS signal currently being received. Without this information, the receiver may have to spend considerable time searching for a signal. In some cases, it may take as long as several minutes for the receiver to provide a position estimate.

From the above discussion, it follows that the HSGPS signal tracking could be facilitated if the receiver got the necessary information from an external source. This is the concept behind assisted GPS (AGPS or AHSGPS). Specifically, when assisted GPS provides the receiver with additional information, the receiver can perform its tasks more efficiently and provide more accurate position information in a timelier manner. The resulting system is also often more power-efficient, since less processor power is required. The concept of AGPS is diagramed in Figure 4.4–3, which shows how a server forwards aiding information to the receiver via broadcast stations.

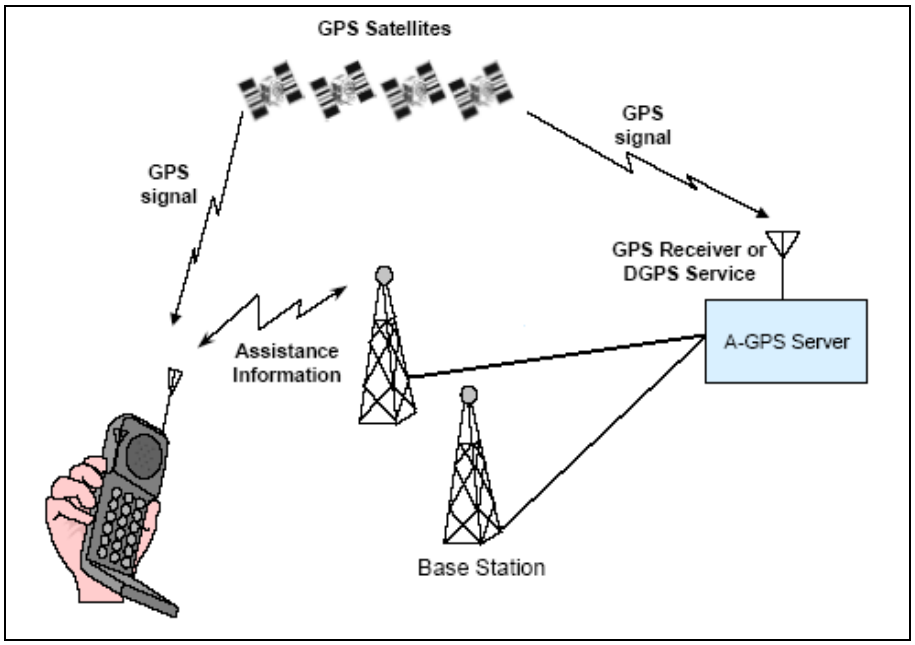


Figure 4.4–3 Assisted GPS Concept

To date, several standards have been developed, primarily by cellular telephone manufacturers. These include standards for: GSM UMTS/IMT; US-TDMA; AMPS; and US-CDMA [all four, Ref. 4.4-3]. The wide range of available standards suggests that integrating AGPS technologies into future vehicles should be feasible. Cellular networks, which can often provide some form of positioning capabilities, provide a natural means of integrating various data sources.

Finally, despite all these benefits of HSGPS and AGPS, their ability to provide reliable position information is still somewhat limited. In particular, since the signals being tracked are so weak, the likelihood of having blundered observations (very poor signal to noise or C/N_0) for the signal resulting in a loss of lock) increases. Unfortunately, traditional methods for identifying and removing blundered observations do not apply if multiple measurements are blundered simultaneously. Consequently, to develop new blunder identification algorithms for the HSGPS environment will require additional research. While some of this work has already been done [Ref. 4.4-4], the efficiency of these algorithms remains a major issue that needs to be addressed.

4.5 Enhanced Digital Maps (EDMaps) and Map Matching Techniques

4.5.1 Map Matching

Map matching was considered a non-primary positioning or positioning aiding technology for EDMap type applications in CAMP 8A. Although this assumption may hold true for map matching techniques as they exist today, map matching applications are limited only by two other factors addressed by EDMap, namely:

1. Vehicle positioning accuracy
2. Accuracy of the digital maps

Both of these capabilities can be developed to a centimeter-level accuracy during the EDMap development. Therefore future map matching techniques will be implemented for mapping onto street lane level rather than the street level mapping existent today. In addition, map matching or similar techniques are needed for assisting in-vehicle positioning system to handle special cases of vehicle navigation such as:

- Vehicle maneuvering including lane changing and passing. It is not likely to have predefined tracks for such maneuvers and therefore vehicle will be transferring from one lane to another
- Similar conditions exists during merge and exist maneuvers in highways and maneuvering in intersections in arterial streets

As EDMap conceptually includes achieving vehicle positioning accuracy down to the individual lane level (or assigning them to individual lanes) and maintaining such accuracy throughout, maintaining such vehicle to lane reference would require transferring vehicle position from lane to lane either within the same street or between streets (i.e. intersection turns). This would require vehicle position transition algorithms for digital maps where map-matching techniques are considered to be the most likely candidate.

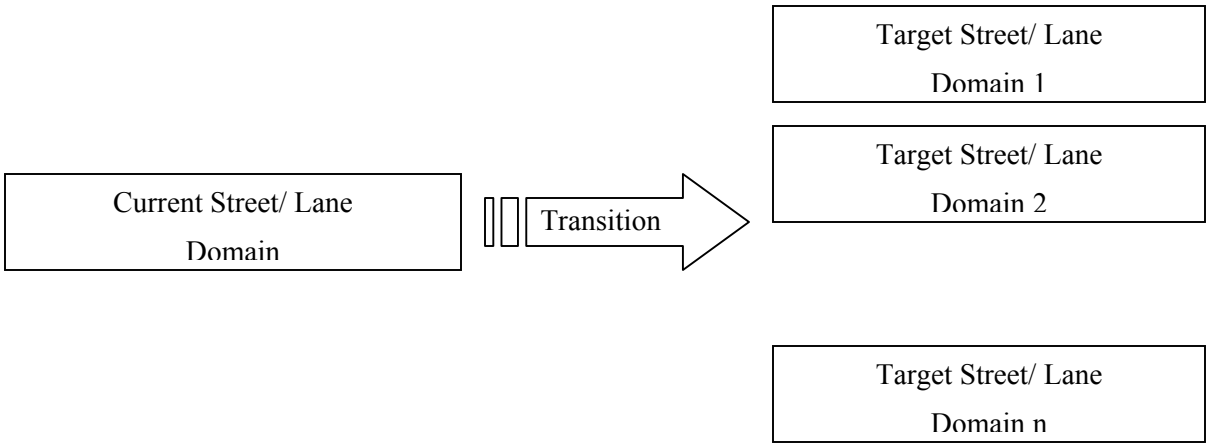


Figure 4.5-1 Maintaining Vehicle Position Street/Lane Reference with EDMap Communication Systems

4.5.2 In-vehicle Communication for EDMap Systems

In-vehicle communication systems are very much likely to be a hybrid system with many technologies for specialized applications. Most of these technologies are discussed more comprehensively and in detail in Chapter 5. Some aspects of the concept are graphically illustrated in Figure 4.5-2.

Real-Time Traffic Monitoring and Driver Information Systems

The objective of providing better, faster and accurate in-vehicle services through EDMap application development will not be fully achieved without providing real-time traffic information and driver assistance information to in-vehicle clients. These information needs, in turn, are dependent on gathering accurate real-time information on traffic activities and short-term traffic prediction. EDMap enabled vehicles are expected to act as a part of traffic monitoring system and as a part of the vehicle-infrastructure system. This concept is illustrated in Figure 4.5-3.

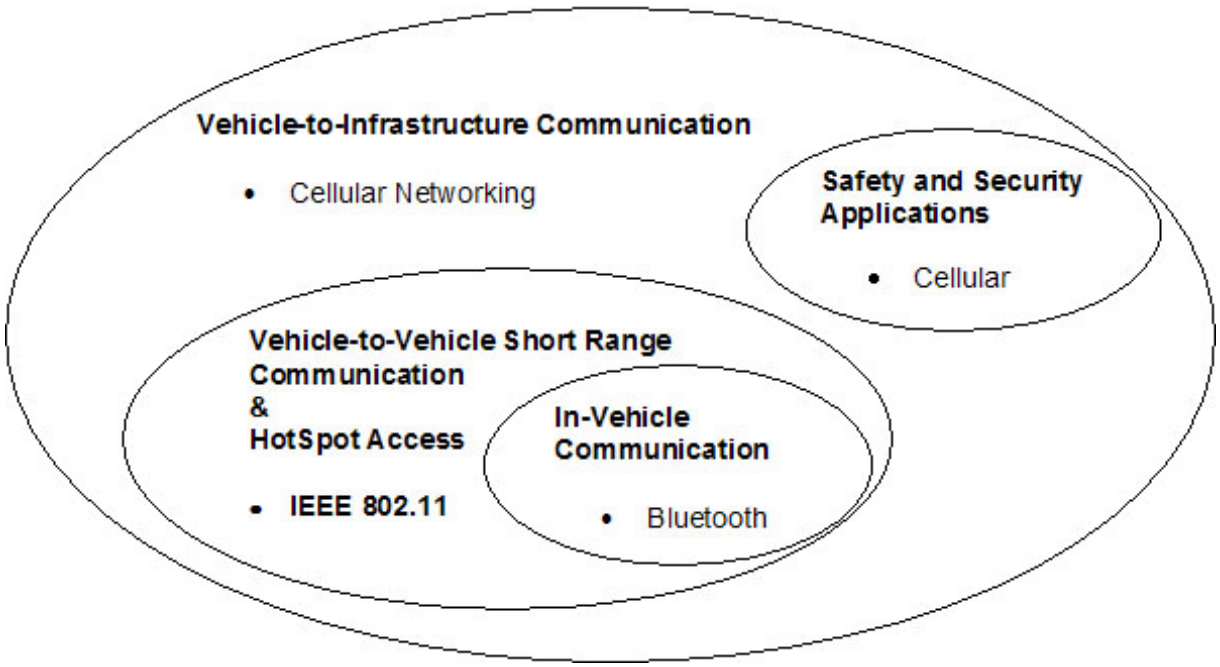


Figure 4.5-2 In-Vehicle Hybrid Communication Systems

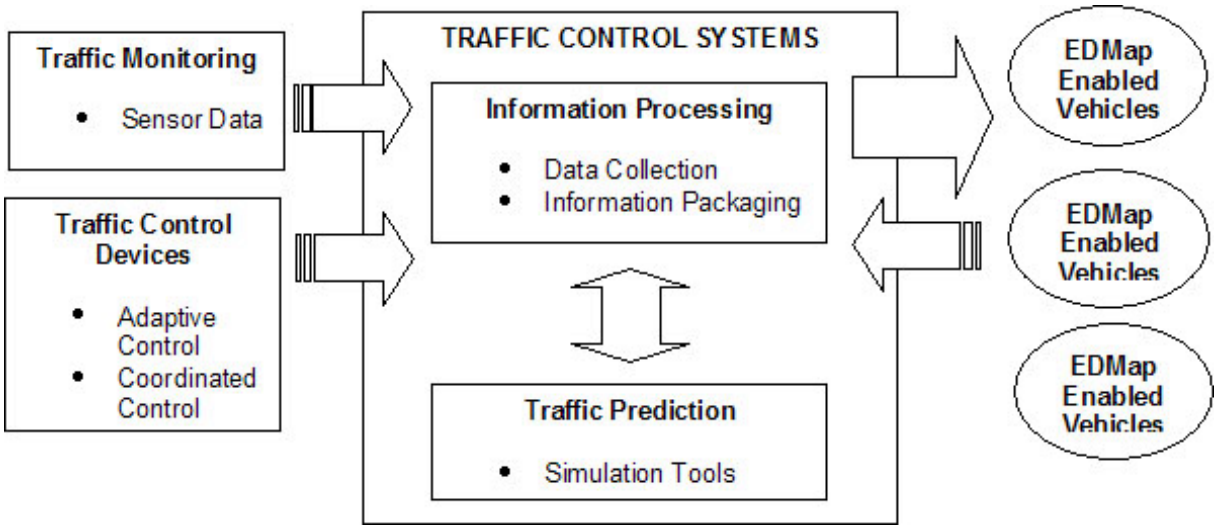


Figure 4.5-3 EDMap Applications in Vehicle and Highway Infrastructure Systems

Time Standards for Traffic Controlling Systems

Traffic controlling systems use time references to change control measures with time of day and coordinate closely located traffic signal, etc. The use of GPS time as the time standard for traffic control systems is expected to be a realistic future possibility following the trend set by commercial banking networks in adopting GPS time standard to maintain their networks. With a vast majority of transportation infrastructure management authorities using GPS for asset tracking, this transition is expected in the near future. Some of the issues on transportation infrastructure reliance on GPS are addressed in Carroll et al (2001).

Collaborative Driving System (CDS)

Considerable research work is being done on extending vehicle cruise control functions on to partial or full automation of driving task by vehicle platoon control concept. Although convincing driver population to accept automation may not be very promising at present, most of the technology exists for automating a vehicle to follow a leader vehicle [Auto21 (2003), Cannon et al (2003) and Kato et al (2002)]. A conceptual CDS is illustrated in Figure 3.5-4.

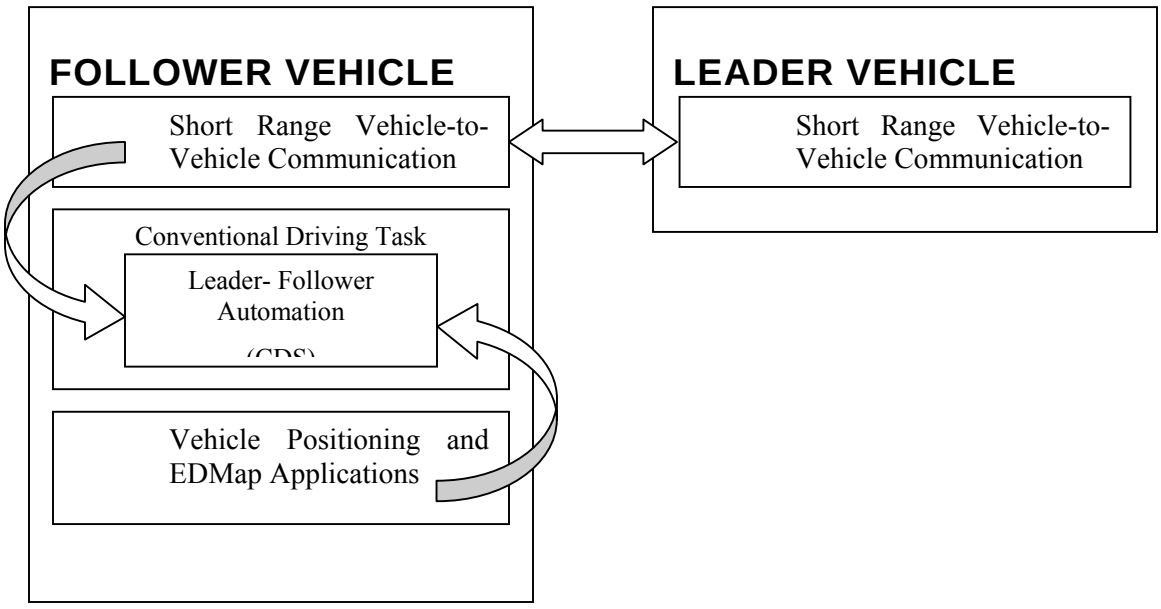


Figure 4.5-4: Collaborative Driving Systems (CDS)

4.6 Infrastructure and Related Technology Developments

This section expands on some aspects of this topic covered in Chapter 2, with more emphasis on expected future infrastructure needs and developments. The following discussion of both external and in-vehicle infrastructure developments is organized according to their importance in providing telematics services.

1. Driver-Telematics Services Interface
2. In-Vehicle Telematics System Architecture and Expandability Issues
3. Communication for Telematics Services
4. In-Vehicle Positioning Systems
5. Content Providers
6. Additional Services

4.6.1 Driver-Telematics Services Interface

Minimizing driver distraction while at the same time providing the full spectrum of telematics services presents a continuing challenge. The telematics that provide in-vehicle security and safety must not be a significant burden on driver concentration. Incorporating voice command capability for in-vehicle telematics infrastructure is the best way to maintain safe driving standards while providing telematics services. The following major developments are expected:

- Improved in-vehicle noise suppression systems
- Advanced speech recognition technology

4.6.2 In-Vehicle Telematics System Architecture and Expandability Issues

Although there is a widely held view that vehicle telematics will soon boom in the automobile industry, its growth has been surprisingly slow in recent years. Since future developments will probably focus on eliminating the causes for slow growth, this report first outlines reasons that are likely to contribute to lower consumer demand for vehicle telematics.

- Almost all the telematics services currently available are highly specific to automobile manufacturers and are almost impossible to upgrade
- While the life cycle for automobile hardware (from concept to end of use) is estimated to be over fifteen years, the life cycle for in-vehicle consumer electronics is much less, typically about two to five years.

These two factors make it extremely difficult, if not impossible, to stay with a single in-vehicle telematics service infrastructure throughout the life cycle of an automobile. For instance, the leader in the vehicle telematics market, ***OnStar***, which was originally designed for analogue cellular communication, must now find ways to incorporate and use the more prevalent digital cellular technology.

There are high expectations for the introduction of modular and expandable in-vehicle telematics infrastructure changes, along with the development of interface standards for such architectures. Rather than restricting the user to a hardwired in-vehicle infrastructure, future systems may serve as platforms for aftermarket products that can be installed, upgraded or uninstalled depending on the user's needs and technology developments. (For more information on current interface development collaborations, see Ref. 4.6–1).

The current consensus in the automotive industry expects that the future in-vehicle telematics infrastructure will have two domains: an auto manufacturer's domain where vehicle hardware is manufacturer-specific and a telematics service domain where all telematics services will operate. Most importantly, to provide the link between the two main domains, this infrastructure will also have a vehicle service interface. This architecture is illustrated in Figure 4.6–1.

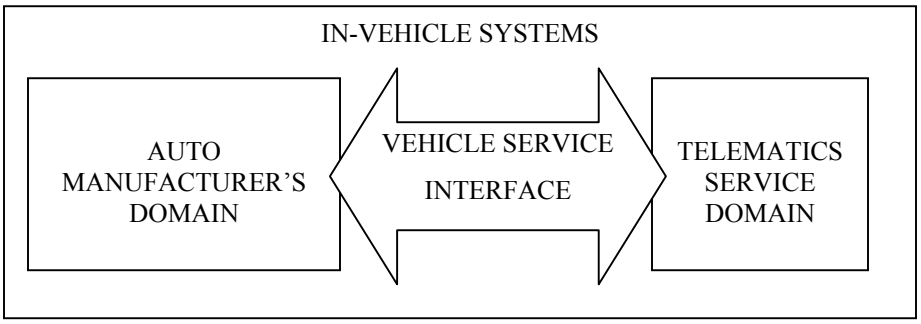


Figure 4.6–1 In-vehicle Telematics Architecture

4.6.3 Communication for Telematics Services

Most cost and coverage issues concerning telematics service lie within the cellular carrier sector, which is currently the dominant communication media for in-vehicle services. These issues, which range from higher service rates to inadequate cellular coverage and quality, are but a subset of the issues that the much larger telecommunication industry faces. The growth of telematics services will therefore largely depend on the future expansion of cellular networks' coverage, quality and rates. More specifically, the following are the most prominent issues that concern the telematics industry:

Wider Coverage and Quality of Service: Telematics services, especially its safety and security features, are always important, regardless of the vehicle's location. Since these services are directly linked with communication system coverage, they are entirely dependent upon the extent and quality of their cellular carrier's coverage.

Compatibility across Boundaries: Service boundaries relate to discontinuities between digital and analogue cellular service providers as well as to those between differing cellular operating systems (FDMA, CDMA, etc.). In-vehicle telematics services should be able to operate in a seamless manner over these boundaries.

In-vehicle Instrumentation Trends: In addition to communicating with service providers, in-vehicle telematics communications have several other important requirements. These include vehicle-to-vehicle short-range communication, faster data downloading in designated zones, and other capabilities. It may not be efficient to rely on cellular networks for all these service categories.

The rapidly changing state of technology makes an accurate prediction of communication technology and infrastructure developments over the next several years a highly subjective exercise. In-vehicle telematics services are nevertheless expected to develop alternative means to minimize their dependence on cellular carriers. Several trends are expected to have wider application in the future:

- In-vehicle Instrumentation: A modular architecture that can be upgraded as necessary will enable a vehicle's system to dock mobile devices or even multiple modes of communication. An in-vehicle Telematics Control Unit (TCU) will coordinate other telematics devices' functions with the communication device. This will enable the vehicle telematics unit to communicate through alternative modes whenever they are available (e.g. larger data downloads in predefined zones with active local communication links).

- In-vehicle Communication: Communication between devices onboard the vehicle through Bluetooth or such short range communication techniques

- Vehicle-to-Vehicle Communication: Within the next 10 to 15 years concepts such as Collaborative Driving are expected to be implemented as an extension of collision avoidance systems and cruise control. These communication requirements may be met by using locally active communication links to minimize the burden on cellular carriers. A likely candidate technology is IEEE 802.11, which has a local coverage distance from 150 meters to a kilometer, depending on the equipment used.

- Info-Fueling: This concept anticipates information hotspots where client vehicles can download large amounts of data (e.g. data files for applications) by using local, short range wireless communication links

4.6.4 Update on Wireless Technology Development Since Task 8A Report

This section and the following Section 4.6.5 both follow closely the recent review of communications-related portions of the January 2002 EDMap Task 8A Report, prepared by Thomas Schaffnit of Schaffnit Consulting, Inc. It provides an updated view of relevant communication technological developments since the Task 8A Report. This section also presents an analysis of whether or not previous assumptions and expectations regarding the relevant communications technologies have changed significantly, and when they have, the ways they have changed are described [Ref. 4.6-2].

Since the Task 8A Report was prepared, wireless technology development has proceeded rapidly in some areas and less rapidly in others. The first part of the current report provides an update of developments in the various wireless technology areas, and describes how this might change the outlook for that particular technology area from that described in the Task 8A Report.

PCS 2.5-3G and Digital Cellular

The situation regarding 2.5-3G PCS and digital cellular developments remains very close to the discussions in the Task 8A Report, which predicted, "2.5G cellular systems will be widely deployed in virtually all major metropolitan centers and surrounding areas." This rollout of data capabilities using 2.5G technologies has proceeded very quickly, as GPRS and 1xRTT data

capabilities are rapidly deployed in the major metropolitan areas. This is accelerating the demise of older CDPD data networks, as many providers plan to shut down CDPD within the next year.

The rapid deployment of the 2.5G data services may actually delay the deployment of such further data enhancements as EDGE for GPRS and 1xEVDO for 1xRTT. The main capability gained by using these enhanced technologies is performance at a greater data rate. So far, the market for data on cellular networks remains soft. The EDGE and 1xEVDO technologies require fairly significant network investments, raising end-users' costs for these enhanced services. Although the enhanced technologies are being put through trials in several major metropolitan centers, most end-users' current assessment is that the extra speed is not really worth the extra cost.

Besides these possible delays to further 2.5G data service enhancements, the existing GPRS and 1xRTT solutions may also delay the eventual movement to 3G cellular network technologies. Unless there is a rapid and extensive expansion in demand for cellular data services, the business case for moving to 3G technologies will not be evident for some time.

Bluetooth

The Bluetooth discussions in the Task 8A Report remain essentially valid. The adoption of the technology is proceeding much more slowly than previously expected. The predicted "widespread adoption of Bluetooth" in the five-year time frame is now more likely to happen several years later than predicted. The "target" price point of less than $5 for the Bluetooth wireless modem has recently been achieved, with the complete incremental bill for materials (not including antennas) now possible at around $4.

Although deployment thus far has not been as widely based as previously expected, handset manufacturers are currently rolling out Bluetooth-equipped units on phone models with large-scale sales. Mobile computers (PDAs, tablets and laptops) are more likely to be equipped with Bluetooth capabilities, or to offer Bluetooth options. Bluetooth cable replacement applications, such as access point print server and PDA-to-cell phone synchronization, remain as the primary strength and anticipated growth path for the Bluetooth technology.

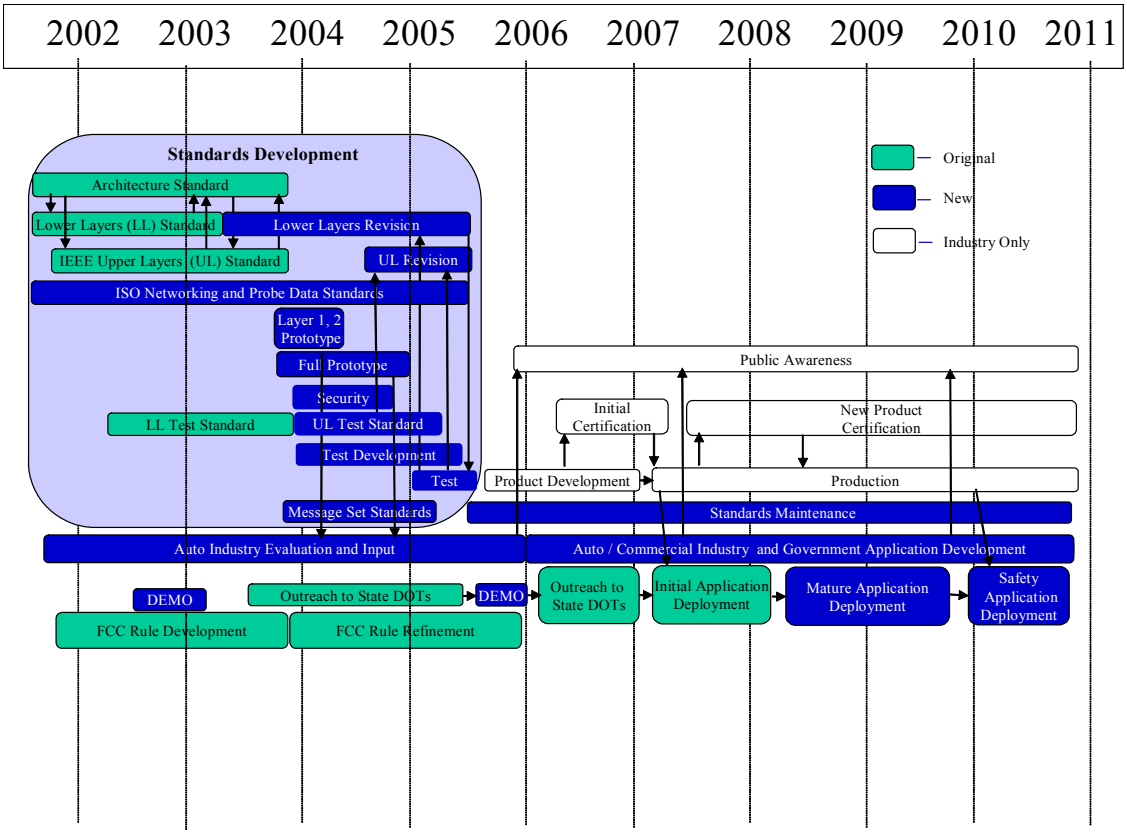
Dedicated (Digital) Short Range Communications (DSRC)

Much progress has been made in the area of DSRC since the Task 8A Report was completed in early 2002. The ASTM standards group completed the lower layer DSRC standard (ASTM 2213-03) in 2003. In February 2004 the FCC published a Report and Order establishing the rules for the use of the 5.9 GHz DSRC spectrum in the United States, which mandate the use of ASTM 2213-03 for operations on this band. The FCC Report and Order also highlights the importance of safety/public safety applications and establishes the priority for these applications in the 5.9 GHz DSCR spectrum.

Automobile manufacturers have actively participated in the DSRC standards development process through the Vehicle Safety Communications (VSC) project. The VSC project is a two-year program, which will both evaluate vehicle safety applications and associated communication requirements and promote their accommodation in developing communications standards. Seven automotive manufacturers: BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and VW, formed the Vehicle Safety Communications Consortium (VSCC) to participate in this Department of Transportation cooperative project.

The IEEE P1609 upper layer WAVE/DSRC and P1556 WAVE/DSRC security standards are now under active development. The current DSRC Standards Writing Group schedule for DSRC is shown in Figure 4.6–2. The initial P1609 standards are expected to be completed by mid-2005,

allowing for expected revisions as a result of validation and testing. The P1556 DSRC security standard should be completed by the second quarter of 2004, and its validation and testing completed by the end of 2004. The SAE standards process is expected to develop Vehicle safety message set specifications during 2004. Validation and testing of the vehicle safety message set should be completed during the first half of 2005.



Source: DSRC Standards Writing Group - January 2004

Figure 4.6–2 GHz DSRC Deployment Schedule

This schedule, which reflects the January 2004 consensus of the DSRC Standards Writing Group, predicts initial application deployments in 2007 and safety application deployment in 2010.

Digital Television (DTV)

Deployment of DTV is progressing in the United States. The previous "hard cut-off" date of 2006 has now been softened. A new provision permits a delay in the deadline for the total transition to digital in a market area where less than 85% of households are equipped with DTV receivers. This delay is the result of lobbying by the broadcasters as well as the recognition that DTV receivers might not be deployed quickly enough to allow analog television to be shut down in 2006.

The technology used in the United States remains the same as that described in the Task 8A Report, that is, 8-Level Vestigial Side-band (8-VSB) modulation. This technology is not well suited for mobile reception, so the potential usefulness of DTV for automotive applications in the United States remains doubtful, as described in the Task 8A Report.

High Altitude Platforms

While progress continues to be made on the electronic components and potential airship designs, there has been no major progress in High Altitude Platform deployment since the Task 8A Report was written. The deployment of these platforms seems to remain at the academic and public sector planning stage, with a multi-million euro research project underway in Europe, led by York University in the United Kingdom [Ref. 4.6–3]. This project, which has a stated goal to provide broadband service to trains, has not addressed the issue of providing service to individual motor vehicles. Although somewhat over-optimistic in retrospect, the Task 8A Report's basic conclusions remain valid. This future technology is still worth monitoring, for example, for potential metropolitan-area broadcasting of map database information.

IEEE 802.11 Wireless LAN

There are no significant deviations from the IEEE 802.11 discussion in the Task 8A Report. "WiFi" prices have continued to drop, and deployment of these devices has proceeded rapidly. The standard for a higher speed version of 802.11b, called 802.11g, has been developed, and a number of manufacturers now produce and market this technology (which is backward-compatible with 802.11b)

The DSRC developments in the United States are the main focus in the near-term future for the adaptation of IEEE 802.11 wireless LAN technologies to support short range, mobile operations. IEEE 802.11 currently has two study groups looking into advanced technologies that may be applicable to mobile applications. One study group is focused on "Fast Roaming," which potentially will allow 802.11 access points to operate like micro-cellular networks for mobile devices. The other study group is newly formed to focus on MESH network technologies and to find how these may be effectively applied to 802.11.

The only additional risk factor that should now be considered is that the overwhelming success of WiFi at 2.4 GHz may slow or stall the large-scale deployment of 5 GHz 802.11a technology. This could have an impact on the prices and availability of 802.11a chipsets. The majority opinion at this time is that 5 GHz 802.11b will probably become increasingly popular as the 2.4 GHz band becomes more crowded and interference in that band increases.

Nationwide Differential Global Positioning System (NDGPS)

The NDGPS discussion in the Task 8A Report remains fairly accurate, except that the expected completion date for nationwide single coverage is now December 2005 rather than 2003. The completion of nationwide double coverage will likely require several years beyond 2005. High accuracy NDGPS is now expected to have four concept demonstration sites by the end of 2004.

Radar

The discussion of radar safety messaging in the Task 8A Report remains pertinent. That discussion's cautionary note concerning transmitter cost and political considerations for the Safety Warning System® (SWS) appears to have been justified. The business case for public sector purchasers of this equipment has been described as difficult, and this appears to have limited the deployment of the transmitters. The tacit encouragement of radar detector proliferation is also not well aligned with the public safety sector's interests.

A number of manufacturers of these SWS transmitters are phasing out of this business. MPH Industries and Innovative Technology of America, for example, were two of the major transmitter suppliers in 2001. MPH Industries no longer manufactures the transmitters and would like to sell its remaining inventory. Although Innovative Technology of America has reduced SWS transmitter prices to as low as $300, it is still "not selling many". The on-board equipment (radar detectors) currently on the market appear to continue to support the reception of the Safety Warning System® messages, so increasing number of vehicles should be able to receive from existing transmitters

Based upon the developments over the past two years, it appears that the SWS technology will not be relevant for EDMap safety applications. Although the use of radar frequencies for roadside-to-vehicle messaging remains a long-term possibility, other technologies, such as WAVE/DSRC, are likely to offer a better option.

Remote Keyless Entry (RKE)

As expected, RKE systems remain basically the same as they were described in the Task 8A Report. Since they are very inexpensive and do their specific job very well, major changes in this technology remain unlikely. The technology implications described in the Task 8A Report remain valid.

Satellite Digital Audio Radio Systems (SDARS)

The discussion of SDARS systems in the Task 8A Report was based upon the initial launch of XM and Sirius satellite radio services in the United States. Since the Task 8A Report, XM has expanded its customer base to over 1.5 million subscribers and in the 2005 model year will be available on 50 GM models as well as many other vehicles. XM is planning to have 20 million subscribers by 2010. Sirius, which is available on Ford, DaimlerChrysler and many other manufacturers' vehicles, estimates that it will have one million subscribers by the end of 2004. Sirius projects that by the end of 2005 it will achieve a cash flow break even point with 2 million subscribers. Many aftermarket and consumer products manufacturers now sell automotive, home and portable radios equipped to receive satellite radio transmissions.

The number of channels available to subscribers has increased for both Sirius and XM, and both services now offer around 100 channels. XM has announced that in March 2004 it will add 21 channels of traffic information and weather for specific major metropolitan areas. The SDARS technology discussion in the Task 8A Report remains pertinent, and the potential remains to use

this technology to provide digital data broadcast services. So far, however, no data services have been announced for deployment on these systems.

Terrestrial Digital Radio

There have been a number of developments in Terrestrial Digital Radio since the Task 8A Report. The regulatory questions in the previous discussion concerning deployment of IBOC technology in the United States have now been positively answered. The FCC has given its approval for In-Band On-Channel (IBOC) digital radio operation for AM and FM broadcast stations. AM stations' digital transmissions, however, will be limited to daylight hours. As previously described, iBiquity Digital developed the IBOC technology and supported its testing and validation through the National Radio Systems Committee (NRSC), whose joint sponsors are the National Association of Broadcasters and the Consumer Electronics Association (http://www.nrscstandards.org). iBiquity, which has branded its IBOC technology as "HD Radio®", is licensing this technology to radio stations and radio receiver manufacturers. By February 2004, almost 300 radio stations in over 100 U.S. markets will have licensed HD Radio® technology from iBiquity Digital.

In January 2004, the first IBOC receiver was sold and installed. Major consumer electronics manufacturers, including Phillips, Kenwood, JVC and Panasonic, either have IBOC receivers available, or plan to have them available in the near future. These developments indicate that the rollout of IBOC is proceeding about one year later than indicated in the Task 8A discussion.

The technical discussion of IBOC in the Task 8A Report remains valid and IBOC's potential for datacasting is still expected to be realized only over a longer time period. Program-related data such as song titles and artists' names are more likely immediate data services. For the longer-term, the previous conclusions regarding the potential distribution of map database updates over IBOC radio broadcasts remain valid.

Two-way Satellite

In the area of two-way satellite systems, little has changed since the discussion in the Task 8A Report. Several of the systems mentioned in that report remain in operation, indicating that business models capable of supporting them have been found. One of the main focus areas for these businesses is asset tracking and location services. The conclusions in the Task 8A Report remain valid for the two-way satellite technology area.

Ultrawideband (UWB)

The technological discussions of Ultrawideband in the Task 8A Report remain pertinent, although FCC rulemaking has now enabled the deployment of UWB [Ref. 4.6–4]. Proceeding cautiously to allow UWB devices to be brought to market, the FCC has altered its Part 15 rule (for unlicensed operations) to allow specific application areas for UWB. Rules for two of these application areas are particularly worth noting:

Vehicular Radar Systems:

Vehicular radars are limited to operation on terrestrial transportation vehicles. The –10 dB bandwidth must be within the 22-29 GHz band and directional antennas must be employed. The center frequency of the emission and the frequency at which the highest radiated emission occurs must be greater than 24.075 GHz. These devices detect the location and movement of objects near a vehicle, enabling features such as near collision avoidance, improved airbag activation, and suspension systems that better respond to road conditions. Attenuation of the emissions below 24

GHz is required above the horizontal plane in order to protect space-borne passive sensors operating in the 23.6-24.0 GHz band.

Communications and Measurement Systems:

This category encompasses a wide variety of other UWB devices, such as high-speed home and business networking devices as well as storage tank measurement devices subject to certain frequency and power limitations. The devices must operate with their −10 dB bandwidth within the frequency band 3.1-10.6 GHz. The equipment must be designed to ensure that it can only operate indoors, although it may be operated anywhere when hand held. Hand held devices may be employed for such activities as peer-to-peer operation." (For UWB petition detail, see Ref. 4.6–4.)

The FCC's regulatory developments have allowed companies to bring products and components to market. Time-Domain, for example, has been selling their evaluation kits to enable the development of applications and advanced product [Ref. 4.6–5]. Time-Domain claims to have shipped over 150 of these UWB evaluation kits in 2003.

Positive FCC rulemaking has thus made the Task 8A Report's conclusions concerning UWB potential much more likely.

4.6.5 Analysis of Previous Communications Technologies Assumptions, Expectations and Conclusions

The development of standards offers one of the main opportunities to exert positive influences on the development of specific wireless technologies. This is especially true for technologies that are likely to be the most critical components in support of the automotive safety applications identified by the EDMap project. This opportunity is now being pursued as part of the CAMP Vehicle Safety Communications (VSC) project. Requirements for vehicle safety communications are being conveyed, interpreted and explained to the various organizations responsible for developing WAVE/DSRC standards. The past two years have been critical for the development of the full range of 5.9 GHz WAVE/DSRC standards. The VSC influence has already helped secure accommodations in the ASTM lower layer standards to better support vehicle safety communications requirements. VSC has also indirectly influenced the recent Report and Order on the use of the 5.9 GHZ DSRC spectrum to provide better support for the needs of vehicle safety applications. WAVE/DSRC continues to be considered the preferred wireless technology to support the communications requirements of many safety applications that the EDMap project has identified.

On the other hand, terrestrial digital radio standards developments for In-Band, On-Channel (IBOC) technology and related FCC rulings have proceeded without influence from the automobile safety perspective. While this technology may not be as directly relevant to vehicle safety applications as DSRC, neglecting IBOC's longer-term potential for regional downloading of map database updates may represent a missed opportunity.

Since the deployment of NDGPS has been proceeding more slowly than previously expected, the acceleration of NDGPS deployment encouraged in the Task 8A Report's discussion has not been realized. The expansion of the number of high accuracy NDGPS demonstration sites is nevertheless encouraging. It remains to be seen whether the high accuracy NDGPS system can provide lane-level accuracy for receivers in moving vehicles over wide areas. If these high accuracy NDGPS demonstration sites prove this technology feasible, it may become the preferred deployment mode for future NDGPS rollout. On the communications portion of NDGPS considerations, broadcasting NDGPS over regional beacons appears to remain the only viable option for reasonable cost, integrity and reliability.

Ultrawideband (UWB) technology has been progressing rapidly, encouraged by favorable, but cautious, FCC rulemaking. This technology, which makes all-digital hardware implementation possible, appears to be very favorable for potential automotive applications since this supports lower costs and higher reliability. At this time, the FCC rules for automotive UWB devices, which focus on sensor applications, confine UWB communications uses to within buildings or between handheld devices over very short ranges. Developments over the past two years nevertheless make the Task 8A Report's conclusions concerning UWB's potential much more likely to be realized.

Developments in wireless communications technology since the Task 8A research was completed has reinforced the conclusion that multiple communications technologies will be required in each vehicle. WAVE/DSRC has emerged strongly as the most likely technology to support such very low latency communications requirements as intersection collision warning. The wider geographical rollout of wireless voice networks provides additional incentives to 'piggy-back' wide-area applications, like Mayday service, as reported in the Task 8A Report's conclusions. SDARS and IBOC systems will also provide entertainment, weather, and traffic information. All these developments serve to strengthen the previous conclusion that "the vehicle will be expected to transparently integrate data received through multiple communications channels into a cohesive set of information to support the relevant applications."

The current review of wireless communications developments has reconfirmed the following two major conclusions presented in the Task 8A Report:

1. Cellular networks will not meet all EDMap communications requirements

2. To meet all EDMap application needs will require more than one communications technology

The current review of relevant wireless communications technological developments supports the earlier Task 8A Report's conclusion that there are "no fundamental wireless technological impediments to the deployment of the types of automotive safety applications being proposed."

4.6.6 Vehicle Positioning Systems

GNSS based positioning is expected to dominate in-vehicle positioning applications. In summary, the following developments, discussed in detail elsewhere in this chapter, are anticipated:

- Enhanced GPS satellites, signals and receivers

- Introduction of additional GNSS systems (Galileo) and augmentations

- Wider coverage of A-GPS

- Wider DGPS coverage

- Better augmentation systems such as the Wide Area Augmentation System for GPS (WAAS)

4.6.7 Content Providers

The expansion of basic telematics service capabilities in the quality, availability and affordability of communication bandwidth, and in the architecture of in-vehicle telematics services, is expected both to widen the scope of existing in-vehicle telematics services and to introduce more services. Since this chapter has already described existing telematics services in detail, only future developments in existing services are discussed here.

4.6.8 Real-Time Traffic Information

The current state of development in Floating Vehicle Data (FVD) usage for generating real-time traffic information shows much promise for the future. The commercial success of FVD systems such as TrafficMaster, [Ref. 4.6–6] leads to the expectation that future FVD systems will make vehicles a part of the traffic-monitoring network.

The dominance of fixed location sensors in traffic detection is expected to decline as traffic-flow-immersed sensing is increasingly introduced into traffic sensor systems. Although fixed sensors such as flow detecting loops that provide aggregate traffic information will still form the basis of traffic data, they will increasingly be supplemented by FVD systems. The following factors will encourage the wider implementation of FVD systems for in-vehicle telematics traffic services:

- Wider GNSS availability, which will improve vehicle positioning accuracy
- Lower cost augmentation technologies
- Decreasing cost of in-vehicle GNSS positioning systems, which will result in larger potential for equipping vehicles with Floating Vehicle Data systems
- Lower cost communication

The following factors, however, also need to be considered:

- Privacy and security issues with vehicle data collection
- Communication bandwidth requirements

4.6.9 Additional Services

While the growth of consumer demand will be the driving force for future in-vehicle telematics demand, it is hard to define a set of rules that will govern how additional services emerge. Demand remains open-ended, as shown in Figure 4.6–3, which also indicates some of the more likely additional in-vehicle services.

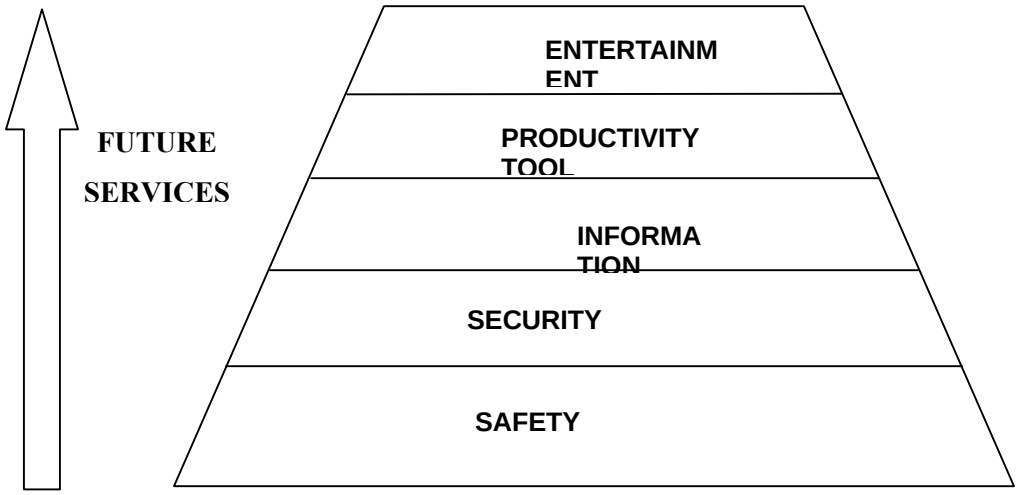


Figure 4.6-3 In-vehicle Telematics Services

4.6.10 Emission Monitoring and Control

As adverse environmental impacts from transportation activities increase, emission monitoring—especially for long-distance commercial transport— is expected to become a telematics enabled service. In light of existing telematics capabilities to monitor vehicle performance remotely, emissions monitoring is likely to be a hybrid of remote vehicle performance monitoring and commercial transport toll collection. This will involve charging tolls for commercial vehicles crossing sensitive areas, or even banning some classes of vehicles in order to minimize environmental impact. For information on a European Galileo based Transnational Environmental Management Support and Information System (TEMSIS), see Ref. 4.6–7.

4.7 Highway, Lane, and In-Lane Tracking: Needs and Techniques

4.7.1 GNSS Processing Methods

There are different GPS (or more general GNSS) data processing methods available depending which type(s) of GPS (GNSS) observation is used. They vary in accuracy as well as in robustness. Not every method is suitable for car navigation.

It is assumed that highway lane tracking (e. g. locating the vehicle on the right lane of the highway or another motorway) requires a positioning accuracy of 1 to 2 m (3σ) or better.

For completeness, Table 4.7–1 summarizes the different GNSS processing methods.

Because of the disadvantages of the “Differential Float Solution” and the “Differential Carrier Phase Corrections” method, only the so-called “Carrier-Smoothed Pseudorange Corrections” can be recommended for automotive applications at the current time. See Table 4.7–2.

This assessment must be reviewed when the three-frequency GPS (using L5) becomes available (full operational capability is expected after 2012, most likely at about 2017), or after 2010 when Galileo will provide multi-carrier frequency observations. More than three frequencies will be available then and more sub-carrier observations of Binary Offset Carrier (BOC) signals will also

be possible. Pure carrier phase methods will then become more robust by taking advantage of the possible instantaneous ambiguity resolution.

Figure 4.7–1 outlines present GPS horizontal accuracy. The corresponding vertical accuracy is worse by factor 1.5 to 3.

Table 4.6–1 Techniques for Highway Lane Tracking

GNSS Stand-Alone Receivers (e.g. using only one receiver engine)	
Precise Positioning Service (PPS)	For **authorized military use**
Standard Positioning Service (SPS) The DoD's intentional signal degradation for civil users, called Selective Availability (SA), was set to zero on May 1, 2000.	For **civil use**

GNSS Differential Methods	
Differential Pseudorange Corrections: Only corrections from pseudoranges are used	**Robust**
Differential Carrier-Smoothed Pseudorange Corrections: Pseudoranges are smoothed using carrier phase data before corrections are computed	**Robust**
Differential Float Solution: Pseudoranges and carrier phases are used, the latter as floating variables in a Kalman filter	**Disadvantage:** Degraded accuracy at the beginning and after a signal loss-of-lock and during filter convergence (for seconds to minutes)
Differential Carrier Phase Corrections: Carrier phase ambiguity uncertainty and corrections are the primary sources of error. Integer ambiguities have to be solved for. The following terms are often used: RTK for real-time kinematic, and static carrier phase DGPS in surveying.	**Disadvantages :** Degraded accuracy at beginning and after loss-of-lock . Seconds to minutes needed for the solution of carrier phase ambiguities (and for reacquiring the signal). Range: only 15 - 20 km from reference station **Note:** With signals at two or more carrier frequencies, reacquisition and solution times can be short, at times nearly instantaneous.

Table 4.6-2 Recommended Transmission Techniques for Differential Corrections

Recommendations:

As mentioned, a wide area service is preferable for automotive applications. WAAS, EGNOS and MSAS have established wide area networks of monitor stations that generate differential GPS (and GLONASS is in EGNOS, too) corrections with very high integrity,* in the order of $1\text{-}10^{-6}$ to $1\text{-}10^{-7}$.

Transmissions from geo-stationary satellites are difficult to receive in urban and high-latitude areas. The differential corrections could be taken directly at the Central Processing Facility (CPF) of the corresponding wide area system and placed into other more available channels. Technical details still have to be investigated. Assuming the approach is feasible, this could be a high-integrity service.

Because of some weakness in the internet transmissions, one would lose a degree of integrity; however, an integrity level of the order of $1\text{-}10^{-4}$ to $1\text{-}10^{-5}$ appears feasible.

Current differential carrier-smoothed pseudorange correction services provide an accuracy of the order of 1 to 2 m (2σ). By filtering with (longer) filter time constants, **one could achieve an accuracy in the 0.7 to 1.2 m (2σ) level**. This would likely require the use of narrow correlator receivers to reduce code noise.

One would need to investigate whether such a degree of smoothing and the time required for the process is acceptable for vehicular applications, and if it is advisable to implement such an approach in the certified CPF software.

One could build up a service—exclusively for a car manufacturer—that could be used over the whole continent with only four to six reference stations. This could be done with moderate funding if integrity levels of about $1\text{-}0^{-4}$ are sufficient.

* Integrity is the assurance that all functions of a system perform within operational limits. Integrity is the ability of the navigation system to provide timely warnings to users when the system should not be used. The integrity risk is the probability of an undetected failure that will result in the loss of the specified accuracy. Parameters of integrity are the integrity level (or risk) and the alarm limit (time to alarm).
Integrity is measured as the probability that all functions of a system perform within acceptable operational limits and this is normally stated as 0.99, 0.99999, or alternately as $1\text{-}10^{-2}$ or $1\text{-}10^{-5}$. Integrity risk is the probability of an undetected failure as indicated above. These values normally range from 10^{-2} to 10^{-8}.

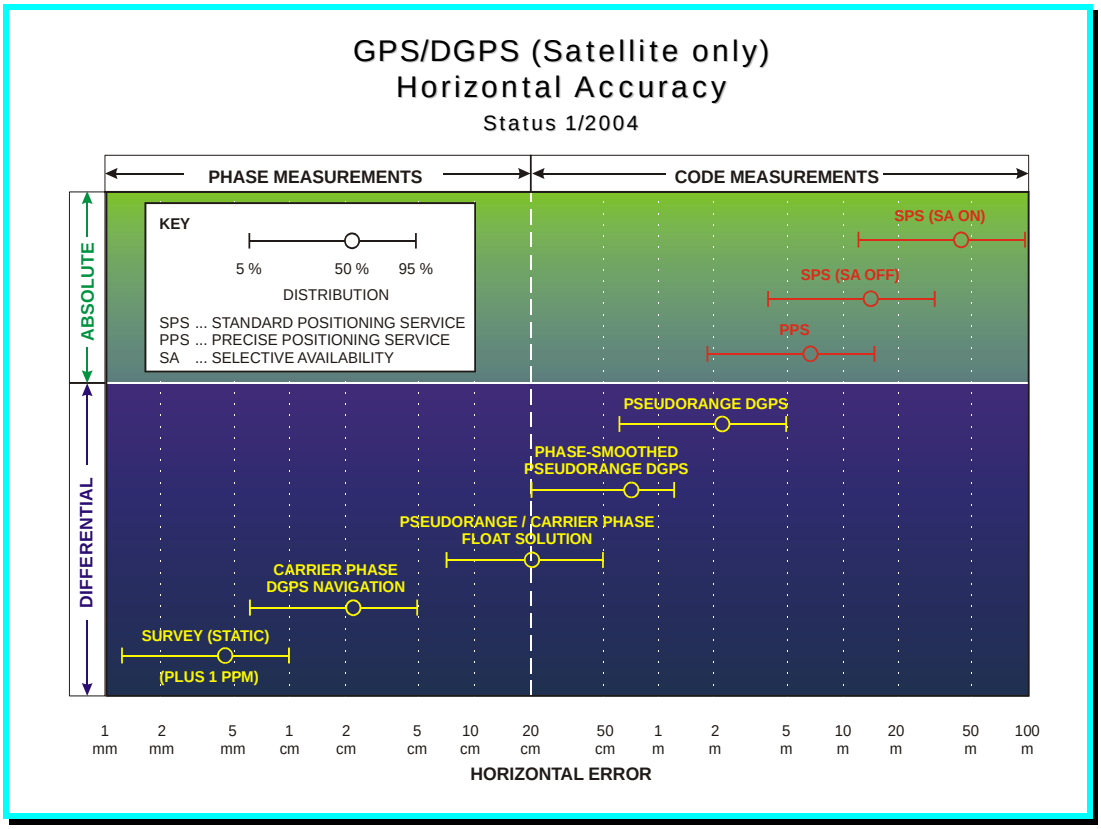


Figure 4.7–1 GPS/DGPS Horizontal Accuracy Performance

4.7.2 GNSS Differential Correction Services

The principle of the GPS differential correction method can be realized easily using a few reference stations over a large area. This will produce numerous services on a local, regional and wide area basis.

These services can be divided between those using:

- Differential Carrier-Smoothed Pseudorange Corrections
- Differential Carrier Phase Corrections

To guarantee centimeter accuracy for the user, the latter service must place a reference station approximately every 40 to 60km. Currently, however, methods for carrier phase ambiguity resolution in short time periods are reliable only over distances of 10 to 20 km from the reference station. This reliability often assumes the use of GPS dual-frequency data. Optimistically one may expect that the distances can be extended perhaps to 30 km or even longer. ***However, at the start of the process and after a complete loss-of-lock, times in the order of up to 30 seconds are needed to solve the ambiguities. This assumes the use of dual-frequency or "codeless" receivers. Single-frequency-receivers may require up to a few minutes.*** During these times, a reduced accuracy would be available (that achieved by Differential Carrier-Smoothed Pseudorange Corrections, say 1 to 2 m). Such a service only makes sense for surveying applications.

For automotive applications a wide area service covering a whole continent such as the U.S. or Canada would be preferable to switching between regional or national services.

The main problem of all GNSS Differential Correction Services is in the reference station data transfer. The issue is how to transfer the corrections to the user in a reliable way. In general, we have the following transmission methods:

1. **Satellites.** Examples are the geo-stationary INMARSAT III satellites used for EGNOS and WAAS using an L-band frequency [Ref. 4.7-1]. This application also uses other commercial satellite communication systems.

2. **LORAN-C / EUROFIX:** a pulsed system operating with low frequencies in the 90 to 110 kHz band, which provides differential GPS corrections on sub-carriers [Ref. 4.7-2]

   Low-frequency transmitters (e.g., the service ALF, Mainflingen, at 123.7 kHz.) [Ref. 4.7-3]

3. **Medium and High Frequency** broadcast transmissions

4. **Marine radio beacons** transmissions in the 300 kHz range [Ref. 4.7-4]

5. **Cellular communication,** especially those in or near the L-band (services such as CDMA2000, GSM, UMTS, etc.)

6. **Internet-Based Reference Station** [Ref. 4.7-5]

7. **Sub-carriers** of RDS, FM radio or Television [Ref. 4.7-6]

8. **Special purpose satellite services**, such as music and news broadcast services specifically addressing vehicular users [Ref. 4.7-7].

Method 1, "Satellites," has the disadvantage that the user needs to have line-of-sight visibility to the satellites. This can be a problem in many areas where "urban canyons" exist, i.e., where buildings obstruct the satellite signal paths except at high elevation angles. Moreover, at the higher latitudes (e.g., in Alaska and northern Canada) conventional geo-stationary satellites are either very low on the horizon or out of view.

Method 2, "LORAN-C/EUROFIX," has certain advantages because of the favorable wave propagation of low frequency waves. The service provided by one or two transmitting stations could cover an entire continent. (e.g. the transmitting station Mainflingen, near Frankfurt, Germany, has a range of more than 2000 km). LORAN-C with DGPS corrections can therefore be received in urban canyons. (Final verifying tests and results for this method, however, are still in process)**.**

Method 3, "Medium and High Frequency," is used to transmit over oceans, but is otherwise limited. It is ineffective in urban areas, where line-of-sight problems arise.

Method 4, "Marine radio beacons," uses the existing US Coast Guard beacon network in the coastal regions. This network covers about 200 km of coastal waters as well as nearly that distance over land. (Figure 2.2–1 in Chapter 2 shows current USCG coverage.)

Method 5, "Cellular communication," is technically a good method, but its expense is an important disadvantage.

Method 6, "Internet-Based Reference Station," is the recommended future method where vehicles have access to the internet. Such a service has already been implemented in Japan and the technique has a number of users in the USA.

Method 7, "Sub-carriers," already used extensively in Japan, assumes that the radio transmitting stations have enough bandwidth to accommodate the necessary differential message (approx. 700 to 800 bits/sec). This is possible in Japan and the U. S., but not in Europe where all frequencies are heavily occupied.

Method 8, "Special purpose satellite services." As implemented in the U.S., satellite digital radio systems might also be a wave of the future. In this case, the footprints of the two geo-stationary satellites (to be launched in 2004) cover the whole continental U.S. A network of about 1500 radio broadcast repeaters supplement the satellite coverage in urban areas where tall buildings and obstructions interfere with the reception.

4.7.3 Deficiencies of Satellite Navigation

The main drawback of satellite navigation is the possibility that the line-of-sight between user antenna and the satellites will be blocked by buildings (in cities), other cars and trucks, and even worse, by tunnels. Three satellites must be in view for a horizontal (two-dimensional) position, while four are needed for a complete three-dimensional position determination.

The Galileo satellite constellation will be optimized for urban applications, so that improvement in the availability of satellite navigation in cities can be expected after 2010. Moreover, the possibility after that of having combined GPS/Galileo receivers, whose two systems will double the number of satellites in the user's view, will reduce the urban canyon problem to very narrow streets among high buildings. In tunnels, satellite reception will remain impossible.

In summary, a full time position determination capability is only feasible by a combination with other sensors, or by the use of map matching techniques and geographical information.

4.8 Integrity and Validation Measures

4.8.1 Integrity Developments

GPS-III as well as Galileo emphasize the provision of integrity to the user. Unfortunately, as yet GPS-III has no detailed integrity concept developed. The following summarizes the main Galileo activities:

- Up to 2008-2010—Regional Integrity of the order of 10^{-7} is provided by the regional augmentations such as WAAS via geo-stationary satellites.
- After 2008-2010—Galileo will transmit via MEOs a SISA (Signal-in-Space Accuracy). This is a quality measure of the provided accuracy performance of Galileo from the space segment
- After 2008-2010—Galileo transmits the global Integrity Flag (as part of the integrity message) via MEOs and provides regional European (and most likely non-European) integrity by EGNOS, WAAS and MSAS.

With regard to integrity from Galileo, the following four developments are expected to be available in 2015:

- The Receiver Autonomous Integrity Monitoring (RAIM) concept, which is feasible and practical for Galileo and GPS users.
- The transition of EGNOS into Galileo
- The Galileo global SISA quality measure provided by the space segment as mentioned
- The Galileo Integrity Flag as part of the integrity message provided by the space segment

4.8.2 Receiver Autonomous Integrity Monitoring (RAIM) and Simulation Results

The extended Receiver Autonomous Integrity Monitoring (RAIM) is feasible because of the large redundancy in satellite observations from both satellite navigation systems (as discussed earlier in this chapter).

RAIM parameters used for these simulations are shown in Table 4.8–1, which assumes that the GIC (Ground Integrity Channel) missed detection probability is equal to 10^{-3} and that the Galileo failure probability is equal to 10^{-4}. The Galileo System Requirement Document set these parameters [Ref. 4.8–1].

Table 4.8-1 RAIM Parameters According to Galileo SRD (2001)

Parameter	Simulation Assumption
Horizontal Alarm Limit [m]	12.0
Vertical Alarm Limit [m]	20.0
Time To Alarm [s]	6.0
False Alarm Probability	6.667×10^{-7}
Missed Detection Probability	2.333×10^{-3}

The following figures give the results of the performed simulations in a spatial representation with reference to a worldwide grid. The color code for the plot of each simulation result is under the corresponding plot. The color code has a linear range whose lower limit is on the left side of the color code in question and whose upper limit is on the right side.

Figure 4.8–1 gives the relative current GPS RAIM availability frequency with respect to horizontal/vertical navigation at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

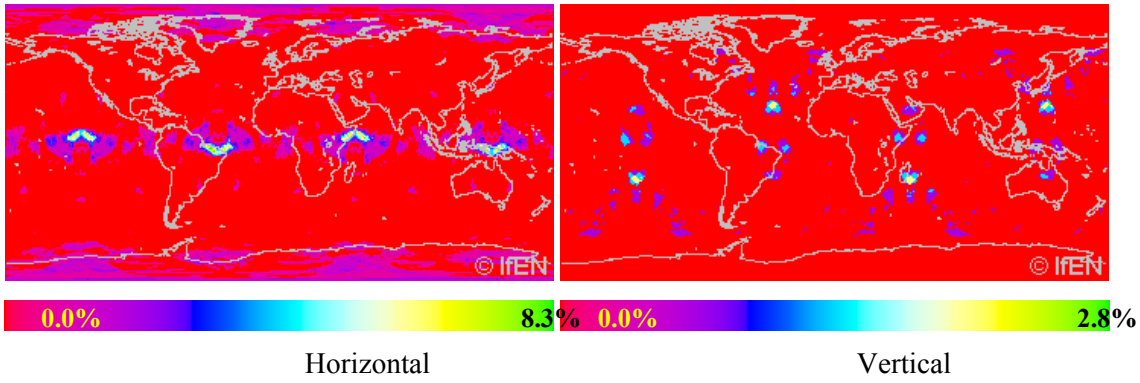


Figure 4.8–1 Relative GPS RAIM Availability Frequency [%] 14 Sept 2004 for 24 hours. Current GPS Performance, User Elevation Mask: 7.5°

The following figure shows the relative Galileo RAIM availability frequency with respect to horizontal/vertical navigation at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

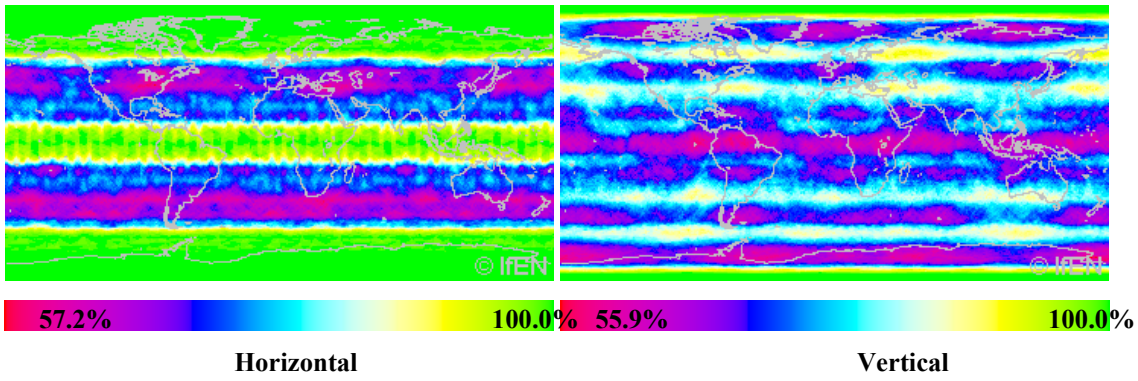


Figure 4.8–2 Relative Galileo RAIM Availability Frequency [%] 14 Sept 2004 for 24 hours. User Elevation Mask: 7.5°

Figure 4.8–3 shows the relative (Galileo + Current GPS) RAIM availability frequency with respect to horizontal/vertical navigation at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

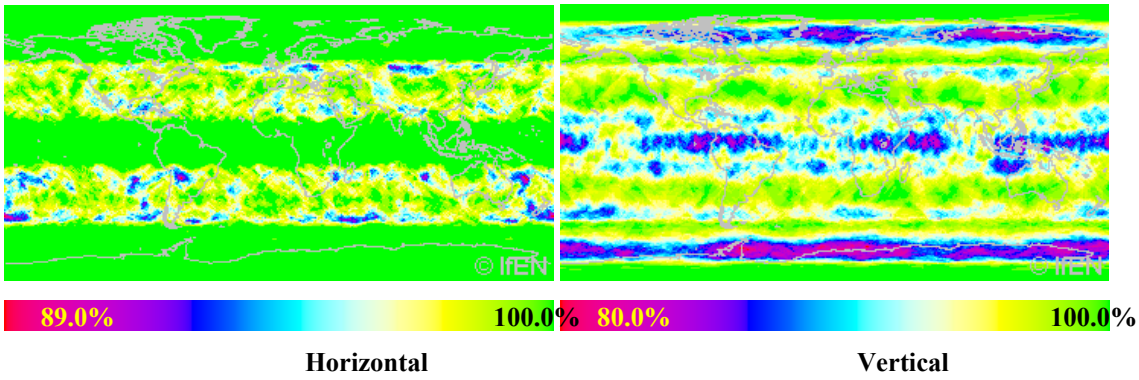


Figure 4.8–3 Relative Galileo+GPS RAIM Availability Frequency [%] 14 Sept 2004 for 24 hours. Current GPS Performance, User Elevation Mask: 7.5°

The following figure shows the relative GPS-III RAIM availability frequency with respect to horizontal/vertical navigation at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

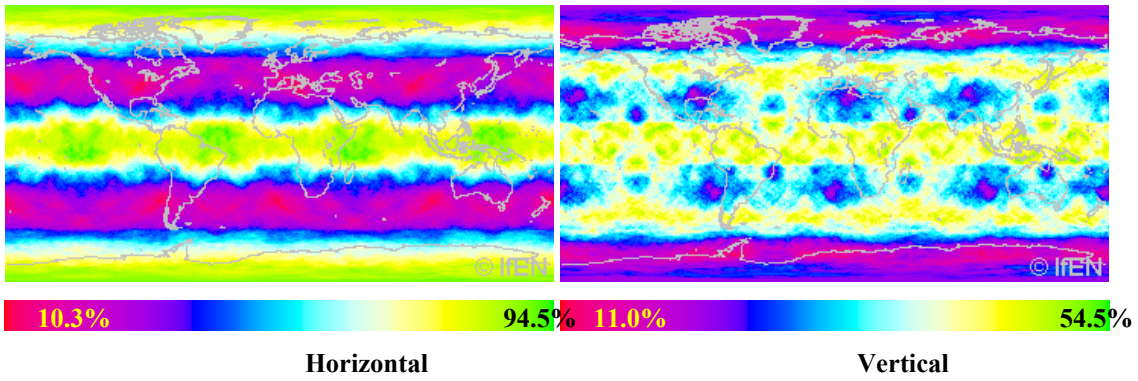


Figure 4.8–4 Relative GPS RAIM Availability Frequency [%] at 14 Sept 2001, 0-24h, Foreseeable GPS-III Performance, User Elevation Mask: 7.5°

The following figure shows the relative (Galileo+GPS-III) RAIM availability frequency with respect to horizontal/vertical navigation at the grid points of a worldwide grid for a user antenna elevation mask angle of 7.5°.

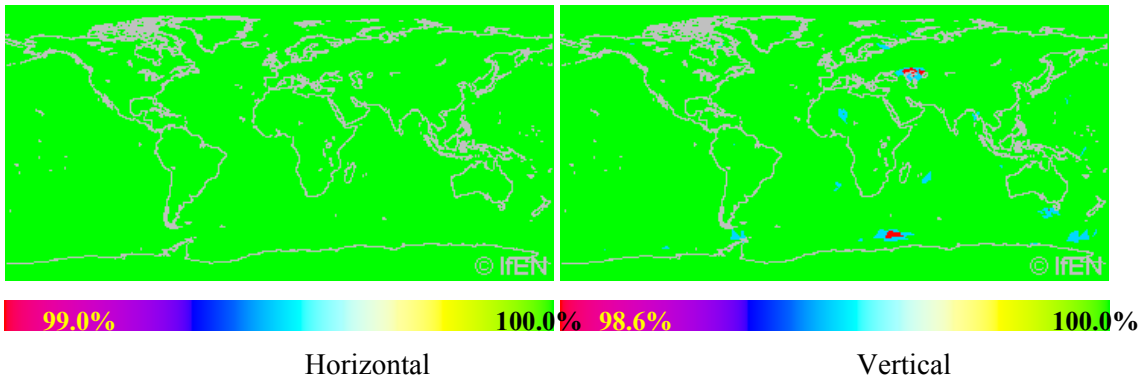


Figure 4.8–5 Relative Galileo+GPS RAIM Availability Frequency [%] at 14.09.2004, 0-24h, Foreseeable GPS-III Performance, User Elevation Mask: 7.5°

Table 4.8–2 RAIM Availability Requirements—Galileo SRD and ICAO SARPS

Parameter	GALILEO SRD (2001) From Requirements For Safety-of-Life Services	SARPS (1999) From CAT I Precision Approach Requirements
Horizontal Alarm Limit [m]	12.0	40.0
Vertical Alarm Limit [m]	20.0	10.0
Time To Alarm [s]	6.0	6.0
False Alarm Probability	$6.6666666666667 \times 10^{-7}$	$6.6666666666667 \times 10^{-8}$
Missed Detection Probability	$2.3333333333333 \times 10^{-3}$	$6.6666666666667 \times 10^{-4}$

Interpretation

- As outlined in Table 4.8–2, all simulations were carried out using RAIM parameters derived from performance requirements for Safety-of-Life services [Ref. 4.8–1]. In comparing these parameters with those derived from Ref. 4.8–2, there are differences in Vertical Alarm Limit and Missed Detection Probability.
- The Galileo Systems Requirements Document (SRD) vertical alarm limit is twice that of the ICAO Standard and Recommended Practices (SARPS) for CAT-I precision approach conditions [Ref. 4.8–1]. There is also a significant difference between the corresponding values for Missed Detection Probability. The Galileo SRD parameters can therefore be considered as “near CAT-1” values.
- The current GPS does not provide near CAT-I RAIM availability.

- Although the performance of the currently planned GPS-III constellation is slightly better, it also cannot provide near CAT-I RAIM availability. GPS-III provides RAIM protections horizontally at 10-95% and vertically at 10-55%. (Note that these computations are for the baseline 24 GPS-III constellation. More recent discussions on GPS-III type spacecraft foresee 27 to 30 satellites.)
- Although its performance with respect to RAIM availability is better than the current 24 satellite GPS II or GPS-III, Galileo, as presently designed, does not provide near CAT-I RAIM availability (horizontally it is in the 95 to 98% range; vertically it is in the 90 to 96% range).
- The combination of the Galileo and the current GPS satellite configuration (most likely after 2008-2010) deliver near CAT-I RAIM availability horizontally in the 95 to 100% range and vertically in the 90 to 100% range.
- The combination of Galileo and GPS-III (most likely after 2015-2017) delivers horizontally and vertically 100% RAIM availability for the near CAT-I parameters of the Galileo SRD.
- When testing the combined Galileo and GPS-III system against the CAT-l parameters from the ICAO Annex 10 Standards and Recommended Practices (SARPS) for 100% RAIM availability, RAIM can only be achieved horizontally. The more important vertical component shows RAIM availabilities in the range of only 60% to 95% (Figure 4.8–6).

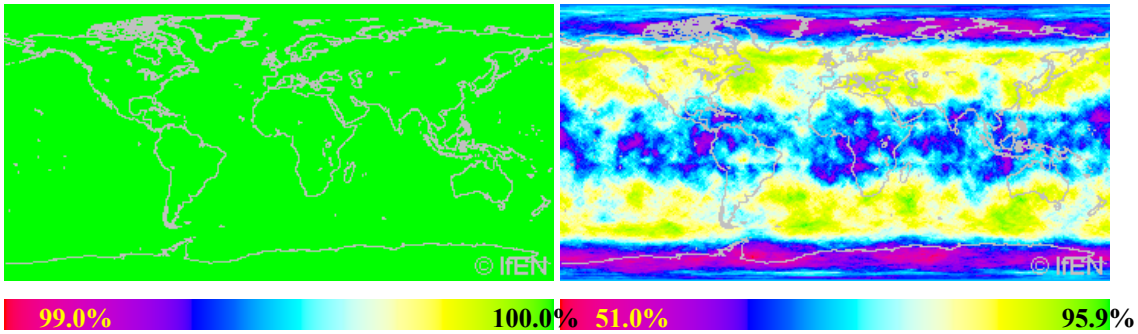


Figure 4.8–6 Relative Galileo/GPS RAIM Availability Frequency [%] at 14 Sept 2004, 0-24h, Foreseeable GPS-III Performance, User Elevation Mask: 7.5°, SARPS (1999)

4.8.3 EGNOS Transition into Galileo

Transmitting EGNOS signals by the use of geo-stationary satellites has serious drawbacks because of the low, or even negative, tracking elevation angles in both northern and southern latitudes. The transition of the EGNOS ground segment into the European Integrity Determination System (EIDS) of Galileo and the replacement of the GEOs by Galileo MEOs are an important steps in overcoming the deficiencies of such present augmentation systems as EGNOS, WAAS and MSAS. These steps will most likely have been completed after 2010.

4.8.4 Integrity Architecture of Galileo (SISA and Integrity Flag)

The overall Galileo integrity system architecture is based on subdividing the Earth into different integrity regions, each of which is served by its own integrity determination system. The Ground Control System (GCS) computes Global Signal-In-Space Accuracy (SISA) values globally for all Galileo satellites, and broadcasts these values to users through navigation data messages. These navigation data messages are regionally validated through an independent check by the European Integrity Determination System (EIDS) for the European integrity region, and through independent checks by the Non-European Integrity Determination Systems (NEIDS) for other integrity regions. Integrity data messages also provide users with integrity flags, which EIDS/NEIDS generates.

Galileo's space segment includes the MEO constellation, which provides navigation and integrity signals, while Galileo's ground segment includes both the GCS and the EIDS. In general, the GCS provides operations for global control of the space segment, and interfaces with navigation service systems and EIDS/NEIDS. In addition to generating and uploading navigation data messages, the GCS also uploads navigation-related data. The EIDS continuously monitors the health of those Galileo satellites visible within the European coverage. It also generates integrity data messages and uploads them to selected Galileo satellites for dissemination over the European coverage. EIDS also uploads the European GPS+GLONASS integrity message.

4.8.5 European Integrity Determination System

The European Integrity Determination System (EIDS) has the following tasks:

- **Real-time independent monitoring of the health of all Galileo satellites visible over Europe.** This satellite health monitoring includes the real-time independent check of the global Signal-In-Space Accuracy (SISA) computed by the Ground Control System (GCS)
- **Generation of up-link Galileo integrity data messages** for all Galileo satellites visible from the European integrity coverage
- **Detailed planning for uploading up-link integrity signals** when the EIDS uses constellation status data that GCS supplies as well as constellation almanac received either through GCS or through reception of navigation signals
- **Uploading of Galileo integrity data messages to selected Galileo satellites**, which are selected so that any user within the European integrity coverage can normally receive integrity messages from at least two satellites with a masking angle of 25°
- **Uploading of European GPS integrity data messages**, received through an external real-time communication interface with EGNOS Control Center, to selected Galileo satellites for dissemination over European coverage

The EIDS configuration for these tasks includes the following elements:

- An Integrity Monitoring Station (IMS) network deployed at sixteen nominal operating sites and at four additional redundant sites
- **One primary Integrity Control Center (ICC)** consisting of:
  - Three Integrity Processing Facilities (IPFs)
  - One Integrity Control Facility (ICF)

  - One integrity Service Center Interface Facility (SCIF)
  - One Integrity Network Management Facility (INMF)
- **One back-up ICC** consisting of:
  - Two IPFs
  - One ICF
  - One integrity SCIF
  - One INMF
- **An Integrity Up-Link Station (IULS) network**. This is deployed at two operating sites and at one additional back-up site. Each IULS network is equipped with 3 tracking antennas, 1 acquisition antenna and 1 back-up antenna
- **An Integrity Data Dissemination Network (IDDN)**

The EIDS generates integrity flags, which users receive through integrity data messages for all Galileo satellites visible over Europe. Integrity flags are generated by the real-time independent monitoring of the health of the satellites. This monitoring includes a real-time independent check of the global SISA values.

This real-time independent satellite health monitoring assumes that:

1) the EIDS uses only the data collected by the IMS network;
2) each Galileo satellite is observed by at least four IMSs simultaneously;
3) the IMS elevation masking angle is 15°; and
4) 4) the IMS locations are determined with an accuracy of 3 cm within the Galileo Terrestrial Reference Frame (GTRF).

The IMS network collects data that consists of one-way range measurements, carrier phase measurements, navigation messages (including the global SISA), and IMS meteorological data. The transfer period is one second for one-way range measurements, carrier phase measurements, and navigation messages, and 60 seconds for IMS meteorological data.

Each IMS pre-processes its raw data in order to provide data quality information. The IPF pre-processes the data that the IMS network collects and subsequently computes the integrity data messages by the aid of this pre-processed data. These integrity data messages are composed of:

- Integrity flag messages, which include the integrity flags for all Galileo satellites (one integrity flag per Galileo satellite), where a integrity flag consists of two bits and contains the following information:
  - Global SISA correct and navigation signal characteristics within specified limits
  - Global SISA incorrect or navigation signal characteristics outside specified limits
  - Satellite not monitored
- Time stamp indicating the latest validation time

4.8.6 Integrity Forecast

- Up until 2008-2010, regional integrity of the order of 10-6 to 10-7 will be available only from the regional augmentations WAAS, EGNOS and MSAS via geostationary satellites.
- From 2010 on, Galileo will transmit global integrity from MEOs worldwide via L1 and E5b. It will be based on approximately 29 worldwide-distributed control and integrity stations (Galileo sensor stations).
- From 2010 on, Galileo will also transmit regional integrity from the European region based on EGNOS and (subject to corresponding agreements) regional integrity from non-European regions.
- From 2010 on, Galileo will transmit a quality parameter of its service, the Signal-in-Space-Accuracy (SISA). This will allow each user to decide whether the provided service fits its own requirements.
- After 2015–2017, GPS-III is expected also to transmit integrity
- When Galileo and GPS achieve interoperability, both systems will have large redundancy in combined tracking, which will open new possibilities for integrity and validation approaches after 2010.

Chapter 5 Communications and Wireless Technology for EDMap

(Note: At the suggestion of our study's project director and with Mr. Schaffnit's permission, this chapter follows, with only minor changes, the Topics 2–6 Reports in Thomas Schaffnit's "EDMap Project: Task 8B Communications Research," of February 2004.)

5.1 Probe Vehicle Approaches for Data Collection

This section describes the results of research on probe vehicle approaches for map database data accumulation. It also identifies and discusses potential communications constraints for these probe vehicle approaches.

5.1.1 Investigation of Probe Vehicle Approaches

There are two major approaches for probe vehicle data collection: one is real time and the other is store and forward. The next two sections describe these two approaches, provide implementation scenarios, and assess potential communications requirements.

The types of data that may be of interest for probe vehicle applications include, for example: vehicle type/class, size/mass, location, speed, heading, acceleration, yaw rate, antenna offset, active suspension activity, ABS activation, temperature, wiper activation, radio tuning and time stamp. Obviously, not all of these data types are relevant for map database accumulation. Advanced applications for map database accumulation may attempt to identify, for example, pothole location and severity based upon processing a number of these data types. For this example, vehicle type/class, size/mass, location, speed, heading, acceleration, yaw rate, antenna offset, active suspension activity and temperature data may all be processed to estimate the pothole location and severity. On the other hand, vehicle type/class, size/mass, location, heading, antenna offset and time stamp data may be the only types required to refine geographical lane-level map database information.

Real Time Data Collection

Real time data collection implies that dynamic data is collected from vehicles instantaneously. The definition of real time must be stretched in actual implementations, however, since all systems impose some latency for transmission and processing. The essential difference for the real time probe vehicle approach is that the data is sent as it occurs. In the case of accumulating information for map databases, a continuous stream of positioning data from each vehicle could represent this. Alternately, a sample could be sent instantaneously on regular intervals, or per triggering event.

Traffic speed per road segment is an example of an application that likely requires real time data collection. This application requires high accuracy database support with dynamic information elements at the local/regional level. In this scenario, the traffic speed per road segment can be considered as a dynamic map database component. In order to keep things fairly simple, probe vehicles in this application scenario might just provide ID, vehicle type/class, size/mass, speed and heading data in real time as they pass fixed data collection points along the designated roadway segments. This information could be processed in aggregate to derive average traffic density and segment speed. This information could then be added as the dynamic component of the database. In this approach, however, accuracy of the information would be limited to the immediate location of the fixed collection points. This approach would require the use of short-range data communications systems with latency low enough to allow the collection of the data

from all vehicles passing the fixed collection point within the time that they remain within the communications zone at up to highway speeds.

An alternate real time scenario for the traffic speed per road segment application might be for probe vehicles to communicate ID, vehicle type/class, size/mass, location, speed, heading, and time stamp every ten seconds. This would allow a more uniform mapping of traffic density and speed onto the various roadway segments. This approach would require the widespread use of wide-area data communications systems with latency measured in seconds.

Store and Forward Data

The store and forward approach implies that data is collected over time aboard the probe vehicle, and then transferred to an accumulation site for post processing. The data can be accumulated for various periods, for example, hours, days, or months. As map databases become more accurate, they also necessarily become more detailed. The map database information increases significantly in size and complexity as the level of detail increases. The store and forward collection approach allows detailed map data to be collected by probe vehicles, uploaded to the accumulation site, post-processed with the data from many other probe vehicles, and integrated in an order fashion with the previous map database information.

Many components of a map database, for example, lane locations in roadway segments, do not change frequently. This implies that data related to such long-term components can be collected and analyzed over time. The aggregation of data from many vehicles traveling over the same roadway segments many times can theoretically provide a very accurate mapping of where vehicles actually travel on these roadway segments. This mapping arguably should have a fairly predictable relationship with the roadway lane markings.

An application scenario for refinement of precise lane locations on roadway segments might use store and forward data techniques to accomplish this task. Implementation may include periodic recording of location, heading and time stamp. If the periodic recording rate in this scenario is once per second, and each recording is 22 bytes (e.g., location – 12 bytes, heading - 8 bytes and time stamp – 2 bytes), then approximately 80 kilobytes of data will accumulate in the probe vehicle during each hour of driving. Further, assuming that the vehicle is driven 1.5 hours per day, 30 days per month, then approximately 3.6 megabytes of data would accumulate per month.

One approach to uploading data from the vehicle in this scenario would be to use a wireless local area network connection as soon as the vehicle enters the garage at its home location. This information could then be relayed to the aggregation site through an Internet connection at the home location. This scenario therefore requires an appropriate wireless local area network and an available Internet connection at the home location.

5.1.2 Potential Communications Constraints for Probe Vehicle Data Collection

In analyzing the two basic application scenarios presented above to illustrate the two different probe vehicle approaches, various potential communications constraints become evident. In the following six sections, these constraints are described within the category of each section.

Potential Wireless Technology Capability Limitations

For the real time traffic speed per road segment scenario using fixed data collection points, the requirement is for a “short-range data communications systems with latency low enough to allow the collection of the data from all vehicles passing the fixed collection point within the time that they remain within the communications zone at up to highway speeds”. Assuming a data packet

size of 19 bytes (ID – 6 bytes, vehicle type/class – 1 bytes, size/mass – 8 bytes, speed – 2 bytes and heading – 2 bytes), the actual transmission of the packet would only take around 25 microseconds at the WAVE/DSRC default data transmission rate of 6 megabits per second. At a highway speed of 120 km/hr, the probe vehicle would travel less than one millimeter in 25 microseconds. The main limitation would occur if "handshaking" were required to establish a connection as the probe vehicle enters the communications zone. This limitation can be readily overcome through simple schemes, however, like every vehicle broadcasting its information 10 times per second. With a more efficient use of the spectrum, the same results could be achieved if a "trigger" signal was sent as the vehicle entered the communications zone, which triggered the vehicle to broadcast the requisite data packet. This triggering approach would also eliminate the need to send the vehicle ID.

For the alternate real time traffic speed per road segment scenario, the probe vehicles would need to communicate ID, vehicle type/class, size/mass, location, speed, heading, and time stamp data every ten seconds. Sending the data would require a "…wide-area data communications systems with latency measured in seconds." With 2.5G wireless network data services already extensively deployed in major metropolitan areas and along major interstate routes, meeting this requirement should be easy in these areas. Both GPRS and 1xRTT data services should be able to provide latency in the "seconds" range, which would meet the requirements of this application scenario.

In the store and forward application scenario for refinement of precise lane locations on roadway segments, an appropriate wireless local area network and an available Internet connection at the home location are required. IEEE 802.11b "WiFi" wireless access points can presently be purchased for under $50. Home use of WiFi is increasing rapidly, although less than 2% of households currently have a wireless network. With the distances involved in a residential garage situation, Bluetooth modules could also be used to connect the probe vehicle to the Internet. Even infrared (IR) technology could likely support the garage communications link from the vehicle. At WiFi data rates, an entire month of probe data (3.6 megabytes) could be uploaded in less than one second. This could be easily accomplished during the time that the vehicle was being driven into the garage, for example.

If WAVE/DSRC technology is deployed in vehicles for collision avoidance-type safety applications, then an IEEE 802.11a access point could be used in the home garage location for the data uploads required for this application scenario. This would be possible since WAVE/DSRC radios will be capable of operating in "native" IEEE 802.11a mode when they are not being used for vehicle safety applications.

Having access to the Internet from home locations should not represent any significant impediment to this store and forward application scenario in the five-year time frame. As of January 2004, approximately 20% of households in the United States (21.5 million households) have Internet access through broadband "high-speed, always-on technologies". By 2008, 40% of United States households are expected to have this type of access, while another 40% are expected to connect to the Internet through dial-up connections.

(http://www.bizjournals.com/sanjose/stories/2004/01/26/daily64.html?jst=s_rs_hl)

Expected Deployment Time Frames

Initial major deployments of WAVE/DSRC are expected to begin around 2010. The number of fixed collection points likely within the ten-year time frame may not adequately support the degree of granularity desired for real time traffic speed per road segment application scenario using fixed collection points.

With the alternate scenario using wide-area wireless networks, the deployment does not seem to be an issue. Major metropolitan areas and major interstate routes are the areas that are already covered by 2.5G wireless data services. In most cases, these are precisely the areas where traffic density and segment speed information would be most useful.

The store and forward application scenario for refinement of precise lane locations on roadway segments would require an appropriate wireless local area network and an available Internet connection at the home location. As mentioned above, the home Internet connection is expected to be available in 80% of United States households by 2008, so there are no anticipated constraints in this regard.

A number of potential wireless technologies could be used to support the upload connection between the probe vehicle and home computer or network system. A number of vehicle models already include Bluetooth gateways to on-board networks for hands-free cellular connectivity. These same Bluetooth radio units in the vehicle might be used to connect to a Bluetooth unit in the home garage. Bluetooth radio modules are currently available at OEM prices below $5.

Another low cost option that might be deployed quickly for the vehicle-to-garage link is IR. Most PDAs, laptops and television remote controls already use this technology, so transceivers are readily available. The expected residential garage communications distances seem to be well within the reliable range for IR devices. The main disadvantage of IR technology is overcome by this type of implementation, since weather conditions represent a challenge to IR devices in outdoor installation locations.

Coverage Considerations

As discussed above, adequate coverage for WAVE/DSRC fixed collection point equipment in the infrastructure may be an issue for supporting the degree of granularity desired for the real time traffic speed per road segment application scenario.

There may be significant constraints if real time probe vehicle data is required outside major metropolitan areas and along major interstate routes, since 2.5G data capabilities are unlikely to be widely deployed in rural areas.

Cost of Data Collection and Transfer

WAVE/DSRC fixed data collection points (roadside units, or RSUs) are estimated to cost around $500, when installed in existing controller cabinets that already have power and data backhaul connections. Installations where foundations must be prepared, equipment cabinets installed, and power and data connections provisioned are likely to be an order of magnitude more costly. These costs may be able to be amortized over a number of applications, both safety and commercial.

The cost of the WAVE/DSRC on-board unit (OBU) is expected to be in the $100 range. For a system-wide cost, this would need to be multiplied by the number of probe vehicles. If the OBU were to be installed in the vehicle to support vehicle safety applications anyway, then the marginal cost for the probe vehicle data collection would be zero.

Data capabilities on 2.5G wireless networks remain costly now. For example, Sprint PCS is presently charging around $120 per month for unlimited 1xRTT data communications usage. AT&T Wireless charges $13 per month for 4 megabytes of data communication, and $100 per month for 100 megabytes. For the alternate wide-area real time traffic speed per road segment scenario, a data packet of 39 bytes (ID – 6 bytes, vehicle type/class – 1 bytes, size/mass – 8 bytes, location – 12 bytes, speed – 2 bytes, heading – 2 bytes, and time stamp – 8 bytes) is sent every ten seconds during probe vehicle operation. If assumptions for this scenario are made similarly to the store and forward scenario, then approximately 632 kilobytes of data will be sent in each month.

Using the AT&T 4 megabyte rate, the proportionate cost for this data would be around $2 per month per probe vehicle. Of course, if the wireless subscriber was already subscribing to an unlimited data usage plan, then the marginal cost for the probe data could be considered zero. At the current costs for unlimited data usage, not many customers have subscribed to this service, and not many are expected to subscribe, as long as the cost remains at the current levels. This wireless connection also requires a cellular modem to be installed and connected to the vehicle network systems as well as a basis monthly subscription fee to be paid to the wireless carrier.

The store and forward scenario appears to offer a fairly low marginal cost for data collection and transfer. If existing Bluetooth radios on the vehicle can be used, and the accumulated probe data can be stored in existing on-board memory locations (in intelligent radios, navigation systems, or telematics boxes, for example), then the only additional equipment required would be the garage-mounted Bluetooth unit, which could probably be around a $50 item. The IR option is likely in a similar cost category.

Privacy Issues

Privacy can be a very real issue with these systems, particularly if an ID is used that can be cross-referenced to vehicle VIN or registration information. For example, if an identifiable vehicle sent out speed information to indicate that it was traveling at 75 miles per hour and the related location information showed that the vehicle was in a 55 mile per hour zone, then automated systems could send a speeding ticket to the registered owner. Of course, not many people would like to buy a new vehicle that has this capability.

In the planned WAVE/DSRC OBUs, a dynamic, random MAC address will be used as the ID. This will allow relative identification to prevent "double counting" probe data, for example, but will not be allow the ID to be traceable to the vehicle VIN or registration. This arrangement also provides privacy from someone knowing exactly where and when a particular, identifiable vehicle has traveled.

Security Requirements and Issues

The main security requirements for probe vehicle data collection systems appear to be fairly minor. This is because data is aggregated from many vehicles, and any data misrepresentation from an individual vehicle would be statistically insignificant. The potential rewards for falsifying probe vehicle data on an individual level seem to be non-existent. At a macro level, the aggregated data will have to be well secured, since much damage could be done if map databases that supported safety applications for example, were corrupted.

Security is also related to privacy. However, if the WAVE/DSRC random MAC address type solution is designed into the system to maintain privacy, then there will be less need to secure the collected data

5.2 Potential Systems to Deliver Detailed Map Database Updates

5.2.1 Potential of DSRC Systems to Deliver Detailed Map Database Updates

This section discusses the potential of DSRC systems to deliver detailed map database updates. It addresses communications requirements for map database updates using DSRC technology, as well as deployment and economic considerations.

DSRC technology has been proposed as one possible approach toward maintaining the currency of on-board map databases in vehicles. There are various potential approaches toward providing the update capability using DSRC. For the purposes of this discussion, three scenarios will be used to illustrate various possible approaches for updating the on-board map databases.

Scenario 1: In this scenario, the relevant updates for an entire major metropolitan area would be available for downloading over DSRC "hotspots" along the main routes approaching the area, as well as at various points within the metropolitan area. This approach would be based upon the transactional capabilities of DSRC, as envisioned by the DSRC Standards Writing Group.

In Scenario 1 each DSRC hotspot broadcasts an announcement of the services available at that location. In this case, the services would include map database updates. The announcement would be able to provide the date of the update, so the vehicle systems could determine whether or not an update was required at this time. The announcement would also provide the DSRC channel to be used for this service. If the vehicle determines that an update is required, then the appropriate DSRC channel would be accessed to establish a wireless connection between the vehicle and the hotspot, and download the updates to the map database.

This approach has the advantage of only providing information as required and requested by vehicles, and provides support for various business models (like paying on a per update basis). The disadvantages are that there may be many vehicles simultaneously requiring map database downloads, stressing the capabilities of the hotspot to multiplex, as well as sending the same information many times (once per vehicle).

Scenario 2: This scenario represents a different scale of map database downloading. In this scenario, each traffic signal and curve speed warning controller, for example, would provide a detailed update of just that immediate geographical area. In the case of the traffic signal, this might include the lane layout of the intersection and approaches, as well as precise stopping lines.

In order to ensure that every vehicle approaching the intersection has the complete and most current map database information for that immediate area, this information would be expected to be received every time the vehicle approaches that intersection. This scenario assumes that a repeating, periodic broadcast of the map database information associated with that particular intersection would be available from a DSRC RSU associated with that intersection.

This scenario has the advantage of being able to support any number of vehicles simultaneously approaching the intersection, since one broadcast message can be received by all approaching vehicles. One potentially negative aspect of this approach is that the DSRC spectrum would be used continuously for the repetitive broadcasts, even if no vehicle were present. Another possible drawback is that this approach would make it difficult, if not impossible, to charge a fee for the information download. If these downloads were providing strictly safety-related information, this may not be a drawback.

Scenario 3: The approach for downloading map database update information to the vehicle in this scenario is to use a wireless local area network connection while the vehicle is in the garage at its home location. The up-to-date map database information for an entire major metropolitan area would be accessed from a website site through an Internet connection at the home location. This approach allows the vehicle to check if appropriate updates are available before requesting a download. This scenario is an inversion of one of the probe vehicle data collection approaches described in Section 6.1, above. This approach requires an appropriate wireless local area network and an available Internet connection at the home location.

One major advantage of this approach is that the required equipment and network connectivity would also support the probe vehicle data collection application and vehicle diagnostic download applications (like service bay trouble code downloading), as well as a number of potential fee-for-

service information or entertainment download applications (like turn-by-turn directions, MP3 music, games or video entertainment files). On the downside, traveling over wider areas would need to be preplanned, unless complete nationwide map database updates were being downloaded.

Data Flow Requirements

Data flow requirements will vary across the three scenarios described above. According to information from discussions with Navigation Technologies, the North American map database is currently in the range of 8 GBytes. The quarterly update requirements for this North American map database are in the range of 400 Mbytes to 4 GBytes. The current target for these quarterly updates is 400 Mbytes, but this could become larger as the complexity of the database increases. The size of the map database for the largest major metropolitan areas, for example, Southern California, would be around 800 Mbytes. If a linear relationship over time is assumed, then a monthly update for the nationwide map database would be in the range of 133 Mbytes – 1.33 GBytes. A quarterly regional map database (major metropolitan area) update would be expected to be 40-400 Mbytes, and a monthly regional update would be 13-133 Mbytes.

In Scenario 1, some vehicles entering a new metropolitan area would require the entire regional map database of around 800 Mbytes, while others might only require the latest monthly update of 73 Mbytes (averaged over 13-133 MByte range). The most stressing data flow situation for the DSRC roadside units (RSUs) would be vehicles approaching the metropolitan area at highway speed and requiring the entire 800 MByte map database download.

For Scenario 2, individual intersection map databases may be smaller than 20 Kbytes. However, a map database of 200 Kbytes has been considered in order to allow for future map databases at increased levels of detail and to provide stressing dataflow communications requirements for this scenario.

Scenario 3 dataflow requirements are similar to those of Scenario 1. However, in order to avoid the negative consequences of roaming to another metropolitan area without pre-planning, and to stress the dataflow requirements, the entire North American map database has been considered as the largest download requirement. It is understood that this would not be a frequent occurrence, so the overall aggregated network impact would not be likely to represent an issue.

Bandwidth Requirements

The most stressing data flow situation for Scenario 1 is where vehicles approach the metropolitan area at highway speed and require an entire 800 MByte map database download. Assuming a speed of 33 meters per second (120 kilometers per hour), a vehicle would traverse a communications zone of 300 meters in around 9 seconds. This implies a required effective bandwidth of around 711 Mbits per second. The maximum data rate for DSRC technology is 27 Mbits per second, and there will be significant network overhead to reduce the effective rate to an even lower amount. As well, the required channel switching and handshaking would take away some amount of the communications time. Even the anticipated monthly map database download of 73 Mbytes would require an effective bandwidth of around 65 Mbits per second. There is clearly a bandwidth problem with using DSRC in this scenario.

For Scenario 2, the effective communications zone is assumed to be 150 meters, since the vehicle should possess the relevant map database by the time it is 150 meters from the center of the intersection. At 25 meters per second (90 kilometers per hour), a vehicle will traverse this communications zone in approximately 6 seconds. With a data flow requirement of 200 Kbytes, the required effective bandwidth would be around 267 Kbits per second. Even allowing for network overhead (of 100%) and channel switching time, the requirement remains well below 1

Mbit per second. With no handshaking required and no multiplication of transmission for multiple vehicles (due to the broadcast approach), the DSRC bandwidth of up to 27 Mbits per second appears to be well-suited to meet this requirement.

Scenario 3 represents the largest potential dataflow requirements. The entire North American map database was considered as the stressing data flow requirement. In this scenario, the vehicle would be within communications range (although not running) for potentially hours at a time (overnight). WAVE/DSRC radios will be capable of operating in "native" IEEE 802.11a mode when they are not being used for vehicle safety applications. In this case, an IEEE 802.11a access point could be used in the home garage location for the data downloads required for this scenario, if the transceiver in the vehicle could be operated while the vehicle is not running. Under these assumptions, the 54 Mbit per second bandwidth of the IEEE 802.11a mode for the DSRC unit would allow the entire 8 GByte map database to be downloaded in around 20 minutes. If the vehicle must be running during this download time, then this approach will try the patience of the end-user, even if this happened infrequently. The expected maximum monthly update for the North American map database, however, would take just over 3 minutes using this approach. This may not be too long to expect someone to wait on a monthly basis for the download to complete with the engine running. The monthly regional map database update of 73 Mbytes, in contrast, would be able to be completed in around 11 seconds. This would likely cause no delay, since starting the vehicle and backing out of the garage would take longer than the download.

Expected Deployment Time Frames

The predicted WAVE/DSRC deployment schedule shows initial application deployments in 2007, and safety application deployment in 2010. Without a significant regulatory initiative, it could be expected to take at least 5-8 years after 2010 to have a majority of intersections and vehicles equipped with WAVE/DSRC transceivers.

On the other hand, Scenario 3 would support deployment on a vehicle-by-vehicle basis, rather than requiring a major infrastructure initiative, in order to provide a useable system. IEEE 802.11a access points are already commercially available. WAVE/DSRC on-board units (OBUs) are expected to be commercially available by 2007. High speed Internet access is expected to be available in 40% of United States households by 2008. These projections lead to the conclusion that individual vehicles with navigation systems (typically higher-end vehicles) could potentially be provided with wireless map database updates using DSRC with the Scenario 3 approach around model year 2008.

Coverage Considerations

Coverage considerations are strongly related to the deployment expectations. With major application deployment beginning in 2010 and requiring 5-8 additional years to achieve majority penetration, the question arises as to how effective partial coverage would be during the initial 5-8 years. One case can be made that the highest priority intersections could be rapidly deployed during the initial stages and infrastructure-based warnings could leverage these intelligent intersections to address the needs of vehicles without the required communications capabilities during the time until the majority of vehicles could be equipped with DSRC transceivers.

The vehicle-by-vehicle deployment possible under Scenario 3 might allow a market-drive approach to proceed more quickly in conjunction with other applications, like driver information and entertainment, which would also use DSRC technology and home garage wireless access points with Internet connectivity. This approach would support deployment in higher-end vehicles initially, beginning around model year 2008, then proceeding toward wider deployment in middle-range vehicles within 3-5 years.

Cost Considerations

As discussed in Section 6.1 in conjunction with probe vehicle data collection, WAVE/DSRC RSUs are expected to cost around $500, when installed in existing controller cabinets that already have power and data backhaul connections. Installations where foundations must be prepared, equipment cabinets installed, and power and data connections provisioned are likely to be an order of magnitude more costly. These costs may be able to be amortized over a number of applications, both safety and commercial. The cost of the WAVE/DSRC OBU is expected to be in the $100 range. IEEE 802.11a access points are currently available at prices around $200 (as of February 2004). In the case where the OBU is installed in the vehicle to support vehicle safety applications as a primary function, then the marginal cost for the map database update capability in the vehicle could be considered to be zero.

5.2.2 Potential of SDARS Systems to Deliver Detailed Map Database Updates

This section discusses the potential of satellite digital audio radio systems (SDARS) to deliver detailed map database updates, or provide a timing source, or both. It also considers communications requirements, system latency and cost considerations for map database updates using SDARS technology.

The two SDARS systems in operation in the United States are XM and Sirius satellite radio services. Although these systems use different satellite approaches, the digital communications technologies are very similar, and both use the same audio compression algorithms. Since these systems have been in operation for nearly two years, and satellite radios are being factory installed in many vehicle models, it is very appealing to consider this wireless technology as a possible delivery mechanism for map database updates. The wireless technologies being used for both systems are inherently digital This means that all the audio data, and any other information content on these systems, is carried as digital “bits” in an integrated bit stream. The concept of “channels” is virtual in this case, since each channel just represents a particular slice out of the bit stream. Since map database information is also inherently digital, the integration of map database information into the SDARS bit stream should be transparent to the system.

The digital information in a SDARS system, whether it represents music or map database information, is transmitted to the entire United States at the same time. With the exception of terrestrial repeaters associated with this system to provide signals in places, like urban canyons, where the satellite signal would be blocked, all the transmitted information is sent from the satellite(s) in a pattern to cover the whole United States. The advantage of such a point-to-multipoint broadcast system is that the same information can be simultaneously sent to, and potentially received by, every vehicle in the United States, with significant coverage extending into Canada and Mexico. The related disadvantage is that information of importance to just one region, for example, map database updates just for a major metropolitan area, must be sent to the entire country.

Three different scenarios are useful to consider the potential of SDARS systems to deliver detailed map database updates. Since the same information is broadcast to the whole United States, the only reasonable map database broadcast approach for this technological approach is to broadcast map database information for the entire country. Each of these three scenarios therefore assumes that the nationwide map database is carried in the SDARS broadcast.

Scenario 1: This assumes that a vehicle needs to receive the entire nationwide map database during the time it is driven in an average day of driving. This scenario is further specified with the assumption that the average vehicle is driven 1.5 hours per day. Furthermore, the SDARS map database transmissions are assumed to be repeated continuously, so that the net effectiveness of

multiple reception periods, like those encountered in a morning and evening commute, would be around 50%.

Scenario 2: The assumptions here are similar to Scenario 1, except that the vehicle is assumed to already have the main map database in place from an initial or subsequent installation from physical media storage (e.g., DVD). This means that the vehicle just needs to receive the monthly update for the map database within its driving day.

Scenario 3: This is the same as Scenario 2, except that the vehicle is allowed to take 30 days of average driving to receive the monthly map database update information.

Data Flow Requirements

In Scenario 1, the total map database size is 8 GBytes. In order to receive the entire map database in one average driving day, under the scenario assumptions, the 1.5 average driving hours must be multiplied by the effectiveness due to repetition of 50%. This provides 45 minutes, or 2700 seconds in which to receive the 8 GBytes of data.

For Scenario 2, the vehicle is assumed to already have the main map database data, and therefore only requires the monthly update. The monthly update size estimate ranges between 133 Mbytes and 1.33 GBytes of data. For data flow requirements, it is probably advisable to consider both the upper and lower ends of this size range. As in Scenario 1, this data must be downloaded in 45 minutes (2700 seconds) for Scenario 2.

Scenario 3 provides more time for the monthly map database download required in Scenario 2. Rather than requiring the 133 Mbytes or 1.33 GBytes of data to be downloaded in 45 minutes, this scenario allows 30 days. Although the merits of this approach from an end-user standpoint could be debated, this assumption allows 22.5 hours in which to download the 133 Mbytes or 1.33 GBytes of data.

Bandwidth Requirements

The data flow requirements of 8 GBytes to be downloaded over 45 minutes for Scenario 1 generate effective bandwidth requirements. To put this into perspective for the SDARS system, the average music channel uses 64 Kbits per second, and there are around 100 channels (although some are talk radio channels using lower bandwidth). The bandwidth requirements of 23.7 Mbits per second for Scenario 1 would require 370 channels of 64 Kbits per second. This represents roughly four times the total capacity of an SDARS system. This scenario is therefore not feasible to support using SDARS technology.

Scenario 2 has maximum data flow requirements of 1.33 GBytes over 45 minutes. This data flow necessitates bandwidth of 3.9 Mbits per second. This would require the equivalent of 62 SDARS music channels. Although this is technically feasible, it would require over half of the total capacity of the SDARS system to support this scenario. In assessing the minimum expected monthly data flow of 133 Mbytes over 45 minutes, the situation improves by an order of magnitude, due to the linear relationships involved. This minimum monthly data flow requires bandwidth of 400 Kbits per second. This would be technically feasible using slightly more than the equivalent of 6 SDARS music channels.

Scenario 3 improves the bandwidth requirement situation by a considerable amount. In this scenario, 22.5 hours of driving time are available during which to download either 133 Mbytes or 1.33 GBytes for the monthly map database update. The maximum 1.33 GBytes of data would require continuous bandwidth of 131 Kbits per second, which is roughly the equivalent of two SDARS music channels. The minimum monthly data flow would require only 13 Kbits per

second. This required bandwidth could likely coexist with a talk show within a single 64 Kbits per second music channel equivalent.

System Latency

System latency is not a major issue for the map database update, except in a very macro sense. As an illustration of the macro view, it is instructive to consider the Scenario 1 data flow requirement. Assuming that only one 64 Kbits per second channel equivalent could be devoted to the Scenario 1 data flow, it would take around 278 continuous hours to download the entire 8 GByte map database at 100% downloading effectiveness.

In the case of considering the SDARS system as a timing source, several issues become evident. Assuming a position on earth directly below a geosynchronous satellite, the time for electromagnetic fields (like radio waves) to propagate to the satellite and return is around 240 milliseconds. As the uplink and downlink sites diverge from the point directly below the satellite, the delay time increases in proportion to the distance. Since only the uplink site location is fixed (the vehicles are mobile), the precise delay time could only be predicted by a complex algorithm related to the specific geographic location of the vehicle. In the case of XM satellite radio system, two geosynchronous satellites, one over the Eastern United States and the other over the Western United States, receive the uplink transmission from the XM digital studio in Washington, D.C., and broadcast this data stream across the United States.

The Sirius satellite radio system uses three satellites in the same elliptical orbit. This orbit has an apogee of around 29,200 miles above the Earth as it passes over North America. The geometry of this elliptical orbit allows each satellite to spend 16 hours a day broadcasting over the United States, and the remaining six hours out of range, speeding through the perigee portion of the orbit. This arrangement allows a much higher elevation angle form the typical vehicle satellite antenna, and limits the number of terrestrial repeaters required by Sirius (compared to the geosynchronous orbit approach of XM). This elliptical orbit arrangement, however, appears to add much greater complexity to the consideration of this SDARS system as a potential timing source.

Cost Considerations

One approach toward developing a rough estimate of the cost of using the SDARS system is to consider a proration of break-even system operation. Sirius indicated that it expected to reach a cash flow break-even situation with 2 million subscribers by the end of 2005. Assuming that the average subscription revenue for Sirius is around $120 per year per subscriber, the estimated total annual revenue at cash flow break-even is $240 million. If this revenue is assumed to be equally distributed over the 100 channels, then this implies a cost of $2.4 million per year for one channel. This may be a low estimate, however, since it is based on cash flow break-even, rather than any amortization of initial system development and deployment cost.

Regarding the on-board equipment in the vehicle, the marginal cost of adding capabilities to extract map data from the overall bit stream and send it out to a navigation system, for example, over a separate data interface may be in the $20 range. Since satellite radio is being installed in an increasing number of production vehicles, this marginal cost may be the only additional cost consideration on the vehicle side to use SDARS to deliver detailed map database updates.

5.3 Potential Synergies

This section identifies implications of current research results for the deployment of communications capabilities to support EDMap type applications. It discusses potential synergies with other vehicle safety applications and with consumer applications. It also notes possibilities

for bundling/cost sharing with consumer telematics type applications and specifically considers place-based commerce applications.

5.3.1 Potential Synergies with Other Vehicle Safety Applications

One of the most pertinent considerations for the likelihood of deployment of EDMap type applications is whether other vehicle safety applications will be able synergistically to share the same on-board hardware and communications systems. If the system costs can be shared over a number of safety applications, the economic justification for any of the individual applications becomes much easier. This sharing also has a potentially significant impact on deployment timing. The incentive to deploy a particular system or technology becomes increasingly compelling as the number of safety applications the system or technology enables increases.

The most pertinent vehicle safety applications for this discussion are those being considered by the DSRC Standards Writing Group, which has had major input from the Vehicle Safety Communications (VSC) project. The following tables present these proposed vehicle safety applications, along with their basic communications requirements. The applications tables are divided into three separate tables, depending upon the potential implementation configuration of the DSRC communications technology: infrastructure-to-vehicle safety applications, vehicle-to-infrastructure safety applications and vehicle-to-vehicle safety applications.

Table 5.3–1 shows potential infrastructure-to-vehicle safety applications being considered for implementation using DSRC technology. Table 5.3–2 indicates the safety applications that would use the DSRC communications capabilities in the reverse direction, from the vehicle to the infrastructure. Table 5.3–3 lists the potential safety applications that would be enabled by vehicle-to-vehicle DSRC communications capabilities. Where applications might be implemented in several different configurations, they appear in multiple tables. The preliminary communications requirements for these applications are also shown in the three tables, in terms of the estimated communications range, latency and data rate.

Table 5.3.1 Infrastructure-to-Vehicle Safety Applications

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
GPS Corrections	100	100	3
Curve Speed Warning	300	200	1
Highway/Rail Collision Warning	300	200	1
Adaptive Headlight Aiming	100	100	1
Adaptive Drivetrain Management	100	100	1
Merge Assistant	100	100	1
Pedestrian Crossing Information	300	200	1
Pedestrian/Children Warning	300	200	1
School Zone Warning	300	200	1
Animal Crossing Zone Information	300	200	1
Sign Information	100	100	1
Low Parking Structure Warning	100	200	1
‘Keep Clear’ Warning	100	100	1

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
Wrong-way Driver Warning	100	100	1
Low Bridge Warning	300	200	1
Work Zone Warning	300	200	1
Left Turn Assistant	100	100	1
Stop Sign Movement Assistance	300	200	1
Infrastructure Intersection Collision Warning	300	100	1
Traffic Signal Warning	300	200	1
Stop Sign Warning	300	200	1
Highway/Rail Intersection Warning	300	200	1

Table 5.3.2 Vehicle-to-Infrastructure Safety Applications

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
Intelligent On-ramp Metering	100	100	1
Intelligent Traffic Lights	300	200	1
SOS Services	300	200	3
Post-Crash Warning	300	200	1
Just-in-Time Repair Notification	100	500	1
Blind Merge Warning	300	200	1

Table 5.3.3 Vehicle-to-Vehicle Safety Applications

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
Merge Assistant	100	100	1
Blind Merge Warning	300	200	1
Highway/Rail Collision Warning	300	200	1
Pre-crash Sensing	300	100	6
Cooperative Glare Reduction	100	200	1
Vehicle-based Road Condition Warning	300	200	1
V-to-V Road Feature Notification	300	200	1
Curve Speed Warning	300	200	1
Electronic Brake Lights	300	50	1
V-to-V Intersection Collision Warning	300	100	1
Lane Change Assistant	100	100	1
Blind Spot Warning	300	200	1
Post-Crash Warning	300	200	1

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
Visibility Enhancer	300	200	1
Cooperative Collision Warning	300	50	12
Approaching Emergency Vehicle Warning	1000	1000	1
Cooperative Adaptive Cruise Control	300	100	3
Hybrid Intersection Collision Warning	300	100	1
Left Turn Assistant	100	100	1
Stop Sign Movement Assistant	100	100	1

Based upon the very similar basic communications requirements, all of these vehicle safety applications were judged by the DSRC Standards Writing Group to be able to be supported by planned DSRC technology. The range requirements are within the intended range of DSRC transmissions. The planned addressing scheme lends itself readily to broadcast-type messages that can be received by vehicles or infrastructure in close proximity. The applications' latency requirements, in most cases, preclude the use of cellular technology or standard wireless local area networking technologies, like IEEE 802.11a, b or g.

If a number of these vehicle safety applications are deployed in the future using DSRC technology in the infrastructure and in the vehicles, then EDMap applications could potentially use the same equipment and systems for little or no marginal cost. It is informative to note that a number of the safety applications proposed for DSRC implementation, like "Traffic Signal Warning" and "Stop Sign Warning", also potentially require the vehicle to have some form of on-board map database. This demonstrates that EDMap type applications are closely intertwined with other potential vehicle safety applications.

For several of the safety applications, the specific deployment sites in the infrastructure appear be ideal for at least selected scenarios for deployment of EDMap applications. For example, the DSRC map database download scenario in which each traffic signal would provide a detailed update of just that immediate geographical area requires a DSRC transmitter at each equipped intersection location. This is the same infrastructure requirement as that required for deployment of a number of DSRC safety applications, such as "Left Turn Assistant", "V-V Intersection Collision Warning" and "Traffic Signal Warning".

In order to ensure that every vehicle approaching the intersection has the complete and most current map database information for that immediate area, this information would be expected to be received every time the vehicle approaches that intersection. This scenario assumes that a repeating, periodic broadcast of the map database information associated with that particular intersection would be available from a DSRC RSU associated with that intersection.

Further in the future, there is a potential for Ultra-Wideband (UWB) vehicle safety sensors to become communications capable. At the present time (February 2004) – FCC rules allow only indoor or handheld UWB units to have communications capabilities, but this could probably be modified if vehicle safety applications could use these capabilities effectively. In any event, the low transmit power allowable for UWB devices in the United States would probably relegate such communications to distances in the 20 meter range. If these were fairly inexpensive vehicle sensor units that were being installed for vehicle safety applications anyway, then the marginal cost of EDMap map database downloads in a home garage situation would be the cost of a garage-mounted transceiver and additional connection charges, if any, for high-speed Internet access.

5.3.2 Potential Synergies with Consumer Applications

Some forms of consumer applications using wireless data communications to and from the vehicle are already being marketed. For example, IEEE 802.11b "WiFi" is being used in aftermarket products to download MP3 music files to vehicles in home garage locations. At the present time, IEEE 802.11b operates at a maximum speed of 11 Mbits per second. At this bandwidth, it would take over an hour and a half to download the nationwide (8 MByte) map database. However, a higher speed version, IEEE 802.11g has recently reached the market. This version is backward compatible with IEEE 802.11b, but provides 54 Mbits per second of data bandwidth. (http://standards.ieee.org/announcements/80211gfinal.html). At the maximum IEEE 802.11g data transmission speed, it would take around 20 minutes to download the nationwide (8 MByte) map database.

Bluetooth is also currently being marketed for automotive applications. At this time it is primarily being used to provide handsfree cellular voice capabilities in the vehicle, using the standard cellular handset for wide area connectivity. Bluetooth has a data rate of 1 Mbits per second. At this data rate, it would take around 18 hours to download the nationwide (8 MByte) map database.

The DSRC Standards Writing Group has considered a number of potential consumer-type applications for possible DSRC deployment. These are presented and discussed in the two following sections. Most of these applications appear to have some commercial potential, although business cases were not part of the DSRC Standards Writing Group considerations of these applications. If some of these applications did prove to be commercially viable, however, they would be able to help defray the costs for safety applications. This situation would provide the best form of synergy with EDMap applications, since they would be subsidized by revenue-producing applications.

Bundling Potential with Place-Based Commerce Applications

Table 5.3–4 shows seven place-based applications considered by the DSRC Standards Writing Group. These range from traveler information like point-of-interest notification, to electronic payments at specific service points. These applications assume that vehicles are equipped with DSRC communications, and that the relevant infrastructure locations are similarly equipped.

Table 5.3.4 Place-Based Applications

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
Point-of-Interest Notification	100	200	1
Toll Collection	50	50	1
Parking Payment	10	500	1
Food Payment	10	500	1
Fuel Payment	10	500	1
Rental Car Processing	50	100	1
Access Control	10	500	1

A number of other place-based commerce applications have been identified in the context of e-commerce. These include electronic advertisements relevant to the immediate geographical location. These could be updated in real time, for example: “Special for the next five minutes, buy a hamburger and get a soft drink for free”.

Additionally, place-based surveys have been proposed. In this application, similar to probe vehicle data collection, the survey would collect information from each passing vehicle to determine, for example, how many vehicles pass this location during different hours of the day.

From a privacy perspective, any of these potentially intrusive applications would need to be permission-based in order to be acceptable to consumers (and, by extension, automobile manufacturers).

Businesses that benefit from these revenue-producing applications may be willing to bundle map database updates with their own services. This may serve the self-interest of the businesses, since accurate on-board map databases would be necessary to support many of the place-based commerce applications. If your business was running a chain of gas stations, for example, it may be very much worthwhile to make sure that vehicles have the latest map database updates, complete with the locations and current information about all of your gas stations.

Cost Sharing Potential with Other Consumer Applications

The DSRC Standards Writing Group has also identified the other consumer applications shown in Table 5.3–5. These include various ITS information and entertainment services, as well as the means to remotely pay for these services. Additionally, vehicle diagnostics, software updates and repair applications have been considered.

Table 5.3.5 Other Consumer Applications

APPLICATION	Comm. Range (meters)	LL Total Latency (millseconds)	Min. Datarate (MBps)
ITS Service Payment	50	50	1
Other ePayments	50	200	1
Probe Data Collection	50	200	1
Traffic Information	50	100	1
Traveller Information	100	100	1
Mobile Internet	100	100	6
Vehicle Registration	100	200	1
Audio Transfer – Streaming	300	100	6
Audio Transfer – Block	10	200	6
Video Transfer – Streaming	1000	500	12
Video Transfer – Block	10	200	12
Repair Service Record	10	500	1
Diagnostic Data Transfer	10	500	1
Vehicle Software Updates	10	500	1
Enhanced Route Guidance and Navigation	100	100	3
Map Downloads and Updates	100	100	6

Music downloading applications, for example, have many of the same system and communications requirements as map database downloads. If the systems are to be used for both purposes, the value equation for the end-user does not have to justify the entire cost of the system just on one of the applications. The system cost can be shared between the different applications, making it more likely that the consumer would choose to make this investment.

5.4 Potential Communications Impediments to Deploying EDMap Type Applications

This section identifies potential impediments to the deployment of EDMap type applications in the identified timeframes due to communications issues. The discussion is based upon issues arising from technological capabilities, deployment time frames and geographical coverage. It also identifies and discusses issues related to cost considerations.

5.4.1 Communications Issues

A number of EDMap type applications depend upon wireless communications capabilities as enabling technology. This section focuses on potential impediments relating to certain wireless technologies. These wireless technologies might both provide timely, detailed map database updates to vehicles and collect probe vehicle data to enhance the accuracy of map databases. The communications portions of GPS systems, as well as Differential GPS systems, are discussed elsewhere.

5.4.2 Technological Capabilities

For 2.5G cellular data networks, there are fairly extreme technological capabilities issues relating to map database downloads and updates. The CDMA version, 1xRTT, which is faster than GPRS, would require around 254 hours of continuous operation to download the 8 GByte nationwide map database.

The higher speed 2.5G EDGE technology for GSM has a theoretical maximum data rate of 384 Kbits per second, but only about 120 Kbits per second realizable in actual practice. At this rate, the nationwide map database could be downloaded in around 46 hours. The 1xEVDO technology has a theoretical maximum data rate of 2.4 Mbits per second, but only about 50% achievable in the field. This technology would be able to download the nationwide map database in around 15 hours.

Bluetooth has similar technological constraints for map database downloading, due to the data speed of this technology. Bluetooth has a data rate of 1 Mbits per second. At this data rate, it would take around 18 hours to download the nationwide (8 GByte) map database.

DSRC has technological constraints relating to some implementation approaches for map database downloading. The most stressing data flow situation identified was where vehicles approach a major metropolitan area at highway speed and require an entire 800 MByte regional map database download. The required bandwidth for this approach would be around 711 Mbits per second. Even the anticipated monthly regional map database update of 73 MBytes would require an effective bandwidth of around 65 Mbits per second. The maximum data rate for DSRC technology is 27 Mbits per second, so there is clearly a bandwidth constraint with using DSRC in this implementation approach.

In a map database downloading approach using DSRC technology in the home garage to communicate to the vehicle, the entire North American map database was considered as the stressing data flow requirement. The WAVE/DSRC radio would be able to operate in “native”

IEEE 802.11a mode. This approach would allow the entire 8 GByte map database to be downloaded in around 20 minutes. The expected maximum monthly update for the North American map database, however, would take just over 3 minutes using this approach.

The digital television (DTV) technology being used in the United States is not well-suited for mobile reception. Therefore, DTV is not expected to be feasible for map database downloads in the United States.

The widely-deployed IEEE 802.11b wireless network technology operates at a maximum speed of 11 Mbits per second. At this bandwidth, it would take over an hour and a half to download the nationwide (8 GByte) map database. A higher speed version, IEEE 802.11g that is backward compatible with IEEE 802.11b, provides 54 Mbits per second of data bandwidth. At this speed, it would take around 20 minutes to download the nationwide (8 GByte) map database.

Based upon the developments over the past two years, it appears that the SWS radar communications technology will not be relevant for EDMap safety applications.

The current capabilities of Remote Keyless entry technology are not conducive to providing support for EDMap applications. Major changes in this technology are not expected, so it will remain unsuitable for EDMap applications.

Satellite Digital Audio Radio Service (SDARS) has serious data flow limitations when considered for map database downloading. One approach considered would require over half of the total capacity of an SDARS system. In a downloading approach that allows 22.5 hours of driving time to download 133 Mbytes for the monthly nationwide map database update, the data flow would require only 13 Kbits per second. This bandwidth is expected to be available within a single 64 Kbits per second music channel equivalent along with other services, for example, a talk radio service. However, if only one 64 Kbits per second channel equivalent was being used to download the entire 8 GByte nationwide map database, it would take around 278 continuous hours. Since this is a satellite-based service, the download time would need to be conducted while the vehicle has a clear view of the satellite. When considering the SDARS system as a potential timing source, the inherent transmission delay, with unpredictability especially relevant to the elliptical orbit system, becomes a major feasibility constraint.

The potential for datacasting over terrestrial digital radio using In-Band, On-Channel (IBOC) technology is expected to be realized only over a long time period. After the expected 10-15 year transition period to digital radio, an all-digital mode of operation can be achieved. This all-digital mode could potentially offer around 200 Kbps of data capacity. With this data rate, the anticipated monthly regional map database update of 73 MBytes would require around 49 minutes of continuous download time.

Available mobile data services using two-way satellite technology have rather limited data capacity. One of the most significant limitations of using satellite-based communications is that generally a clear path must exist from the antenna on the vehicle to the relevant satellite. Satellite technology does not work in garages, urban canyons or under dense foliage.

The potential for low-cost, small size UWB devices, to be used in an integrated communications, positioning and radar solution, makes UWB a possible future communications technology for EDMap applications. This technology is still very new, so it is likely to take a number of years before its true potential for EDMap applications can be assessed. Under the present FCC rules, the low transmit power allowable for UWB devices in the United States probably relegates UWB communications to maximum distances around 20 meters.

5.4.3 Deployment Time Frames

The present rapid deployment of the 2.5G data services is likely to delay the deployment of higher speed cellular data technologies, like EDGE for GPRS, and 1xEVDO for 1xRTT. The installed base of current of existing GPRS and 1xRTT technologies may also delay the eventual movement to 3G cellular network technologies. There may also be significant communications constraints for these technologies outside major metropolitan areas and along major interstate routes, since 2.5G data capabilities are unlikely to be widely deployed in rural areas

There are still indications that Bluetooth technology will achieve major deployment penetration. Although sales of 88 million units are expected in 2004, the widespread adoption of Bluetooth technology is likely to be several years later than previously predicted, and the previous forecasts of ubiquitous deployment are no longer common.

The DSRC Standards Writing Group schedule for IEEE P1609 upper layer WAVE/DSRC and P1556 WAVE/DSRC security standards predicts completion of these standards by mid-2005. The SAE vehicle safety message set standards are also expected to be developed, validated and tested in the same time frame. This schedule predicts initial WAVE/DSRC application deployments in 2007, and safety application deployment 2010. However, without a significant regulatory initiative, it could be expected to take at least 5-8 years after 2010 to have a majority of intersections and vehicles equipped with WAVE/DSRC transceivers.

For probe vehicle data collection, initial major deployments of WAVE/DSRC are also expected to begin around 2010. However, the number of fixed collection points likely within the ten-year time frame may not adequately support the degree of granularity desired for real time traffic speed per road segment application scenario using fixed collection points.

The deployment of High Altitude Platforms seems to remain at the academic and public sector planning stage. There has been no major progress in High Altitude Platform deployment since the Task 8A report was written. Until there are valid deployment plans, this technology must be considered as not relevant for EDMap applications.

IEEE 801.11b “WiFi” prices have continued to drop, and deployment of these devices has proceeded rapidly. The risk factor that should be considered is that the overwhelming success of WiFi at 2.4 GHz may slow or stall the large-scale deployment of 5 GHz 802.11a technology. This could have an impact on the prices and availability of 5 GHZ 802.11 chipsets, which could also negatively affect WAVE/DSRC deployment.

The expected completion date for NDGPS nationwide single coverage is now December 2005, rather than 2003. The completion of nationwide double coverage will likely require several years beyond 2005. If these completion dates continue to slip, this may present an impediment to the deployment of EDMap applications in the anticipated time frames.

Useful deployment of effective datacasting IBOC technology is expected to be realized only over a long time period. Only after the expected 10-15 year transition period to digital radio will the all-digital mode of operation be achieved, enabling useful datacasting bandwidth.

The deployment of UWB has recently been enabled by FCC rulemaking. With the positive FCC rulemaking, the potential of UWB for very short range communications can be explored. However, longer range applications that require higher transmission power may not be allowed in the United States.

5.4.4 Geographic Coverage

For DSRC, coverage considerations are strongly related to the deployment expectations. Major application deployment is not expected to begin until 2010, and this is expected to require 5-8 additional years to achieve major geographic coverage. A vehicle-by-vehicle, market-driven approach might allow private coverage to develop more quickly in conjunction with other applications, like driver information and entertainment, which would also use DSRC technology and home garage wireless access points with Internet connectivity.

The digital information in a SDARS system is transmitted to the entire United States at the same time. In a point-to-multipoint broadcast system like SDARS, the same information can be simultaneously sent to, and potentially received by, every vehicle in the United States, with significant coverage extending into Canada and Mexico. The related constraint is that information of importance to just one region must be sent to the entire country.

5.4.5 Cost Considerations

Data capabilities on 2.5G wireless networks remain costly at the present time. For example, Sprint PCS is presently charging around $120 per month for unlimited 1xRTT data communications usage. AT&T Wireless charges $13 per month for 4 megabytes of data communication, and $100 per month for 100 megabytes, plus $.001 per kilobyte over 100 megabytes. Using the AT&T cost structure, it would cost approximately $8000 to download the nationwide map database. The higher speed EDGE and 1xEVDO technologies require fairly significant network investments, and costs to end-users for these enhanced services are therefore higher.

For one of the approaches to probe vehicle data collection, where a small packet of data is sent every ten seconds of vehicle operation, approximately 632 kilobytes of data will be sent in each month. Using the AT&T 4 megabyte rate, the proportionate cost for this data would be around $2 per month per probe vehicle. This wireless connection also requires a cellular modem to be installed and connected to the vehicle network systems as well as a basis monthly subscription fee (around $10-15 per month) to be paid to the wireless carrier.

WAVE/DSRC roadside units (RSUs) for probe vehicle data collection are expected to cost around $500, when installed in existing controller cabinets that already have power and data backhaul connections. Installations where foundations must be prepared, equipment cabinets installed, and power and data connections provisioned are likely to be an order of magnitude more costly. The cost of the WAVE/DSRC on-board unit (OBU) is expected to be in the $100 range. IEEE 802.11a access points are currently available at prices around $200. In the case where the OBU is installed in the vehicle to support vehicle safety applications as a primary function, then the marginal cost for the map database update capability in the vehicle might be considered to be zero.

A rough estimate of the cost of using the SDARS system was developed by using a proration of break-even system operation. Based upon financial information from Sirius satellite radio, and a series of assumptions, a cost of $2.4 million per year for one channel was estimated. For the on-board equipment in the vehicle, the marginal cost of adding capabilities to extract map data from the overall bit stream and send it out to a navigation system, for example, over a separate data interface was estimated to be in the $20 range.

If fairly inexpensive UWB vehicle sensor units were being widely installed for vehicle safety applications, then the marginal cost of adding EDMap map database download capabilities in a home garage situation would be the cost of a garage-mounted transceiver and additional connection charges, if any, for high-speed Internet access.

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Appendix C Technical Information

Vehicular Navigation and Positioning Deployment Study

Introduction

Figure A1–1. Background of CAMP Task 8 Report 1.1a

Motivation and Goals (for Task 8 Studies)

- Provide an overview of in-vehicle and infrastructure-related equipment and capabilities for enhanced digital map (EDMap) safety-focused applications.
- EDMap Project concentrates on – specification, – formation and – maintainability of EDMap databases for vehicle applications with high safety benefit potential.
- Investigate factors external to EDMap Project but of relevance and importance: – vehicle positioning and – communications.
- Provide a reality check to insure that vehicle positioning and communications developments will be able to support EDMap applications.

Parts of Task 8

- 8A – At beginning of the EDMap Project; provides advice to Project and serves as reference point for addressing organizations to influence development of capabilities beneficial to DOT and OEM safety application interest.
- 8B – Near end of EDMap Project; addresses advances made during the project and clarifies policy, institutional and technology concerns and potential.

Independent Consultants Contracted with for Task 8A Study

- Honeywell Sensor and Guidance Products Division – Vehicle positioning study
- Schaffnit Consulting – Communication study

K.O. McDonald Rev. 1, 2.20.04

Vehicular Navigation and Positioning Deployment Study

Figure A1–2. Conclusions and Findings of 8A Report (2/4) 1.2b

At Interim Point (2002), View for Positioning was:

- GPS modernization enhancements, including two more civil signals (at L2 and L5) should improve standalone receiver performance to 20cm. early in next decade.
- Removal of Selective Availability in May, 2000 has resulted in reduced DGPS network interest, especially in the National DGPS covering the continental U.S.
- Availability of DGPS corrections appears to be limiting capability in positioning
- Extending NDGPS to continental coverage with an upgrade to provide carrier phase corrections appears necessary for accuracies consistent with IMU developments.
- investigations into synchronizing NDGPS signals with GPS should be supported
- Micro electronic machine (MEM) technology IMU developments have progressed to where the 10^{+} year expectations now appear viable in a 5 year period.
- MEMs IMU cost is primarily a function of production volume.

K.O. McDonald Rev. 1, 2.20.04

Vehicular Navigation and Positioning Deployment Study

Figure A1–3. Conclusions and Findings of 8A Report (3/4)

1.2c

Key Findings: At Interim Point (2002), View for Communications was:

- EDMap communication needs are not going to be met by cellular networks
- More than one comm. technology will be required to meet all EDMap needs
- Candidates include: – digital TV, – digital radio, – 3G cellular and especially – Digital Short Range Communications (DSRC)
- With comm. combinations, it appears that all EDMap needs can be met
- Communication market predictions are very difficult and are affected by – financial health of the nation, almost as much as – technological issues
- Keeping maps up-to-date is critical for many EDMap applications
- Several developing technologies may provide this capability within 10 years
- Earlier deployment of EDMap would require a clear push from industry

K.O. McDonald Rev. 1, 2.28.04

Vehicular Navigation and Positioning Deployment Study

Figure A1–4. Recommendations of 8A Report

1.2e

Recommendations:

1. **Encourage deployment of a nationwide NDGPS network providing time synchronized carrier phase corrections.**
2. **Ensure that INS developments are available to commercial markets and not restricted in their use.**
3. **Ensure that DSRC can support EDMap applications in vehicle-to-vehicle and vehicle-to-infrastructure scenarios**
4. **Encourage the deployment of digital terrestrial broadcast capabilities for the local (tens of miles) distribution of data.**

K.O. McDonald Rev. 1, 2.28.04

Appendix D Glossary of Terms

The following pages contain a glossary of terms for GPS. They are not specific to vehicular navigation. A glossary for communications technology can be found at the website: www.gsmworld.com/technology/glossary.shtml.

GPS Glossary of Terms

Based upon the acronyms on the web page of the IGEB (Interagency GPS Executive Board) Modified and updated by Keith D. McDonald, Navtech Seminars

Absolute Positioning

Positioning mode in which a position is identified with respect to a well-defined coordinate system, commonly a geocentric system (i.e., a system whose point of origin coincides with the center of mass of the earth).

Accuracy

The degree of conformance between the estimated or measured position, velocity, and/or time of a GPS receiver and its true position, time and/or velocity as compared with an accepted standard. Radionavigation accuracy is usually presented as a statistical measure of error and can be characterized as follows:

- **Predictable** The accuracy of a radionavigation system's position solution with respect to the geodetic or the most accurately known position information. Both the navigation system position solution and the reference information must be based upon or converted to the same geodetic datum.

- **Repeatable** The accuracy with which a user of a navigation system can return to a position whose coordinates have been measured at a previous time with the same navigation system.

- **Relative** The accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time. For real time applications, this normally requires the use of a data link between the two.

Almanac

A data file for a given constellation that contains coarse orbit information for all satellites. At times the almanac is considered to also include clock corrections and atmospheric delay parameters but these are provided in separate sub frames of the GPS data message. Each GPS satellite transmits the almanac in order to facilitate rapid satellite vehicle acquisition by GPS receivers.

Ambiguity or carrier cycle ambiguity

The number (N) of whole carrier signal wavelengths (cycles) between a GPS satellite and a GPS receiver. This is important in the use of relative carrier phase measurement techniques.

Analog

A type of transmission characterized by variable values representing information, contrasted with the typical binary or n-ary characteristics of digital data. A clock with moving hands is an analog device, whereas a clock with electronically displayed numbers is a digital device. Modern computers are invariably digital, but when they communicate over telephone lines, their signals must be converted to analog form using a modem (a modulator/ demodulator). The analog signal is converted back to a digital form before being delivered to the destination computer.

Anti-Spoofing

Anti-spoofing (A-S) in GPS is the process whereby the P-codes used in the precise positioning service (PPS) are encrypted. The resulting encrypted codes are known as the Y-code. The Y-codes can be used only by receivers with decryption capability. This mode of operation provides protection to equipped GPS user equipment from signal spoofing, or the transmission of signals replicating the true GPS signals, by adversaries. The use of these signals could cause hazardous and misleading information to GPS users unless anti-spoofing methods, such as signal encryption, are employed.

Anywhere Fix

The ability of a receiver to start position calculations without being given an approximate location and time.

Apogee

The point in the orbit of a satellite that is the greatest distance from the center of the earth or other central force field.

Application Software

These programs accomplish the specialized tasks of the user, while operating system software allows the computer to functionally operate as designed. A computer-aided dispatch system is application software, as are word processing and graphics programs.

Automatic Vehicle Location—AVL

A type of system using any technology to track or automatically locate a vehicle.

Availability

The percentage of time that the services of a navigation system can be used within a particular coverage area. Signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the operational environment and the technical capabilities of the transmitter facilities.

Bandwidth

The range of frequencies, usually specified at a given power spectral and receiver density level.

Baseline

A baseline consists of the resultant three dimensional vector between a pair of GPS stations for which simultaneous GPS data is obtained. Also, the vector distance between two points.

Base Station

A base station is a GPS receiver set up at a known position specifically to collect differential correction data for other GPS receivers. Base station data is used to calculate errors relative to its known position. The "relative difference" between the base station's known position and the position calculated from GPS satellite signals become the corrections for other GPS receivers collecting data during the same time period. Correction can be transmitted in real-time, or used during later post-processing. Also called a reference station.

Block I, II, IIR, IIF Satellites or Spacecraft (S/C)

The various generations of GPS satellites: Block I were prototype satellites that began launch in 1978; Block II satellites are operational spacecraft used to populate the 24 operation slots in the NAVSTAR constellation; Block IIR S/C are replenishment satellites; and Block IIF S/C are the follow-on generation of GPS S/C.

Bluetooth

A short range wireless communication technique.

C/A-Code

The coarse/acquisition code is modulated onto the GPS L1 signal. This code is a sequence of 1023 pseudorandom binary bits modulated on the GPS carrier at a chipping rate of 1.023 Mcps, resulting in a code repetition period of 1 millisecond. The code was selected to provide good acquisition properties. Also known as the "civil code."

Carrier

A radio signal having frequency and amplitude that may be varied from a reference value by modulation.

Carrier-Aided Tracking

A signal processing technique that uses the GPS carrier signal to reduce the noise level of the pseudorandom code.

Carrier Frequency

The frequency of the unmodulated fundamental output of a radio transmitter. The GPS L1 carrier frequency, for example, is 1575.42 MHz.

Carrier Phase

In GPS relative phase, measurements based on the L1 or L2 carrier signals.

Cartesian/Geocentric Coordinates

A system of defining position, which has its origin at the center of the earth with the x- and y-axes in the plane of the equator. Typically, the x-axis passes through the meridian of Greenwich, and the z-axis coincided with the earth's axis of rotation.

Channel

A channel of a GPS receiver consists of the circuitry necessary to receive the signal from a single GPS satellite.

Chip

The length of time to transmit either a "0" or a "1" in a binary pulse code. Also, an integrated circuit.

Chip rate

Number of chips per second. For example, C/A code = 1.023 MHz.

Circular Error Probable—CEP

In a circular normal distribution, the radius of the circle containing 50 percent of the individual measurements being made, or the radius of the circle within which there is a 50 percent probability of being located.

Clock bias

The difference between the GPS receiver clock's indicated time and GPS time as established by the control segment.

Clock Offset

The difference in the time reading between two clocks.

Code Division Multiple Access—CDMA

A method of frequency reuse whereby many radios use the same frequency but each one has a unique code. GPS uses CDMA techniques with Gold's codes for their unique cross-correlation properties.

Code Phase GPS

GPS measurements based on the pseudo random code (C/A or P) as opposed to the carrier of that signal.

Compass Engine

A device that converts an earth reference magnetic signal to an analog or digital indication of direction relative to true north.

Control Point

A point at which coordinates have been assigned. These coordinates can be held fixed and used in other dependent surveys

Control Segment

A worldwide network of GPS monitor and control stations that ensure the accuracy of satellite positions and their clocks.

Coordinate System

One of a number of mapping systems used to represent positions. Examples are latitude/longitude and state plane.

Cycle Slip

A discontinuity in the measured carrier beat phase resulting from a temporary loss-of-lock in the carrier-tracking loop of a GPS receiver.

Data Message

A message included in the GPS signal, which reports the satellite's location, clock corrections and health. Included is rough information about the other satellites in the constellation.

Datum

A datum is a horizontal or vertical reference system for making survey measurements and computations. Horizontal datums are typically referred to as ellipsoids, the State Plane Coordinate System, or the Universal Transverse Mercator Grid System. Vertical datums are typically referred to as the geoid. Improving technology has led to more precise values for the same geographic points over time. To use recently collected data in conjunction with preexisting data, it is necessary to match datum and coordinate systems between the data sets. Some examples of datums are NAD-27 and WGS-84 (North American Datum 1927, World Geodetic System 1984).

Differential GPS—DGPS

A technique used to improve positioning or navigation accuracy by determining the positioning error at a known location and subsequently incorporating a differential correction factor (by real-time transmission of corrections or by postprocessing) into the position calculations of another receiver operating in the same area and simultaneously tracking the same satellites.

Differential Correction

A process for canceling out man-made and natural errors in the GPS signal. Requires the use of another GPS receiver set up on a position with known location. The receiver on the known location computes its location with the GPS satellite data and compares this position with the known value for its actual, known, position. This difference (hence differential) is the error in the transmitted GPS signal. The differential value is then used for correcting, either in real-time or during post processing, the positions collected by other GPS receivers during the same time period, observing the same satellites.

Digital

Generally, information is expressed, stored and transmitted by either analog or digital means. In a digital form, this information is seen in a binary state as either a one or a zero, a plus or a minus. The computer uses digital technology for most actions.

Digital Map

Computer Database containing roadway map data.

Dilution of Precision—DOP

A description of the purely geometrical contribution to the uncertainty in a position fix. Standard terms for the GPS application are: GDOP: Geometric (3 position coordinates plus clock offset in the solution) PDOP: Position (3 coordinates) HDOP: Horizontal (2 horizontal coordinates) VDOP: Vertical (height only) TDOP: Time (clock offset only) RDOP: Relative (normalized to 60 seconds).

Distance Root Mean Square—drms

The root-mean-square value of the distances from the true location point of the position fixes in a collection of measurements. As typically used in GPS positioning, 2 drms is the radius of a circle that contains at least 95 percent of all possible fixes that can be obtained with a system at any one place.

Dithering

The deliberate introduction of digital noise. This is the process the DoD used to add inaccuracy to GPS signals to induce Selective Availability.

Doppler-Aiding

A signal processing strategy that uses a measured doppler shift to help the receiver smoothly track the GPS signal. Allows more precise velocity and position measurement.

Doppler Shift

The apparent change in the frequency of a signal caused by the relative motion of the transmitter and receiver.

Earth-Centered Earth-Fixed—ECEF

Cartesian coordinate system where the X direction is the intersection of the prime meridian (Greenwich) with the equator. The vectors rotate with the earth. Z is the direction of the spin axis.

Eccentricity

The ratio of the distance from the center of an ellipse to its foci on the semi major axis.

Elevation

The height above a point of reference. For example, height above mean sea level, or vertical distance above the geoid.

Elevation Mask Angle

Usually a user definable angle (in degrees) below which a satellite will be tracked, but not used as a data source for position calculations. This value is set to avoid interference problems caused by ionospheric refraction, multipath errors, obstructions such as buildings and trees, etc.

Ellipsoid

In geodesy, a mathematical figure formed by revolving an ellipse about its minor axis. It is often used interchangeably with spheroid. Two quantities define an ellipsoid, the length of the semi major axis, a, and the flattening, f = (a - b)/a, where b is the length of the semiminor axis. Prolate and triaxial ellipsoids are always described as such.

Ellipsoid Height

The measure of vertical distance above the ellipsoid. Not the same as elevation above sea level.

Ephemeris

The predictions of current satellite positions transmitted to the user in the data message. A list of accurate positions or locations of a celestial object as a function of time. Available as "broadcast ephemeris" or as postprocessed "precise ephemeris."

Epoch

Measurement interval or data frequency, as in making observations every 15 seconds.

External Oscillator

A stable frequency unit typically used as a clock, external to the device that it is used with, such as a GPS receiver

Fast-Multiplexing Channel

See Fast-switching channel

Fast-Switching Channel

A single channel, which rapidly samples a number of satellite ranges. "Fast" means that the switching time is sufficiently fast (2 to 5 milliseconds) to recover the data message.

Floating Car Data Collection

Data collection based on automobiles becoming information fathering agents for traffic monitoring systems.

Frequency Spectrum

The distribution of signal amplitudes as a function of frequency of the constituent signal waves.

Geodesy

The science related to the determination of the size and shape of the Earth (geoid) by direct measurements.

Geodetic Datum

A mathematical model designed to best fit part or all of the geoid. It is defined by an ellipsoid and the relationship between the ellipsoid and a point on the topographic surface established as the origin of datum.

Geodetic Surveys

Global surveys done to establish control networks (comprised of reference or control points) as a basis for accurate land mapping.

Geoid

The particular equipotential surface that coincides with mean sea level and that may be imagined to extend through the continents. This surface is everywhere perpendicular to the force of gravity.

Geoid Height

The height above the geoid is often called elevation above mean sea level.

Geometric Dilution of Precision (GDOP)

see Dilution of Precision

Global Navigation Satellite System—GLONASS

The Russian equivalent to the American NAVSTAR GPS. GLONASS was designed to provide worldwide coverage. GLONASS has three orbital planes containing eight satellites each, when all slots are filled. GLONASS satellites are failing at a much higher rate than they are being replenished, leaving the system operating a diminishing capacity.

Global Navigation Satellite System—GNSS

Organizing concept of a system that would incorporate GPS, GLONASS, and other space-based and ground-based segments to support all forms of navigation.

Global Positioning System—GPS

A DOD conceived, implemented and operated constellation of 24 satellites orbiting the earth at a nominal altitude of 11,000 miles. GPS satellites transmit signals that allow the accurate determination of GPS receiver locations. Receivers can be located at fixed locations, moving on the earth's surface, in the earth's atmosphere, or in low-Earth orbit. GPS is used in air, land and sea navigation, mapping, surveying and other applications where precise positioning is necessary. The GPS signal is provided free of charge to anyone on or near the planet with a GPS receiver and an unobstructed view of the satellites.

GPS ICD-200

The GPS Interface Control Document is a government document that contains the full technical description of the interface between the satellites and the user.

Handover Word

The word in the GPS message that contains synchronization information for the transfer of tracking from the C/A to the P-code.

Hardware

The physical components of a system that uses coded instructions to accomplish a task or operation. Reference is often made to computer "hardware" and "software"; in that context, 'hardware" consists of the computer (case, motherboard, etc) input and output devices and other peripheral equipment.

Integrity

The ability of a system to provide timely warnings to users when the system should not be used for navigation as a result of errors or failures in the system.

Interface

A shared boundary between various systems or programs. An interface is also the equipment or device that facilitates the interoperation of two or more systems.

Interferometry

Process of measuring phase difference between two antennae to establish angular direction.

Ionosphere

The band of charged particles between the stratosphere and the exosphere 50 to 250 miles above the earth's surface which represent a nonhomogeneous and dispersive medium for radio signals.

Ionospheric Delay

A wave propagating through the ionosphere experiences delay. Phase delay depends on electron content and affects carrier signals. Group delay depends on dispersion in the ionosphere as well and affects signal modulation (codes). The phase and group delay are of the same magnitude but opposite sign.

Ionospheric Refraction

The change in the propagation speed of a signal as it passes through the ionosphere.

Kalman Filter

A numerical method used to track a time-varying signal in the presence of noise.

L-Band

The group of radio frequencies extending from 390 MHz to 1550 MHz. The GPS carrier frequencies (1227.6 MHz and 1575.42 MHz) are in the L-band.

L1 Signal

The primary L-band signal transmitted by each GPS satellite at 1575.42 MHz. The L1 broadcast is modulated with the C/A and P-codes and with the navigation message.

L2 Signal

The second L-band signal is centered at 1227.60 MHz and carries the P-code and navigation message.

L5 Signal

The third L-band signal is centered at 1176.45 MHz, and carries pseudorange data at present. It will be upgraded in the future.

MDT—Mobile Data Terminal

A device, typically installed in a vehicle consisting of a small screen, a keyboard or other operator interface, and various amounts of memory and processing capabilities.

Monitor Stations

One of the worldwide group of stations used in the GPS control segment to track satellite clock and orbital parameters. Data collected at monitor stations are linked to a master control station at which corrections are calculated and from which correction data is uploaded to the satellites as needed.

Multichannel Receiver

A receiver containing multiple independent channels, each of which tracks one satellite continuously, so that position solutions are derived from simultaneous calculations of pseudoranges.

Multipath

Errors caused by the interference of a signal that has reached the receiver antenna by two or more different paths. Usually caused by one path being bounced or reflected from nearby structures or other reflective surfaces. Signals traveling longer paths produce higher (erroneous) pseudorange estimates and, consequently, positioning errors.

Multiplexing Channel

A receiver channel through which a series of signals from different satellites can be sequenced.

NAD-27

North American Datum of 1927. Obsolete horizontal datum of North America. NAD 27 depends upon an early approximation of the shape of the earth, known as the Clarke Spheroid of 1866, designed to fit only the shape of the conterminous United States, and utilizing a specific Earth surface coordinate pair as its center of reference.

NAD-83

North American Datum of 1983. NAD 83 relies on the more precise Geodetic Reference System of 1980 (GRS 80).

NAVD-88

North American Vertical Datum of 1988. Effort underway by the National Geodetic Survey (NGS) to readjust the North American Vertical Datum. The NAVD 88 readjustment will remove distortions from the continent-wide vertical geodetic (height) reference system.

Nanosecond

One billionth of a second.

Nav Message

The 1500-bit navigation message broadcast by each GPS satellite at 50 bps on the L1 and/or L2 signals. This message contains system time, clock correction parameters, ionospheric delay model parameters, and the vehicle's ephemeris and health. The information is used to process GPS signals to give user time, position, and velocity.

NAVSTAR

The name given to the American GPS satellite constellation. NAVSTAR is an acronym for NAVigation Satellite Timing and Ranging. . The fully operational constellation is composed of six orbital planes, each containing four satellites. At present, a total of 27 healthy satellites are aloft in the NAVSTAR system; the full complement of 24 along with the 3 additional satellites that are used as spares. Follow-on satellites are constructed and awaiting launch as needed or desired.

Observation

The period of time over which GPS two or more receivers collect GPS data simultaneously.

P-code

The precise or precision code of the GPS signal, typically used alone by U.S. and allied military receivers. A very long sequence of pseudo-random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz, which repeats about every 267 days. Each one-week segment of this code is unique to one GPS satellite and is reset each week.

PDOP—Position Dilution of Precision

A figure of merit (used without units) expressing the relationship between the error in user position and the error in satellite position, which is a function of the configuration of satellites from which signals are derived in positioning (see DOP). Geometrically, PDOP is proportional to 1 divided by the volume of the pyramid formed by lines running from the receiver to four observed satellites. Small values, such as "3", are good for positioning while higher values produce less accurate position solutions. Small PDOP is associated with widely separated satellites.

PDOP Mask

Usually a user-definable upper limit for the PDOP you will tolerate during collection of a dataset. If PDOP rises above the pre-set limit, GPS data collection will be suspended until the PDOP decreases below the limit.

Perigee

The point in the orbit of a satellite that is the least distant from the center of the earth.

Phase Lock

The technique whereby the phase of an oscillator signal is made to follow exactly the phase of a reference signal. The receiver first compares the phases of the two signals, then uses the resulting phase difference signal to adjust the reference oscillator frequency. This eliminates phase difference when the two signals are next compared.

Point Positioning

A geographic position produced from one receiver in a standalone mode.

Position

The latitude, longitude, and altitude of a point. An estimate of error is often associated with a position.

Post-Processed Differential GPS

Using post-processed differential GPS data collection techniques, base and roving receivers have no data link between them. Each receiver independently records data that will allow differential correction when processed with data from other receivers collecting during the same time period. During collection, the same set of satellites must be in view of all receivers collecting data for later combined processing. Differential correction software is used to combine and process the data collected.

Precise (or Protected) Code (P-Code)

A sequence of pseudo-random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz, which repeats every 267 days. Each 1-week segment of code is unique to a particular satellite and is generally reset each week.

Precise Positioning Service (PPS)

The highest level of military dynamic positioning accuracy provided by GPS, using the dual-frequency P-code.

Proportional error

One means of expressing positional accuracy, expressed as the position error divided by the distance to the origin of the coordinate system used, stated in parts per million (ppm).

Pseudolite (shortened form of pseudo-satellite)

A ground-based transmitter that mimics a GPS satellite. Intended to improve geometric solutions in a local area. The data portion of the signal may also contain differential corrections that can be used by receivers to correct for GPS errors.

PRN—Pseudorandom Noise

A sequence of digital 1's and 0's that appear to be randomly distributed like noise but that can be reproduced exactly. Their most important property is a low autocorrelation value for all delays or lags except when they coincide exactly. Each GPS satellite has unique C/A and P pseudorandom-noise codes.

Pseudorange

A distance measurement, based on the correlation of a satellite-transmitted code and the local receiver's reference code, that has not been corrected for errors in synchronization between the transmitter's clock and the receiver's clock.

Radionavigation

The determination of position, or the obtaining of information relative to position, for the purpose of navigation by means of the propagation properties of radio waves. GPS is a method of radionavigation.

Range

A fixed distance between two points, such as between a starting and an ending waypoint or a satellite and a GPS receiver.

Range Rate

The rate of change between a satellite and receiver. The range to a satellite changes due to satellite and observer motions. Range rate is determined by measuring the Doppler shift of the satellite beacon carrier.

Real-Time Differential GPS

A data collection process whereby a GPS receiver gets real-time correction data from another source in order to filter out the effects of SA and other sources of error. One way to get correction data is from a GPS receiver located at a known position (known as a base station). The GPS receiver at the known position computes, formats, and transmits corrections usually through a data link (e.g., VHF radio or cellular telephone) with each new GPS observation. The roving unit requires some sort of data link equipment to receive the GPS corrections so that the correction factor can be applied to its current observations. Other sources of correction data are Satellite-based systems (like OMNISTAR), CORS stations, etc.

Selective Availability—SA

A DOD program that was used to control the accuracy of pseudorange measurements, degrading the signal available to unauthorized users by dithering

the spacecraft clock time and modifying the ephemeris data provided in the navigation message. SA was discontinued May 1, 2000 (EST).

SNR

Signal to Noise Ratio. A measure of the information content of the signal relative to the signal's noise. A higher number is desirable.

Space Segment

The portion of the GPS system that is located in space, that is, the GPS satellites and any ancillary spacecraft that provide GPS augmentation information (i.e., differential corrections, integrity messages, etc.)

Spread Spectrum

The received GPS signal is wide-bandwidth and low-power (-160 dBW). The L-band signal is modulated with a PRN code to spread the signal energy over a much wider bandwidth than the signal information bandwidth. This provides the ability to receive all satellites unambiguously and to give some resistance to noise and multipath.

Spherical Error Probable—SEP

The radius of a sphere within which there is a 50 percent probability of locating a point or being located. SEP is the three-dimensional analogue of CEP.

SPS

See standard positioning service

Squaring-Type Channel

A GPS receiver channel that multiplies the received signal by itself to obtain a second harmonic of the carriers that does not contain the code modulation. Used in "codeless" receiver equipment.

Standard Deviation (Sigma)

A measure of the dispersion of random errors about the mean value. If a large number of measurements or observations of the same quantity are made, the standard deviation is the square root of the sum of the squares of deviations from the mean value divided by the number of observations less one.

Standard Positioning Service (SPS)

The normal civilian positioning accuracy obtained by using the single frequency C/A code. Under selective availability conditions, guaranteed to be no worse than 100 meters 95 percent of the time (2 drms).

Static Positioning

Location determination accomplished with a stationary receiver. This allows the use of various averaging or differential techniques.

SV

Satellite vehicle or space vehicle.

Tropospheric Correction

The correction applied to the measurement to account for tropospheric delay.

Telematics
The use of satellite data for driver usage in navigation.

TrafficMaster
A specific Floating Vehicle Data system.

URA
See user range accuracy.

Universal Time Coordinated (UTC)
An international, highly accurate and stable uniform atomic time system kept very close, by offsets, to the universal time corrected for seasonal variations in the earth's rotation rate. Maintained by the U.S. Naval Observatory. GPS time is directly relatable to UTC: UTC-GPS = seconds. (The changing constant = 5 seconds in 1988.)

User Segment
The portion of the GPS with major components that can be directly interfaced by the user (E.g., GPS receivers)

URA
See user range accuracy.

User Interface
The hardware and operating software by which a receiver operator executes procedures on equipment (such as a GPS receiver) and the means by which the equipment conveys information to the person using it: the controls and displays.

User Range Accuracy—URA
The contribution to the range-measurement error from an individual error source (apparent clock and ephemeris prediction accuracies). This is converted into range units, assuming that the error source is uncorrelated with all other error sources. Values < 10 are preferred.

User Segment
The part of the whole GPS system that includes the receivers of GPS signals.

UTC
See universal time coordinated

World Geodetic System
A consistent set of parameters describing the size and shape of the Earth, the positions of a network of points with respect to the center of mass of the Earth,

transformations from major geodetic datums, and the potential of the Earth (usually in terms of harmonic coefficients).

WGS-84 (World Geodetic System 1984)

The mathematical ellipsoid used by GPS since January, 1987.

Y-code

The encrypted version of the P-code.

Appendix E Acronyms

Listing of GPS Acronyms

Based upon the acronyms on the web page of the IGEB (***Interagency GPS Executive Board***)
Modified and updated by Keith D. McDonald, Navtech Seminars

A/D	Analog to Digital	**A&T**	Acquisition and Technology
ADS	Automatic Dependent Surveillance	**ATA**	Air Transport Association
AEEC	Airlines Electronic Engineering Committee	**ATC**	Air Traffic Control
AFB	Air Force Base	**ATE**	Automatic Test Equipment
AFI	Automatic Fault Indication	**ATM**	Air Traffic Management
AFS	Air Force Station	**ATON**	Aids to Navigation
A/G	Air/Ground	**AUTONAV**	AUTOnomous NAVigation
AHRS	Attitude and Heading Reference System	**AVL**	Automatic Vehicle Location
AIMS	Airspace Traffic Control Radar Beacon System	**AWOS**	Automated Weather Observing System
A/J	Anti-Jamming	**BCD**	Binary Coded Decimal
AoA	Analysis of Alternatives	**BIH**	Bureau International de L'Heure
AOC	Auxiliary Output Chip	**BIPM**	International Bureau of Weights and Measures
AOPA	Aircraft Owners and Pilots Association	**BIT**	Built-In-Test
APL	Airport pseudolites	**BPSK**	Bi-Phase Shift Keying
APT	Asia Pacific Telecommunity	**BTS**	Bureau of Transportation Statistics
ARNS	Aeronautical Radionavigation Service	**C3I**	Command, Control, Communications and Intelligence
A-S	Anti-Spoofing	**C/A**	Coarse /Acquisition (Code)
ASIC	Application Specific Integrated Circuit	**CAA**	Civil Aviation Authority
ASOS	Automated Surface Observing System	**CADC**	Central Air Data Computer

Source: IGEB, http://www.igeb.gov/ 1 Reprinted 2001 by Navtech Seminars, Inc. www.gpsetc.com

Listing of GPS Acronyms (cont.)

CARD	Cost Analysis Requirements Document	**DAC**	Digital to Analog Converter
CC	Composite Clock	**dB**	Decibel
CDMA	Code Division Multiple Access	**DGPS**	Differential GPS
CDU	Control Display Unit	**D-Level**	Depot Level
CEP	Circular Error Probable	**DLM**	Data Loader Module
CEPT	European Conference of Posts & Telecommunications	**DLR**	Data Loader Receptacle
CGSIC	Civil GPS Service Interface Committee	**DLS**	Data Loader System
CJCS	Chairman, Joint Chiefs of Staff	**DMA**	Defense Mapping Agency (now NIMA)
CMOS	Complementary Metal Oxide Semiconductor	**DME**	Distance Measuring Equipment
C/No	Carrier Energy to Noise Density Ratio	**DOC**	U.S. Department of Commerce
CNS	Communications, Navigation and Surveillance	**DOD**	U.S. Department of Defense
CORS	Continuously Operating Reference Station	**DOI**	U.S. Department of Interior
CPFF	Cost Plus Fixed Fee	**DOJ**	U.S. Department of Justice
CRAF	Civil Reserve Air Fleet	**DOP**	Dilution of Precision
CRPA	Controlled Radiation Pattern Antenna	**DOT**	U.S. Department of Transportation
Cs	Cesium	**drms**	Distance Root Mean Square
CS	Control Segment	**DRS**	Dead Reckoning System
CSOC	Consolidated Space Operations Center	**DT&E**	Development Test and Evaluation
CW	Continuous Wave		

Source: IGEB, http://www.igeb.gov/ 2 Reprinted 2001 by Navtech Seminars, Inc. www.gpsetc.com

Listing of GPS Acronyms (cont.)

ECDIS	Electronic Chart Display & Information System
ECEF	Earth-Centered Earth-Fixed
ECP	Engineering Change Proposal
EDM	Electronic Distance Measurement
EELV	Evolved Expendable Launch Vehicle
EEZ	Exclusive Economic Zone
EFIS	Electronic Flight Instrument System
EM	Electromagnetic
EMCON	Emission Control
EMD	Engineering Manufacturing Development
ESGN	Electrically Suspended Gyro Navigator
FAA	Federal Aviation Administration
FDE, FDI	Fault Detection and Exclusion, Isolation
FHWA	Federal Highway Administration
FMS	Foreign Military Sales
FOC	Full Operational Capability
FOM	Figure Of Merit
FRA	Federal Railroad Administration
FRP	Federal Radionavigation Plan
FRPA	Fixed Radiation Pattern Antenna
FRPA-GP	FRPA Ground Plane
FTA	Federal Transit Administration
GaAs	Gallium Arsenide
GATM	Global Air Traffic Management (Air Force)
GDOP	Geometric Dilution of Precision
GEO	Geostationary Earth Orbit, or Geosynchronous Earth Orbit
GES	Ground Earth Station
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
HOW	Hand Over Word
HSI	Horizontal Situation Indicator
HV	Host Vehicle
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
ICS	Initial Control System
IF	Intermediate Frequency

Source: IGEB, http://www.igeb.gov/

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Listing of GPS Acronyms (cont.)

IFF	Identification Friend or Foe
IFR	Instrument Flight Rules
IGEB	Interagency GPS Executive Board
I-Level	Intermediate Level
ILS	Instrument Landing System
INMARSAT	International Maritime Satellite Organization
INS	Inertial Navigation System
IMT	Improved Mobile Telecommunications
IOC	Initial Operational Capability
ION	Institute of Navigation
IOT&E	Initial Operational Test and Evaluation
IP	Instrumentation Port
ITS	Intermediate Level Test Set
ITS-JPO	Intelligent Transportation System Joint Program Office
ITU	International Telecommunications Union
JCS, JS	Joint Chiefs of Staff
JGPSC	Japan GPS Council
JPALS	Joint Precision Approach and Landing System
JPO	Joint Program Office (as in GPS JPO)
J/S	Jamming to Signal power ratio
JSC	Joint Spectrum Center, Johnson Space Center
JTIDS	Joint Tactical Information Distribution System
LAAS	Local Area Augmentation System
L1	GPS primary carrier frequency, 1575.42 MHz
L2	GPS secondary carrier frequency, 1227.6 MHz
L5	GPS 3rd civil frequency, 1176.45 MHz
LEP	Linear Error Probable
LRIP	Low Rate Initial Production
LRU	Line Replaceable Unit
LO	Local Oscillator
MARAD	Maritime Administration (DOT)
mB, mBar	Millibar
MC&G	Mapping, Charting and Geodesy
MCS	Master Control Station
MCT	Mean Corrective Maintenance Time
MHz	Megahertz
MIDS	Multi-function Information Distribution System
MLS	Microwave Landing System

Source: IGEB, http://www.igeb.gov/

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Listing of GPS Acronyms (cont.)

MLV	Medium Launch Vehicle
$M_{mst}CT$	Maximum Corrective Maintenance Time
MMD	Mean Mission Duration
MMLS	Mobile MLS
MMR	Multi-Mode Receiver
MOA	Memorandum of Agreement
MOPS	Minimum Operation Performance Standard
MOU	Memorandum of Understanding
MPNTP	Master Positioning, Navigation &Timing Plan
M/S	Meters per Second
MSL	Mean Sea Level
MSS	Mobile Satellite Services
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
NANU	Notice Advisory to Navigation Users
NAS	National Airspace System
NASA	National Aeronautics & Space Administration
NAV-msg.	Navigation Message
NAVWAR	Navigation Warfare
NATO	North Atlantic Treaty Organization
NCA	National Command Authority
NDB	NonDirectional RadioBeacons
NDGPS	Nationwide Differential GPS
NIMA	National Imagery and Mapping Agency (was DMA)
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NOSC	Naval Ocean Systems Center
NOTAM	Notice To Airmen
NPA	Non-Precision Approach
NRL	Naval Research Laboratory
ns, NS	Nanosecond (10^{-9} seconds)
NSA	National Security Agency
NTIA	National Telecommunications and Information Administration
NTDS	Navy Tactical Data System
NTS	Navigation Technology Satellite
OBS	Omni Bearing Select
OCS	Operational Control System or Segment
O-Level	Organization Level

Source: IGEB, http://www.igeb.gov/

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Listing of GPS Acronyms (cont.)

OTHT	Over The Horizon Targeting
P-Code	Precise Code
PDD	Presidential Decision Directive
PDOP	Position Dilution of Precision
PIR	Portable ILS Receiver
PLSS	Precision Location Strike System
PPM, ppm	Parts Per Million
PPS	Precise Positioning Service
PPS-SM	PPS Security Module
PRN, PN	Pseudo Random Noise (modulation)
PTTI	Precise Time and Time Interval
PVT	Position, Velocity and Time
RAIM	Receiver Autonomous Integrity Monitoring
RAM	Reliability and Maintainability
RAM	Random Access Memory
Rb	Rubidium
RCVR, rcvr	Receiver
RDF	Radio Direction Finder
RF	Radio Frequency
RMS	Root Mean Square
RNAV	Area Navigation
RSPA	Research & Special Programs Administration (DOT)
RSS	Root Sum Square
RT	Remote Terminal
RTCA	Radio Technical Commission for Aeronautics
RTCM	Ratio Technical Commission for Maritime Services
SA	Selective Availability
SAMSO	Space and Missile Systems Organization
SBAS	Space-Based Augmentation System
SBB	Smart Buffer Box Special Committee
SCAT-I	Special Category-I (Approach and Landing System)
SDF	Simplified Direction Finder
SEP	Spherical Error Probable
SI	International System of Units
SIL	System Integration Laboratory
SINS	Shipborne INS (Inertial Navigation System)
SLSDC	St. Lawrence Seaway Development Corporation
SPS	Standard Positioning Service
SRU	Shop Replaceable Unit

Source: IGEB, http://www.igeb.gov/

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Listing of GPS Acronyms (cont.)

STDCDU	Standard CDU
SVN	Space Vehicle Number (or Satellite Vehicle Number)
TACAN	TACtical Air Navigation
TAI	International Atomic Time
TD	Time Difference
TDOP	Time Dilution of Precision
TDWR	Terminal Doppler Weather Radar
TFOM	Time Figure of Merit
TIS	Traffic Information Services
TLS	Transponder Landing System
TTFF	Time to First Fix
UE	User Equipment
UERE	User Equivalent Range Error
UHF	Ultra High Frequency
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
USD	Under Secretary of Defense
USDA	U.S. Department of Agriculture
USGIC	U.S. GPS Industry Council
USGS	U.S. Geological Survey
USNO	U.S. Naval Observatory
UT	Universal Time
UTC	Universal Time Coordinated
VDOP	Vertical Dilution of Precision
VFR	Visual Flight Rules
VHF	Very High Frequency
VHSIC	Very High Speed Integrated Circuit
VLSIC	Very Large Scale Integrated Circuit
VOR	VHF Omnidirectional Range
VTS	Vessel Traffic Services
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic System - 1984
WMS	Wide-area Master Stations
WRS	Wide-area Reference Stations
YPG	Yuma Proving Ground

Source: IGEB, http://www.igeb.gov/

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Navtech Acronyms and Abbreviations of Navigation Technical Terms

0dBi	0 decibels isotropic (unity gain)—the gain of an idealized omnidirectional antenna
1D, 1-D	One-dimensional
2D, 2-D	Two-dimensional
2DRMS	Two-dimensional root mean square (standard deviation)
3D, 3-D	Three-dimensional
ABS	Anti-Lock Braking System
A/C	Aircraft
ACSM	American Congress of Surveying & Mapping
ACU	Antenna control unit
A/D	Analog/digital converter
ADC	Analog to digital converter
ADF	Automatic direction finder
ADI	Attitude direction indicator
ADR	Accumulated delta range
ADS	Automatic dependent surveillance
AE	Antenna electronics
AEEC	Airlines Electronic Engineering Committee
AES	Aerospace and Electronics Systems Society
AFB	Air force base
AFCRL	Air Force Cambridge Research Center (now Phillips Lab)
AFGD	Air Force Geophysics Lab (was AFRCL)
AFSCF	Air Force satellite Control facility
AGD	Australian geodetic Datum
AGL	Above ground level
A-GPS	Assisted Global Positioning System
AHRS	Attitude and heading Reference Systems
AJ	Anti-jamming
AKM	Apogee kick motor
AMIC	Automotive Multimedia Interface Collaboration
AMPS	Advanced Mobile Phone Standard
AOL	Airborne optical laser
ARCS	Automatic Route Control System
ARINC	Aeronautical Radio, Inc. (establishes avionics standards)
ARTCC	Air Route Traffic Control Center (FAA facility)
A-S	Anti-spoof
ASAT	Anti-satellite
ASCII	American Standard Code for Information Interchange
ASIC	Application Specific Integrated Circuit
ATE	Automatic test equipment
AVCS	Attitude and Velocity Control System
AVLN	Automatic Vehicle Location and Navigation
BBS	Computer bulletin board service
BOC	Binary Offset Carrier

C/A	Coarse/Acquisition GPS signal
CAD	Computer aided design
CAMP	Crash Avoidance Metric Partnership
CDMA	Code Division Multiple Access
CDS	Collaborative Driving System
CDU	Control display unit
CEP	Circular error probable
Ces	Cesium (-Beam Automatic standard Clock)
CGIC	Civil GPS Information Center
CIGNET	Cooperative International GPS Network
CIS	Conventional inertial system
cm	centimeter
CNS	Communications, navigation and surveillance
Comm.	Communications
CONUS	Continental United States
cos	cosine
CPM	Carrier phase measurement
CRPA	Controlled radiation (reception) patterned antenna
CRT	Cathode ray tube
CSOC	Consolidated Space Operations Center (at Schriever AFB, Colorado Springs, CO)
D to A, D/A	Digital to analog
DARPA	Defense Advanced Research Projects Agency
dBw	decibels relative to a watt
deg	degree
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential GPS
DL	Data link
DMA	Defense Mapping Agency
DME	Distance measuring equipment
DOC	Department of Commerce
DoD	Department of Defense
DOP	Dilution of precision
DoT, DOT	Department of Transportation
DPR, dPR	Differential pseudorange
DPRC	Differential pseudorange correction
DR	Delta range, or dead deduced reckoning
DRMS, drms	Distance root mean square
DSARC	Defense Systems Acquisition Review Council
DTC	Dry term correction
DT&E	Development, test and evaluation
ECEF	Earth-centered, Earth-fixed
ED	European Datum
EDM	Electronic distance measurement
EDMap	Enhanced Digital Map
EGNOS	European Integrity Determination System

EIRP	Effective instantaneous radiated power
ELINT	Electronic Intelligence
ELV's	Expendable launch vehicles
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
EOL	End of life
EPS	Electrical power system
ERP	Effective radiated power
ESA	European Space Agency
ETA	Estimated time of arrival
EW	Electronic warfare
FAA	Federal Aviation Administration (part of DoT)
FANS	Future Air Navigation Systems activity of ICAO
FCC	Federal Communications Commission
FCC	Fire Control Computer (JPO version)
FDMA	Frequency division multiple access
FOC	Full operation capability
FOM	Figure of merit (sometimes called FM)
FMI	Flexible modular interface
FBM	Fleet Ballistic Missile
FGCC	Federal Geodetic Control Committee
FRPA	Fixed radiation pattern antenna
FRP	Federal Radio-navigation Plan
FY	Fiscal year
GRS	Geodetic Reference System
GCS	Ground Control System
GEO	Geosynchronous Orbit Satellite
GPS	Global Positioning System
GDM	General Development Model
GDOP	Geometric dilution of precision
GJU	Galileo Joint Undertaking
GLONASS	Global Orbiting Navigation Satellite System of the Russian Federation
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System (GPS, GLONASS, Galileo, others)
GPRS	General Packet Radio Service
GPS	Global Positioning System
GRS	Geodetic Reference System
GSM	Global System for Mobile Communications
GSTB	Galileo Satellite Test Bed
HD	High Dynamic
HDUE	High dynamic user equipment
HF	High frequency
HOL	High order language (for computer programming)

HOW	Hand-over word (in GPS data message)
HPA	High power amplifier
hrs	hours
HSGPS	High Sensitivity GPS
HSI	Horizontal situation indicator
HUD	Head-up display
Hz	Hertz
IAG	International Civil Aviation Organization
ICD	Interface Control Document
ICF	Integrity Control Facility
IEC	International Electro-Technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IERS	International Earth Rotation Service
I-FOG	Interferometric Fiber Optic Gyro
IFRB	International Frequency Review Board
IGEB	Interagency GPS Executive Board
ILS	Instrument landing system
IMS	Integrity Monitoring System
IMU	Inertial measurement unit
IMO	International Maritime Organization
INMARSAT	International Maritime Satellite Communication Organization
INMF	Integrity Network Management Facility
INS	Inertial navigation system
Intelsat	International Satellite Telecommunications Organization
I/O	Input/Output
IOC	Initial operational capability
ION	Institute of Navigation
iono	ionosphere
IONDS	Integrated Operational Nuclear detection System
IOT&E	Initial operational test and evaluation
INS	Inertial navigation system
IPF	Integrity Processing Facility
IR	Infra-red
IRU	Inertial reference units
ISU	International system of units
ITRF	International Terrestrial Reference Frame
ITU	International Telecommunications Union
IULS	Integrity Up Link Station
IVHS	Intelligent Vehicle-Highway System
JCS	Joint Chiefs of Staff
JPO	Joint Program Office
J/S	Jamming/signal ratio
kg	kilogram
KHz, kHz	Kilohertz
km	kilometer
L1	GPS L-band signal 1 (1575.42 MHz)

L2	GPS L-band signal 2 (1227.6 MHz)
L3	GPS L-band signal 3 (1176.45 MHz)
LAN	Longitude of the ascending node in orbit mechanics or local area network)
L-band	L-band frequency (1-2 GHz region)
LCD	Liquid crystal display
LD	Low dynamic
LED	Light emitting diode
LEP	Linear error probable (50 percent)
LF	Low frequency
LO	Local oscillator
LOP	Line of position
LOS	Line of sight
LRU	Line replaceable unit
LORAN	Long range Navigation System
m	meter(s) or milli (0.001)
µ	micro
MAGR	Miniaturized Aviation GPS Receiver
MARAD	Maritime Administration
Mbps	Mega bits per second
MCS	Master Control Station (for GPS at Colorado Springs, CO)
MD	Medium dynamic
MEMS	Micro Electro Mechanical System
MEO	Medium Earth Orbit
MHz	Mega Hertz (1million Hz)
MLS	Microwave Landing System
MLV	Medium launch vehicle (e.g. Delta II)
mm	millimeter
M max CT	Maintenance maximum corrective time
MMD	Mean mission duration
M mean CT	Maintenance mean corrective time
MOPS	Minimum operational performance standards
MP	Manpack
MPS, mps	Meters per second
mrad	milliradian (0.001 radian)
ms	millisecond
MSL	Mean sea level
MSS	Mobile Satellite Service
MTBF	Mean time between failures
MTBM	Mean time between maintenance
MTSTAT	Multifunctional Transport Satellite Space Based Augmentation System
MVUE	Man/vehicular user equipment
NAD-27, 83	North American Datum (1927,1983)
NANUS	Navigation Notices to Users
NASA	National Aeronautics and Space Administration

NATO	North Atlantic Treaty Organization
nav	navigation
NAVSTAR	Navigation System with Timing & Ranging
NBS	National Bureau of Standards (now the National Institute of Standards and Technology)
NCO	Number controlled oscillator
NDB	Non-directional beacon
NDGPS	National DGPS
NDS	Navigation Development Satellite
NET	Not Earlier Than
NGS	National Geodetic Survey
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
nm, n.mi.	Nautical mile (6080 feet)
NNSS	Navy Navigation Satellite System (Transit)
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council of the National Academies of Science and Engineering
NSA	National Security Agency
nsec, ns	nanosecond
NTDS	Naval Tactical Data System
NUDET	Nuclear detection
OCC	Operational Control Center
OCS	Operational Control Segment
OEM	Original equipment manufacturer
OMB	Office of Management and Budget
OSD	Office of the Secretary of Defense
P-channel	Precision code channel
PCM	Pulse code modulation
P-code	Precision code—provided for military GPS users and selected others
PDF	Probability density function
PDOP	Position dilution of precision (x, y, z)
PL	Pseudolite
PLGR	P-code Lightweight GPS Receiver
PLL	Phase lock loop
PLRS	Position Location and reporting System
PN	Pseudo noise (for pseudo random noise)
ppm	parts per million
PPS	Precise Positioning Service
PR	Pseudorange
PRC	Pseudorange correction
PRE	Pseudorange error
PRN	Pseudo random noise
PSK	Phase shift key
PTTI	Precise Time and Time Interval
P/Y-code	Precision-code or /encrypted P-code

RAIM	Receiver autonomous integrity monitoring
RAJPO	Range Applications Joint Program Office (now RISPO)
RAAN	Right ascension of the ascending node
Rb	Rubidium (type of atomic standard clock)
rcvr	receiver
R&D	Research and development
RDSS	Radio Determination Satellite Service
RF	Radio frequency
RINEX	Receiver Independent Exchange (format)
RISPO	Range Instrumentation System Program Office
RLG	Ring laser gyro
RMS, rms	Root mean square
RNAV	Area navigation
RNPC	required Navigation Performance Capability
RPU	Receiver processing unit
RPV	Remotely piloted vehicle
RSPA	Research and Special Programs Administration of DoT
RSS, rss	Root sum square
RTCA	Radio Technical Commission for Aeronautics (now RTCA, Inc.)
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-time Kinematic
S-band	Microwave frequency band (2-4 GHz region)
SA	Selective availability (turned to zero on 1 May 2000)
SAC	Strategic Air Command
SBAS	Satellite Based Augmentation System
SC, S/C	Space craft
SC-155	RTCA Special Committee on future CNS for navigation
SC-159	RTCA Special Committee on MOPS for GNSS
SCF	Satellite Control facility
SCIF	Service Center Interface Facility
SDOF, SDF	Single degree of freedom
SESC	Satellite and Environmental Service Center
SEP	Spherical error probable (50 percent)
sigma, σ	Standard deviation symbol
SGLS	Space-Ground Link, S-band
SISA	Signal in Space Accuracy
SLAM	Standoff Land Attack Missile
SLGR	Small Lightweight GPS Receiver
SNR	Signal to noise ratio
SPS	Standard Positioning Service
STOL	Short take-off and landing
STS	Space Transportation System
SUNS	Small Unit Navigation System
SV, S/V	Space vehicle
TAC	tactical Air Command
TACAN	Tactical Air Navigation System

TBA	To be announced
TBD	To be determined
TCU	Telematics Control Unit
TD	Tokyo Datum
TDOF, TDF	Two degrees of freedom
TDOP	Time dilution of precision
TDMA	Time division multiple access
TDRSS	Tracking and Data Relay Satellite System
TEC	Total electron content
tropo	troposphere
TT&C	Tracking, telemetry and control
TTFF	Time to first fix
TTSF	Time to subsequent fix
UDRE	User differential ranging error
UE	User equipment
UERE	User equivalent range error
UHF	Ultra high frequency
UMTA	Urban Mass Transit Administration
UMTS	Universal Mobile Telecommunications System
URE	User range error
USAF	U.S. Air Force
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
USMC	U.S. Marine Corps
USN	U.S. Navy
USNO	U.S. Naval Observatory
UT	Universal Time
UTC	Universal Time Coordinated
UV	Ultra violet
VAFB	Vandenburg Air Force Base
VDOP	Vertical dilution of precision (z)
VHF	Very high frequency
VLBI	Very long baseline Interferometry
VLF	very low frequency
VLSI	Very large scale integration
VOR	VHF omni-range navigation system
VPA	Vehicle power adapter
WAAS	Wide Area Augmentation System
WARC	World Administrative Radio Conference
WADGPS	Wide area differential GPS
WDOP	Weighted dilution of precision
WGS-72, 84	World Geodetic System (1972 and 1984)
w.r.t.	with respect to
WWDGPS	World wide differential GPS
Y-code	Encrypted P-code
YPG	Yuma Providing Ground