Communication, Storage, and Processing Load Requirements of Alternative Intelligent Vehicle Highway Systems Architectures

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ABSTRACT

The MlTRE Corporation is supporting the Federal Highway Administration (FHWA) in the development of a national architecture for Intelligent Vehicle Highway Systems (IVHS). This report examines the communication, processing, and storage load requirements of alternative IVHS architectures. The architectures are characterized by the location of the route selection function, the vehicle-infrastructure communication system, and the degree of coupling between route selection and traffic control. The study methodology involves defining communication messages, estimating traffic and communication system parameters, and estimating message lengths and transmission frequencies. The results of sensitivity analyses conducted highlight the dependence of the load requirements on vehicle traffic and communication system parameters. The message definitions provide a starting point for developing message standards. The analysis is based on five potential architectures that were examined *in An Initial Evaluation of Alternative Intelligent Vehicle Highway Systems Architectures* (MTR-92WO63).

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Suggested Keywords: Intelligent Vehicle Highway Systems, System Architecture, Advanced Traveler Information Systems, Advanced Traffic Management Systems, Communication Loads, Communication Messages, Communication Technologies, Route Selection, System Evolution

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EXECUTIVE SUMMARY

BACKGROUND

The Intelligent Vehicle Highway Systems (IVHS) program has been established to use advanced technology to improve the efficiency of the nation's highway transportation resources . One of the early requirements in the IVHS program is a system architecture to guide development and implementation decisions. The MITRE Corporation has been evaluating several different types of architectures, focusing on the provision of the major Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS) functions. In previous studies, five strawman architectures have been considered (Cheslow et al. 1992a, 1992b).

The objective of the current study was to estimate the demands placed upon the communications, storage, and processing technologies by different types of architectures. We were able to estimate the communication load requirements for the various architectures. However, because of current uncertainty about the processing algorithms needed for IVHS, the results were more limited for the computer processors and storage systems.

THREE KEY ARCHITECTURE ATTRIBUTES

The IVHS strawman architectures focused on three key attributes that highlight differences among the alternatives. The three attributes are:

- Vehicle-infrastructure communication alternatives;
- Location of the route selection function; and
- Degree of coupling between route selection and traffic control.

VEHICLEINFRASTRUCTURE COMMUNICATIONS

A major issue within the M-IS program is the approach for communicating traffic information from a Traffic Management Center (TMC) to vehicles, and sending information from the vehicles to a TMC. Four different communication alternatives have been considered in our studies. These are the following:

- Two-way localized beacons
- Two-way wide-area coverage radio systems
- Two-way cellular-like radio systems
- One-way broadcast radio systems (utilizing an FM subcarrier)

LOCATION OF THE ROUTE SELECTION FUNCTION

The route selection process provides recommended routes that am used by the route guidance function in the vehicle. Two alternative locations for route selection have been considered:

- In the vehicle
- In the infrastructure

An in-vehicle route selection processor would be provided with dynamic traffic information from the TMC. This information consists of link travel times, incidents, and other temporary restrictions.

Alternatively, route selection could be performed within the infrastructure. In this approach, individual vehicles transmit current locations and destinations to the infrastructure. This information would then be used to predict traffic loads, and to select routes for all equipped vehicles. Each vehicle would receive its individualized route.

DEGREE OF COUPLING BETWEEN ROUTE SELECTION AND TRAFFIC CONTROL

Coupling refers to the extent to which the TMC knows the vehicles' intended routes and exercises control over the selection of these routes, while it is optimizing the traffic control functions. We have considered three levels of coupling:

- Fully *coupled:* TMC has knowledge of equipped vehicles' origin-destination information, which is used to jointly optimize traffic controls and routes.

- *Uncoupled:* Traffic control optimization is carried out without real-time knowledge of equipped vehicles' routes or origin-destination information.

- *Partially coupled:* TMC has real-time knowledge of the routes selected by equipped vehicles, as well as their origin-destination information. This information is used to optimize traffic controls.

FIVE STRAWMAN ARCHITECTURES

Five strawman architectures were developed that reflect logical combinations of the three key architectural attributes. Table ES-l lists the major features that discriminate the architectures from one another. These features are the three key attributes, plus whether there is a need for an in-vehicle map database. Each architecture provides a different framework upon which required IVHS services can be assembled.

Table ES-l. Overview of Strawman Architectures

	Architecture 1	Architecture 2	Architecture 3	Architecture 4	Architecture 5
Communication Technology	Two-way wide-area radio	Two-way localized beacon	Two-way cellular radio (digital technology)	Two-way localized beacon	One-way broadcast (FM subcarrier) to **vehicles**
Route Selection (Centralized)			Centralized route selection (with real-time data)	Centralized route selection	
Route Selection (In Vehicle)	In-vehicle **route** selection	in-vehicle route selection	In-vehicle route selection (with static data) when real-time route selection is unavailable		In-vehicle route selection
Level of Coupling	Uncoupled route selection/traffic control	Partially coupled route selection/traffic control	Fully coupled route selection/traffic control	Uncoupled route selection/traffic control	Uncoupled route selection/traffic control
In Vehicle Map Database	In-vehicle map database	In-vehicle map database	In-vehicle map database		In-vehicle map database

Although the first four architectures differ in important ways, they all have the same basic capabilities, e.g., some form of vehicle routing, two-way communications, and advanced traffic management. The fifth alternative is an architecture with less functionality, mainly because it does not provide an inbound communication link. This alternative was included because it could be deployed more easily than the others.

GENERAL APPROACH FOR LOADS ANALYSIS

The methodology for estimating communications loads was performed in seven steps. The estimation of dynamic storage loads and some important processor characteristics were calculated in two additional steps. The nine-step process is shown in figure ES- 1.

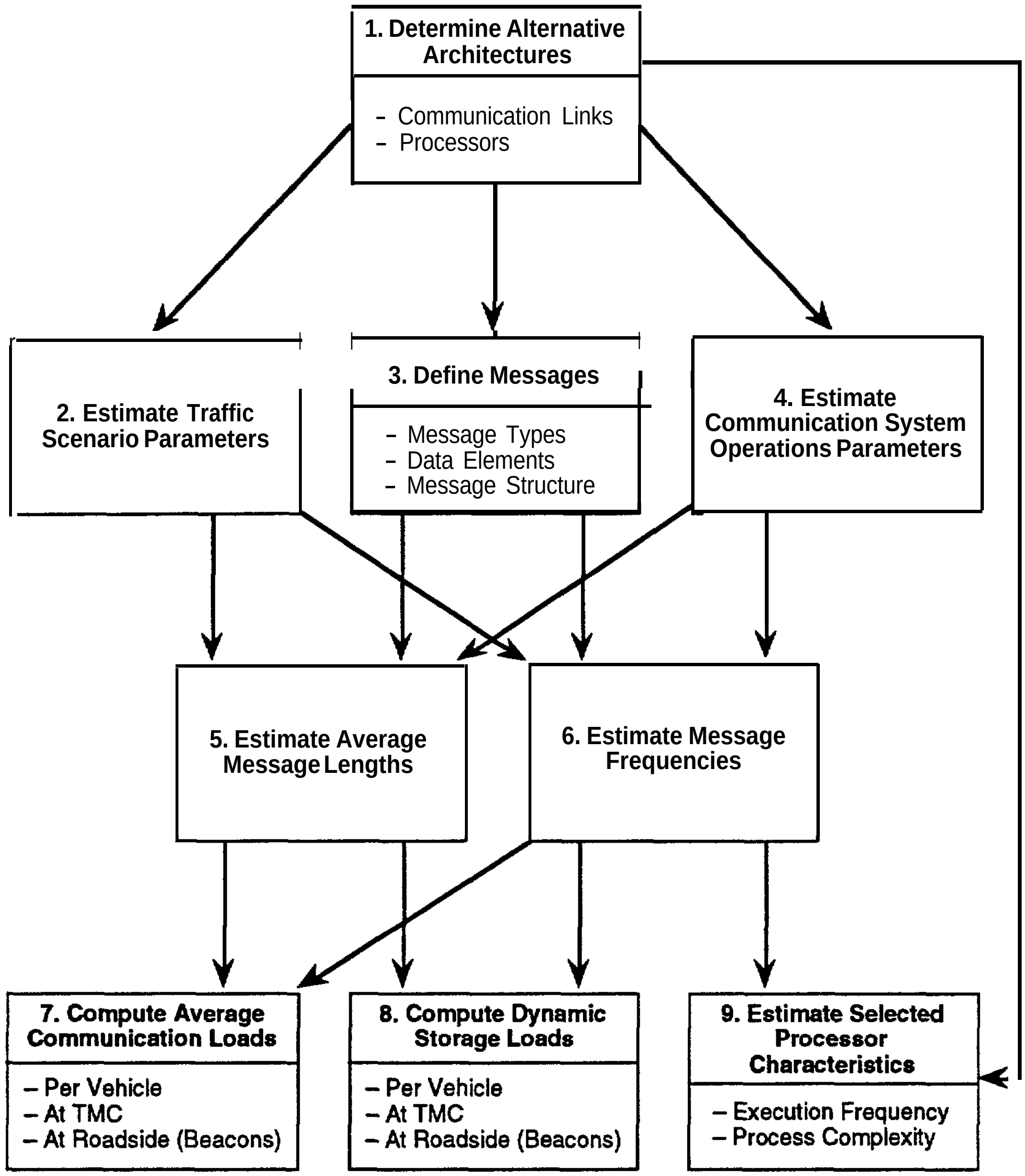

Figure ES-l. Overview of Methodology: System Architecture Communication and Processor Load Requirements

The analysis used a steady-state model of information flow. This provides an appropriate first cut at estimating communication loads. The load requirements were estimated for messages only between the vehicle and the infrastructure. The study estimated the requirements placed upon alternative communications technologies, but did not attempt to develop specific designs that could meet the requirements.

The loads were estimated for a single scenario — a hypothetical urban area of about two million population. This scenario was selected as representative of a large metropolitan area, but one that might have metropolitan traffic control performed by only one TMC. The scenario was selected to generate loads high enough to "stress the system."

Several characteristics of the analysis area were estimated: population, miles of roadway, automobiles and other motor vehicles, trips per vehicle, average trip length, average speed, and vehicle miles traveled. The load analysis was performed for a peak traffic period of about three hours each day. We estimated that during the peak period, the average trip rate is 6600 trips per minute, and that 174,000 vehicles are on the road at any one instant.

The shortest one-way road segment for which speed or travel time data would be of interest was defined as a link, and the average link length was assumed to be 0.25 miles. The communication of probe data from vehicles, and of link data to vehicles, was limited to arterials and freeways — termed reportable links.

ROUTE SELECTION ASSUMPTIONS

Fifty percent of the vehicles on the road during the peak period were assumed either to have in-vehicle route selection equipment, or to use centralized routing messages (depending on the architecture). This high level of market penetration was selected so that the data loads of the various architectures could be compared for mature, rather than start-up, systems.

It was assumed that 60 percent of vehicles with in-vehicle route selection would make a route change in a 20-minute period. In architectures with partial coupling, such as strawman 2, this route change would be communicated to the TMC.

With centralized route selection, we have assumed that drivers will request a route about once every ten minutes, and that five percent of these requests would result in actual changes. We further assumed that the average route change occurs after about one-third of a trip is completed. In addition to the manual routing request, an automated position update and route check is assumed to be transmitted to the TMC every two minutes. New routes are sent five percent of the time. The position update is necessary to keep the TMC informed of the current positions of equipped vehicles, and to provide the means for rerouting vehicles when traffic characteristics change.

An incident rate of 16 per million VMT was estimated; only events that close at least one lane of traffic were included. It was assumed that the equipped vehicles might request assistance, not only for an incident, but for other more frequent vehicle breakdowns, and for medical emergencies. A rate five times larger than the incident rate was assumed for these requests.

SELECTION OF COMMUNICATION SYSTEM PARAMETERS

Several important communication system parameters were estimated. Most information update cycles were assumed to be five minutes. A "vehicle position check cycle" of two minutes was assumed for Architecture 3, which uses centralized route selection. A short and a long cycle (one and five minutes, respectively) were used for broadcasting link time data in architectures with in-vehicle route selection. All "critical" links (e.g., freeways and many major arterials), and 20 percent of the non-critical links would be transmitted on a short update cycle. A different set of non-critical links is reported on each short cycle, so that all reportable links are updated in five minutes. This strategy enables users just beginning their journey to receive critical links in a timely fashion. It was assumed that each vehicle transmits a probe report after traversing four reportable links.

Additional assumptions were made for beacon systems: We assumed that one beacon controller and several beacon heads will be necessary at each beacon communication point. Beacons would be placed on arterials and freeways, but not on lower-class facilities. The beacon controller communicates with the TMC, and with each beacon head under its control. Processing capability at beacon locations would be used to reduce communication load requirements for some messages. Each beacon head is assumed to be able to cover a single traffic approach at an intersection. It could also probably serve two or three freeway lanes.

Several numerical assumptions were also made for the analysis of beacon systems:

- Average road distance between beacons is one mile.
- Area has about 700 beacon processors (based on area size and miles of roadway).
- On average, one beacon processor serves somewhat less than four beacon heads; 3.8 heads were assumed.
- The range of a beacon head is 200 feet.

We have assumed that the cellular infrastructure for IVHS is shared by cellular phone applications. That is, we assume that the cellular IVHS service is not provided by an independent, stand-alone system. With a shared system, a limited number of channels might be dedicated exclusively for traffic information, or for traffic and other data applications. These data channels might support connectionless communications protocols, eliminating the need for call set-up and tear-down.

Analysis of the cellular system required an estimate of the number of cells in the urban area. We considered a shared cellular system where there would be fewer, but larger, cells for IVHS than for the phone system. The IVHS cells would be multiples of the phone system cells, and use appropriate portions of the base station infrastructure. The IVHS cells could be dubbed "super cells." We considered a simple design where ten cells would be used.

MESSAGE CONTENT AND STRUCTURE

Communication messages contain the information that must be sent between the subsystems (e.g., the vehicle and the TMC). In this analysis, the messages are focused on vehicle-infrastructure information exchange, although roadside-TMC messages are included for beacon systems.

Messages that include the same essential information, but vary in structure among the architectures, are categorized as the same "message type." The message types am summarized in table ES-2. For each message type, the communication source and sink, and the applicable strawman architectures are given.

A data field structure was developed for each message. The field type, field size in bits, and field format were estimated. Only data fields containing information bits were considered. This means that no protocol overhead, e.g., error checking, start and stop bits, was estimated.

COMMUNICATION LOAD REQUIREMENTS RESULTS

The communication load requirements for each of the strawman architectures were estimated by carrying out steps 5,6, and 7 of the methodology shown in figure ES-l. A description of these three steps is as follows:

- Determine average message length (in bits) using the message structure and message length parameters.
- Calculate average message frequency from a single source, e.g., a vehicle or a beacon. Where appropriate, calculate message frequency from all sources. Message frequency assumptions, and communication and traffic parameters are used here.
- Compute required communication load as the product of average message length and average message frequency.

Table ES-3 provides a summary of the total loads for each of the strawman architectures.

Table ES-2. General List of the Communication Messages

Message Type	Souce-Sink	Architectures
Assistance Requests	V-TMC; V-RS RS-TMC	1, 2, 3, 4
Assistance Response	TMC-V; RS-V TMC-RS	1, 2, 3, 4
Vehicle ID Assignment	RS-V; TMC-V	2, 3, 4
Vehicle ID Request	V-RS; V-TMC	2, 3, 4
Dynamic Link Times	TMC-V; TMC-RS RS-V	1, 2, 5
Probe Data	RS-TMC	2, 4
Probe Data	V-TMC; V-RS	1, 2, 3, 4
Recommended Routes Sent to Individual Vehicle	TMC-V	3
Route Status OK	TMC-V	3
Selected Routes – Network	TMC-RS	4
Beacon Routing Request	V-RS	4
Position Update	RS-V	4
Localized Routing Data	RS-V	4
Route and Destination	V-RS; RS-TMC	2
Routing Request	V-TMC	3
Alternate Route Recommendations	TMC-V	5
Traffic/Safety Advisories	TMC-RS; RS-V TMC-V	1, 2, 3, 4, 5
Database Changes/Updates	TMC-V; TMC-RS RS-V	1, 2, 3, 4, 5
System Status/ Parameters	TMC-V; TMC-RS RS-V	1, 2, 3, 4, 5
Exception Reporting Rules	TMC-V	1, 3
Trip Completed	V-TMC	1, 3

Table ES-3. Summary of Communication Loads by Architecture
Urban Scenario of 2 Million Population and 50 Percent IVHS Market Penetration

	Total Load Transmltted.... (in kilobits per second)					
	From TMC To All Vehicles or All Beacons	To TMC From All Vehicles or All Beacons	From a Base Stat bn To Vehicles	To a Base Station From Vehicles	From Each Beacon Head To Passing Vehicles	To Each Beacon Head From Passing Vehicles
ARCHITECTURE 1 • Two-way wide-area radio • In-vehicle route selection • Uncoupled route select/traffic control	3.5	111				
ARCHITECTURE 2 • Two-way localized beacons • In-vehicle route selection • Partially coupled route select/traffic control	808*	31*			48	0.12
ARCHITECTURE 3 • Two-way cellular radio • Centraliied route selection • Fully coupled route select/traffic control	83*	189*	8.3	19		
ARCHITECTURE 4 • Two-way localized beacons • Centralized route selection • Uncoupled route select/traffic control • No in-vehicle map database	32*	5.5*			0.10	0.05
ARCHITECTURE 5 • One-way FM subcarrier broadcast • In-vehide route selection • Uncoupled route select/traffic control	3.5					

*Could be provided with landlines (twisted pair, coaxial cable, fiber optics, etc.)

ARCHITECTURE 1

Approximately 3.5 kilobits per second (kbps) are required for transmission from the TMC to vehicles, with 99 percent coming from the dynamic link times. Traffic/safety advisories did not appear to be a significant factor.

For vehicle to TMC messages, the transmission frequency from a single vehicle is multiplied by the number of equipped vehicles operating simultaneously to determine the inbound communication load at the TMC. About 111 kbps is required. Over 97 percent of this load is due to vehicle probe reports. This information content may be more than a single inbound radio channel can handle. Assuming 100 percent overhead, about 23 channels at 9.6 kbps per channel would be needed if link times for all freeway and arterial links are reported.

ARCHITECTURE 2

The messages for Architecture 2 are similar to those of Architecture 1, since in-vehicle route selection is used in both cases. However, in Architecture 2, vehicles also send a route and destination message, which is necessary for partial coupling, to the TMC. Dynamic link time messages that are sent to vehicles in this architecture also differ from those in Architecture 1.

The dynamic link time message produces over 99 percent of the load from the TMC to beacons, and from beacon heads to vehicles. The 48 kbps required from beacon heads to vehicles is significant for infrared or microwave technology, although not prohibitive. In addition, the communication load from vehicles to each beacon head (0.12 kbps) appears to be insignificant. The route and destination message account for the majority of this load to a beacon head. Hence, it appears that only the communication load from the beacon head to passing vehicles may be significant with this system architecture.

ARCHITECTURE 3

Because centralized route selection is used in Architecture 3, the messages differ substantially from those in the previous two architectures. Rather than broadcasting dynamic link times, the TMC sends recommended (selected) route messages to the vehicles. Each driver must request a route from the TMC at the beginning of the trip, and may also request new routes during the trip. Periodic position updates are sent by the vehicle, automatically.

Communication loads were computed as if there was a wide-area radio system, and then divided by the total number of cells in the area to obtain the load on a single cellular base station. The messages from the TMC to the base stations were assumed to be passed between the base stations and vehicles without modification. This simplification ignores the communication overhead required for cellular operation, especially that related to the Mobile

Telephone Switching Office (MTSO). We assumed that the TMC is hard-wired to the MTSO.

The inbound load of 189 kbps from all base stations to the TMC is substantially larger than the 83 kbps required for outbound messages from the TMC to the base stations, even though individualized routes are being sent to vehicles. With 10 cells in the metropolitan area, the average load per base station is 19 kbps for inbound messages and 8.3 kbps for outbound messages. With a 19.2 kbps data rate per channel and 100 percent overhead, this would require at least two inbound channels per cell. Probe data and routing requests, in particular the automated check message, produce most of the inbound load. Recommended route messages dominate the outbound load.

ARCHITECTURE 4

Beacons provide the communication media in this architecture, and the loads are calculated in the same way as for Architecture 2. The major messages differ, however, because Architecture 4 employs centralized route selection without an in-vehicle map database. A vehicle sends its destination to every beacon that it passes, and receives localized routing data (including map and turning information) to support the trip to the next beacon. Position updates must also be sent to each vehicle from the beacon to correct for accumulated position location errors. At each TMC-beacon update, the TMC distributes the set of recommended “localized routes” to each beacon. All of the communication load requirements for Architecture 4 are fairly small, and, as expected, the main contributors are probe data and routing data.

ARCHITECTURE 5

The TMC to vehicle loads are similar to those in Architecture 1, with the most significant difference being that no assistance response message is present in Architecture 5. The assumptions about the dynamic link time message are identical to those in Architecture 1. This architecture does not contain any messages that originate from vehicles, since it provides only a one-way broadcast over FM subcarrier.

SUMMARY

We have been able to determine which messages contribute the most to communication loads. For messages from the vehicle to the TMC, vehicle probe data produce the highest load. Other messages are also important for some of the architectures. These messages are vehicle position updates necessary for centralized routing, and the chosen vehicle routes that must be sent when there is in-vehicle routing with partial coupling.

For messages from the TMC to the vehicles, the major message depends on whether route selection is performed in the vehicle or in the TMC. Link travel time data produce most of the communication load for architectures with in-vehicle route selection. Alternatively, selected route messages dominate architectures with centralized route selection.

For both inbound and outbound communications, all other messages place minor load requirements on any communication system. These minor messages include ones such as driver assistance requests and responses, traffic and safety advisories, and vehicle database updates.

It should be emphasized that the steady-state loads that have been calculated should not be used as design values. The minute-by-minute variations in the communication loads must be accounted for in a system design, and techniques to handle channel saturation must be considered. The design loads would necessarily be higher than the average loads.

STORAGE LOAD REQUIREMENTS FOR COMMUNICATION DATA

The storage load analysis focused only on the storage needed for transmitted and received data. It excluded consideration of the permanent storage needed for historical or other fixed databases (such as map data). The analysis also excluded data storage needs associated with processing functions.

The storage analysis relies heavily on the communication load results. For each architecture, the storage load at the vehicle, TMC, and beacon processor were obtained by summing across all applicable incoming and outgoing messages. As with communication loads, average rather than peak loads were computed.

Table ES-4 provides a summary of the storage results. These results indicate that the overall communication data storage loads vary substantially with the choice of the system architecture, particularly the loads at the TMC. However, the loads appear to be technically feasible in all cases. The TMC storage load in Architecture 2 is the largest, because of the need to send a unique set of link times to each beacon site. The storage loads for beacons and vehicles do not appear to be problematic in any of the architectures.

PROCESSING LOAD REQUIREMENTS

Our analysis of processing loads focused on the differences in processing requirements among the architectural alternatives. In a previous report, where the strawman architectures were defined, the major processes relevant for ATIS and ATMS functions were identified (Cheslow et al. 1992a). Only two in-vehicle processes, *Communication Input/Output* and *Route Selection,* vary significantly among the strawman architectures. Of the TMC processes, *five* vary. *These are Traffic Assignment, Traffic Prediction, Data Fusion, Route*

Table ES-4. Summary of Communication Data Storage Loads by Architecture

	STORAGE LOAD (in kilobytes)		
ARCHITECTURE	Per Vehicle	Per Beacon Processor	TMC
1	74		720
2	34	53	24,000
3	2		6,400
4	<I	10	1,400
5	74		75

Selection, and *Communication Input/Output.* Also included in this analysis were the processes carried out at localized beacons. Because the algorithms and computational methodology for many of the processes under consideration are uncertain, a quantitative estimate of processing loads could not be made.

The parameters that have major impacts on the processing requirements for the relevant processes am the following:

- Number of reportable links and nodes in area
- Number of dynamic time periods
- Average number of links in a vehicle's route
- Number of routes computed per O-D pair
- Average number of beacon heads per beacon processor
- Average number of links served by a beacon processor
- Average flow rate of equipped vehicles passing a point
- Communications load

A few preliminary conclusions have been reached about the processing loads. Independent of the communication technology used between vehicles and the infrastructure, the other two key architecture attributes — location of route selection and the level of coupling — have major impacts on the processing loads of an architecture. Centralized route selection has more complex processing requirements at the TMC than does in-vehicle route selection. In addition, the coupling of route selection and traffic control increases the complexity of traffic prediction and traffic assignment. (It would also affect the traffic controller optimization process, which was not considered in this report) The magnitude of the differences in processing requirements for the various levels of coupling can not be estimated at this time. Our results also show that the use of the processing capability of localized beacons can significantly reduce the processing requirements of the TMC.

COMMUNICATION LOADS OF ALTERNATIVE ARCHITECTURES

The five strawman architectures that have been discussed up to this point, were selected from a larger number of possible mixes of the three key attributes (communication technology, location of route selection, and level of coupling). It was determined during this study that the communication loads of architectures with different mixes of the three key attributes could be estimated with little additional effort.

The communication loads for the following five additional architectures were calculated:

- Wide-area radio with in-vehicle route selection and partial coupling.
- Cellular radio with in-vehicle route selection and no coupling.
- Cellular radio with in-vehicle route selection and partial coupling.
- Beacons with in-vehicle route selection and no coupling.
- Wide-area radio with centralized route selection and no coupling.

This extension of the analysis produced a summary chart of the communication loads for the major message types cross-classified by the communication technology used. The results for the five original strawmen, as well as for the five alternative architectures are summarized in table ES-5 The table describes the load requirements (in kilobits per second) for the major communication messages.

Some observations have been made about which loads shown in the table appear to push the capabilities of the communication technologies.

Wide-area radio may have problems with several different message types, and therefore with several alternative architectures. The largest load comes from vehicle probe data, which could produce uplinked messages to the TMC at over 100 kbps. Other messages could also produce high data rates with wide-area radio, depending on the specific architecture. These

Table ES-5. Major Message Load Requirements Placed on Four Communication Technologies: Scenario of 2 Million Population and 50 Percent IVHS Penetration

(kilobits per second)

	Communication Loads Communication Technology			
Location of Route Selection and Direction of Message / **Major Messages**	**FM Subcarrier**	**Wide Area Radio**	**Celluar Radio (Based on 10 Cells) (Single Base Station)**	**Local Beacon (Single Beacon–Vehicles)**
In-Vehicle Routing Architectures				
Vehicle to TMC (or Roadside)				
Probe Data	NA	108	12	0.04
Routes (Partial Coupling Only)	NA	75	7.5	0.07
TMC (or Roadside) to Vehicle				
Link Times	3.5	3.5	3.5	CBD: 48 FWY: 96
Central Routing Architectures				
Vehicle to TMC (or Roadside)				
Probe Data	NA	108	12	0.04
Position Update	NA	52	5.2	NA
Driver Route Request	NA	14	1.4	0.01
TMC (or Roadside) to Vehicle				
Routes	NA	77	7.7	0.05
Route Status OK	NA	3.6	0.4	NA

[shaded] = Appears Critical
NA = Not Applicable

messages could require multiple communication channels for the urban scenario considered, if each channel was limited to, say, 19.2 kbps.

If wide-area radio were used with in-vehicle route selection to send only link data to the vehicles, there would probably be no load problem. However, in this case, the PM subcarrier might perform just as well. The information bit rate of 3500 bps may be small enough to not pose a design problem.

Cellular radio may provide communication services similar to those provided by wide-area radio, but the system-wide channel requirements would be less if multiple base stations were used. In the scenario analyzed in this report, the large metropolitan area has ten equal-sized cells. Hence, at a first approximation, each base station only requires 10 percent of the channel capacity as does wide-area radio.

A beacon system has minimal communication load requirements for all message types shown in the table, except for sending link times from a beacon head to the passing vehicles. On an arterial with average speeds of 35 MPH, the beacons would have to send this message at a rate of 48 kbps. On freeways with speeds of 70 MPH, the required communication rate would be twice as high, about 96 kbps. Special designs, such as multiple beacon heads per direction, might be used in these situations.

CONCLUSIONS

Some important conclusions about the communication load requirements of the architectures have been reached. The first is that the overall requirements vary substantially with the choice of the *system* architecture. This is because the load requirements vary with the key characteristics of the architecture. In other words, the communication technology used, and the location of the route selection function affect both the messages needed, and the structure of the messages. The use of localized beacons rather than a broadcast system, in particular, can make a major impact on the size of the communication load requirements. The requirements also vary with many important scenario characteristics, such as the size of the metropolitan area, or the market share of IVHS equipped vehicles.

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The U.S. Department of Transportation (DOT), through the Federal Highway Administration (FHWA), has established the Intelligent Vehicle Highway Systems (IVHS) program to use advanced technology to improve the efficiency of the nation's highway transportation resources (FHWA, 1991). IVHS has been defined as those advanced communications, navigation, sensors, control, and information systems that can be used to improve highway travel. The IVHS program is divided into six major areas:

- Advanced Traffic Management Systems (ATMS);
- Advanced Traveler Information Systems (ATIS);
- Advanced Vehicle Control Systems (AVCS);
- Advanced Rural Transportation Systems (ARTS);
- Advanced Public Transportation Systems (ARTS); and
- Commercial Vehicle Operations (CVO).

One of the early requirements in the M-IS program is a system architecture to guide development and implementation decisions. An architecture provides the framework, or structure, for defining the functions that provide M-IS services, and for describing the way these functions are divided among subsystems in the vehicle, at the roadside, or in one or more traffic management centers (TMC). It also defines the information flows and interfaces between functions.

Two previous reports (Cheslow et al., 1992a, 1992b) developed five IVHS strawman architectures, and carried out an initial qualitative evaluation of the architectures. The strawmen were created to focus on several key architectural issues, rather than encompass all IVHS functions and services. These strawman architectures were limited to providing the major ATMS and ATIS functions. They *can be* described *as end-state* architectures, since they were developed to support the provision of fully developed services.

The work described in the previous reports represents two parts of a process of defining and implementing an IVHS architecture. This process has the following basic steps:

- Define goals and objectives for IVHS systems;
- Identify alternative functions and architectures that may meet these goals;
- Assess and refine the alternatives;
- Synthesize the alternatives into a logical overall architecture; and
- Design and implement the systems in accordance with the architecture.

Information from this analysis will be provided to contractor teams that will participate in the development of a national IVHS architecture (Department of Transportation, 1992).

1.2 PURPOSE OF THIS REPORT

The evaluation that was carried out in (Cheslow et al., 1992b) was limited to qualitative aspects of the strawman architectures. The current report extends that study by considering some important quantitative characteristics of the architectures. The objective of this study is to estimate the demands placed upon the communications, storage, and processing technology by different types of architectures, while providing the major ATMS and ATIS functions. The study estimates the load requirements placed on the communication system and, to a lesser extent, on the various computer processors and databases within vehicles or the traffic management infrastructure.

Thus far, there have been no simulations or operational tests to produce data that could be used for this type of evaluation. Therefore, with the current level of technical uncertainty, it is not possible to conclude that one future end state architecture is best. Instead, this evaluation leads to some initial conclusions about which aspects of end-state architectures are more or less promising.

This study developed a basic set of communication messages that are described in section 5. These messages can serve as a starting point for developing ATIS message standards.

1.3 ORGANIZATION OF THIS REPORT

Section 2 reviews the five strawman architectures and discusses the key architectural issues that were considered in selecting them. Section 3 provides an overview of the methodology used in this study to calculate the communication and processor load requirements. Section 4 describes the urban traffic scenario that was used for the analysis, along with the assumptions that were made about some of the traffic variables.

In section 5, a detailed description of the communication messages that would be required is presented. This is followed in section 6 with a discussion of several assumptions about how the communication systems would be operated in the urban scenario, including how message frequencies were estimated.

Sections 7,8, and 9 present the analytical results of the study for the five strawman Architectures. Section 7 provides the results of the communication loads analysis. Section 8 discusses the dynamic data storage requirements of the communication messages. Section 9 provides an initial investigation of processing loads in the vehicle, the TMC, and at roadside.

Section 10 extends the analysis of communication loads presented in section 7 to consider the loads for several additional architectures and for alternative scenarios. This section also contains a discussion of hybrid architectures that have more than one communication technology.

Finally, section 11 integrates the results of the earlier sections, and provides several important conclusions about the communication, processing, and data storage requirements of the architectures.

SECTION 2

OVERVIEW OF STRAWMAN ARCHITECTURES

This section provides a summary of the five strawman IVHS architectures that are evaluated in this report, beginning with a description of the key architectural attributes that define them. A complete discussion of the architectures, along with the approach used to develop them, is documented in (Cheslow et al., 1992a). Each of the five architectures highlights a different functional approach to providing IVHS services. The NHS architecture that finally evolves may not be identical to any of these five architectures, because it may combine features of several, or add features not found in any of them. For this reason, we refer to the five architectures as “strawman” architectures.

2.1 KEY ATTRIBUTES OF STRAWMAN ARCHITECTURES

Our architecture definition process focused on three critical system attributes that highlight major differences among IVHS alternatives. These three elements, which are discussed in the next sections, are:

- Vehicle-infrastructure communication alternatives;
- Location of the route selection function; and
- Degree of coupling between route selection and traffic control.

This report identities the strengths and weaknesses of several communication alternatives with respect to the other two key attributes.

2.1.1 Vehicle-Infrastructure Communications

A critical issue for the IVHS program is the choice of an effective and economical approach for communicating traffic information between vehicles and a TMC. Two-way communications between the traffic management infrastructure and vehicles will be required in order to transmit vehicle probe reports and assistance requests from vehicles, and receive appropriate traffic information from the infrastructure. Each strawman architecture uses one of four communication alternatives. These are:

- Two-way localized beacons;
- Two-way wide-area coverage radio systems;
- Two-way cellular radio systems; and
- One-way broadcast radio systems (utilizing an FM subcarrier).

These four options were chosen to represent a range of technological capability. Each has specific advantages and disadvantages for supporting the various functions and services envisioned within IVHS. Section 2.2 summarizes the four communication alternatives. With one exception, the communication options represent alternatives for providing two-way communication services. Because of the focus of the strawmen on the ATIS/ATMS functions, some communication technologies were not considered appropriate for the strawman architectures. One technology that was omitted is satellite communications, which is being used for managing commercial truck fleets, for tracking critical payloads, and for determining vehicle location. Alternatives for communication among the infrastructure components have also not been considered.

2.1.2 Location of the Route Selection Function

A distinguishing feature of the strawmen is the location of the route selection function. Route selection provides recommended routes that are used by the route guidance function in the vehicle. Route selection involves the calculation of a "best" route of travel between a specified origin and destination (O-D) pair, based upon current (dynamic) data, static data, or a combination of both. The route selection algorithm will have to be periodically rerun to account for dynamically changing traffic conditions. Two alternative locations for route selection have been considered: in the vehicle, and in the infrastructure (specifically, centralized).

Fully distributed route selection has the function occur within individual vehicles (but without coordination with other vehicles). The in-vehicle route selection processor is provided with dynamic traffic information from the TMC. This traffic information consists of changes in link travel times, incidents, and other temporary restrictions (exception-type data). The in-vehicle system could also operate without reliance upon external (infrastructure) support when outside a TMC's communication coverage area, or at times when dynamic traffic information is not available. In this case, traffic information used for route selection would only consist of static information stored in the map database.

The alternative location for the route selection function is the infrastructure. In this approach, individual vehicles transmit their current locations and destinations to the infrastructure. This information is then used to predict traffic loads and to select routes for all the equipped vehicles that have provided O-D information. Each of these vehicles receives individualized route recommendations. The vehicles periodically send updates of their current location to the infrastructure and, if necessary, receives new routing instructions for the remaining set of road links to be traveled. A vehicle might or might not utilize a map database to assist the display of the selected route to the traveler.

The strawman architectures were selected to represent both of the described approaches for implementing route selection. *In this report, the additional assumption is made that infrastructure-based route selection is performed centrally, at a single TMC.* This assumption is important to the concept of coupling between route selection and traffic control, as described in the following paragraphs.

2.1.3 Degree of Coupling Between Route Selection and Traffic Control

Coupling refers to the extent to which the TMC knows the vehicles' intended routes and exercises control over the selection of these routes, while it is simultaneously optimizing traffic control functions. We have considered three alternative levels of coupling, which are summarized in figures 2-la, b, and c:

- *Fully coupled:* TMC has knowledge of equipped vehicles' origin-destination information, which is used to jointly optimize traffic controls and routes.

- *Uncoupled:* Traffic control optimization is carried out without real-time knowledge of equipped vehicles' origin-destination and route information.

- *Partially coupled:* TMC has real-time knowledge of the routes selected by equipped vehicles, as well as their origin-destination information. The route information is used in traffic control optimization.

With a fully coupled system, the TMC determines the optimal settings for all traffic control devices, and selects the (optimum) routes for all equipped vehicles. The joint optimization of the two functions must be performed so that all the parameters are internally consistent. This capability at the TMC requires full knowledge of the current locations and destinations of a significant fraction of all vehicles. With this information, as well as traffic data obtained from traffic sensors and vehicle probes, the TMC concurrently performs several functions:

- Prediction of future traffic loads and link times on the road network;
- Optimization of settings for the traffic control devices; and
- Route selection for all equipped vehicles.

Figure 2- 1 a provides a simple representation of full coupling.

With no coupling, vehicles do not send either origin-destination or intended route information to the TMC. The TMC will use only information from traffic sensors (including vehicle probes) and historical traffic data to predict traffic loads on the network. It then optimizes the traffic control system based upon these more limited predictions. The link times from this optimization process are sent to the route selection processor. The traffic controller settings are not affected by information about selected routes; however, the traffic control optimization can affect the route selection process (through the link times). Figure 2- 1 b characterizes an uncoupled architecture. It should be noted that with this approach, route selection could occur either in vehicles or in the infrastructure.

With partial coupling, the TMC obtains planned destinations and selected routes from equipped vehicles. This information differentiates the partially coupled architecture from an uncoupled one. Based on traffic sensor and vehicle probe inputs, plus the selected routes

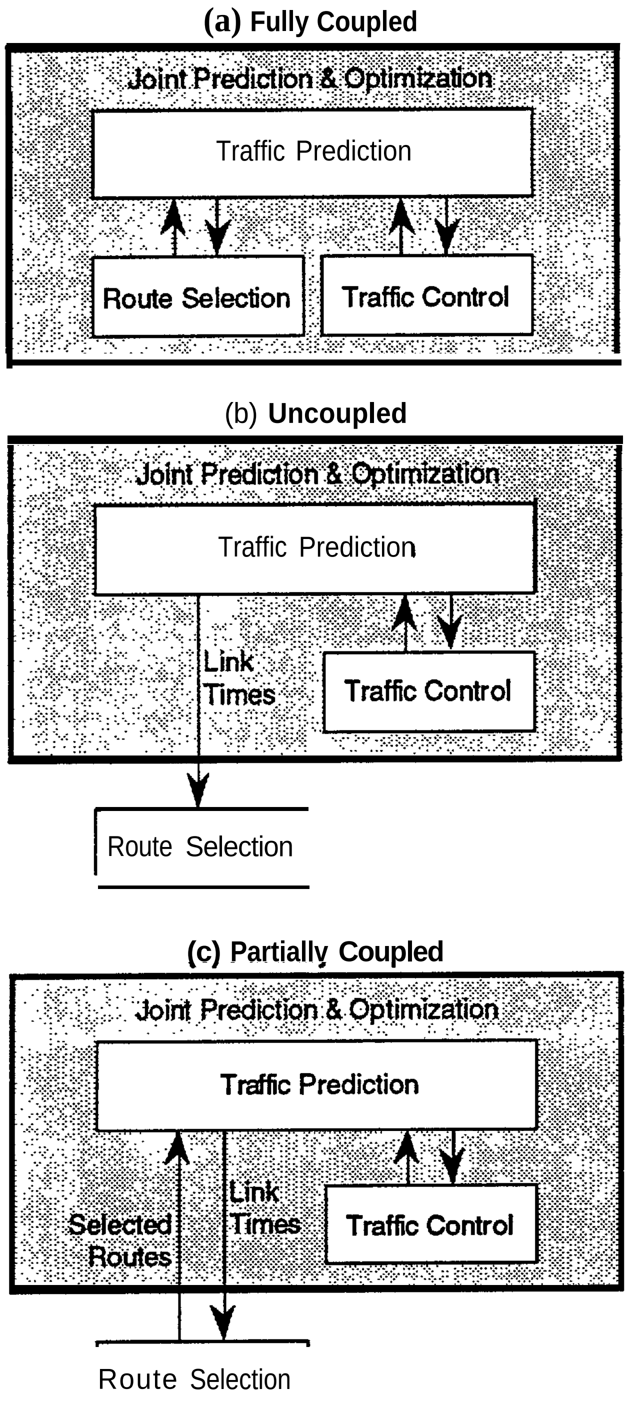

Figure 2-1. Degree of Coupling Between Route Selection and Traffic Control

and destinations, the TMC predicts traffic loads and optimizes traffic control systems. Figure 2-1c characterizes a partially coupled control architecture. This approach also allows route selection to occur either in vehicles or in the infrastructure.

2.2 THE COMMUNICATION TECH.NOLOGIES

This section provides short descriptions of the characteristics of the four communication technologies.

2.2.1 Localized Beacons

Beacons located on the roadside support short-range, two-way transfer of traffic and routing information to or from vehicles in the proximity of the beacon. (The term beacon is used generically in this report to mean any localized two-way communication device.) A variety of communication wavelengths, including infrared, radio, and microwave, could be used for the beacon implementation. Localized beacons have the potential for spatially distributing the communication loads within the infrastructure. This can permit location-specific traffic information to be presented to the vehicles within range of the beacon.

Beacons allow the segmentation of the equipped vehicle population into subsets (such as vehicles with a single direction of travel at an intersection), and can simplify the vehicle-to-infrastructure multiple-access communications protocols. Beacons also provide a mechanism for uniquely determining a vehicle's position. There are some limitations to the use of beacons, because some IVHS services can be provided only for vehicles within the range of the beacon transponder. (Examples of these services are warnings of accidents or other road hazards, and transmission by a driver of a "MAYDAY'* call for assistance).

2.2.2 Wide-Area Radio System

A wide-area radio system provides a two-way broadcast capability between vehicles and the infrastructure. The communication range is sufficiently large to cover a substantial portion of a metropolitan area (or critical segments of interstate highways or rural areas). One or more dedicated pairs of radio frequencies are used to transmit and receive traffic information. A wide-area radio system would broadcast the same traffic information to all vehicles within receiving range, relying on in-vehicle processors to sort out the relevant data, based upon the vehicle location and planned route of travel, or based on unique destination addresses in the message headers. This type of communication system allows the transmission and reception of information such as warning messages and "MAYDAY" assistance requests at any location within the coverage area. Wide-area systems must deal with requirements for multiple communication channels (especially for vehicle transmission of probe data to the TMC) and potential contention for each channel.

2.2.3 **Digital Cellular Radio System**

A digital cellular transmission system can support two-way communications between vehicles and the infrastructure within an entire metropolitan area. The coverage area is broken into cells, each served by a base station and a low-power transmitter. This essentially provides increased communication channel capacity. A set of communication channels can be used in several cells simultaneously throughout the network, which reduces the number of required channels compared to wide area radio.

We have assumed that much of the cellular infrastructure for IVHS is shared by other cellular applications (e. g., phone use). That is, we assume that the cellular IVHS service is not provided by an independent, stand-alone system. With a shared system, a limited number of channels might be dedicated exclusively for traffic information, or for traffic and other data applications. These data channels might support connectionless communications protocols, eliminating the need for call set-up and tear-down.

2.2.4 One-Way FM Subcarrier

A one-way FM subcarrier broadcast can be used to send traffic information from the infrastructure to properly equipped vehicles within receiving range, covering a metropolitan area or other region of interest. This communication alternative is the only one considered that does not support two-way communications (e.g., does not support vehicle probe reports). This communication option provides an efficient and relatively low-cost means of broadcasting traffic information to many users. A similar system, Radio Data System (RDS), already exists in Europe, and is proposed for use in the United States. Although the technology discussed in the report is FM subcarrier, other one-way, wide-area broadcast technologies are applicable (e.g., a television station subcarrier).

2.3 SUMMARY OF FIVE STRAWMAN ARCHITECTURES

Five strawman architectures were selected previously that reflect logical combinations of the three key architectural attributes described above (Cheslow et al., 1992a). Table 2-4 lists the major features that discriminate the architectures from one another. These features are the three key attributes, plus whether there is a need for an in-vehicle map database. Each architecture provides a different framework upon which required IVHS services can be assembled. Although there is a certain amount of arbitrariness in the way the key attributes were mixed to produce five strawmen, Architectures 1 and 4 were selected to resemble currently used approaches to providing ATIS and ATMS services. Table 2-l serves as a useful summary of the architectures to which the reader can refer throughout the remainder of the report.

Although the first four architectures differ in important ways, they all have essentially the same basic capabilities, e.g., some form of vehicle routing, two-way communications, advanced traffic management, etc. The fifth alternative represents an IVHS architecture,

Table 2-l. Overview of Strawman Architectures

	Architecture 1	Architecture 2	Architecture 3	Architecture 4	Architecture 5
Communication Technology	Two-way wide-area radio	Two-way localized beacon	Two-way cellular radio (digital technology)	Two-way localized beacon	One-way broadcast (FM subcarrier) to vehicles
Route Selection (Centralized)			Centralized route selection (with real-time data)	Centralized route selection	
Route **Selection (In Vehicle)**	In-vehicle route selection	In-vehicle route selection	in-vehicle route selection (with static data) when real-time route selection is unavailable		In-vehicle route selection
Level of **Coupling**	Uncoupled route selection/traffic control	Partially coupled route selection/traffic control	Fully coupled route selection/traff ic control	Uncoupled route selection/traffic control	Uncoupled route selection/traff ic control
In Vehicle Map Database	In-vehicle map database	In-vehicle map database	In-vehicle map database		In-vehicle map database

with less functionality, mainly because it does not provide an inbound (vehicle-to-infrastructure) communication link. This alternative was included, however, because it could be deployed more easily than the others.

The strawman architectures are focused on the previously described key attributes; however, several additional ATMS and ATIS components/functions have been included. A descriptive overview of each architecture alternative is provided below. For more details about the strawman architectures, see (Cheslow et al., 1992a).

Figure 2-2 provides a simplified pictorial representation of Architecture 1. The other strawmen are simple variations of this figure. Detailed figures of each of the alternatives, which highlight the key architectural elements, the processing functions, and information flows between the vehicle and the traffic management infrastructure, are presented in the Appendix.

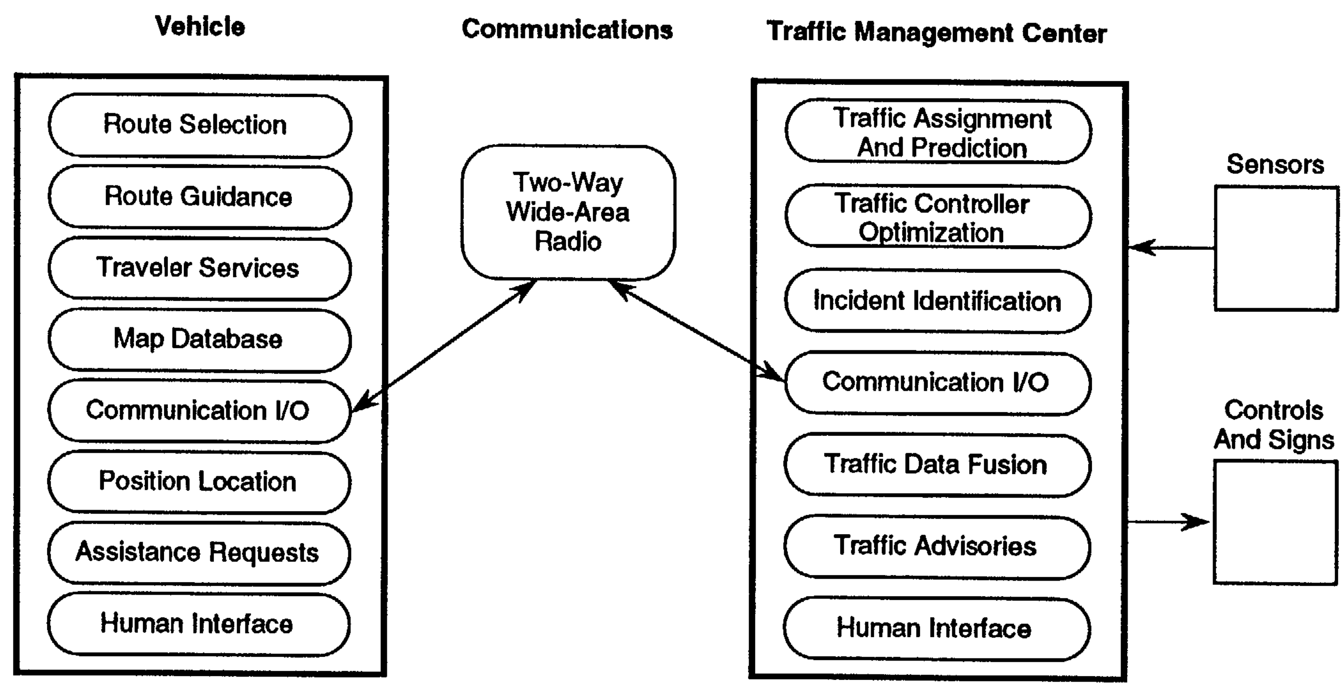

Figure 2-2. Simplified Diagram of Strawman Architecture #1

The architectures are defined at a relatively high level, and many details are not included, such as the exact flow of data between functions in a processor, and the characteristics of transmitters and receivers that are required for communication. These details, while important to the design of an actual working system, are beyond the scope of an architecture study.

2.3.1 Strawman Architecture 1

Architecture 1 has route selection and guidance capability in the vehicle with no coupling between vehicle routing and the traffic control system. The in-vehicle unit communicates with the TMC via a two-way wide-area radio system. This communication system transmits traffic data describing all necessary link times to all vehicles that have route selection capability. The in-vehicle systems will perform position location, route selection, and en-route guidance functions. Position location within the vehicle is based upon land-based or satellite radio trilateration, dead reckoning, and map matching. The in-vehicle navigation and routing unit contains a map database that supports traveler services and “yellow pages” data. A variety of trip planning and route selection options is available in-vehicle to support the traveler.

2.3.2 Strawman Architecture 2

This strawman is similar to Architecture 1, with some important modifications. The major structural difference between the two architectures is in the vehicle to TMC communications. This architecture differs from Architecture 1 by using two-way localized beacons instead of a wide-area broadcast. Each beacon must transmit traffic information describing the complete network to the vehicles to allow them to carry out the route selection process.

Like Architecture 1, all position location and routing functions are performed in the vehicle, and all high-level traffic control functions in the TMC. However, Architecture 2 has partial coupling of the traffic control and routing functions. This level of coupling is accomplished by the transmission of vehicles’ selected routes to the TMC, where they are used, with other traffic data, to enhance the accuracy of traffic prediction and traffic control functions. In the TMC, there is an additional requirement for fusing the selected route data with other traffic information.

2.3.3 Strawman Architecture 3

This strawman has full coupling of the traffic management and traveler information systems. The simultaneous determination of the traffic control and route selection parameters requires that communication between the two processes take place frequently and efficiently. This is accomplished by having both processes take place in a single facility, namely a TMC. Therefore, this strawman has the selection of traffic routings determined centrally, rather than in individual vehicles. An in-vehicle route guidance processor utilizes the recommended routing data to provide route guidance advice to the traveler. Each vehicle is assumed to be able to perform in-vehicle route selection with a static map database when routing recommendations are not available from the central facility; however, TMC routing recommendations are assumed to be available in this report

For this strawman, the communication link is assumed to be two-way digital cellular radio. The routing data for each vehicle must be coded with the vehicle's identification, so that the vehicle can select out the messages addressed to it.

2.3.4 Strawman Architecture 4

Architecture 4 has uncoupled route selection and traffic control, with centralized route selection. Similar to Architecture 2, localized beacons are used for communications between the infrastructure and vehicles.

Communication from the infrastructure to vehicles is required for any route guidance to be displayed, even using static data. With this centralized approach, a map database is not required in the vehicle, potentially lowering the cost of the in-vehicle unit. Thus, Architecture 4 represents a highly infrastructure-dependent architecture. However, even though both route selection and the determination of control system parameters are carried out centrally, there is no direct coupling between these two functions. The two functions need not be carried out at the same facility, and could conceivably be handled by different organizations. For example, route selection could be performed by a private subscription service, while traffic management is provided by a public agency.

2.3.5 S trawman Architecture 5

This architecture has uncoupled route selection and traffic control with a one-way, subcarrier broadcast for communication of real-time traffic conditions from the infrastructure to the vehicles. The broadcast is assumed to transmit in digital format. Traffic management in this architecture is similar to that of Architecture 1, except that no vehicle probe data is collected.

The communication infrastructure is assumed to be developed primarily to provide information to vehicles with route selection and route guidance processors, but also allows vehicles with only FM subcarrier receivers to obtain some of the transmitted information. Both equipment options can be accommodated with one overall architecture and are intended to operate together in the same area. In addition to carrying general traffic advisories and warnings, the one-way traffic channel is used to broadcast link travel times that can be used for routing purposes. The main limitations of this architecture, compared to the previous four architectures, are that it does not support assistance requests or vehicle probe traffic data.

SECTION 3

GENERAL APPROACH FOR LOADS ANALYSIS

This section describes the general methodology that was used to calculate the communications, storage, and processing load requirements for the various IVHS architectures. Some additional details about the specific procedures used are given in sections 7,8, and 9.

The loads were estimated for a single scenario — an urban area of about two million population. This scenario was selected as representative of a large metropolitan area, but one that might still be small enough to have complete metropolitan traffic control performed by one TMC. A discussion of the characteristics of the scenario is presented in section 4. Although analyzing only one scenario may limit the range of useful information about the architectures, the scenario was selected so that there would be loads high enough to "stress the system."

The communication load requirements were estimated only for messages between the vehicle and the infrastructure; the information flows between various infrastructure components were not addressed. One exception to this is the inclusion of all data flows that ultimately come from or go to vehicles in architectures with beacon or cellular systems.

The study estimated the requirements placed upon alternative communications and processing technologies, but did not attempt to develop specific designs that could meet the requirements. This means, for example, that no methods for data compression were examined. The study did consider, however, reducing the amount of data that needs to be sent, by relying on exception reporting of some data elements. Communication message formats were developed for the required information bits. Focusing only on the information components of the messages meant that no protocol overhead (e.g., error checking, start and stop bits) was estimated. From analogy with other experience, it is expected that protocol overhead could add 50 to 150 percent to the estimated message lengths, with data compression reducing this somewhat.

The analysis performed for this study used a steady-state model of information flows. The model did not take into account the minute-to-minute variations that can occur due to statistical variability within a chosen time interval. Therefore, this analysis was not able to calculate the instantaneous peak loads that would be required for the alternative architectures. To include this variability would require the detailed simulation of both vehicle and communications traffic, a complex procedure that was not carried out at this time. However, a steady-state model provides an appropriate first cut at estimating communication loads, because it is relatively easy to develop, modify and operate. This approach allows critical issues related to communication loads to be identified at an early stage of the architecture analysis process.

The steady-state model was built with the premise that the average communication and processing loads could be assumed to be in a steady state if they were calculated for a time

The steady-state model was built with the premise that the average communication and processing loads could be assumed to be in a steady state if they were calculated for a time interval that was long enough to be larger than either the time to transmit a message, or the repeat frequency of periodic messages. The chosen time interval was taken to be 20 minutes, but, in retrospect, its value does not actually affect the communication or processing *rates* that are required. (The same results would have been obtained with a steady state time of 10 minutes or 30 minutes.)

The methodology for estimating communications loads can be divided into seven basic steps. The estimation of dynamic storage loads and some important processor characteristics are calculated in two additional steps. The nine-step process is shown in figure 3-l.

- Step one was the determination of the strawman architectures and their key characteristics. This step was carried out in previous work (Cheslow et al., 1992a), and summarized in section 2.

- Step two involved the estimation of the various demographic and traffic parameters that are defined by the analysis scenario. This process is discussed in section 4.

- Step three involved the identification of the required types of messages that must be sent between the vehicles and a traffic management center. The messages differ somewhat depending on the key attributes of the architecture. The message types were determined from the information flows requited by each architecture that were identified in (Cheslow et al., 1992a). Then the data elements for each message type were determined and formatted into a possible message structure. The formats were made as common as possible to allow a comparison among the architectures. The details of the development of the messages are described in section 5.

- Step four estimated the localized spatial distribution of the equipment and facilities that are used to provide communications capabilities for each of the architectures. This step was relevant for cellular or beacon-based communication systems, where the traffic flow rate for individual cells or beacons must be estimated. The selection of parameters for this step is described in section 6.

- In step five, the number of information bits for each message was estimated. Some of the data elements were dependent on either the number of vehicles that would communicate with a traffic management center, or on the number of road links for which traffic data would be calculated or communicated. The calculation of the message lengths therefore involved the use of the outputs from step three, where the messages were defined, as well as step two, where the traffic parameters were determined.

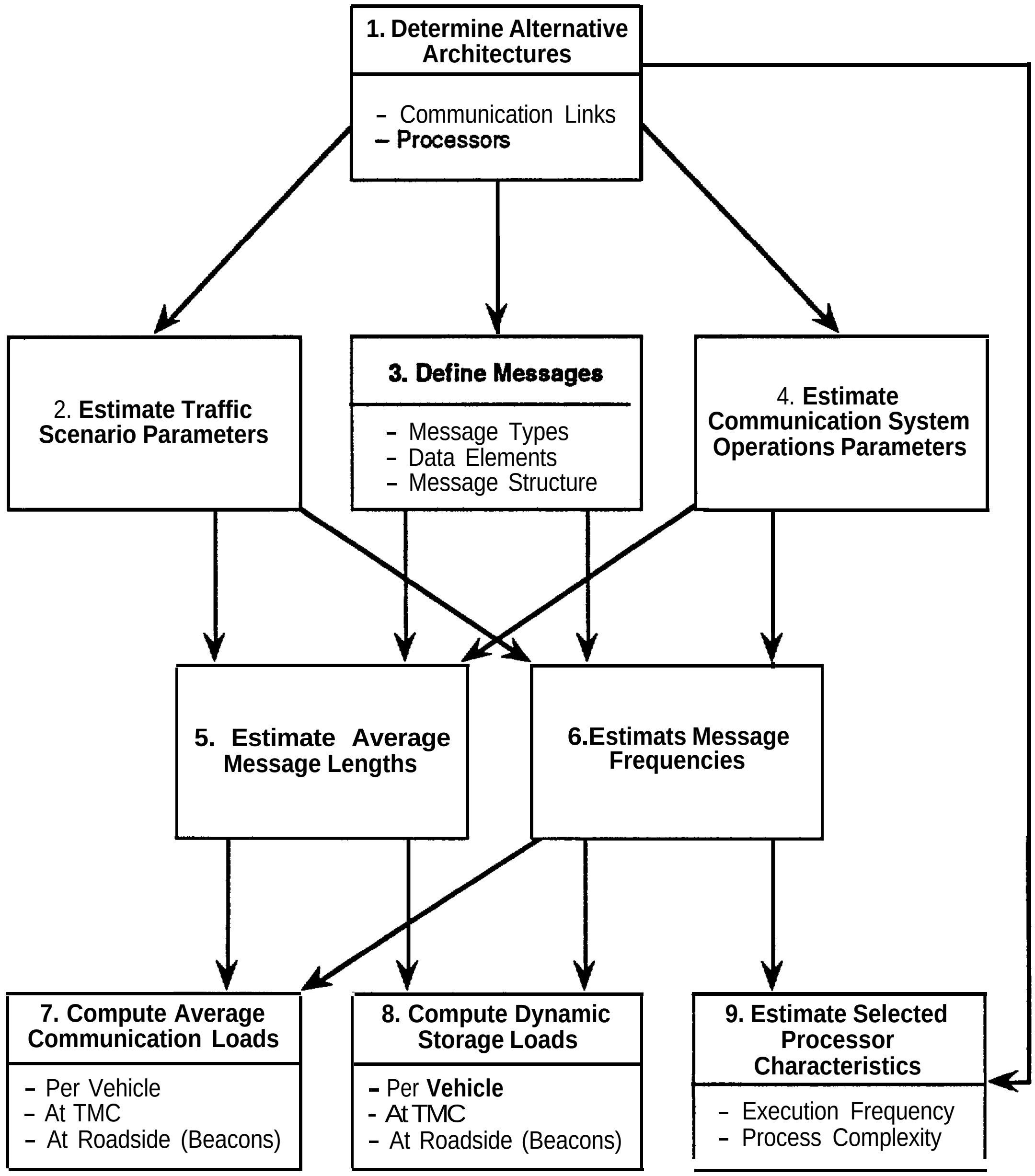

Figure 3-1. Overview of Methodology

- In step six, the frequency of sending each message type was estimated. The frequency was measured in messages per minute. As indicated above, the analysis determined the average message frequency for a time period in which the messages can be assumed to be in a steady state. The estimation of message lengths and message frequencies is discussed in section 7. In a few cases, algorithms were hypothesized that would reduce the message length. But in general, the structuring of messages and the estimation of frequencies relied on straightforward brute force.

- Finally, step seven combined the message length and message frequency calculations to produce estimates of the communication load requirements. This combination is also discussed in section 7. These loads, which were estimates for each message type, as well as for the aggregates going to and from vehicles and to and from the infrastructure, were measured in bits per second. Architectures for which the requirements might go beyond the capabilities of the communications technology that was used were identified. On the basis of these results, some hybrid architectures were hypothesized; these are discussed in section 10.

- Step eight used the communication message lengths and frequencies to estimate the dynamic storage required to handle the incoming and outgoing communication messages. The static storage requirements (e.g., map database) have not been addressed in this analysis, nor have the storage requirements generated by the non-communication related processors.

- In step nine, the important characteristics of the major processes that had been identified in the architectural definition study (Cheslow et al., 1992a) were analyzed. The information flows into and out of the processes were identified, and the major processing functions that each processor would perform were estimated. The actual algorithms that might be used for each function could not be identified at this time. Instead, the “complexity” of the algorithms was estimated. The processing functions that appear to place the severest demands on the choice of computer hardware or software were identified.

SECTION 4

THE ANALYSIS SCENARIO

This section discusses the estimation of traffic scenario parameters — step 2 in the overall methodology shown in figure 3-l. A scenario was selected for analyzing the communication and processing requirements of the alternative architectures that would place large loads upon the system. A large urban area was chosen, because of the high traffic densities that would exist there. However, it was decided to make the analysis area smaller than the very largest metropolitan areas such as New York, Los Angeles, or Chicago, because those areas might require several TMCs to control traffic among a multitude of jurisdictions, and the communication and processing loads at a single center would depend on the actual sharing arrangement. A hypothetical area of about two million population was selected that would have a lower probability of requiring multiple TMCs.

The aggregate demographic and traffic characteristics of this area were determined by calculating the average values of five areas of the selected size, namely Baltimore, Minneapolis-St. Paul, Phoenix, San Diego, and St. Louis. The characteristics of the five areas and the average values were taken from (Federal Highway Administration, 1990). and are listed in table 4-l. The data that were used were population, area, miles of roadway, and the daily vehicle miles traveled (WIT), the latter two parameters for various road classes, such as freeway or arterial. As can be seen at the bottom of table 4-1, an average of 82 percent of the average daily VMT occurs on freeways and arterials, even though they provide only 18 percent of the roadway. Because of these statistics, we have limited the reporting of probe data from vehicles, and of link data to vehicles, to traffic on freeways and arterials.

Information for large urban areas, in general, was obtained from other sources, and applied to the scenario area (Hu and Young, 1992; Federal Highway Administration, 1990). This information included automobiles per person, other motor vehicles, daily trips per vehicle, and average trip length. These values are shown in the top half of table 4-2. For this analysis, all trips were assumed to be of average length. As a consistency check, the values of trips per vehicle and average trip length can be multiplied to produce an estimate for the daily VMT that essentially agreed with the value shown in table 4-l.

The loads analysis was performed for the peak daily traffic period, which lasts about three hours each day. Traffic parameters for this peak period were estimated from (Hanks and Lomax, 1991; Hu and Young, 1992), and from the daily parameters. These include fraction of trips in the peak, average trip length, and average speed.

Table 4-1. Demographic and Traffic Characteristics of Five Metropolitan Areas (1990)

	Baltimore	Minn.-St. Paul	Phoenix	San Diego	St. Louis	Average
DEMOGRAPHICS						
Population (thousands)	1991	2055	1920	2294	1950	2042
Square miles	765	996	971	680	694	821
persons per square mile	2603	2063	1977	3374	2810	2487
MILEAGE						
Freeways & expressways	237	294	98	230	266	225
Other principal arterials	406	132	731	243	529	408
Minor arterial	512	916	536	764	679	681
Total freeway & arterials	1155	1342	1365	1237	1474	1315
Collectors & local	4793	7609	8031	4461	5690	6117
Total mileage	5948	8951	9396	5698	7164	7431
Miles roadway/1000 persons	3.0	4.4	4.9	2.5	3.7	3.6
Freeways/square mile	0.31	0.30	0.10	0.34	0.38	0.27
Freeway & arterials/square mile	1.51	1.35	1.41	1.82	2.12	1.60
DAILY VMT (millions)						
Freeways and expressways	15.8	17.8	7.9	27.7	18.4	17.5
Other principal arterials	9.8	3.6	17.5	6.8	11.2	9.8
Minor arterial	5.7	11.3	4.7	10.7	7.7	8.0
Total freeway and arterials	31.4	32.8	30.1	45.2	37.3	35.9
Collector & local	5.0	10.4	9.5	6.4	8.0	7.9
Total DVMT	36.4	43.2	39.7	51.6	45.3	43.2
OTHER STATISTICS						
Freeway & arterial DVMT/mileage (1000s)	27.2	24.4	22.1	36.6	25.3	26.9
Freeways as % of total mileage	4%	3%	1%	4%	4%	3%
% DVMT served by freeways	43%	41%	20%	54%	41%	41%
Freeways & arterials as % of total mileage	19%	15%	15%	22%	21%	18%
% DVMT on freeways & arterials	86%	76%	76%	88%	82%	82%

Table 4-2. Area-Wide Daily and Peak Period Traffic Data for Analysis Scenario

Variables	Value	Units	Code	Basis
Area-Wide Traffic				
Population of metro area	2000	1000s	Pop	Based on 5 Metro areas
Size of metro area	820	sq. mi.		Based on 5 Metro areas
Miles of freeways and arterials	1315	miles	MFA	Based on 5 Metro areas
Avg. side of square grid for area	28.6	miles		
Number of automobiles	1140	1000s	Autos	=.57 * Pop
Number of vehicles	1530	1000s	Veh	=1.34 * Autos
Trips per vehicle per day	3.0		TVD	Estimated
Average trip length	9.5	miles		Estimated
Total daily vehicle trips	4580	1000s	Trips	= Veh * TVD
Total daily VMT	43.5	millions	DVMT	= Trips * TripLength
Peak Period				
Length of AM or PM peak period	3	hours	PL	Estimated
Fraction of VMT in peak period	0.30		PkFr	Estimated
VMT in peak period	13.1	millions	pkVMT	= DVMT * PkFr
Avg. speed in peak	25	mph	Spd	Estimated
Avg. trip length in peak	11.0	miles	TL	Estimated
Average trip time in peak	26.4	minutes	TT	= TL / Spd
Number of trips in peak period	1190	1000s	PkTp	= pkVMT / TL
Trip rate during peak	6600	per minute	Rate	= PkTp / PL
Steady state time period within peak	20	minutes	M	Est. Steady State: > Cycle time; < Avg. trip time
Avg. number of vehicles on road during peak (steady state)	174	1000s	VoR	=Rate'IT
Fraction of peak VMT on major roads (freeways and arterials)	.82		FVMR	Estimated
Incidents per vehicle in M minutes	.00013		IVM	Derived from 16 per million VMT
No of (reportable) incidents on major roads in M minutes	19			= IVM . VoR . FVMR

The average trip speed was based on the distribution of VMT among the various road classes. This estimate used a previous assessment of speed on congested facilities by facility type (Cheslow, 1992). Average trip time was calculated from the speed and trip length. The number of trips by all vehicles on the network in the peak period was assumed equal to the VMT in the peak period divided by average peak period trip length. The average steady-state trip rate in the peak was assumed equal to the number of trips in the peak period divided by the length of the period (three hours).

The average number of vehicles on the road during the steady-state period was assumed to be determined from the equation:

Avg. vehicles on road = (Avg. trip rate) * (Avg. trip time)

A rate of incidents of 16 per million VMT was estimated from the assessment in (Cheslow, 1992). That source pointed out that there is no agreed-upon definition of what is defined as an incident. For this analysis, only events that close at least one lane of traffic are included. The duration of an average incident corresponds to this incident definition, but there is a great amount of uncertainty about these aggregate incident data. Several peak period parameters are listed in the bottom half of table 4-2.

In order to estimate the data flows from vehicle probes, as well as to carry out the loads analysis for architectures using beacons, it was necessary to make estimates of the local vehicle flow on an average road link. For this analysis, a link is defined as the shortest one-way road segment for which speed or travel time data would be of interest. The average link length was assumed to be 0.25 miles, a value that has also been used by other researchers (Bhat et al., 1992). With an average trip length of 11 miles, an average trip includes 44 links. Links on arterials and freeways were defined *as reportable links* (Links involved road segments only; turning movements and exits were not identified as separate links.)

The average vehicle separation on these links was calculated as 213 feet, using an assumption of two lanes in each direction- At an average speed of 25 miles per hour, this separation is not unreasonable. The aggregate values of speed and number of vehicles per mile of road-way produce an average one-way flow rate past a point on the reportable links of about one vehicle every three seconds (on both lanes combined). This same value can be derived from the separation estimate. The local network data such as those that have been discussed here are listed in table 4-3.

Several variables were needed for this analysis that are related to the number of vehicles that have IVHS equipment, and to the number of assistance requests and route changes made. The values that were used are listed in table 4-4. Fifty percent of the vehicles on the road during the analysis period were assumed either to have in-vehicle route selection equipment or to use centralized routing messages (depending on the architecture). This high level of market penetration was selected so that the data loads of the various architectures could be compared for mature rather than start-up systems.

Table 4-3. Network Data

Variables	Value	Units	Code	Basis
Avg. length of a link	0.25	miles	LL	Assumed
Avg. # Links in a vehicle's route	44		Lr	= INT [TL/LL]
Number of reportable one-way links in area (freeways, major & minor arterials)	10,520		RL	= MFA (from Table 4-2) * 2 / LL
Number of link intersections (nodes) area-wide	2775		N	Estimated; based on RL & square area
Avg. # lanes per reportable link	2		NLa	Estimated
Fraction of a vehicle's trip time on *reportable links* (freeways and arterials)	.75		FR	Estimated
Avg. # vehicles per reportable one-way link during peak (steady-state)	12.4			= VoR * FR / RL
Avg. vehicle spacing per lane on reportable links during peak (steady-state)	213	feet	Sep	= MFA * 2 * 5280 * NLa / (VoR * FR)
Avg. vehicles separation (time) per lane on reportable links during peak (steady-state)	5.80	seconds		= Sep / Spd
Flow of all vehicles passing a point on a one-way link (2 lanes)	20.7	per minute		= Spd * NLa / Sep

Table 4-4. Data Related to Route Selection aud Assistance Requests by Equipped Vehicles

Variables	Value	Units	Code	Basis
Market share of IVHS-equipped **vehicles**	**50**	**percent**	**MS**	Assumed
Avg. equipped trip rate during peak	**3300**	**per minute**		= Rate • MS
Avg. equipped vehicles on road during peak	**87.1**	**1000s**	**EVoR**	=VoR*MS
Avg. number of vehicles on reportable links during peak	**65.3**	**1000s**		=EVoR*FR
No of equipped trips started in M minutes	**66.0**	**1000s**		=Rate*MS*M
No of equipped trips ended in M minutes	**66.0**	**1000s**		
No of times vehicle changes selected route in M minutes (vehicle routing)	0.6			Estimated (.6 in 20 minutes)
No of times driver asks for changed route or to check route in M minutes (central routing)	2			Estimated (2 in 20 minutes)
Fraction of route changes calculated by TMC in response to periodic check or driier request	0.05			Assumed
Avg. # links in a vehicle's route after changing routes/ receiving new route	25		Lnr	Assume avg. of 65% of trip
Assistance requests by an EQUIPPED vehicle in M minutes	0.0006			=5*IVM

For architectures with in-vehicle route selection, it was assumed that, on average, 60 percent of the vehicles would make a route change in a 20 minute period. It should be noted that the driver might request a change more frequently than this, but the route selection software would not always find a better route than the one already being traveled. Only in architectures with partial coupling, such as strawman 2, would this route change be communicated to the TMC.

For architectures with centralized route selection, it was assumed that an average driver asked for two route changes in 20 minutes, and that five percent of these requests resulted in actual changes. In addition, as will be discussed in section 6, periodic position reports by the vehicle to the TMC result in new routes being sent five percent of the time. The combination of the driver and vehicle communications to the TMC results in an average vehicle making 0.6 route changes in 20 minutes.

Irrespective of the location of the route selection equipment, it was assumed that the average route change occurred after about one-third of a trip was completed, leaving 25 links remaining in the route.

It was assumed that the equipped vehicles might call for assistance, not only for a situation that was classified as an incident, but for other more frequent vehicle breakdowns and for medical emergencies. A rate five times larger than the per vehicle incident rate was assumed for these requests.

SECTION 5

DESCRIPTION OF THE COMMUNI CATION MESSAGES

This section describes the development of the contents and structure of the communication messages — step 3 in the overall methodology shown in figure 3-1. These messages contain the data that need to be communicated among the various subsystems (e.g., the vehicle and the TMC) in the five strawman architectures. They are focused on vehicle-infrastructure information exchange, although roadside-TMC messages are defmed for beacon communication systems (Architectures 2 and 4). The analysis in this report does not cover messages that would originate and end within the infrastructure, such as those needed for operating traffic signals, or for performing traffic surveillance by means of traffic sensors.

The messages discussed here support the provision of the ATIS user services that were used to define the strawman architectures originally. These services are:

- In-vehicle trip planning (excluding dynamic public transit information);
- Position location;
- Route selection;
- Route guidance;
- Traffic and safety advisories (from the TMC);
- Assistance requests; and
- Traveler information services (in-vehicle).

Excluded in this analysis are messages related to the user services (e.g., traveler information services) that are provided entirely within one of the subsystems in the architectures. Also excluded are GPS satellite data, or differential GPS correction messages that could be used for position location.

The messages developed here can be used as a starting point for future IVHS message standards and protocols development efforts. In particular, they could be used in the initial phase of application-layer IVHS message format standardization efforts as related to vehicle-infrastructure communication. Ideally, these messages should be periodically reviewed and revised in order to reflect changing assumptions for the various messages or different architecture concepts.

5.1 GENERAL DESCRIPTION OF MESSAGES

A general description of each of the messages is provided in table 5- 1. Messages that include the same kind of information but vary in structure among the architectures are categorized as the same "message type." For each message type, a message number, the communication

Table 5-1. General Description of the Communication Messages

No.	Message Type	source-Sink	Architectures	Description
1A 18	Assistance Requests	v-TMC V-RS RS-TMC	1,2,3,4	A manual or automated "call for help" over the communication link in response to an incident, car trouble, crime, or other emergency situation
2A 2B	Assistance Response	TMC-V RS-V TMC-RS	1,2,3,4	Operator response to an assistance request; provides positive acknowledgement and necessary instructions
3	Vehicle ID Assignment	RS-V TMC-V	2,3,4	Contains a "randomly" assigned ID (to protect privacy) for architectures that require vehicle IDS; response to vehicle ID request
4	Vehicle ID Request	V-RS V-TMC	2,3,4	Request for a "random" ID to be used by the vehicle during the current trip
5A 58	Dynamic Link Times	TMC-V TMC-RS RS-V	1,2,5	Contains current/predicted link travel times (or factors) for the network or portions of the network to be updated necessary for architectures with in-vehicle route selection
7	Probe Data	RS-TMC	2.4	Contains aggregated link travel time experience reports; Combines data from individual vehicles (message 8)
8	Probe Data	V-TMC V-RS	1,2,3,4	Contains individual link travel time experience reports
9A 9Bl	Recommended Routes Sent to Individual Vehicle	TMC-V	3	Contains selected route information from the TMC in response to message 16; valid only for architectures with centralized route selection
9B2	Route Status OK	TMC-V	3	A short message sent in response to a routing request when the currently stored route is still favorable (as determined at the TMC)

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center

Table 5-l. (Continued)

No.	Message Type	Source-Sink	Architectures	Description
10	Selected Routes – Network	TMC-RS	4	Contains the currently favored localized route segments from one beacon to the rest of the network (one origin to all destinations); localized route segments consist of routing information to the next beacon
11	Beacon Routing Request	V-RS	4	A message from vehicles requesting the next localized route segment along the path to a final destination
12	Position Update	RS-V	4	A position update from a beacon that is used to correct the in-vehicle position location information
13	Localized Routing Data	RS-V	4	Response to message 11; contains detailed focalized route segment information such as recommended lane, exit turning code, distance, etc. for each link that can be used by a navigation processor for route guidance recommended lane (begin)
14 **15**	Route and Destination	RS-TMC V-RS	2	Contains selected route information from vehicles that is used in architectures with partial coupling
16	Routing Request	v-TMC	**3**	Driverrequest for a route from the TMC; similar to message 11; can also be used to keep the TMC informed on current location and allow for rerouting if needed
20	Alternate Route Recommendations	TMC-V	**5**	A text message similar to a traffic/ safety advisory, but gives specific recommendations on rerouting in response to non-recurrent congestion

Notes:

No. = message ID number; V = Vehicle; RS = Roadside: TMC = Traffic Management Center

Table 5-1. (Concluded)

No.	Message Type	Source-Sink	Architectures	Description
21 22	Traffic/Safety Advisories	TMC-RS RS-V TMC-V	1, 2, 3,4, 5	Coded message containing information on traffic accidents or other incidents, severe weather, road hazards, traffic delays, etc. (It is assumed that the message follows RDS-TMC format with minor additions, and that a message database resides in the cars)
24 25	Database Changes/Updates	TMC-V TMC-RS RS-V	1, 2,3,4,5	This message contains all of the significant changes to the map data since the last issue of the database; could be used to change historiil travel time data
26	System Status/ Parameters	TMC-V TMC-RS RS-V	1, 2,3,4,5	Thismessage ensures that the in-vehicle system is properly equipped for operation by providing current time, city and region ID, map database version, etc.
27	Position Reporting	TMC-V	193	Used to limit the quantity of vehicle probe reports by relaying reporting "rules;" could be facility type, zone, or link dependent
28	Trip Completed	V-TMC	193	This message could be used for planning purposes or historical analysis and to "de-assign" vehicle IDS, making them available for use again

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center

source and sink (or origin and destination), and the applicable strawman architectures are given in the table. The list includes the messages required in each of the five architectures, although not all messages apply to all architectures. The communication message flows between the vehicle and the traffic management infrastructure for each strawman architecture are depicted in the Appendix.

The roadside source/sink message types apply only to Architectures 2 and 4, which have roadside beacons. During the process of carrying out the analysis, some initially defined types of messages were subdivided into two message numbers, as differences in the required contents for various architectures or source-sink pairs were discovered. In the table, these subdivided messages have been grouped according to their basic message type rather than listed solely by message number. On the other hand, some initially defmed message types were later combined, resulting in the appearance of missing message numbers (e.g., 6 and 23) in table 5-1. The message number is provided only for ease of reference and is not meant to imply any particular ordering scheme.

5.2 MESSAGE CONTENT AND STRUCTURE

Each of the messages listed in table 5-l has been given a specific data field structure. The message type, communication source and sink, and data field structure for each message are compiled in table 5-2. For each data field contained in the message, the field type (I-integer, A-alphanumeric, F-floating point), field size in bits, and field format (F-fixed length or VL-variable length) are also provided. Italicized words are used in the table for explanatory purposes and do not refer to actual information bits in the message. Several variables appear in the table under the "Data Fields" and "Field Size Required" columns; these variables are used in the estimation of message lengths and are defined in section 6. Discussions of the estimation of field size requirements and the assumed message structure are provided in subsections 5.2.2 and 5.2.3.

Note that only the data fields containing information bits have been defined. We have not addressed error checking or other communication overhead. This is an important simplification because it results in communication load requirements (calculated in the next section) that underestimate the actual load. Even so, a comparative analysis of the information transfer requirements associated with the architectures is of substantial value.

In some cases, processing capability is assumed to be resident at beacon locations that would be used to reduce communication load requirements. For example, we assume that the link-by-link route information received from cars in message 15 is converted to a unique route ID by each beacon, which is transmitted to the TMC in message 14. This requires both a route ID database and the processing capability needed to determine the appropriate route ID for each set of links received from vehicles.

Table 5-2. Message Contents and Format

No.	Message Type	Source Sink	Architec-tureo	Data Fields	Reid Type	Field Size Required (bits)	Field Format
1A	Assistance Requests	V-TMC V-RS	1,2,3,4	message type	I	6	F
				permanent vehicle ID			
				lii plate (state abbrev. plus 7 char)	A	72	F
				car make and model (8 char)	A	64	F
				car color	I	8	F
				location			
				link ID	1	19	F
				offset (increments of 0.01 miles)	1	8	F
				(2,4 don't need loc from car to beacon)			
				time stamp (one second increments)	1	17	F
				type of assistance required code	1	4	F
				# characters in special text message (C)	1	7	F
				special text field (80 char maximum)	A	8*C	VL
1B	Assistance Requests	RS-TMC	2,4	message type		6	F
				Beacon ID	1	14	F
				permanent vehicle ID			
				license plate	A	72	F
				car make/model	A	64	F
				car color	1	8	F
				time stamp (one second increments)	1	17	F
				type of assistance required code	1	4	F
				# characters in special text message (C)	1	7	F
				special text field (80 char maximum)	A	8*C	VL
2A	Assistance Response	TMC-V RS-V	1,2,3,4	message type	1	6	F
				acknowledgment (perm vehicle ID- license)	A	72	F
				time stamp (one second increments)		17	F
				type of assistance provided (planned) code	I	4	F
				# characters in special text message (D)	1	7	F
				Special text field (to give instructions, special messages, etc.)	A	8*D	VL
2B	Assistance Response	TMC-RS	2,4	message type	1	6	F
				beacon ID	1	14	F
				acknowledgment (perm vehicle ID licensee)	A	72	F
				time stamp (one second increments)	1	17	F
				type of assistance provided (planned) code	I	4	F
				# characters in special text message (D)	I	7	F
				special text field (to give instructions, special messages, etc,)	A	8*D	VL

Notes:

No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center; I = Integer; A = Alphanumeric; F = Floating Point; F = Fixed Length; VL = Variable Length

Table 5-2. (Continued)

No.	Message Type	Souce-Sink	Architectures	Data Fields	Field Type	Field Size Required (bits)	Field Format
3	Vehicle ID Assignment	RS-V TMC-V	2, 3, 4	message type transaction # (originally sent from car) assigned ID	I I I	6 10 20	F F F
4	Vehicle ID Request	V-RS V-TMC	2, 3, 4	message type transaction # (randomly picked)	I I	6 10	F F
5A	Dynamic Link Times	TMC-V	1, 5	message type sequence # time stamp of message # of links reported in message (L) *(repeating group)* link ID travel time 1 (or factor) 1st 5 min. travel time 2 (or factor) 2nd 5 min. travel time 3 (or factor) * travel time 4 (or factor) * travel time 5 (or factor) * travel time 6 (or factor) * *{repeat for each link to be updated}*	I I I I I I I I I I I	6 3 17 12 19 6 6 6 6 6 6	F F F F F F F F F F F
5B	Dynamic Link Times	TMC-RS RS-V	2	message type beacon ID (for TMC-RS only) sequence # time stamp of message # of links reported in message (RL) *(repeating group)* link ID travel time (or factor) *{value depends on travel time from beacon to the link}* *{repeat for each link to be updated}*	I I I I I I I	6 14 3 17 12 19 6	F F F F F F F
7	Probe Data	RS-TMC	2, 4	message type beacon ID # of links to report (Lb) *(repeating group)* link ID # of reports travel times (avg., std dev.) waiting (parked) times (avg., std dev.) *{repeat for all link IDs served by beacon}*	I I I I I F, F F, F	6 14 6 19 9 64 64	F F F F F F F

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center; I = Integer;
A = Alphanumeric; F = Floating Point; F = Fixed Length; VL = Variable Length

Table 5-2. (Continued)

No.	Message Type	Souce-Sink	Architec-tures	Data Fields	Field Type	Field Size Required (bits)	Field Format
8	Probe Data	V-TMC V-RS	1, 3 2, 4	message type assigned vehicle ID (*arch 3 only*) link time database version (for exceptions) # of links (Lpb or Lp) (*repeating group*) link ID travel time (in seconds) waiting (parked) time (in seconds) time stamp at end of link (in seconds) {*repeat for other link IDs when vehicle stores up more than one*}	I I I I I I I I	6 20 4 4 19 10 10 17	F F F F F F F F
9A	Recom-mended Routes Sent to Individual Vehicle at Trip Start	TMC-V	3	message type assigned vehicle ID origin (link #) destination (link #) # links in route (Lr) route link IDs (1-Lr from O-D, *repeating field*)	I I I I I I	6 20 19 19 8 19*Lr	F F F F F VL
9B1	Recom-mended Routes Sent to Individual Vehicle after Trip in Progress	TMC-V	3	message type assigned vehicle ID current position (link #) destination (link #) # links remaining in route (Lnr) route link IDs (1-Lnr, repeating *field*)	I I I I I I	6 20 19 19 8 19*Lr	F F F F F VL
9B2	Route Status OK	TMC-V	3	message type assigned vehicle ID	I I	6 20	F F
10	Selected Routes - Network	TMC-RS	4	message type beacon ID # route IDs in message (Rb) {*first repeating group*} localized route ID (link IDs prestored at RS) # destination zones for that route (DZ) {*second repeating group*} destination zone (or group of zones) weighting value (for each destination zone, assume increments of 10%) (*Assuming can send cars with same O-D on multiple routes*)	I I I I I I I	6 14 8 8 9 11 4	F F F F F F F
11	Beacon Routing Request	V-RS	4	message type assigned vehicle ID destination zone (ID)	I I I	6 20 11	F F F

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center; I = Integer;
A = Alphanumeric; F = Floating Point; F = Fixed Length; VL = Variable Length

Table 5-2. (Continued)

No.	Message Type	Souce-Sink	Architec-tures	Data Fields	Field Type	Field Size Required (bits)	Field Format
12	Position Update	RS-V	4	message type	I	6	F
				beacon ID	I	14	F
				position update (you are here on this link)			
				link ID	I	19	F
				offset	I	8	F
				(assume same given to all cars on approach)			
13	Localized Routing Data	RS-V	4	message type	I	6	F
				assigned vehicle ID	I	20	F
				destination zone (ID)	I	11	F
				# links in localized route to next beacon (Lpb)	I	8	F
				{*repeating group*}			
				Link ID	I	19	F
				# lanes	I	3	F
				recommended lane (begin)	I	4	F
				recommended lane (end)	I	4	F
				recommended offset to be in end lane	I	8	F
				turning code at end of link	I	3	F
				offset for turn readiness	I	8	F
				link distance	I	8	F
				confidence angle (for dead-reckoning)	I	4	F
14	Route and Destination	RS-TMC	2	message type	I	6	F
				beacon ID	I	14	F
				# of unique destinations reported by vehicles in a beacon-TMC update cycle (UD)	I	19	F
				{*first repeating group*}			
				destination link ID	I	19	F
				# of unique routes per destination (Rd)	I	4	F
				[*second repeating group*]			
				route ID	I	4	F
				# of vehicles with that dest..-route (V)	I	9	F
				assigned vehicle IDs (*repeating field*)	I	20*V	VL
				(Summary Report)			
15	Route and Destination	V-RS	2	message type	I	6	F
				assigned vehicle ID	I	20	F
				destination link ID	I	19	F
				# links in route (Lr)	I	8	F
				selected route [link-by-link IDs]	I	19*Lr	VL

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center; I = Integer;
A = Alphanumeric; F = Floating Point; F = Fixed Length; VL = Variable Length

Table 5-2. (Continued)

No.	Message Type	Souce-Sink	Architec-tures	Data Fields	Field Type	Field Size Required (bits)	Field Format
16	Routing Request	V-TMC	3	message type	I	6	F
				assigned vehicle ID	I	20	F
				current location or origin			
				link ID	I	19	F
				offset (0.01 mile increments)	I	8	F
				destination			
				link ID	I	19	F
				(this message will be used to keep the TMC informed on current location and allow for rerouting if needed)			
20	Alternate Route Recommen-dations	TMC-V	5	message type	I	6	F
				# characters in text message (A)	I	7	F
				TEXT message (80 characters maximum)	A	8*A	VL
21	Traffic/Safety Advisories	TMC-RS	2, 4	message type	I	6	F
				beacon ID	I	14	F
				message #	I	8	F
				sequence #	I	3	F
				beacon-head ID code (if direction specific)	I	8	.
				advisory type (code, like RDS-TMC)	I	58	F
				additional information (severity, delays, etc.)	I		
				{*assume one standard + one optional TMC message -- ALERT C protocol, but detailed location code is link ID*}			
				location (street names, etc.) (assume 16 char to describe)	A	128	F
				[Assume message database resides in car, such as RDS-TMC]			
22	Traffic/Safety Advisories	RS-V TMC-V	2, 4 1, 3, 5	{same as message type 21, except no beacon ID or beacon-head ID code}	I, A	203	F
24	Database Changes/Upd ates	TMC-V RS-V	1, 2, 3, 5	message type	I	6	F
				US Region ID	I	4	F
				City ID	I	8	F
				Database version #	I	4	F
				Sequence #	I	2	F
				# of map updates in message (U)	I	8	F
				{*repeating group*}			
				Update Code	I	5	F
				# links changed in this update (Lu)	I	5	F
				Link ID(s)	I	19*Lu	VL
				update value/information	I	8	F
				(all updates since beginning of year/ version #)			

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center; I = Integer;
A = Alphanumeric; F = Floating Point; F = Fixed Length; VL = Variable Length

Table 5-2. (Concluded)

No.	Message Type	Souce-Sink	Architec-tures	Data Fields	Field Type	Field Size Required (bits)	Field Format
25	Database Changes/ Updates	TMC-RS	2, 4	message type	I	6	F
				Beacon ID	I	14	F
				Database version #	I	4	F
				Update Message #	I	8	F
				Sequence #	I	2	F
				Update Code	I	5	F
				# links changed in this update (Lu)	I	5	F
				Link ID(s)	I	19*Lu	VL
				update value/information	I	8	F
				duration code	I	4	F
				(as they happen, send one at a time)			
26	System Status/ Parameters	TMC-V TMC-RS RS-V	1, 2, 3, 4, 5	message type	I	6	F
				Time	I	17	F
				Date (7 for year, 4 for month, 5 day)	I	16	F
				US Region ID	I	4	F
				City ID	I	8	F
				Map database version #	I	4	F
				Field ID for Global Travel Time Changes	I	3	F
				Indicator of global changes (yes or no)	I	1	F
				Global Travel Time Changes Code	(I)	(2)	(F)
				Facility type code	(I)	(4)	(F)
				Travel time factor	(I)	(6)	(F)
27	Exception Reporting Rules *(Probe exception reporting rules/ changes by facility type, zones, link IDs, etc.)*	TMC-V	1, 3	message type	I	6	F
				# exceptions rules in message (E)	I	5	F
				{repeating group}			
				Exception Rules Code (1-4)	I	3	F
				(one of the following)			
				1. Facility type Code	I	4	F
				Value (thresholds)	I	6	F
				2. Zone Code ID	I	11	F
				Value (thresholds)	I	6	F
				3. # links in message	I	6	F
				{repeating group}			
				Link ID	I	19	F
				Value (thresholds)	I	6	F
				4. Global Value (thresholds for whole systems)	I	6	F
28	Trip Completed	V-TMC	1, 3	message type	I	6	F
				Assigned Vehicle ID (architecture 3 only)	I	20	F
				Origin Link ID	I	19	F
				Destination Link ID	I	19	F
				Travel Time (nearest minute)	I	8	F

Notes:
No. = message ID number; V = Vehicle; RS = Roadside; TMC = Traffic Management Center; I = Integer;
A = Alphanumeric; F = Floating Point; F = Fixed Length; VL = Variable Length

5.2.1 Assumptions about the Contents of Specific Messages

This subsection discusses the following types of messages: those related to route selection, traffic and safety advisories, and probe data. Several assumptions were made concerning the content of messages related to route selection. Links, which represent one-way segments of road between driver decision points (or nodes), were described numerically by link identifiers (Link IDS) as opposed to latitude and longitude coordinates. A high degree of time specificity in the link-time prediction was provided for all architectures. Each link updated in the dynamic link times message (message 5) was thus given predicted link travel times (or factors) for six consecutive five-minute intervals. Selected routes were described as an ordered series of links to be followed (messages 9A, 9B 1, 15).

Messages 10 and 13 are unique to Architecture 4 (centralized route selection with beacons) because, in this architecture, the vehicle is not equipped with a map database. In these messages, geographic zones instead of exact links are used as destinations. Each beacon has only **to** support a set of localized route segments, which enable a vehicle to reach the next beacon along the best path to its destination. Therefore, localized route IDS can be stored at both the TMC and the beacon, eliminating the need to send detailed routes from the TMC to each beacon (in message 10). The format of message 10 allows for multiple routes to be utilized for one O-D pair if necessary. As for message 13, the routing data transmitted to vehicles has to be detailed enough to provide route guidance for each vehicle maneuver (e.g., lane change, right turn), because no detailed map database is provided in the vehicle. In effect, a localized part of the network map is downloaded to the vehicle.

Traffic and safety advisories (messages 21 and 22) are assumed to follow the ALERT-C message protocol for RDS-TMC systems with minor additions (RDS ALERT Consortium, 1990). In particular, a detailed link ID and a text location with actual street names were added. This approach requires a traffic advisory message database to reside in the vehicle. A detailed categorization of these advisory messages is not warranted in this analysis, primarily because they are common across all architectures, and are unlikely to have high communication requirements when compared to probe or routing messages.

Probe data transmitted from a vehicle (message 8) consists of travel time, waiting time (when a vehicle is stopped or nearly stopped), and the time when the vehicle traversed the end of the link, for each reported link. Since beacons could be used to preprocess some of this information, we have assumed that beacon architectures compile summary statistics for the probe data during each communication update cycle (see message 7), and send only this summary data to the TMC. This summarization greatly reduces the message loads sent to the TMC when compared to non-beacon architectures.

5.2.2 Field Size Estimation

The required field sizes (in bits) were estimated for each data field in each message. For simplicity, a fixed rather than a variable field size was usually assumed. A conservative approach was used so that large field sizes were generally adopted to account for large metropolitan areas with heavy traffic. For example, over 500,000 unique link IDS could be supported by the assumed 19-bit field size, which would likely handle any given metropolitan area. Data elements that appear in several messages, such as link ID, were given identical field size values in each message.

Wherever possible, data fields were assumed to be of an integer type, in order to minimize the field size required. In determining the information bits needed, integer data fields were not required to begin and end at octet boundaries; thus, these field sizes did not have to be rounded up to the nearest multiple of 8. The typical 8-bit (or one byte) per character assumption was used for text fields and other fields requiring alphanumeric character representation. The IEEE floating point format of 32 bits (4 bytes) was used to represent each real number.

5.2.3 Message Structure

Because fixed field sizes were assumed for nearly all messages, a fairly simple message structure could be developed. It was assumed that the message structure can be decoded by the vehicle or TMC processors, so that field IDs and field length information do not normally need to be transmitted. Standardizing message structures in this way reduces the overhead bits that would need to be transmitted. For messages that could not be given a fixed length, a nested repeating group structure was used, as shown in figure 5-1. The size of each repeating group varies from one data field to several fields with secondary repeating groups. Messages with repeating groups are so noted in the "Data Fields" column of table 5-2. For example, Dynamic Link Times (messages 5A and 5B) has one repeating group, which occurs for each link reported in the message. Only two messages (10 and 14) have secondary repeating groups.

In the case of a fairly long message, it would likely be necessary to transmit pieces of the message at a time, which would induce additional overhead; however, considering the impacts on overhead is beyond the scope of this document.

As part of the process of selecting fixed or standardized field sizes, we examined ways of reducing wasteful bits for data fields that appear frequently in more than one message. The "Link ID" data field is a good example; this 19-bit field appears frequently in several important messages. However, for a medium-sized city, 19 bits to identify each link is substantially higher than necessary. One approach to this problem would be to include link ID field size as a data field in each message with link IDs; in this case, the field size could be optimized for each city or region. Another approach would be to include a separate message for the same purpose. These implementation options are beyond the scope of this report

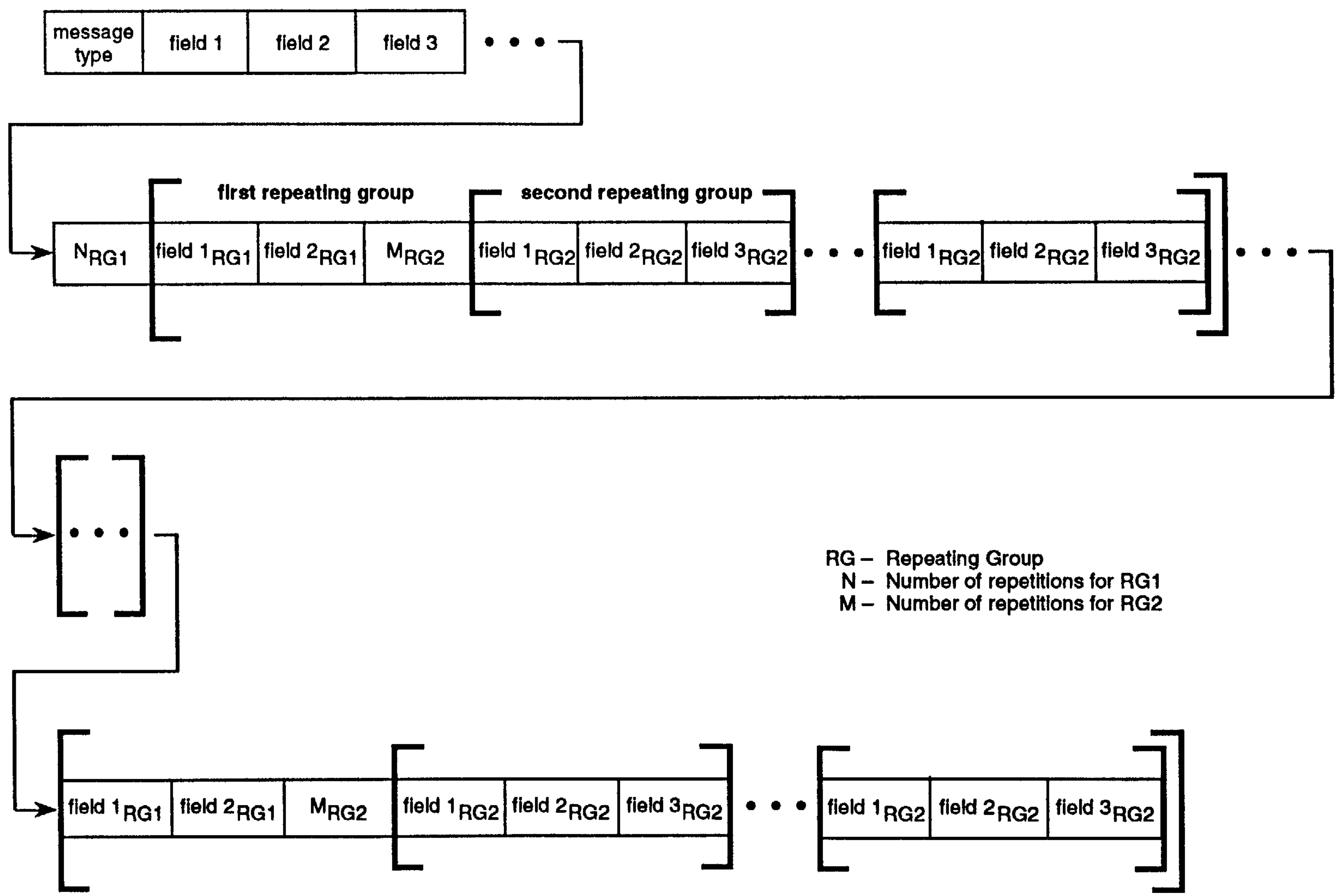

Figure 5-1. Nested Repeating Group Message Structure

SECTION 6

OPERATION OF THE COMMUNICATION SYSTEMS

This section describes the assumptions that were made concerning the operational characteristics of the communication systems, and defines several parameters of the operational systems. It represents step 4 in the overall methodology. The emphasis in the section is on explaining the rationale used for determining the message rates for different messages. Included are three subsections that discuss several general operational assumptions, the categorization of message frequency parameters, and the selection of the values of the operational parameters. The unique nature of beacon systems is highlighted throughout the discussion.

6.1 GENERAL OPERATIONAL ASSUMPTIONS

This subsection provides a description of the main operational attributes assumed for each of the four communication systems. A short description of each communication alternative was provided in section 2.2; more details about each can be found in (Cheslow et al., 1992b).

6.1.1 Broadcast Systems: Wide-Area Radio, Cellular Radio, One-Way FM Subcarrier

Although each of the broadcast-type alternatives has distinguishing characteristics, the operational assumptions for each are similar. Thus, we have grouped them together for ease of presentation.

Outbound Messages (TMC to Vehicles). A broadcast (one to many) dissemination mode is assumed for each. The same messages are transmitted to all vehicles in the communication range, relying on in-vehicle processors to sort out the data relevant for an individual vehicle's location and planned route of travel. For cellular systems, though, different messages can be broadcast in different cells, thus allowing for a more targeted set of messages to be transmitted in each cell. A Mobile Telephone Switching Office (MTSO), **which** provides message supervision and handoff control, and serves as the communication link to the TMC, is also required for cellular operations.

Inbound Messages (Vehicles to TMC). Each vehicle is assumed to send its own set of messages by means of a low-power transmission. No assumption is made here as to the type of communication media access protocol that would be used. For cellular systems, vehicles transmit messages to the cell base station in which it is currently operating. FM subcarrier does not have any inbound messages.

6.1.2 Localized Beacons

The localized nature of beacon transmissions and roadside processing necessitates a separate explanation of a beacon system's operational characteristics. We assumed that one beacon controller and several beacon heads will be necessary at each roadway intersection designated as a communication point. We further assumed that beacons will be placed on arterials and freeways, but *will not be installed on lower-class facilities* A representation of a beacon system is shown in figure 6- 1.

The beacon controller, which contains a processor and database, communicates with the TMC (probably using land lines). It also communicates with each beacon head under its control. It ensures that the messages needed by a particular vehicle are transmitted to the correct traffic approach (direction and lane).

Each beacon head is assumed to cover a single traffic approach at an intersection. A single head could probably serve two or three traffic lanes. These assumptions are based on the directional, near line-of-sight requirements of some infrared or microwave beacon systems. A beacon head can both transmit and receive vehicular messages.

Outbound Messages (TMC to Vehicles). Outbound messages have a TMC-to-roadside and a roadside-to-vehicle component. For the TMC to roadside component, we generally assume that location-specific information will be transmitted to each beacon controller, and that land lines could be employed to provide the communication link; however, no specific assumptions have been made regarding controller network connectivity. For simplicity, we have assumed that the TMC-to-roadside communication load is proportional to the total number of beacon controllers in the area.

For the roadside-to-vehicle component, each beacon head is assumed to transmit messages to all vehicles in its receiving range. Of course, some of the messages will apply only to a specific vehicle, but others will apply to all vehicles passing by. No assumption is made about the type of communication protocol that would be used.

Inbound Messages (Vehicles to TMC) Inbound messages also have two components. For the roadside-to-TMC component, each beacon controller transmits a unique set of messages to the TMC. The operational assumptions are therefore similar to those for outbound messages.

For the vehicle-to-roadside link, each vehicle is assumed to send its own set of messages by means of a low-power transmission that will be received by the beacon head pointed in its direction.

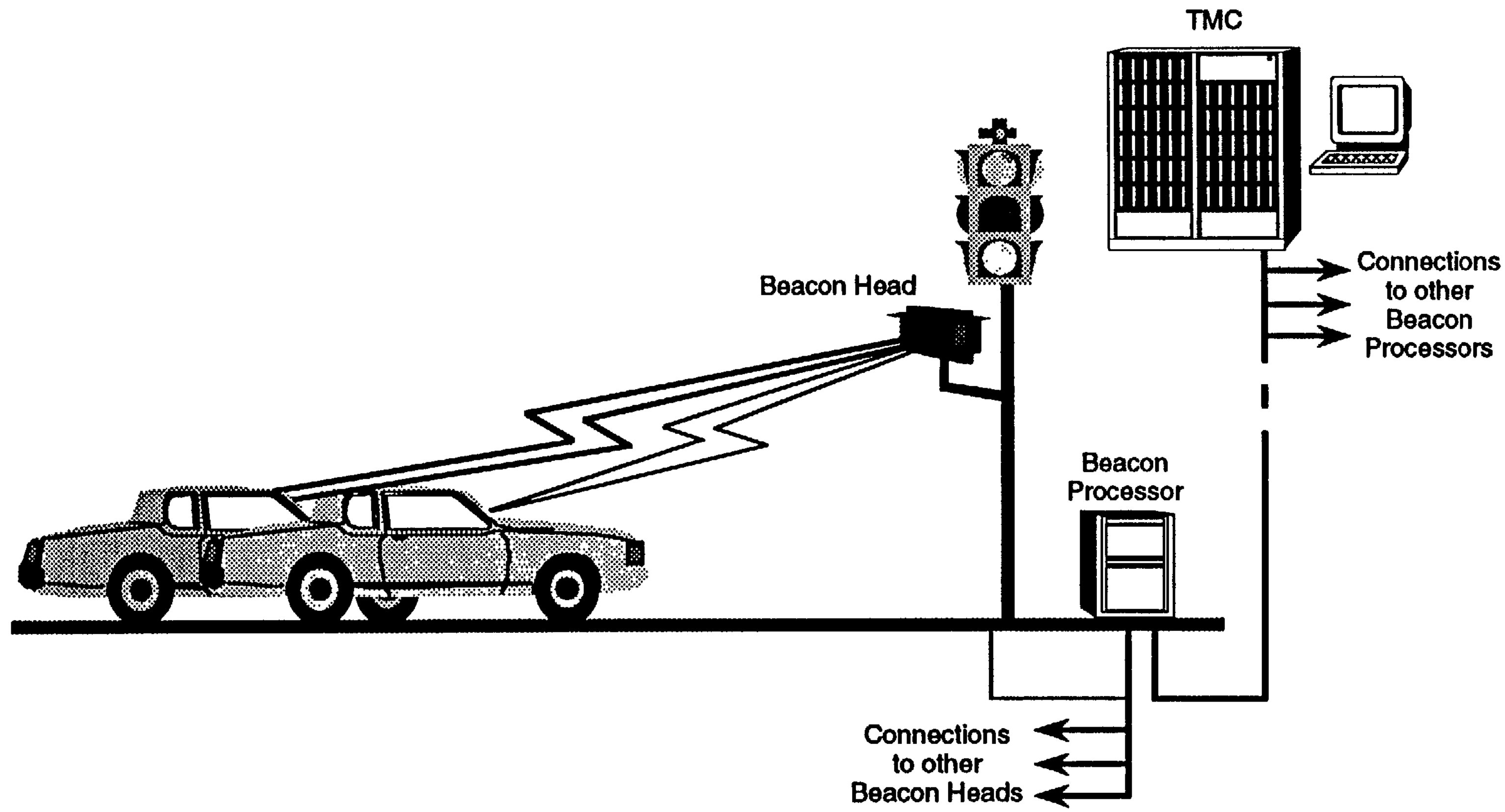

Figure 6-1. Representation of a Beacon Communication System

6.2 CATEGORIZATION OF MESSAGE FREQUENCY PARAMETERS

The frequency with which each message is transmitted is one of two major determinants of the communication load (the other being the message size). This subsection presents a discussion of how the message rates of the different messages were categorized; that is, **determiniug** whether a message was sent once per fixed time period, once per trip, once per occurrence, etc. The values selected for several of the messages are presented in section 6-3. Detailed listings of the frequencies for each message in each architecture are presented in section 7.

6.2.1 Broadcast Systems: Wide-Area Radio, Cellular Radio, One-Way FM Subcarrier

Table 6-l lists the message frequency categories for single-source messages associated with broadcast-type architectures. Single source refers to one equipped vehicle or the TMC. The "other" category in the table captures phenomena that cannot be described by a simple assumption.

Outbound Messages (TMC to Vehicles). Periodic update cycles are used to represent the frequencies of several of the outbound messages. For these messages, the number of equipped vehicles does not affect the message frequency. However, some outbound messages are triggered by inbound messages (e.g., Vehicle ID Assignment or Recommended Routes messages in Architecture 3); in those cases, the total number of equipped vehicles operating is a multiplicative factor in the computation of overall frequency.

Inbound Messages (Vehicles to TMC). All of the message frequency categories in table 6-1 other than the TMC update cycle apply to inbound messages. These single source frequencies must be multiplied by the total number of equipped vehicles operating in order to obtain the total inbound demand at the TMC. The "time to travel Y links" is assumed to be a constant in this study.

6.2.2 Localized Beacons

Table 6-2 contains the single-source message frequency assumptions for architectures using beacons. Single source here refers to a one equipped vehicle, one beacon, or the TMC. Only the message frequency categories that are unique to beacon systems are discussed here; some of the categories listed in table 6-l also apply to beacons, such as per vehicle trip and per occurrence.

Outbound Messages (TMC to Vehicles). A fixed TMC-beacon update cycle is used as the frequency of several messages from the TMC to beacon controllers. Several other frequency assumptions listed in table 6-l are applicable for certain types of messages in beacon systems. The total communication load from the TMC to the roadside is proportional to the total number of beacon controllers in the area.

Table 6-l. Message Frequency Categories for Broadcast Systems

Single Source Message Frequency Category (once...)	Example Applicable Messages (Message Number)
Per TMC update cycle	Dynamic Link Times (# 5A) Database Changes/Updates (# 24) Svstem Status/Parameters (# 26)
Per vehicle trip	Vehicle ID Request (# 4) Vehicle ID Assignment (# 3) Recommended Routes at Trip Start (# 9A) Trip Completed (# 28)
Per occurrence (e.g., incident, breakdown)	Assistance Requests (# 1 A, # 1 B) Assistance Response (# 2A, # 28) Traffic/Safety Advisories (# 21, # 22) Driver Routing Request after tripstart (# 16A2)
Per X minutes (similar to update cycle)	Position Update and Route Check (# 16B)
Per time to travel Y links	Probe Data (# 8)
Other	Route Status OK (# 9B2)

Table 6-2. Message Frequency Categories Unique to Beacon Systems

Single Source Message Frequency Category (once...)	Example Applicable Messages (Message Number)
Per TMC-beacon update cycle	Dynamic Link Times (# 58) Traffic/Safety Advisories (# 21) Selected Routes-Network (# 10)
Per beacon-TMC update cycle	Probe Data (# 7) Route and Destination (# 14)
Per vehicle-beacon transaction	Probe Data (# 8) Destination for Routing Request (# 11) Localized Routing Data (# 13)
Per time to travel the beacon contact range	Dynamic Link Times (# 58) Traffic/Safety Advisories (# 22)

For the beacon-to-vehicle transmission, there are two frequency assumptions that are unique to beacons: once per vehicle-beacon contact and once per time to travel the beacon contact range. For the first of these, the average flow rate of equipped vehicles is used to represent the required message frequency at the beacon head. The latter frequency, the time to travel the beacon contact range, depends only on the average vehicle speed and the communication range of the beacon head. This frequency assumption is used in cases in which the same message is required by all passing vehicles; it is equivalent to a localized broadcast

Inbound Messages (Vehicles to TMC). A beacon-TMC update cycle is used as the frequency of several inbound messages from the beacon controllers to the TMC. For our purposes, the beacon-TMC update cycle is assumed to be the same as the TMC-beacon update cycle, although this would not have to be the case in practice. Similar to the outbound messages, the communication load from all roadside beacons to the TMC is proportional to the total number of beacon controllers in the area.

For vehicle to beacon messages, the vehicle-beacon transaction assumption is the only one unique to beacon systems. It is assumed that each vehicle sends these messages at the rate at which it passes beacons. Correspondingly, the average flow rate of equipped vehicles is used to represent the total demand at each beacon head.

6.3 SELECTION OF COMMUNICATION SYSTEM PARAMETERS

The important communication system and message parameters that were required to calculate communication and processing loads are presented in this subsection. Table 6-3 lists those parameters that describe the operational characteristics of the communication systems, such as the TMC update cycle length. In addition, several parameters that were used in the calculation of message lengths are specified in the lower half of the table. Parameter codes listed here are used in the equations in the tables in section 7. Table 6-3 also specifies the values of many of the message length parameters that were originally defined in table 5-2.

As indicated in table 6-3, the period of most update cycles was assumed to be five minutes. This value was chosen because a one-minute cycle was thought be too short for significant changes to occur, but a ten-minute cycle would be too long. A “vehicle position check cycle” of two minutes was assumed for Architecture 3, which uses centralized route selection, to allow for a reasonable number of opportunities for rerouting.

Table 6-3. Communication System Message Parameters and Their Values

Parameter	Value	Units	Code[1]	Basis
Link time long update cycle (vehicle routing)	5	minutes		Assumed
Link time short update cycle (vehicle routing)	1	minutes		Assumed
TMC update cycle	5	minutes		Assumed
TMC-beacon processor update cycle	5	minutes		Assumed
Beacon processor-TMC update cycle	5	minutes		Assumed
Vehicle position check cycle	2	minutes		Assumed
Number of links reported in a probe report	4		Lp	Assumed
Minutes between each vehicle's probe report	2.4	minutes		Lp*LL/Spd
Fraction of reportable links that MUST be sent in short update cycle (critical links)	0.20			Estimated
Number of links sent in the link-time short update cycle	3790		L	Critical plus other
Avg. # text characters in Alternate Route Recommendation	60		A	Assumed
Avg. # text characters in Assistance Request	30		C	Assumed
Avg. # text characters in Assistance Response	30		D	Assumed
Avg. # of exception reporting rules in message 27	2		E	Assumed
Number of map database updates in TMC update cycle	100		U	Estimated
Number of links changed in each map update	2		Lu	Assumed

1 Parameter codes are used in tables 7-1 through 7-5 in section 7.

A short and a long cycle (one and five minutes, respectively) were used for broadcasting link time data in Architectures 1 and 5, which have in-vehicle route selection. All critical links (e.g., freeways and many major arterials), and 20 percent of the non-critical links are transmitted on a short update cycle. A different set of noncritical links is reported on each short cycle, so that all reportable links are updated in five minutes. This strategy enables users just beginning their journey to receive critical links in a timely fashion, while still being updated on all reportable links every five minutes.

Table 6-4 lists the parameters that describe the characteristics of beacon and cellular radio communication systems. The analysis of the beacon system required assumptions about the number of and spacing between beacons on the highway network. In addition, it was necessary to estimate the range of transmission of a beacon head. The following estimates were made for this study:

- The average travel distance between beacons is assumed to be one mile.
- There are 692 beacon processors in the area (based on the size of the urban area and the miles of roadway).
- On average, one beacon processor serves somewhat less than four beacon heads; 3.8 heads per processor was assumed.
- The communication contact range of a beacon head is 200 feet.

Several parameters related to the message lengths for the beacon architectures were estimated, and these are also presented in table 6-4.

The load analysis of the cellular system required an estimate of the number of cells for the hypothetical urban area. Because the design of a complete cellular system was not undertaken, it was not possible to precisely estimate the number of cells; but several possibilities were considered. It was estimated that about 100 cells might be required to handle the digital cellular telephone service in the analysis area, based on the current number of cells for an analog telephone service, and a current cellular phone market penetration of five percent. As our analysis progressed, it became apparent that with 100 cells, the communication loads to a single base station would require less than one channel. Therefore, we considered an operational approach for a shared cellular system where there would be fewer, but larger, cells for IVHS than for the phone system. The IVHS cells would be multiples of the phone system cells, and use appropriate portions of the base station infrastructure. The IVHS cells could be dubbed “super cells.”

With a channel capacity of 9600 bps, we estimated that 20 to 30 super cells might be required if only one pair of channels per cell were dedicated for M-IS services. Alternatively, we considered a simple design where seven cells would be used — one in the center of the area and six surrounding it. There was some concern about whether the center cell could handle

Table 6-4. Characteristics of Beacon and Cellular Radio Systems

Parameter	Value	Units	Code[1]	Basis
DATA FOR BEACONS				
Avg. distance between beacons	1	miles	DB	Assumed
Avg. no of beacon heads per direction	1			Assumed
Contact range of a beacon head	200	feet		Assumed
Number of beacon heads area-wide	2630			Derived from DB and network arterial and freeway miles
Vehicle-beacon transaction cycle	2.4	minutes		Time between beacon contacts
Avg. rate of equipped vehicles passing one beacon head	10.35	per minute	Q	From speed • density • market share
No of beacon heads passed by a vehicle in M minutes	8.3			M*DB/Spd
!Avg. # of links reported by a vehicle at a beacon head (avg. links traveled between beacons)	4		Lpb	DB/LL
Time for vehicle to travel the beacon range	5.45	seconds		
Avg. # of traffic flow directions per beacon processor	3.6			Estimated
Avg. # of beacon heads per beacon processor	3.8		AHpb	
Number of beacon processors area-wide	692			Calculated from beacon head data
Avg. # of unique destinations reported by vehicles in a beacon processor-TMC update cycle	197		UD	# vehicles passing beacon processor in update cycle
Avg. # links served by a beacon processor for probe reports	15		Lb	(direction/processor) • (dist/beacon) / (dist/link)
Avg. # of routes supported by a beacon processor	7.5		Rb	Estimated based on Lb
Avg. # of destination zones per selected route from beacon	120		**DZ**	Est. based on Rb and total zones (some super zones)
Avg. # of unique routes per destination	1		Rd	Estimated
Avg. # of vehicles with same destination and route in a beacon-TMC update cycle	1		V	Estimated
DATA FOR CELLULAR RADIO				
Number of cells (and base stations)	10			Estimated
Avg. area sewed by one base station	82	Sq. Mi.		Based on 10 cells
Required range of transmitter	5.1	Miles		Calculated

1 Parameter codes appear in tables 7-1 through 7-5 in section 7.

the traffic density in the center of the area. A variation with the center cell split into four cells was posited; this gave a total of ten cells. It was decided to use ten cells for the analysis of the cellular architectures. Because all cells were assumed to have the same average traffic loads, it is simple for the reader to alter this assumption.

SECTION 7

COMMUNICATION LOAD REQUIREMENTS: RESULTS FOR THE STRAWMAN ARCHITECTURES

This section describes the results of the communication load requirements analysis for the five strawman architectures. It includes steps 5,6, and 7 of the general methodology that was shown previously in figure 3-1. A detailed description of these three steps is as follows:

For each message

- Step 5. Determine the average message length (in bits) using the message structure provided in section 5 and applying the message length parameters given in section 6. Although many of the messages will actually be of variable length, using the average value is satisfactory for calculating average communication loads.

- Step 6. Calculate the average message frequency from a single source (e.g., a vehicle or a beacon). For some of the messages, calculate the overall message frequency from *all* sources. The message frequency assumptions and communication and traffic parameters discussed in section 6 are used in this step. More detail on this step will be presented in this section.

- Step 7. Compute the required communication load as the product of the average message length and the average message frequency.

7.1 BASELINE RESULTS FOR STRAWMAN ARCHITECTURES

This subsection describes the communication load requirements for each of the strawman architectures. As a reminder to the reader, the key attributes of each strawman are listed with the discussion. The communication loads are assumed to be in a steady state (i.e., at a constant level over time). We will refer to the results in this subsection *as the baseline* results, since the parameter values defined in sections 4 and 6 have been applied without modification.

In the remainder of section 7.1, the term TMC-V refers to transmission from the TMC to vehicles, and V-TMC indicates transmission from vehicles to the TMC. Similar terms apply to transmissions involving beacons, where RS is used to indicate roadside.

7.1.1- Architecture 1

The key characteristics of Architecture 1 are:

- Uncoupled route selection/traffic control;
- In-vehicle route selection;
- In-vehicle map database; and
- Two-way wide-area radio communications.

The communication load requirements for Architecture 1 are given in table 7- 1. The table provides, for each of the applicable messages, the source-sink, message length, message frequency, and average communication load. In addition, the total loads between all vehicles and the TMC, the percent of the total load by individual message type, and the message frequency assumption is given. Because wide-area radio, which is used for communication between the TMC and the vehicles, is a broadcast mode, it is assumed to provide the same information from the TMC to every vehicle in the urban area.

Approximately 3500 bits per second are required for TMC-V transmission, with 99 percent of the load coming from the dynamic link times for reportable links. As mentioned in section 6.3, a short and long cycle (one and five minutes, respectively) are used to broadcast the required link time data; all critical links (assumed to be freeways and a few important arterials) and a fraction of the remaining (non-critical) links are transmitted on the short update cycle, with a different set of non-critical links being reported each short cycle, so that all have been reported in five minutes. This strategy enables users just beginning their journey to receive critical links in a timely fashion, while still being updated on all reportable links every five minutes. The remaining TMC-V messages combined account for just over 1 percent of the total load. Traffic/safety advisories do not appear to be a significant factor in this loads analysis.

For vehicle-TMC messages, the transmission frequency from a single vehicle must be multiplied by the total number of equipped vehicles operating simultaneously in order to determine the total load at the TMC. Thus, the total number of vehicles is a major driver of the total load. About 111 kilobits per second is required for the inbound communication load. Over 97 percent of this is due to vehicle probe reports. This is certainly more than a single inbound radio channel could handle. Assuming 100 percent overhead on top of the information load, about 23 channels at 9600 bps per channel would be needed. Note that this calculation is based **on** the assumption that travel times for all of the freeway and arterial links traversed are reported. It was also assumed that each vehicle transmits a probe report after traversing four reportable links.

Table 7-1. Communication Load Requirements: Architecture 1

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency from One Vehicle (per minute)	Message Frequency (per minute)	Avg. Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source–Sink	Assumption for Single Source Message Frequency
1A	Assistance Requests	V-TMC	205+8C	445	0.00003	3	22	0.0%	Rate for breakdowns, accidents, vehicle crimes, etc. (random)
8	Probe Data	V-TMC	14+56Lp	238	0.42	27,210	107,934	97.4%	Once per time to travel Lp links if reporting all links
28	Trip Completed	V-TMC	52	52	0.038	3,298	2,858	2.6%	Once per vehicle-trip
	Total for all vehicles to TMC						**110,814**	**100%**	
2A	Assistance Response	TMC-V	106+8D	346		3	17	0.5%	Rate for breakdowns, accidents, vehicle crimes, etc. (random)
5A	Dynamic Link Times	TMC-V	38+55L	208,323		1.0	3,472	98.8%	Once per link time short update cycle
22	Traffic/Safety Advisories	TMC-V	203	203		2.0	7	0.2%	Frequency of traffic exceptions: incidents, congestion, bad wx, etc. (send for each incident)
24	Database Changes/ Updates	TMC-V	32+U (18+19 Lu)	5,632		0.2	19	0.5%	Once per TMC-vehicle update cycle
26	System Status/ Parameters	TMC-V	59	59		0.2	0.2	0.0%	Once per TMC-vehicle update cycle
27	(Exception Reporting Rules)	TMC-V	11+64E	139		0	0	0.0%	Once per TMC-vehicle update cycle
	Total for TMC to all vehicles						**3,514**	**100%**	

Note: Architecture 1 uses in-vehicle route selection, wide-area radio communications, and uncoupled route selection/traffic control.

7.1.2 Architecture 2

The key characteristics of Architecture 2 are:

- Partially coupled route selection/traffic control;
- In-vehicle route selection;
- In-vehicle map database; and
- Two-way localized (beacon) communications.

The communication load requirements for Architecture 2 are given in table 7-2. Since beacons are used for communication, the loads are calculated in two stages: first, the average loads between vehicles and a single beacon head are computed (V-RS RS-V), then the loads between a single beacon processor and the TMC are calculated (RS-TMC, TMC-RS). The load between a single beacon processor and the TMC is then multiplied by the total number of beacon processors to obtain the total network load on the TMC. Most of the messages have both a V-RS and a RS-TMC component, or vice-versa. We assumed that each beacon head is hard-wired to the beacon processor but do not explicitly model this connection. See section 6 for a discussion of the operations of beacon communication systems and a list of the system characteristics used in the analysis.

A discussion of the important messages should help to clarify the table. The messages are similar to those of Architecture 1, since routes are calculated in individual vehicles. Vehicles also send a route and destination message to the TMC, which is necessary for partial coupling, as discussed in section 2. We assume that vehicles send this message at each beacon they encounter in order to enhance the traffic prediction function at the TMC. Probe data describing the links traversed between beacon transactions is sent from vehicles to each beacon along their route. The beacon processor stores the probe data from all vehicles passing since the last beacon-TMC update cycle, computes summary statistics for each link reported, and sends the summary information to the TMC during the next update cycle. Thus, each beacon acts as a preprocessor for probe reports, which lessens the communication and processing load at the TMC. This aspect of the beacon system is very important in differentiating it from other communication media.

The characteristics of the dynamic link times message differ from those in Architecture 1:

- Only one predicted travel time per link is sent to vehicles (the value depends on the projected travel time from that beacon to the link)

- The full set of reportable links is “continuously transmitted” by each beacon head in numbered blocks so that each passing car can receive the full set of blocks, regardless of which block is received first

- A unique set of link times is sent by the TMC to each beacon processor, although neighboring processors may receive similar sets

Table 7-2. Communication Load Requirements: Architecture 2

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency between Vehicles & Avg. Beacon Head (per minute)	Message Frequency between TMC & Avg. Beacon Processor (per minute)	Avg. Comm. Load to/from Beacon Head (bps)	Avg. Comm. Load to/from Avg. Beacon Processor (bps)	Avg. Total Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source–Sink	Assumption for Single Source Message Frequency
1A	Assistance Requests	V-RS	178+8C	418	0.001		0.0			0.0%	Rate for breakdowns, accidents, vehicle crimes, etc.
4	Vehicle ID Request	V-RS	16	16	1.3		0.3			0.3%	Once per vehicle-trip
8	Probe Data	V-RS	14+56Lpb	238	10.3		41			33.5%	Once per vehicle-beacon transaction
15	Route and Destination	V-RS	53+19 (0.5)Lr	471	10.3		81			66.2%	Once per vehicle-beacon transaction
	Total from passing vehicles to each beacon head						**123**			**100%**	
1B	Assistance Requests	RS-TMC	192+8C	432		0.001		0.0	16	0.1%	Rate for breakdowns, accidents, vehicle crimes, etc.
7	Probe Data	RS-TMC	26+156Lb	2,366		0.2		7.9	5,458	17.6%	Once per beacon-TMC update cycle
14	Route and Destination	RS-TMC	39+UD[23+ Rd(13+20V)]	11,047		0.2		36.8	25,486	82.3%	Once per beacon-TMC update cycle
	Total from beacon processor(s) to TMC							**45**	**30,960**	**100%**	

Note: Architecture 2 uses in-vehicle route selection, localized beacon communications, and partially coupled route selection/traffic control.

Table 7-2. (Concluded)

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency between Vehicles & Avg. Beacon Head (per minute)	Message Frequency between TMC & Avg. Beacon Processor (per minute)	Avg. Comm. Load to/from Beacon Head (bps)	Avg. Comm. Load to/from Avg. Beacon Processor (bps)	Avg. Total Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source–Sink	Assumption for Single Source Message Frequency
2B	Assistance Response	TMC-RS	120+8D	360		0.001		0.0	13	0.0%	Rate for breakdowns, accidents, vehicle crimes, etc.
5B	Dynamic Link Times	TMC-RS	52+25RL	263,052		0.2		877	606,866	99.9%	Once per TMC-beacon update cycle
21	Traffic/Safety Advisories	TMC-RS	225	225		0.2		0.8	519	0.1%	Once per TMC-beacon update cycle
25	Database Changes/ Updates at Roadside	TMC-RS	56+19Lu	94		0.017		0.0	18	0.0%	Once per database update needed (assume previous changes already pre-stored at beacons)
26	System Status/ Parameters	TMC-RS	59	59		0.2		0.2	136	0.02%	Once per vehicle-trip (e.g., along with assigned ID)
	Total from TMC to beacon processor(s)							**878**	**607,552**	**100%**	
2A	Assistance Response	RS-V	106+8D	346	0.001		0.0			0.0%	Rate for breakdowns, accidents, vehicle crimes, etc.
3	Vehicle ID Assignment	RS-V	36	36	1.3		0.8			0.0%	Once per vehicle-trip
5B	Dynamic Link Times	RS-V	38+25RL	263,038	11.0		48,224			99.7%	Send all links in small number of blocks, continuously; one complete cycle sent while car within beacon range
22	Traffic/Safety Advisories	RS-V	203	203	11.0		37			0.1%	Same as message 5 (RS-V)
24	Database Changes/ Updates	RS-V	32+U (18+19Lu)	5,632	1.3		118			0.2%	Once per vehicle-trip
26	System Status/ Parameters	RS-V	59	59	1.3		1.2			0.0%	Once per vehicle-trip
	Total from each beacon head to passing vehicles						**48,381**			**100%**	

Note: Architecture 2 uses in-vehicle route selection, localized beacon communications, and partially coupled route selection/traffic control.

As shown in table 7-2, the dynamic link times message produces over 99 percent of the total load from the TMC to beacons and from beacon heads to vehicles. The 48 kbps required from beacon heads to vehicles is significant, although not prohibitive with infrared or microwave technology. Assuming land lines could interconnect the beacon processors with the TMC, the TMC-to-beacon and beacon-to-TMC loads do not appear to be a problem. In addition, the communication load from passing vehicles to each beacon head (0.12 kbps) appears to be rather insignificant. The route and destination message accounts for the majority of this load. In other words, only the communication load from the beacon head to passing vehicles may be significant with a beacon system.

Remember that these are average communication loads for an average beacon, with no distinction made between different facility types. A beacon on a freeway has been treated the same as a beacon on an arterial. However, the communication load requirements for a beacon on a freeway are likely to be higher than those for an arterial beacon. The reason is that both vehicle speed and flow rate are the crucial variables affecting the message frequency required, and both would be higher on freeways than arterials. Although a detailed analysis has not been completed, increasing the average loads by a factor of two to four should serve as a better estimate of the loads on freeway beacons.

7.1.3 Architecture 3

The key characteristics of Architecture 3 are:

- Fully coupled route selection/traffic control;
- Centralized route selection;
- In-vehicle map database; and
- Two-way cellular radio communications.

The communication load requirements for Architecture 3 are given in table 7-3. Because centralized route selection is used, the messages differ substantially from those in the previous two architectures. Rather than broadcasting dynamic link times, the TMC sends recommended (selected) route messages to the vehicles. In addition to sending probe data, drivers must request routes from the TMC at the beginning of the trip; they may also manually request a new route during the trip. We have assumed that drivers will request that the TMC alert them of a new best route, if available, an average of about once every ten minutes of driving time. Although this might seem high for some drivers, it is possible that others (impatient drivers) would almost continuously request new and better routes.

In addition to the manual routing request, an automated position update and route check (message 16B) is assumed to be transmitted to the TMC every two minutes. This message is necessary to keep the TMC informed of the current positions of equipped vehicles, and to provide the means for rerouting vehicles when traffic characteristics change. It is also critical in the context of a fully coupled system, since the TMC needs up-to-date position information to make frequent and accurate traffic predictions.

Table 7-3. Communication Load Requirements: Architecture 3

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency from One Vehicle (per minute)	Message Frequency (per minute)	Avg. Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source–Sink	Assumption for Single Source Message Frequency
1A	Assistance Requests	V-TMC	205+8C	445	0.00003	3	22	0.0%	Rate for breakdowns, accidents, vehicle crimes, etc. (random)
4	Vehicle ID Request	V-TMC	16	16	0.038	3,298	880	0.5%	Once per vehicle-trip
8	Probe Data	V-TMC	34+56Lp	258	0.42	27,210	117,005	62.1%	Once per time to travel Lp links if reporting all links
16A1	Driver Routing Request at Trip Start	V-TMC	72	72	0.038	3,298	3,958	2.1%	Once per vehicle-trip
16A2	Driver Routing Request after Trip in Progress	V-TMC	72	72	0.10	8,707	10,449	5.5%	Once per route change initiated by driver—changes route/dest or wants to check route
16B	Position Update & Route Check	V-TMC	72	72	0.50	43,537	52,244	27.7%	Periodic check message (once per vehicle position check cycle)
28	Trip Completed	V-TMC	72	72	0.038	3,298	3,958	2.1%	Once per vehicle-trip
	Total from all base stations to TMC						**188,514**	**100%**	
	Total for vehicles to a single base station[1]						**18,851**		

Note: Architecture 3 uses centralized route selection, cellular radio communications, and fully coupled route selection/traffic control.

[1]Total number of base stations (cells) assumed is 10.

Table 7-3. (Concluded)

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency from One Vehicle (per minute)	Message Frequency (per minute)	Avg. Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source–Sink	Assumption for Single Source Message Frequency
2A	Assistance Response	TMC-V	106+8D	346	0.00003	3	17	0.0%	Rate for breakdowns, accidents, vehicle crimes, etc. (random)
3	Vehicle ID Assignment	TMC-V	36	36	0.038	3,298	1,979	2.4%	Once per vehicle-trip
9A	Recommended Routes Sent to Vehicle at Trip Start	TMC-V	72+19Lr	908	0.038	3,298	49,913	60.4%	Once per time to travel Lp links if reporting all links
9B1	Recommended Routes Sent to Vehicle after Trip in Progress	TMC-V	72+19Lnr	623	0.030	2,612	27,123	32.8%	Once per vehicle-trip
9B2	Route Status OK	TMC-V	26	26	0.095	8,272	3,585	4.3%	Once per route change initiated by driver—changes route/dest or wants to check route
22	Traffic/Safety Advisories	TMC-V	203	203		2.0	7	0.0%	Periodic check message (once per vehicle position check cycle)
24	Database Changes/ Updates	TMC-V	32+U(18+19Lu)	5,632		0.20	19	0.0%	Once per vehicle-trip
26	System Status/ Parameters	TMC-V	59	59		0.20	0.2	0.0%	Once per TMC-vehicle update cycle
27	Exception Reporting Rules	TMC-V	11+64E	139		0.20	0.5	0.0%	Once per TMC-vehicle update cycle
	Total from TMC to all base stations						**82,643**	**100%**	
	Total for single base station to vehicles[1]						**8,287**		

Note: Architecture 3 uses centralized route selection, cellular radio communications, and fully coupled route selection/traffic control.

[1]Total number of base stations (cells) assumed is 10.

We made specific operational assumptions regarding the response of the TMC to the various types of routing request messages. In response to the driver routing request at trip start message (#16Al), the TMC must send a recommended route message to the vehicle (#A). In response to the manual driver routing request after trip in progress message (#16A2), the TMC either sends a new recommended route message (#9B 1) to the vehicle, or sends a route status OK message (#9B2) that alerts the driver that the currently stored route is still recommended. In response to the automated position update and route check message (#16B), the TMC either sends a new recommended route message (#9B 1) to the vehicle, or sends *nothing* if the currently stored route is still recommended. It was thought that positive feedback, resulting from the route status OK message, would be needed by the driver who manually requested the TMC to check for a better route. However, we did not think that a route status OK message would be required in response to the automated position update.

Even though this architecture uses a cellular communication system, the approach taken was to compute total loads to and from the TMC the same way as for wide-area radio, then divide the loads by the number of cells in the area to obtain the load on a single cellular base station. This approach is based on the assumption that the cells serve only to distribute the overall load, and do not provide significant processing functions in the architecture. In other words, the messages from the TMC to the base stations are simply passed from the base stations to vehicles, and vice versa, without modification. Of course, this simplification ignores the communication overhead required for cellular operation, especially that related to the MTSO. We assume that the TMC is hard-wired to the MTSO.

Interestingly, the total inbound load of 189 kilobits per second (kbps) from all base stations to the TMC is substantially larger than the 83 kbps required for messages from the TMC to the base stations, even though individual&d routes are being sent to drivers. Assuming the metropolitan area is divided into 10 cells, the average load per base station is 18.9 kbps for inbound messages and 8.3 kbps for outbound messages. With a 19.2 kbps data rate per channel and 100 percent overhead on top of the information load, this would require at least two channels per cell. Probe data and routing requests, in particular the automated check message, produce most of the inbound load. As expected, recommended route messages dominate the outbound load (93 percent of total load).

7.1.4 Architecture 4

The key characteristics of Architecture 4 are:

- Uncoupled route selection/traffic control;
- Centralized route selection;
- *No in-vehicle map database;* and
- Two-way localized (beacon) communications.

The communication load requirements for Architecture 4 are given in table 7-4. Since beacons are used for communication, the loads are calculated in the two stages described in

Table 7-4. Communication Load Requirements: Architecture 4

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency between Vehicles & Avg. Beacon Head (per minute)	Message Frequency between TMC & Avg. Beacon Processor (per minute)	Avg. Comm. Load to/from Beacon Head (bps)	Avg. Comm. Load to/from Avg. Beacon Processor (bps)	Avg. Total Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source-Sink	Assumption for Single Source Message Frequency
1A	Assistance Requests	V-RS	178+8C	418	0.001		0.0			0.0%	Rate for breakdowns, accidents, vehicle crimes, etc.
4	Vehicle ID Request	V-RS	16	16	1.3		0.3			0.7%	Once per vehicle-trip
8	Probe Data	V-RS	14+56Lpb	238	10.3		41			85.9%	Once per vehicle-beacon transaction
11	Beacon Routing Request	V-RS	37	37	10.3		6			13.4%	Once per vehicle-beacon transaction
	Total from passing vehicles to each beacon head						**48**			**100%**	
1B	Assistance Requests	RS-TMC	192+8C	432		0.001		0.0	16	0.3%	Rate for breakdowns, accidents, vehicle crimes, etc.
7	Probe Data	RS-TMC	26+156Lb	2,366		0.2		7.9	5,458	99.7%	Once per beacon-TMC update cycle
	Total from beacon processor(s) to TMC							**8**	**5,474**	**100%**	
2B	Assistance Response	TMC-RS	120+8D	360		0.001		0.0	13	0.0%	Rate for breakdowns, accidents, vehicle crimes, etc.
10	Selected Routes – Network	TMC-RS	28+Rb (17+15DZ)	13,656		0.2		45.5	31,503	98.0%	Once per TMC-beacon update cycle
21	Traffic/Safety Advisories	TMC-RS	225	225		0.2		0.8	519	1.6%	Once per TMC-beacon update cycle
25	Database Changes/ Updates at Roadside	TMC-RS	56+19 Lu	94		0.017		0.0	18	0.1%	Assume just one update in the peak hour
26	System Status/ Parameters	TMC-RS	39	39		0.2		0.1	90	0.3%	Once per vehicle-trip (e.g., along with assigned ID)
	Total from TMC to beacon processor(s)							**46**	**32,144**	**100%**	

Note: Architecture 4 uses centralized route selection, localized beacon communications, and uncoupled route selection/traffic control.

Table 7-4. (Concluded)

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency between Vehicles & Avg. Beacon Head (per minute)	Message Frequency between TMC & Avg. Beacon Processor (per minute)	Avg. Comm. Load to/from Beacon Head (bps)	Avg. Comm. Load to/from Avg. Beacon Processor (bps)	Avg. Total Comm. Load to/from TMC (bps)	Percent of Comm. Load per Message by Source-Sink	Assumption for Single Source Message Frequency
2A	Assistance Response	RS-V	106+8D	346	0.001		0.0			0.0%	Rate for breakdowns, accidents, vehicle crimes, etc.
3	Vehicle ID Assignment	RS-V	36	36	1.3		0.8			0.8%	Once per vehicle-trip
12	Position Update	RS-V	47	47	10.3		8			8.4%	Once per vehicle-beacon transaction
13	Localized Routing Data	RS-V	45+61Lpb	289	10.3		50			51.5%	Once per vehicle-beacon transaction
22	Traffic/Safety Advisories	RS-V	203	203	11.0		37			38.5%	Send all links in small number of blocks, continuously; one complete cycle sent while car within beacon range
26	System Status/Parameters	RS-V	39	39	1.3		0.8			0.8	Once per vehicle-trip
	Total from each beacon head to passing vehicle						**97**			**100%**	

Note: Architecture 4 uses centralized route selection, localized beacon communications, and uncoupled route selection/traffic control.

section 7.1.2. Several of the messages and assumptions are similar to those in Architecture 2. The main differences result from the fact that this architecture employs centralized route selection without an in-vehicle map database. Vehicles send their destination to every beacon they pass and receive localized routing data (including map and turning information) to support the trip segment to the next beacon along the recommended route. A position update must also be sent to each vehicle to correct for position location errors accumulated between beacons. For each TMC-beacon update cycle (five minutes in this case), the TMC distributes the current set of recommended "localized routes" to each beacon.

All of the computed loads are fairly small, especially when compared to those in Architecture 2. This architecture appears to be quite viable from a communication load standpoint. It is simpler than Architecture 3 (which has centralized route selection), because only localized route information in the proximity of a beacon needs to be sent to each vehicle. As expected, the main contributors to the loads are probe data and routing data.

7.1.5 Architecture 5

The key characteristics of Architecture 5 are:

- Uncoupled route selection/traffic control;
- In-vehicle route selection;
- In-vehicle map database; and
- One-way broadcast (FM subcarrier) to vehicles for communications.

The communication load requirements for Architecture 5 are given in table 7-5. The TMC-V loads are similar to those in Architecture 1, with the most significant difference being that no assistance response message is present in Architecture 5. The assumptions about the dynamic link time message are identical to those in Architecture 1. This architecture does not contain any messages that originate from vehicles, since it provides only a one-way broadcast over FM subcarrier.

7.1.6 Summary

These results indicate that the overall communication requirements vary substantially with the choice of the system architecture. Vehicle probe data place a very demanding requirement on the wide-area radio and cellular communication systems, at least for those systems without methods such as throttling or sampling that could be used to reduce the load. This latter possibility is discussed in section 7.2. Beacons appear to be the most efficient in terms of distributing the vehicle-to-TMC communication load. For messages from the TMC to vehicles, link travel time data places the heaviest load on the communication system for architectures with in-vehicle route selection, while recommended route messages dominate those architectures with infrastructure-based route selection.

Table 7-5. Communication Load Requirements: Architecture 5

No.	Message Type	Source–Sink	Message Length Formula (bits)	Message Length (bits)	Message Frequency (per minute)	Avg. Comm. Load from TMC (bps)	Percent of Comm. Load per Message	Assumption for Single Source Message Frequency
5A	Dynamic Link Times	TMC-V	38+55L	208,323	1.0	3,472	99.2%	Once per link time short update cycle
20	Alternate Route Recommendations	TMC-V	13+8A	493	0.48	4	0.1%	1/2 incident report rate
22	Traffic/Safety Advisories	TMC-V	203	203	2.0	7	0.2%	Frequency of traffic exceptions: incidents, congestion, bad wx, etc. (send for each incident)
24	Database Changes/ Updates	TMC-V	32+U (18+19Lu)	5,632	0.20	19	0.5%	Once per TMC-vehicle update cycle
26	System Status/ Parameters	TMC-V	59	59	0.20	0.2	0.01%	Once per TMC-vehicle update cycle
	Total for TMC to vehicle					**3,502**	**100%**	

Note: Architecture 5 uses in-vehicle route selection, FM subcarrier communications, and uncoupled route selection/traffic control.

Table 7-6 provides a summary of the results presented in this section. The load transmitted to the TMC is larger than that transmitted from the TMC for Architectures 1 and 3. Although the total loads are largest for Architecture 2 and 3, the intermediate infrastructure in these alternatives (beacons and cells) serves to distribute the load. In both architectures, land lines could be used between the TMC and the intermediate infrastructure; thus, these loads should not be problematic.

It should be emphasized that the steady-state loads calculated in this section would not be appropriate as design values, even for a city that perfectly matched our urban scenario. The minute-by-minute variations in the communication loads must be accounted for in a system design, and techniques to handle channel saturation must be developed. The design loads would necessarily be higher than the average loads calculated here.

7.2 EXCEPTION REPORTING OF LINK TRAVEL TIMES

The dynamic link times and probe data communication loads described in section 7.1 were based on the assumption that *the complete set* of reportable links are updated in every update cycle. Given the fact that these two messages generally account for much of the total load, it is desirable to consider ways to reduce their impacts. In fact, complete reporting may not be necessary, since only a fraction of the links would likely be operating under "congested" traffic conditions at any one time. "Exception reporting" is used here to mean reporting only those links that are not operating under normal conditions, where "normal" is discussed below.

For the dynamic link times message, only those links that differed significantly from historical or normal data would need to be broadcast. For those links that are not updated, the stored data in the vehicle would be used to perform route selection. Thus, the route selection processor would use both current and historical data.

As for probe data, limiting the number of messages could be accomplished by means of reporting travel times for only those links that were operating under "congested conditions." To determine whether or not the link was operating under "congested conditions," a comparison between the normal travel time and the experienced travel time would have to be made in the vehicle. The normal travel time could even vary by time of day to account for recurrent congestion. The preliminary design of the communication system in the ADVANCE Operational Test accounts for the possibility of "throttling" probe reports in order to avoid overloading the system (Kirsen et al., 1992). This could be accomplished by sending travel-time thresholds for specific links or types of roads that would, in effect, provide a "rule" for reporting: if the travel time exceeded the threshold, then the vehicle would transmit a probe report; otherwise, it would not. An additional sampling scheme would likely be necessary to ensure valid data collection; however, such complexity is beyond the scope of this report.

Table 7-6. Summary of Baseline Communication Loads by Architecture

(in kilobits per second)

Total Load Transmitted...	From the TMC [a]	From a base station to vehicles	From each beacon head to passing vehicles	To the TMC [b]	To a base station from vehicles	To each beacon head from passing vehicles
Architecture 1	**3.5**			110.8		
Architecture 2	607.6		48.4	31.0*		0.1
Architecture 3	82.6 •	8.3		188.5 •		
Architecture 4	32.1 •		0.1	5.5 •		0.05
Architecture 5	3.5					

• Could be provided with landlines (twisted pair, coaxial cable, fiber optics, etc.).

a From the TMC to all vehicles or ail beacons.

b From **all** vehicles or ail beacons to the TMC.

To test the effect of exception reporting, the communication loads for the dynamic link times and probe data messages were recomputed with the following changes in assumptions:

- Dynamic link times for Architectures 1 and 5
  - The distinction between critical and non-critical links was dropped
  - The distinction between the short and long update cycles was dropped
  - Exception links are reported every minute; other links are not reported

- Dynamic link times for Architecture 2
  - Only exception links are reported; other links are not reported
  - All other assumptions remain unchanged

- Probe data for Architectures 1 and 3
  - Data for only one link at a time is transmitted per message, instead of information on four links
  - Only exception links are transmitted

Since the beacon communication systems did not have significant problems with probe data, no changes were made to probe messages in Architectures 2 and 4.

To account for the effect of these assumption changes versus the use of exception reporting, loads were calculated with only the assumptions changing. In this situation, the communication loads are higher than the baseline loads reported in section 7.1. The effect is highest for the dynamic link times message in Architectures 1 and 5, which produces a load 2.8 times higher than the baseline load, since all reportable links would have to be transmitted within a minute under the new scheme.

To calculate the communication loads with exception reporting, and with the new message structure, a new parameter was introduced to represent the fraction of links that would be reported in the messages under consideration. Table 7-7 contains the results of the analysis, which are based on a comparison with the baseline loads (from section 7.1) for each affected message. The table contains the results of three different model runs, which provide a range of estimates for the reduced communication loads using exception reporting in our urban scenario.

Although the data needed to estimate the fraction of links that operate under exception conditions is relatively sparse, rough estimates were made from two sources of congestion estimates (Hanks and Lomax, 1991; Department of Transportation, 1991). For the analysis, we made the simplifying assumption that exception reports will be generated for those links that are operating under congested conditions. Congested roads were defined as those having a volume/capacity (V/C) ratio of 0.8 or higher, or a Level-of-Service (LOS) of D or worse, during the peak period. The last result reported in table 7-7 is based on a lower level of congestion than estimated in the references. The communication loads for dynamic link

Table 7-7. Results of Exception Reporting Communication Load Analysis

Architecture	Message Type	Source-Sink	% of Links Reported	Ratio of Computed Load to Baseline Load[1]
Model Run 1: Based on ITI Estimates of Congestion				
1,5	Dynamic Link Times	TMC-V	**21**	0.58
2	Dynamic Link Times	RS-V	**21**	0.21
1	Probe Data	V-TMC	43	0.51
3	Probe Data	V-TMC	43	**0.60**
Model Run 2: Based on DOT Estimates of Congestion				
1,5	Dynamic Link Times	TMC-V	26	0.72
2	Dynamic Link Times	RS-V	**26**	**0.26**
1	Probe Data	V-TMC	**54**	**0.64**
3	Probe Data	V-TMC	**54**	**0.75**
Model Run 3: Lower Level of Congestion				
1,5	Dynamic Link Times	TMC-V	10	**0.28**
2	Dynamic Link Times	RS-V	10	0.10
1	Probe Data	V-TMC	**25**	**0.29**
3	Probe Data	V-TMC	**25**	**0.35**

1 Ratio of the communication load for the affected message under exception reporting assumptions (including the % of links repotted) to the baseline load for that message computed in section 7.1.

times appear more manageable, particularly for Architecture 2. Although the loads for probe data decrease significantly for this case, they still appear to be problematic, at least for wide-area radio.

Note that the "% of links reported" column uses two different values in each model run, one for dynamic link times and one for probe data. This is because the percentage of *traveled links* under exception conditions (used for probe data) is likely not equal to the percentage of *actual links* operating under those conditions, since a greater amount of travel will occur on congested links than uncongested links. This assumes that the same exception rules are applied to both the messages. The difference in loads for probe data between Architectures 1 and 3 can be attributed to the different message lengths (a vehicle ID data field is included in Architecture 3 but not in Architecture 1).

The coarseness of this analysis has limited its ability to capture important subtleties, such as the granularity of the historical, time-of-day link travel time database. If a finely grained, accurate database could be used to provide average travel times under recurring congestion, the number of reports required could be reduced even further. Another complication that is ignored here relates to the five-minute predicted travel times included in link time messages; the effect of "predicted exceptions" on a link and time increment level has not been considered. In other words, all six five-minute travel times on one link might be exception data, while only two five-minute travel times on another link would be, and so on. Lastly, this analysis has ignored the potential for dynamic communication load management through transmission of the "exception reporting rules" message (#27). In effect, this message would allow the exception reporting rules used in the vehicle to vary depending on the current traffic situation.

In spite of the above caveats, this analysis indicates that the use of exception reporting has the potential to reduce the communication load requirements of the two message types considered from 25 percent to 90 percent, depending on the prevailing traffic conditions.

SECTION 8

COMMUNICATION DATA STORAGE LOADS

This section describes the estimation of the dynamic storage load requirements for the five strawman architectures. It represents step 8 in the general methodology chart shown in figure 3-l.

The analysis is focused only on the storage allocation needed for the data used in transmitted and received messages. The analysis excludes consideration of the permanent storage needed for historical or other fixed databases (such as map data). With the exception of the m-vehicle map database, the fixed databases do not vary significantly across architectures. The analysis also excludes data storage needs associated with processing functions; these cannot be addressed until the processing requirements and algorithms are more fully defined.

The analysis relies heavily on the communication load results from section 7. To ensure that the storage loads are consistent with the rest of the report, the identical urban scenario and traffic parameters are also applied here. The average message lengths and transmission frequencies are the key parameters used to estimate communication storage loads. Additionally, several assumptions regarding temporary storage needs were made in order to complete the analysis. The methodology used in this section can be described by the following assumptions:

<u>For each message</u>

- The average message length transmitted or received by a vehicle is equivalent to the storage load for each vehicle.

- If the *same* information is broadcast to all vehicles, the storage load at *the TMC* is equivalent to the average message length transmitted by the TMC. *If different* information needs to be transmitted to or received from all vehicles (or beacons), the message length must be multiplied by the overall message frequency and an estimated storage duration to produce the storage load *for the TMC.*

- If the *same* information is transmitted to all vehicles in a beacon system, the storage load *for each beacon processor* is equivalent to the average message length transmitted by a beacon head. *If different* information needs to be transmitted to or received from all vehicles, the message length must be multiplied by the overall message frequency and an estimated storage duration to produce the storage load *for each beacon processor* For messages between the beacon processors and the TMC, the storage load at the *beacon processor* is equivalent to its message length.

For each architecture, the storage load at the vehicle, TMC, and beacon processor are obtained by summing across all applicable incoming and outgoing messages.

The remainder of this section describes the communication data storage loads for each of the strawman architectures. As in section 7, average rather than peak loads were computed. However, if storage allocation can be shared for some of the messages, then the true loads may be lower than the calculated values.

8.1 ARCHITECTURE 1

The communication data storage loads for Architecture 1 are given in table 8-l. The table provides, for each of the applicable messages, the storage load per vehicle and at the TMC. Storage assumptions are given for loads that need additional explanation or that do not correspond with the general assumptions listed in the introduction to this section. The total storage loads for a vehicle and for the TMC are also provided at the bottom of the table. Bytes instead of bits are used to represent the loads (eight bits per byte).

About 74 kilobytes of communication storage are required per vehicle, with most of the load coming from the dynamic link times message. The storage load must account for all reportable links, which are updated every five minutes.

The TMC communication data storage load is 716 kilobytes. Most of this load results from probe data messages. The TMC would not need to save every probe report for a long period of time. The assumption was made that the ten most recent updates plus the previous average travel and delay time for each link would be saved.

8.2 ARCHITECTURE 2

The communication data storage loads for Architecture 2 are given in table 8-2. Since beacons are used for communication, the loads are calculated for the beacon sites as well as for vehicles and the TMC.

The total communication data storage load for a vehicle is about 34 kilobytes, the majority coming from the dynamic link times message. The total TMC communication storage load is about 24 Megabytes. The main reason that it is so much higher than in Architecture 1 is because the 692 beacon processors require unique dynamic link time sets, as described in section 7.1.2.

Table 8-l. Communication Data Storage Loads: Architecture 1

No.	Message Type	Source-Sink	Required **Storage** Load per Vehicle (bytes)	Required Storage Load at TMC (bytes)	Storage Aerumpttonr: Vehicle	Storage Asaumptfons: TMC
1A	Assistance Requests	V-TMC	56	4843		l/2-hour duration
8	Probe Data	V-TMC	30	526,000		Last 10 obs plus previous avg per reportable link
28	Trlp Completed	V-TMC	7	107,192		5-min. duration
2A	Assistance Response	TMC-V	43	3,755		l/2-hour duration
5A	Dynamic Link Times	TMC-V	72,325	72,325	All reportable links in long update cycle	
22	Traffic/Safety Advlsorles	TMC-V	991	1.405	All advisories In 20 min.	1/2-hour duration
24	Database Changes/Updates	TMC-V	704	704		
26	System Status/Parameters	TMC-V	7	7		
27	Exception Reporting Rules	TMC-V	17	17		
	Total storage load for a vehicle		74.2 kllobytes			
	Total storage load for TMC			716.3 kllobytes		

Note: Architecture 1 uses in-vehicle route selection, wide-area radio communications, and uncoupled route selection/traffic control.

Table 8-2. Communication Data Storage Loads: Architecture 2

No.	Message Type	Source-Slnk	Required storage Load per Vehlcls (bytes)	Requires storage Load per Beacon Proceeror (bytes)	Required Storage Load at TMC (bytes)	Storage Assumptions: Vehicles	storage Assumptlons: Beacon Processor	Storage Aesumptlons: TMC
1A	Assistance Requests	V-RS	52	157			3 messages	
4	Vehicle ID Request	V-RS	2	10			l-min. duration	
8	Probe **Data**	**V-RS**	**30**	**5,040**			5-min. duration	
15	Route and Destination	V-RS	244	11,573		100 links	5-min. duration	
1B	Assistance Response	RS-TMC			3,526		3 messages	1/2-hour duration
7	Probe Data	RS-TMC		296	204.696			692 bacons • mess. length
14	Route and Destination	RS-TMC		1381	955,737			692 beacons • mess. length
2B	Assistance Response	TMCRS			2,939		3 messages	W-hour duration
5B	Dynamic Link Times	TMCRS		32,882	22,829,800			692 beacons l mess. length
21	Traffic/Safety Advisories	TMCRS		20	1,668			1/2-hour duration
25	Database Changes/Updates at Roadside	TMC-RS		12	12			
26	System Status/Parameters	TMC-RS		7	7			
2A	Assistance Response	RS-V	43	139			3 messages	
3	Vehicle ID Assignment	RS-V	5	357			W-hour duration	
5B	Dynamlo Link Times	RS-V	32,880				See TMGRS component	
22	Traffic/Safety Advisories	RS-V	203			All advisories In 26 min.	See TMC-RS component	
24	Database Changes/Updates	RS-V	704	764				
26	System Status/Parameters	RS-V	7					
	Total storage load for a vehicle		34.2 **Kilobytes**					
	Total Storage load for a beacon processor			53.4 **kilobytes**				
	Total storage load for TMC				24.0 **Megabytes**			

Note: Architecture 2 uses in-vehicle route selection, localized beacon communications, and **partially** coupled route selection/traffic control.

The total communication data storage load at a beacon processor site is not excessive at 53 kilobytes. Dynamic link times and the route and destination messages produce most of this load. Most of the messages have two components (a V-RS and a RS-TMC component, or vice-versa); the storage load at a beacon can usually be computed from either of these. However, probe data and route and destination messages are exceptions, since processing functions related to these messages occur at the beacon, implying that the message that is passed from the beacon is different than that which was received. This calculation excludes the permanently stored database of selected routes and their unique identifiers, which is necessary for the conversion of selected routes described in links to route IDS.

8.3 ARCHITECTURE 3

The communication data storage loads for Architecture 3 are given in table 8-3. Because centralized route selection is used, the storage loads differ substantially from those of the previous architectures. Rather than broadcasting dynamic link times, the TMC sends recommended (selected) route messages to the vehicles. Thus, the vehicle storage load of two kilobytes is rather minimal.

The communication storage load at the TMC is moderate at about 6.4 Megabytes. The largest component of this load comes from the selected route database, which is shown in table 8-3, for all equipped vehicles currently operating in the network. For each vehicle, this database contains vehicle ID, location and time at the last position update, and the currently selected route.

Based on the assumption that the cells only serve to distribute the overall load, and do not provide significant processing functions in the architecture, we have ignored the storage load at each cellular base station. However, some storage would be required at each base station for overhead related to processing communication messages.

8.4 ARCHITECTURE 4

The communication data storage loads for Architecture 4 are given in table 8-4. Since beacons are used for communication, as in Architecture 2, the loads are calculated for the beacon sites as well as for vehicles and the TMC. Recall that Architecture 4 employs centralized route selection without an in-vehicle map database. For each TMC-beacon update cycle, the TMC distributes the current set of recommended “localized routes” to each beacon.

All of the computed loads are fairly small, especially those for the vehicle and the beacon processor. Because only localized route information in the proximity of a beacon needs to be sent to each vehicle, the storage requirement at each beacon is minimized. The main contributors to the storage loads at beacon sites are probe data and routing data.

Table 8-3. Communication Data Storage Loads: Architecture 3

No.	Message Type	Source-Slnk	Required Storage Load per vehicle (bytes)	Requlred Storage Load at TMC (bytes)	Storage Assumptions: vehicle	Storage Assumptlons: TMC
1A	Assistance Requests	V-TMC	56	4,043		l/2-hour duration
4	Vehicle ID Request	V-TMC	2	6,596		1-min. duration
8	Probe Data	V-TMC	32	526,000		Last 10 obs plus previous avg. per reportable link
16	Driver Routing Request & Position Update	V-TMC	9			
26	Trip Completed	V-TMC	9	146,420		
2A	Assistance Response	TMC-V	43	3,766		5-min duration
3	vehicel ID Assignment	TMC-V	5	247,367		1/2-hour duration
9	Recommended Routes Sent to Vehicle	TMC-V	247	5,442,100	100 links	l/2-hour duration
22	Traffic/Safety Advisories	TMC-V	991	1,466	All advisories in 20 min.	Selected Routes DB
24	Database Changes/Updates	TMC-V	704	704		l/2-hour duration
26	System Status/Parameters	TMC-V	7	7		
27	Exception Reporting Rules	TMC-V	17	17		
	Total storage load for a vehicle		**2.1 kilobytes**			
	Total storage load for TMC			6.36 **Megabytes**		

Note: Architecture 3 uses centralized route selection, cellular radio communications, and fully coupled route selection/traffic control.

Table 8-4. Communication Data Storage Loads: Architecture 4

No.	Message Type	Source-Slnk	Requlred Storage Load per Vehicle (bytes)	Required Storage Load per Beacon Processor (bytes)	Required Storage Load at TMC (bytes)	Storage Assumptions: Vehicle	Storage Assumptlons: Beacon Processor	Storage Assumptions: TMC
1 A	Assistance Requests	V-RS	52	157			3 messages	
4	Vehlde ID Request	V-RS	2	10			1-min. duration	
8	Probe Data	V-RS	30	5,646			5-min. duration	
11	Beacon Routing Request	V-RS	5	909			5-min. duration	
1 B	Assistance Requests	RS-TMC			3,526			1 R-hour duration
7	Probe Data	RS-TMC		296	204,690			692 beacons • mess. length
2B	Assistance Response	TMC-RS			2939		3 messages	1/2-hour duration
10	Selected Routes - Network	TMC-RS		1,707	1,181,380			692 beacons • mess. length
21	**Traffic/Safety Advisories**	**TMGRS**		26	1,666			1/2-hour duration
25	Database Changes/Updates at Roadside	TMGRS		12	12			
26	System Status/Parameters	TMC-RS		5	5			
2A	Assistance Response	RS-V	43	130			3 messages	
3	Vehicle ID Assignment	RS-V	5	357			1/2-hour duration	
12	Position Update	RS-V	6	24				
13	Localized Routing Data	RS-V	36	361			10 local routes • mess. length	
22	Traffic/Safety Advisories	RS-V	203			All advisories in 20 min.	See TMC-RS component	
26	System Status/Parameters	RS-V	5					
	Total storage load for a vehlcle		0.4 **kilobytes**					
	Total storage load for a beacon processor			**9.6 kilobytes**				
	Total storage load for TMC				**1.39 Megabytes**			

Note: Architecture 4 uses centralized route selection, localized beacon communications, and uncoupled route selection/traffic control, The total TMC communication storage load for this architecture is about 1.4 Megabytes. Similar to beacons, probe data and selected route data produce most of this load.

8.5 ARCHITECTURE 5

The communication data storage loads for Architecture 5 are given in table 8-5. The storage assumptions for the messages listed are identical to those in Architecture 1. The communication data storage load per vehicle is similar to that of Architecture 1. The communication data storage load at the TMC is only 75 kilobytes, because of the absence of any inbound messages, such as probe data, in this architecture.

8.6 SUMMARY

Table 8-6 provides a summary of the results presented in this section. These results indicate that the overall communication data storage loads vary substantially with the choice of the system architecture, particularly those at the TMC. However, the loads appear to be feasible in all cases. The storage load at the TMC in Architecture 2 is the largest, because of the need to send a unique set of link times to each beacon site. The storage loads for beacons and vehicles do not appear to be problematic in any of the architectures.

These results should be used with caution, since communication data storage requirements only represent a portion of the total storage requirements.

Table 8-5. Communication Data Storage Loads: Architecture 5

No.	Message Type	Source-Sink	Required Storage Load per Vehicle (bytes)	Required Storage Load at TMC (bytes)	Storage Aesumptlons: Vehicle	Storage Assumptions: TMC
5A	Dynamic Link Times	TMC-V	73325	72325		
20	Alternate Route Recommendations	TMC-V	62	680		l/2-hour duration
22	Traffic/Safety Advisories	TMC-V	991	1466	All advisories In 20 min.	1/2-hour duration
24	Database Changes/Updates	TMC-V	704	704		
26	System Status/Parameters	TMC-V	7	7		
	Total storage load for a vehicle		**74.1 kllobytss**			
	Total storage load for TMC			75.4 **kilobytes**		

Note: Architecture 5 uses In-vehicle route selection, FM subcarrier communications, and uncoupled route selection/traffic control.

Table 8-6. Summary of Communication Data Storage Loads by Architecture (in kilobytes)

	STORAGE LOAD		
ARCHITECTURE	**Per Vehicle**	**Per Beacon Processor**	**TMC**
1	74		720
2	34	53	24,000
3	2		6400
4	<I	10	**1400**
5	74		75

SECTION 9

PROCESSING LOAD REQUIREMENTS

This section describes the processing load requirements analysis for the five strawman architectures. The section represents step 9 in the methodology shown in figure 3- 1.

In the previous report, where the strawman architectures were defined, the major processes relevant for ATIS and ATMS functions were identified (Cheslow et al., 1992a). These processes are shown in figures in the Appendix. Six were listed as being in-vehicle, for at least some of the strawmen:

- Human Interface: Input and Output
- Communication Input/Output
- Position Location
- Route Selection
- Route Guidance
- Traveler Services

Of these processes, only the two related to *Communication Input/Output* and *Route Selection* vary significantly among the five strawman architectures. These two were selected for analysis in the current study, in order to focus on the differences in processing requirements among the architectural alternatives.

In the TMC, several other processes were identified for the various strawmen:

- Human Interface
- Communication Input/Output
- Data Fusion
- Traffic Management and Modeling, which contains the following:
  - Traffic Assignment
  - Traffic Prediction
  - Traffic Controller Optimization
  - Incident Identification
- Signal and Sign Control
- Route Selection

Of these TMC processes, five were identified for study *in this* section: *Traffic Assignment, Traffic Prediction, Data Fusion, Route Selection,* and *Communication Input/Output. These* five processes vary among the five strawman architectures. Traffic assignment and traffic prediction vary because of the differing level of simultaneous optimization that must occur for the fully and partially coupled architectures.

In addition to the processes identified for analysis in the vehicle or in the TMC, the major processes carried out at localized beacons are examined in this section.

The processing load analysis in this section considers each of the identified processes independently. Only the processes that differ among the alternative architectures are analyzed to determine how the processing load requirements of the different architectures may vary. For an overall computer system work load study, the complete set of processes should be included, since the other processes may have a potential to cause a bottleneck and impact overall system performance.

Because the algorithms and computational methodology for many of the processes under consideration are uncertain, detailed quantitative estimates of processing loads could not be made at this time. Instead, the results are presented at a higher level of detail than in the previous two sections.

For each of the processes that is considered, the following is provided:

- A description of the process analyzed;
- Definition of the key parameters involved in its primary functions;
- Identification of the related messages and execution frequencies; and
- Results of the analysis.

The discussion in this section is structured to reflect the different configurations of the system architectures, and to be sensitive to the major parameters of these architectures. The precision of the results in this report is not critical; however, the sensitivity to the different architecture configurations is important.

9.1 PROCESSES ANALYZED

The processes under consideration are described in this subsection. They are organized with respect to their location in the system: *TMC,* vehicle, and beacon sites.

9.1.1 TMC Processes

Traffic Prediction: The traffic prediction process has algorithms that can predict traffic loads and link times in the transportation network. The predictions may cover time periods from a few minutes to hours ahead, based on current traffic loads, historical data, available probe information from vehicles, and the O-D requests of drivers. The calculations performed by this process must be finished in a very short time frame (a few minutes), so that the signal control and traffic messages can be continually updated. This process predicts link times for all links and generates the O-D trip matrix based on the fused database and current link prediction database.

Traffic Assignment: The traffic assignment process assigns O-D trips to network routes based on computed loads on network paths over dynamic time periods. This process performs traffic assignment using optimization algorithms that consider traveler responses as well as overall network responses. The impacts of the traffic control devices and incidents on the traveler decisions may be included in the assignment algorithms. The quality of the assignment process depends heavily on the quality and the frequency of information available to it. The assignment process works very closely with the prediction process; both share a lot of historical and dynamic data.

Route Selection: This process uses the information resulting from the traffic prediction and traffic assignment processes. It involves the computation of individual vehicle routes based on some predefmed criteria The quality of the route selection process is dependent on the accuracy of short-term traffic predictions, which is partially dependent on the results of other related processes. In Architecture 3, route selection and traffic control are fully coupled; therefore, the TMC route selection process will calculate optimal routes simultaneously with the traffic controller settings. In Architecture 4, the route selection process calculates selected routes for all O-D pairs based on real-time traffic conditions. The reliability requirements of the process are very high since most drivers of equipped vehicles will rely on the route selection information.

Data Fusion: The data fusion process analyzes the data from a variety of information sources, integrates this diversity of information, and makes it available to other processes such as the traffic assignment or traffic prediction processes. The data fusion process carries the integration of all the input data so that unique estimates can be made of traffic volumes, speeds, and incident locations. This may require special programs, such as expert systems and statistical packages, that can estimate the traffic conditions from a set of inconsistent data with a high level of confidence and within a reasonable time frame. The processing complexity varies across the architectures based on whether or not probe data is available, and whether or not beacons are used to process localized probe data.

Communication Input/Output: The TMC communications process prepares data to send to the vehicles and other infrastructure devices such as beacon processors. This process also receives message data from vehicles and beacons, and allocates these messages to appropriate processes. Since the major purpose of this process is to transfer data among the processes, the sizing and frequency of the messages is critical.

9.12 In Vehicle Processes

Route Selection: The in-vehicle route selection process enables the traveler to select a desired route for a specific O-D pair based on the information from the map database, real-time link data, and driver's preferences. The selected routes will be periodically updated based on the dynamic link times that are transmitted to the vehicles from the infrastructure.

Communication Input/Output The in-vehicle communications process prepares the messages to be sent to the infrastructure communications facilities. It also receives messages from the infrastructure and allocates them to the suitable on-board processes or display units.

9.1.3 Beacon Processes

Localzed Probe Data Processing: This process uses the probe data messages transmitted by vehicles to compute summary statistics on the individual network links in the localized beacon area. It is assumed that the average and standard deviation of link travel times and link waiting (parked) times would be calculated.

Localized Route Rata Processing (Architecture 2 only): This process involves converting a series of link IDs to unique route IDs for further processing at the TMC. This process is used to convert the selected route data in message #15 to the format used in message #14 in table 5-2. Although such a conversion is not required, it serves to reduce communication loads between beacons and the TMC. This process is used in conjunction with partial coupling, which requires that selected routes from vehicles be passed to the TMC.

Localized Route Selection (Architecture 4 only): Based on the destination of the driver, this process selects the appropriate localized route data from the current set of recommended routes available to the beacon processor. Because the network routes have already been calculated at the TMC, this process is basically a table look-up function.

Communication Input/Output The beacon communications input/output process is similar to the TMC and in-vehicle communications processes; the major function is to transfer data to/from vehicles and the TMC. One of the major purposes of the beacons is to provide an intermediate point of contact between vehicles and the TMC so that the total communication load can be distributed.

9.2 KEY PARAMETERS

The parameters that have major impacts on the processing requirements for the processes under consideration are listed in table 9-l. The parameters are a subset of the basic traffic and network data defined in the previous sections. The parameter "ComLd" represents the communications load, which is the product of message lengths and message frequencies

Table 9-l. Key Parameters Impacting the Processes

Parameter	Description	Basis
RL	# of reportable one-way links in area	Table 4-3
N	# of nodes in area	Table 4-3
TP	# of dynamic time Modes	
Lr	Average # of links in a vehicle's route	Table 4-3
K	# of routes computed per O-D pair	
AHpb	Average # of beacon heads per beacon processor	Table 6-4
Lb	Average # of links served by a beacon processor	Table 6-4
Q	Average flow rate of equipped vehicles passing a point in the network	Table 6-4
ComLd	Communications load	Section 7

related to the specific process. (The details of sizing and frequency assumptions are discussed in section 7 of this report.)

The primary functions and key parameters of each process are listed in tables 9-2, 9-3, and 9-4. The key parameters involved are expressed in terms of function "f" instead of detailed equations.

Note that the complexity of the algorithms of each process is difficult to estimate due to a variety of algorithms available, many of which are still under research and development. However, for the purpose of comparison, certain functions that need to calculate the complete origin-destination matrix will be marked with 'N**2."

9.3 RELATED MESSAGES AND EXECUTION FREQUENCIES

The defined processes usually are invoked either by transmitted messages or by internal time-based messages. Under a specific architecture, the process may be related to many messages directly or indirectly; but on the other hand, a message may involve several processes in order to get meaningful information. For example, a route request message may invoke the TMC communications process and the route selection process to get a route recommendation. When calculating the impacts of transmitted messages on the frequency of execution of the process, we only consider the messages that actually invoke the process to avoid double counts on the frequency calculation for a specific process.

Table 9-2. Key Parameters and Functions of the TMC Processes

Processes	Functions	Key Parameters
Traffic Prediction		
	Read fused data	f (RL,TP)
	Compare to current link DB	f (RL)
	Predict link time	f (RL,TP)
	Process incident report	f (TP)
	Update link prediction DB	f (RL,TP)
	Generate O-D trip matrix	f (N**2,TP)
Traffic Assignment		
	Read current link prediction DB	f (RL,TP)
	Read O-D trip matrix	f (N**2,TP)
	Perform assignments for all O-Ds	f (N**2, K, TP)
Route Selection		
	Read routing request	
	Read assigned routes for the O-D pairs	f (K,Lr,TP)
	Compare to the selected route DB	f (K,Lr,TP)
	Select route for the O-D	f(K)
Data Fusion		
	Read data from databases	f (RL,TP)
	Analyze data	f (RL,TP)
	Integrate fused DB	f (RL,TP)
	Estimate incidents	f W-1
Communications I/O		
	Process messages to/from vehicles	ComLd
	Process messages to/from beacons	ComLd

Table 9-3. Key Parameters and Functions of the In-Vehicle Processes

Processes	Functions	Key Parameters
Communications I/O		
	Process messages to/from infrastructure	ComLd
(Route Selection		
	Read link times	f (RL,TP)
	Perform route selection for the O-D	f (K,N)
	Compare with previous route	f (K,Lr)
	Decide route for the O-D	f (K)

Table 9-4. Key Parameters and Functions of the Beacon Processes

Processes	Functions	Key Parameters
Localized Probe Data Processing		
	Summarize probe data	**f (Lb, Q)**
Localized Route Data Processing		
	Convert series of links to route-IDS	**If (Q, N, AHpb)**
Localized Route Selection		
	Read routing request	
	Perform localized route selection	f (K, Lb)
Communication I/O		
	Convert messages to/from vehicles	**ComLd**
	Convert messages to/from infrastructure	ComLd

Note that the messages that invoke the prediction, assignment, and data fusion processes are dominated by time-based processing requirements, since these processes in general are automatically executed on a preset time period. For instance, the TMC link prediction process updates the new link time database once every five minutes.

In this report, we assume that the traffic prediction and traffic assignment processes are performed once every five minutes, the data fusion process is executed once every minute, and the TMC route selection process in Architecture 4 is performed once every five minutes. In addition, localized probe data and localized route data processes in beacon architectures are assumed to be executed every five minutes. The value of five minutes was selected to correspond with the period of the TMC update cycle for communication message transfer. The other processes are message-based and will be executed when invoking messages are received.

9.4 RESULTS

Tables 9-5 to 9-9 summarize the characteristics of the processes considered for the five strawman architectures. In these tables — one for each strawman architecture — the related messages include the input and output messages that invoke the process, are generated by the process, or are used as input data for the process. The related message column lists only the message numbers; see table 5-l for a description of each message. The messages invoking the processes are listed in the "Invoking Messages" column. The frequencies with which the processes are executed (or invoked) are listed in the "Execution Frequency" column. The execution frequencies for those processes that are invoked by communication messages are derived from section 7 results. The key parameters are taken from table 9-2. The ones listed have major impact on the processing time. For the processing complexity column, three levels of relative complexity are assumed: L represents a low level of complexity; M represents a medium level of complexity; and H represents a high level of complexity. Finally, the "Assumptions" column highlights important assumptions about the processes, typically related to the execution frequency or the primary functions.

The characteristics of the major processes in Architecture 1 are presented in table 9-5. The TMC prediction and assignment processes are executed once every five minutes; the TMC data fusion process is executed every minute. These processes are assumed to have medium to high processing complexities. The other message-based processes are executed with the frequency of the arrivals of invoking messages. The TMC communication input/output process has the highest frequency requirement with 30,5 18 per minute. Most of this value results from probe data messages. This architecture implements in-vehicle route selection; since the dynamic link times update message is assumed to arrive every minute, the execution frequency is shown as 1.0 per minute.

The characteristics of the major processes in Architecture 2 are presented in table 9-6. Localized beacons are used for communications; thus, beacon processes are included in the

Table 9-5. Architecture 1 Process Characteristics

Processes	Related Messages1	Invoking Messages	Execution Frequency per Minute 2	Key Parameters 3	Processing Complexlty4	Assumptions
TMC						
Traffic Prediction	5A, 8, 22	Time-based	0.2	RL. TP, N	N**2 calculation (M)	
Traffic Assignment	24.28	Time-based	0.2	RL, TP. N, K	N**2, iterative calculation (H)	
Data Fusion	1A, 8, 28	Time-based	1.0	RL. N, K	statistical analysis (M)	
Communication I/O	IA, 2A, 5A, 8.22,24,26,27,28	All related messages	30,518	ComLd	**Data transfer (L)**	See section 7 toad analysts
In **Vehicle**						
Communication I/O	IA, 2A, 5A, 8,22,24,26,27,28	All related messages	3.8	ComLd	Data transfer (L)	See section 7 load analysts
Route Selection	5A	5A	1.0	K, Lr. TP, N	Route selection for an O-D(L)	Execute once per link update

1 For the definitions of message numbers, see table 5-l.
2 See table 7-l for details by message.
3 For the definitions of variables, see table 41. The llsted variables have major impacts on the processing time.
4 L = low-level; M = medium-level; H 3 highlevel processing complexities.

Table 9-6. Architecture 2 Process Characteristics

Processes	Related Messages1	Invoking Messages	Execution Frequency per Minute2	Key Parameters 3	Processing Complexity4	Assumptions
TMC						
Traffk **Prediction**	5B, 7, 14	Time-based	0.2	RL, TP, N	**N**2, partially coupled calculation** (H)	
Traffic Assignment	14	Time-based	0 . 2	Rl, TP, N, K	N**2, iterative, partially coupled calculation (H)	
Data Fusion	1B, 7	Time-based	1 .O	RL, N, K	Statistical analysis (M)	
Communication I/O	1B,2B,5B, 7, 14,21,25,28	All related messages	**705**	ComLd	Data transfer (L)	692 beacon processors
In Vehicle						
Communication I/O	IA, 2A, 3,4,5B. 8, 15,22, **24,26**	All related messages	**67.3**	ComLd	Data transfer (L)	8 messages/time to travel **a** beacon range (5.5 sec.)
Route Selection	5B, 15	5B	**0.4**	K, Lr, TP	Route selection for an O-D(L)	Travel time between beacon contacts (2.4 min.)
Beacon						
Communication I/O	All messages in table 7-2	All related messages	182	ComLd	Data transfer (L)	AHpb = 3.5
Localized Probe Data Processing	7, 8	Time-based	0.2	Lb, Q	statistical analysis (L)	Execute once every beacon-TMC update cycle
Localized Route Data Processing	**14,15**	Time-based	0.2	Q, N, AHpb	Link conversion (L)	Convert links to route-IDS

1 For the definitions of message numbers, see table 5-l.
2 See table 7-l for details by message.
3 For the definitions of variables, see table 41. The listed variables have major impacts on the processing time.
4 L = low-level; M =: medium-level; H = high-level processing complexities.

Table 9-7. Architecture 3 Process Characteristics

Processes	Related Messages[1]	Invoking Messages	Execution Frequency per Minute[2]	Key Parameters[3]	Processing Complexity[4]	Assumptions
TMC						
Traffic Prediction	8, 22	TIme-based	0.2	RL, TP, N	N**2, fully coupled calculation (H)	
Traffic Assignment	24	Time-based	0.2	RL, TP, N, K	N**2, Iterattve, fully coupled calculation (H)	
Route Selection	9A,9B1,9B2,16AI. **16A2,16B**	16AI,I6A2, 16B	55,542	K, Lr, TP	Compare/decide route (L)	Based on **assignment** process
Data Fusion	1A. 8,28	Time-based	1 .O	RL, N, K	Statistical analysis (M)	
Communication I/O	Ail messages in table 7-3	Ail related **messages**	106,838	ComLd	Data transfer (L)	**See** section **7 load analysis**
In Vehicle						
Communication I/O	Ail messages in table 7-3	All related messages	3.9	ComLd	Data transfer (L)	See section 7 load analysis

1 For the definitions of message numbers, see table 5-l.
2 See table 7-l for details by message.
3 For the definitions of variables, see table 41. The listed variables have major impacts on the processing time.
4 L = low-level; M = medium-level; H = high-level processing complexities.

Table 9-8. Architecture 4 Process Characteristics

Processes	Related Messaged	Invoking Messages	Execution Frequency per Minute[2]	Key Parameters[3]	Processing Complexity[4]	Assumptions
TMC						
Traffic Prediction	7, 10	Time-based	0.2	RL, TP, N	N**2 calculation (M)	
Traffic Assignment	7,25	Time-based	0.2	RL, TP, N, K	N**2. iterative calculation (H)	
Route Selection	10, 25	Time-based	0.2	K, Lr, Tp, N	Select routes for all O-Ds (M)	Execute once per TMC-beacon update cycle
Data Fusion	1B, 7	Time-based	1.0	RL, N. K	Statistical analysis (M)	
Communication I/O	**IB,2B, 7,10,21,25,26**	Ail related messages	566	ComLd	Data transfer (L)	692 beacon processors
In **Vehicle**						
Communication I/O	IA, 2A, 3,4.8, 11, 12, 13,22,26	Ail related **messages**	87.3	ComLd	**Data transfer (L)**	**8 messages/time to travel a** beacon range (5.5 sec.)
Beacon						
Communication I/O	Ail messages In table 7-4	All related messages	214	ComLd	**Data transfer (L)**	AHpb = 3.8
Localized Probe Data Processing	7,8	Time-based	0.2	Lb, Cl	Statistical analysis (L)	Execute once every beacon-NC update cycle
Localized Route Selection	11,13	11	39.3	K, Lb	Table look-up (L)	

1 For the definitions of message numbers, see table **5-l.**
2 See table 7-1 for details by message.
3 For the definitions of variables, see table 41. The listed variables have major impacts on the processing time.
4 L = low-level: M = medium-level; H = high-level processing complexities.

Table 9-9. Architecture 5 Process Characteristics

Processes	Related Messages[1]	Invoking Messages	Execution Frequency per Minute[2]	Key Parameters[3]	Processing Complexity[4]	Assumptions
TMC						
Traffic Prediction	5A, 20	Time-based	0.2	RL TP. N	N**2 calculation (M)	
Traffic Assignment	24	Time-based	0.2	RL, TP, N, K	N**2, iterative calculation (H)	
Data Fusion	20,22	Time-based	1.O	RL, N, K	Statistlcal analysis (M)	
Communication I/O	5A, 20,22,24,25	All related messages	3.5	ComLd	Data transfer (L)	See section 7 bad analysis
In Vehlcls						
Communication I/0	5A, 20,22,24.25	All related messages	3.3	ComLd	Data transfer (L)	See section 7 load anaiysis
Route Selection	5A, 20,24	5A	1.0	K, Lr, TP, N	Route selection for an O-D (L)	Execute once per link update cycle

1 For the definitlons of message numbers, see table 5-l.
2 See table 7-1 for details by message.
3 For the definitions of variables, see table 9-l. The listed variables have major impacts on the processing time.
4 L = low-level; M = medium-level; H = high-level processing complexities.

analysis. Because this architecture uses partial coupling between route selection and traffic control, the processing complexity for traffic prediction and traffic assignment is greater than in Architecture 1. This increased complexity is related to the use of selected route information from equipped vehicles in these processes. The execution frequency of route selection is less than in Architecture 1, because of the fact that no link time information is available when the traveler is not within the contact range of a beacon head. This constraint could have an impact on the overall performance of the architecture.

Because of the need to process messages while in the communication range of a beacon head, the execution frequency requirement for the in-vehicle communications process is 87 per minute in this architecture, compared to 3.8 per minute in Architecture 1. The execution frequency requirement for communication input/output at TMC is lower than that of Architecture 1, since beacons serve to aggregate individual vehicle messages. We assume that the localized probe data and localized route data beacon processes are executed every five minutes.

The characteristics of the major processes in Architecture 3 are presented in table 9-7. Because this architecture uses centralized route selection and full coupling of route selection and traffic control, the processing requirements at the TMC are greater than those of the other architectures. The execution frequency requirements for the TMC route selection and the communication input/output process are about 56,000 per minute and 107,000 per minute, respectively. The majority of this frequency is generated by routing related messages such as driver routing request at trip start, driver routing request after trip in progress, position update and route check, and recommended routes from the TMC. Significant processing power is required to handle route selection. Due to the fully coupled nature (simultaneous determination of the traffic control and routing) of this architecture, the processing requirements of the traffic prediction and traffic assignment processes are more complicated than those of other architectures.

The characteristics of the major processes in Architecture 4 are presented in table 9-8. Localized beacons are used for communications; thus, beacon processes are included in the analysis. Since route selection and traffic control processes are not coupled, the processing requirements of the TMC traffic prediction and traffic assignment processes are less demanding than those of fully coupled (Architecture 3) and partially coupled (Architecture 2) architectures. The execution frequency requirements for the TMC processes of this architecture are fairly small compared to Architecture 3, even though both use centralized route selection. The main difference is that beacons are used for localized route selection in this architecture.

The characteristics of the major processes in Architecture 5 are presented in table 9-9. The processing characteristics of this architecture are very similar to those of Architecture 1; the main difference is that the TMC communication input/output process in Architecture 5 does not receive any inbound messages.

9.5 **SUMMARY**

Although these results are very preliminary, a few conclusions can be reached. Independent of the communication technology used between vehicles and the infrastructure, the other two key architecture attributes — location of route selection and the level of coupling — can have major impacts on the processing loads of an architecture. Centralized route selection has more complex processing requirements at the TMC than does in-vehicle route selection. In addition, the coupling of route selection and traffic control increases the complexity of traffic prediction and traffic assignment. It would also affect the traffic controller optimization process, which was not considered in this report Unfortunately, little is known at this time about the magnitude of the differences in processing requirements for the various levels of coupling.

The results also show that the use of processing capability of localized beacons can significantly reduce the processing requirements of the TMC. This statement applies to all beacon processes considered.

SECTION 10

ADDITIONAL **ARCHITECTURES AND SCENARIOS**

This section extends the analysis of communication loads that was presented in section 7. The section includes the results of studies conducted to generalize beyond the limitations of one scenario and five pre-defined architectures. These additional analyses address the following topics:

- The communication load requirements of additional architectures composed of a different mix of the three key architectural features.
- The potential of hybrid communication systems that are composed of two different communication technologies.
- Sensitivity studies of several important assumptions, such as market penetration, network size, and communication update cycles.

10.1 **ADDITIONAL ARCHITECTURES**

The five strawman architectures that were developed in our earlier report (Cheslow et al., 1992a), and discussed up to this point, were selected from a larger number of possible mixes of the three key attributes (communication technology, location of route selection, and level of coupling). Because of the breadth of the earlier work, it was necessary to limit those analyses to a small number of strawmen.

However, it was determined during the present study that the communication loads of additional architectures with different mixes of the three key attributes could be estimated with little additional effort Table 10-l presents a matrix indicating which of the architectures that could be built from the three key architectural elements have been analyzed. The numbered cells represent the five strawman architectures. The communication load requirements of five other architectures were found to be relatively easy to estimate from the five strawmen. These are indicated in the table by letters "A" to '8."

Table 10-l includes cells for architectures with in-vehicle route selection, and either no or partial coupling of route selection and traffic control. The communication messages and loads are similar for either coupling possibility, except that vehicles send their selected routes to the TMC when there is partial coupling. The table also includes cells for architectures with centralized route selection, and either full or no coupling. The key communication messages and loads are identical, independent of the level of coupling. Therefore, these additional alternatives for the common cases were marked "not analyzed." Only one realistic

Table 10-l. Expanded Set of Architectures Analyzed as Strawmen or as Additional Alternatives

		Architecture Number: Strawman or Additional Alternative			
		Communication Technology			
Location of Route Selection	**Level of Coupling**	**FM Subcarrier**	**Wide-Area Radio**	**Cellular**	**Beacons**
In-Vehicle	None	5	1	B	D
	Partial	NP	A	C	2
Centralized	None	NP	E	NA	4
	Full	NP	NA	3	NA

Notes:

- 1,2,3,4,5 correspond to strawman numbers.
- A, B, C, D, E indicate an additional architecture.
- NA indicates that the architecture was Not Analyzed because communication messages for centralized architectures with no coupling or full coupling do not differ.
- NP indicates that the archiiecture is Not Possible.

architecture with an FM subcarrier can be created from the list of key elements, because of this communication technology's inability to carry messages from the vehicle to the TMC. Therefore, all other possibilities in the table are marked "not possible."

The communication loads for the five additional architectures were calculated for the urban scenario described in section 4. The following additional architectures were analyzed:

- Wide-area radio with in-vehicle route selection and partial coupling (Alternative A).
- Cellular radio with in-vehicle route selection and no coupling (Alternative B).
- Cellular radio with in-vehicle route selection and partial coupling (Alternative C).
- Beacons with in-vehicle route selection and no coupling (Alternative D).
- Wide-area radio with centralized route selection and no coupling (Alternative E).

The information on loads for alternatives A and C was developed by estimating new message lists for an architecture with partial coupling, like strawman 2, but with a broadcast communication system, rather than with beacons. The other new alternatives were similarly derived from other strawmen.

The extension of the communication loads analysis was used to produce a summary chart of the loads for the major message types cross-classified by the communication technology used. The results for the five original strawmen, as well as for the five additional architectures, are summarized in table 10-2. The table describes the load requirements in kilobits per second of only the major messages that are sent to or received from the fleet of equipped vehicles. All of the baseline scenario parameter values used in section 7.1 were applied.

The analysis in this section omits any attempt to design communication systems for handling the load requirements. Furthermore, sophisticated data compression schemes or the use of exception data have not been considered. Nonetheless, some crude observations can be made about which loads shown in table 10-2 appear to push the capabilities of the communication technologies.

In this discussion, the broadcast media are considered first, followed by beacon-based systems. The FM subcarrier technology provides only limited message capability, namely the transmission of link times to vehicles. However, the information bit rate of 3500 bps may be small enough to not pose a design problem.

The wide-area radio system may have problems with several different message types, and therefore with several alternative architectures. The largest load comes from the vehicle probe data that could be required with either in-vehicle or central routing. Vehicle probes could produce uplinked messages to the TMC at over 100 kbps. The wide-area radio system has other messages with high data rates depending on the specific architecture. For example, with central routing, routes would be sent from the TMC to vehicles at a rate of 77 kbps, and position updates would be sent to the TMC at a 52 kbps rate. With in-vehicle route selection and partial coupling, routes would be received by the TMC at a rate of 75 kbps. All of the

Table 10-2. Communication Load Requirements for Major Messages: Scenario of Two Million Population and 50 Percent IVHS Penetration

(kilobits per second)

Location of Route Selection and Direction of Message / Major Messages	Communication Technology: FM Subcarrier	Wide-Area Radio	Celluar Radio[1] (Single Base Station)	Local Beacon (Single Beacon–Vehicles)
In-Vehicle Routing Architectures[2]	*#5*	*#1; #A*	*#B; #C*	*#D; #2*
Vehicle to TMC (or Roadside)				
Probe Data	NA	108	12	0.04
Routes (Partial Coupling Only)	NA	75	7.5	0.07
TMC (or Roadside) to Vehicle				
Link Times	3.5	3.5	3.5	CBD: 48 FWY: 96
Central Routing Architectures[2]	—	*#E*	*#3*	*#4*
Vehicle to TMC (or Roadside)				
Probe Data	NA	108	12	0.04
Position Update	NA	52	5.2	NA
Driver Route Request	NA	14	1.4	0.01
TMC (or Roadside) to Vehicle				
Routes	NA	77	7.7	0.05
Route Status OK	NA	3.6	0.4	NA

[shaded] = Appears Critical (shaded cells: Wide-Area Radio 108, 75, 108, 52, 77; Local Beacon FWY: 96)

NA = Not Applicable

1 Based on 10 cells

2 Architecture numbers, given in italics, refer to cells in Table 10-1.

messages discussed in this paragraph could require multiple communication channels if each channel was limited to, say, 19.2 kbps, at least in the scenario being analyzed. If wide-area radio were used with in-vehicle route selection to send only link data to the vehicles, there would probably be no load problem. However, in this case, the FM subcarrier might perform just as well.

Cellular radio may be able to provide communication services similar to that provided by wide-area radio, but the system-wide channel requirements would be less if multiple base stations were used. In the scenario analyzed in this report, the large metropolitan area has ten equal-sized cells. Hence, at a first approximation, each base station only requires 10 percent of the channel capacity as does wide-area radio. Even for large levels of probe data, the information content would provide a load of about 12 kbps. This could be provided with modest channel requirements for a cellular network in the metropolitan area.

A beacon-based system appears to have minimal communication load requirements for all the major message types shown in table 10-2, except possibly for sending link times from a beacon head to the passing vehicles. On an arterial with average speeds of 35 MPH, the beacons would have to send this message at a rate of 48 kbps. On freeways with speeds of 70 MPH, the communication rate would have to be twice as frequent, about 96 kbps. This requirement on freeways might be extreme for current beacon technology, especially for microwave beacons. However, special designs, such as multiple beacon heads per direction, could be used in these situations — albeit at an increased cost.

10.2 HYBRID ARCHITECTURES

In section 10.1, we compared the communication loads for the five strawman architectures and five additional alternatives. We indicated there that the load requirements appeared to be high for some of the alternatives, in particular for those with wide-area radio and beacons. The concept of a hybrid architecture is presented here as a way of eliminating these potential problems. A hybrid is defined as an architecture that provides either a mixture, or a duplication, of at least one of its key attributes.[1]

For this study, two hybrid architectures were considered that might eliminate problems with a beacon architecture. The first, hybrid #l, would use an FM subcarrier system to broadcast link times (and the other information provided in strawman 5) throughout the metropolitan area. A beacon system would be used for all other messages. Vehicles would have to be equipped to interact with both communication systems. This architecture would eliminate

1 For example, one type of hybrid could have in-vehicle equipment that would work with either in-vehicle or centralized route selection. It would identify whether the TMC was sending messages containing routes or ones containing link information.

the need to send link times via the beacons. As was indicated in table 10-2, the link times provide very large loads between the beacons and passing vehicles.

The second hybrid, hybrid #2, would provide a beacon system only on the streets in the central business district (CBD) and other similar areas that have high vehicle densities and low speeds. The remainder of the metropolitan area would be served by a cellular radio system. This architecture would not have to send messages **to** high speed vehicles via a beacon system, and would eliminate the highest beacon loads that were indicated in table 10-l. The hybrid would not have to rely on the cellular system in the CBD and areas with a high vehicle density, and therefore would not have to take account of handoff problems with very small cell sizes.

A summary of the loads for the two hybrids is shown in table 10-3.

10.3 SENSITIVITY ANALYSIS

10.3.1 Variation of Metropolitan Size

It is important to investigate how the communication load requirements would change under different scenarios, so that other analysts concerned with IVHS architectures can understand the effects of changing parameters. In particular, two scenario variations were considered. The first variation represents a metropolitan area one tenth the size of our primary scenario area. All relevant parameters were reduced by a factor of 10: population, number of vehicles, metropolitan area, and miles of roadway. The IVHS market penetration remained at 50 percent. Average peak hour trip length remained unchanged. An average link was still defined as 0.25 miles and the average spacing between beacons remained at one mile.

The major effects of this variation are shown in table 10-4, which has the same format as table 10-2. It can be seen that in this smaller urban area, most of the potential load problems have disappeared. Perhaps there are still difficulties with wide-area radio for both in-vehicle and central routing, but data compression or other coding methods could probably solve them. The potential problems of beacons providing link times on freeways appeared to have been eliminated. Hence, we see that M-IS communications will be easier to provide in medium-sized areas than in the largest urban areas.

10.3.2 Variation of NHS Market Penetration

The second major scenario variation reduced the market penetration by a factor of ten to a level of only five percent, but kept all other parameters of the primary scenario unchanged. The major effects of this modification are shown in table 10-5. The loads for wide-area radio are the same as those shown in table 10-4 (except for the dynamic link times message). Hence, the same comments apply. When the IVHS market penetration is low, at least below

Table 10-3. Communication Load Requirements for Hybrid Systems: Scenario of Two Million Population and 50 Percent IVHS Penetration

(kilobits per second)

Location of Route Selection and Direction of Message / Major Messages	Communication Technology		
	Hybrid 1: Beacons and FM Subcarrier1	Hybrid 2: Beacon8 in CBD Cellular Elsewhere	
In-Vehicle Routing Architecture8			
Vehicle to TMC (or Roadside)		CBD	**Elsewhere**
Probe Data	0.04	0.04	12
Routes (Partial Coupling Only)	0.07	0.07	7.5
TMC (or Roadside) to Vehicle			
Link Times	3.5	48	3.5
Central Routing Architecture8			
Vehicle to TMC (or Roadside)			
Probe Data	0.04	0.04	12
Position Update	NA	NA	5.2
Driver Route Request	0.01	0.01	1.4
TMC (or Roadside) to Vehicle			
Routes	0.05	0.05	7.7
Route Status OK	NA	NA	0.4

NA = Not Applicable

1 FM subcarrier used to broadcast link times; beacons used for all other major messages.

Table 10-4. Communication Load Requirements for Major Messages: Scenario of 200 Thousand Population and 50 Percent IVHS Penetration

(kilobits per second)

	Communication Technology			
Location of Route Selection and Direction of Message / **Major Messages**	**FM Subcarrier**	**Communication Technology Wide Area Radio**	**Celluar Radio[1] (Single Base Station)**	**Local Beacon (Single Beacon–Vehicles)**
In-Vehicle Routing Architectures				
Vehicle to TMC (or Roadside)				
Probe Data	NA	10.8	1.20	0.04
Routes (Partial Coupling Only)	NA	7.5	0.75	0.07
TMC (or Roadside) to Vehicle				
Link Times	0.35	0.35	0.35	CBD: 4.8 FWY: 9.6
Central Routing Architectures				
Vehicle to TMC (or Roadside)				
Probe Data	NA	10.8	1.20	0.04
Position Update	NA	5.2	0.52	NA
Driver Route Request	NA	1.4	0.14	0.01
TMC (or Roadside) to Vehicle				
Routes	NA	7.7	0.77	0.05
Route Status OK	NA	0.36	0.04	NA

[shaded] = Appears Critical

NA = Not Applicable

1 Based on 10 cells

Table 10-5. Communication Load Requirements for Major Messages: Scenario of Two Million Population and 5 Percent IVHS Penetration

(kilobits per second)

Location of Route Selection and Direction of Message / Major Messages	Communication Technology: FM Subcarrier	Communication Technology Wide Area Radio	Celluar Radio[1] (Single Base Station)	Local Beacon (Single Beacon–Vehicles)
In-Vehicle Routing Architectures				
Vehicle to TMC (or Roadside)				
Probe Data	NA	10.8	1.08	0.00
Routes (Partial Coupling Only)	NA	7.5	0.75	0.01
TMC (or Roadside) to Vehicle				
Link Times	3.5	3.5	3.5	CBD: 48 FWY: 96
Central Routing Architectures				
Vehicle to TMC (or Roadside)				
Probe Data	NA	10.8	1.08	0.00
Position Update	NA	5.2	0.52	NA
Driver Route Request	NA	1.4	0.14	0.00
TMC (or Roadside) to Vehicle				
Routes	NA	7.7	0.77	0.05
Route Status OK	NA	0.36	0.04	NA

[shaded] = Appears Critical

NA = Not Applicable

1 Based on 10 cells

five or ten percent, wide area radio probably can provide for any communication requirements. One important result of this variation of market penetration is the observation that beacons might have a problem providing link times on freeways, even with very low penetrations. This is because information about the complete network must be passed to any equipped vehicle while it travels within the range of a beacon head. The communication rate is influenced by the speed of the vehicles and the number of links, not by the number of equipped vehicles.

10.3.3 Other Sensitivity Calculations

Several additional sensitivity investigations were carried out involving many of the independent traffic and communication system variables. In general, the results were not very informative or surprising. Almost all dependent variables either varied linearly with the change, or were independent. For example, table 10-6 shows the results obtained when link length was doubled from .25 miles to SO miles.

Table 10-6. Effect of Doubling Link Length from .25 Miles to .50 Miles

Communication Load	No Impact	Load Reduced by Half
Probe Data		X
Dynamic Link Times from TMC		X
Routing Requests from Vehicle	X	
Recommended Routes Sent to Vehicles (Arch 3)		X
Selected Routes – TMC to Beacon (Arch 4)	X	
Route and Destination Info. – Beacons to TMC (Arch 2)	X	

SECTION 11

CONCLUSIONS

In this final section, we present several conclusions that have been reached from analyzing the communication, processing, and storage loads. Although most of this study has involved only the five strawman architectures, we have been able to extend the communication loads analysis to include several additional architectures. This has allowed us to obtain broader insights that produce more robust conclusions. This section begins with a discussion of the general conclusions that can be drawn from the communication load requirements analysis. It then provides some conclusions relative to the key architectural attributes: communication technology, location of route selection, and level of coupling between route selection and traffic control. Greater attention has been paid to the communication technologies, because we have obtained more information about communication loads than about processing and storage loads. Because of the importance of system evolution in the selection of architectures (see Cheslow et al., 1992b), we have tried to emphasize some of the issues that are related to the growth of market penetration levels.

This analysis supplements and extends a qualitative evaluation of the five strawman architectures that considered a broader range of evaluation criteria (Cheslow et al., 1992b). That evaluation reached some of the same conclusions that are presented here, but without the support of any quantitative analysis. Although the current study provides many useful conclusions about the architectures, the reader should be aware of the following caveats:

- The analysis was for a hypothetical urban area with a population of two million; the characteristics of the area were derived from data for five actual metropolitan areas.
- The analysis was for a scenario with a 50 percent market penetration of IVHS technology in vehicles.
- The communication loads analysis was based on steady-state loads during the peak traffic period.
- The communication load requirements were estimated without trying to optimize the communication system design.
- The storage loads analysis focused only on the storage required to support the transmission of messages.
- The processing loads analysis was not quantitative, because of uncertainty about the algorithms that would be used for traffic control, prediction, data fusion, etc.

11.1 GENERAL CONCLUSIONS ABOUT COMMUNICATION LOAD REQUIREMENTS

Some important conclusions about the communication load requirements of the architectures have been reached. The first is that the communication load requirements vary substantially with the key characteristics of the architecture. In other words, the communication technology used and the location of the route selection function affect both the messages needed, and the structure of the messages. The use of localized beacons rather than a broadcast system, in particular, can make a major impact on the size of the communication load requirements. The requirements also vary with many important scenario characteristics, such as the size of the metropolitan area, or the market share of IVHS equipped vehicles.

We have been able to determine which messages contribute the most to mobile media communication loads. For inbound messages from the vehicle to the TMC, vehicle probe data produce the highest load. Other messages are also important for some of the architectures. These messages are vehicle position updates necessary for centralized routing, and the chosen vehicle routes that must be sent when there is in-vehicle routing with partial coupling.

For outbound messages from the TMC to the vehicles, the major message depends on whether route selection is performed in the vehicle or in the TMC. Link travel time data produce most of the communication load for architectures with in-vehicle route selection. Alternatively, selected route messages dominate architectures with centralized route selection.

For both inbound and outbound communications, all other messages place minor load requirements on any communication system. These minor messages include ones such as driver assistance requests and responses, traffic and safety advisories, and vehicle database updates.

11.2 IMPLICATIONS FOR THE COMMUNICATION TECHNOLOGIES

The results of our analyses have implications about the load requirements for specific communication technologies: wide-area radio, cellular radio, localized beacons, and FM subcarrier.

11.2.1 Wide-Area Radio

The wide-area broadcast system was generally found to have the most demanding communication load requirements of the four communication technologies. In particular, for the scenario that was analyzed (i.e., two million population urban area with an M-IS market penetration of 50 percent), probe data required a data rate of over 100 kbps for the application information, not counting overhead. This is with an approach that sends data from all probes to the TMC. If only exception reports were transmitted to the TMC, this requirement could be reduced to a level as low as 30 kbps to 50 kbps. We have not investigated how much techniques such as data compression could further reduce this requirement. But it is likely that even with data compression, several transmission channels would be required when overhead needs are factored in. High data rates would also be required to send route information for an architecture with centralized route selection (TMC to vehicle), or an architecture with in-vehicle route selection and partial coupling (vehicle to TMC).

The communication load requirements for wide-area radio are strongly related to the number of equipped vehicles, because the vehicle-specific data mentioned above dominate the general broadcast information. The sensitivity analysis presented in section 10.3 provides the relevant results. The data rates for probe or route data for a scenario with one-tenth the number of equipped vehicles would drop to one-tenth those necessary in the baseline scenario. From these results, one can surmise that for very low market penetration, and for small market areas, wide-area radio would not have difficulty carrying the required communication load.

11.23 FM Subcarrier

The major information item that a subcarrier broadcast can provide to vehicles is the network link times. The data rate for the analysis scenario is estimated at 3500 bps for the information bits. Overhead might double this requirement. A 9600 bps subcarrier system is currently being investigated that could meet these needs (Chadwick and Patel, 1992). It should be pointed out that the link time information was estimated to consist of predictions for all major links for six separate time intervals. Therefore, one could reduce the requirements to two or three time intervals if the subcarrier service were not able to be successful at 9600 bps. These results would apply to other one-way, wide-area broadcast systems.

11.2.3 Digital Cellular Radio

Cellular radio can be designed to have little or no communication load problem by sufficiently increasing the number of cells in the coverage area. This conclusion is quite robust, since it applies to all the cellular architectures that were examined. However, the addition of capacity to an IVHS system utilizing cellular radio may depend upon the operational and administrative characteristics of the shared cellular system infrastructure. With the analysis area divided into ten cells as in the analyzed scenario, probe messages would require 12 kbps in an average cell, for information bits only. This load might require more than one set of channels if they operated at 19.6 kbps. But, the use of ten cells was selected arbitrarily. This number could easily be increased to, say, 50, which would still be less than the number of cellular phone system base stations in the area. With this many cells, the message rate from probe data in an average cell would only be 2400 bps.

A more significant problem with cellular radio might occur in a small area with a high density of equipped vehicles. A significant number of vehicles might lead to a requirement for a large number of two-way channels. A normal solution to this problem is to make the cell sixes smaller in the CBD, thus reducing the number of vehicles in a cell. But this might require that hand-offs occur too frequently.

A creative approach for addressing the problem of a high density of equipped vehicles in a small localized area is to introduce a hybrid communication system. (See section 10.2.). One concept would provide a beacon system in the high density areas, and cellular radio elsewhere. Although this approach could eliminate hand-off problems for cellular radio in a CBD, none of the hybrid's other characteristics has yet been examined by the IVHS community.

Cellular IVHS systems have an advantage over the other communication technologies, because the infrastructure investment can grow with the market. When the market penetration is small, relatively few base stations are needed, possibly at few as ten in a metropolitan area. Then, as the market size grows, the existing cells can be subdivided. If the IVHS cellular system were fully integrated with a cellular phone service, then it should be possible to use as many cells as the phone service provides, currently 100 or more for analog service in large urban areas.

11.2.4 Localized Beacons

Beacons can provide a very attractive way of handling probe data for any architecture. In this analysis, an implementation scheme was selected such that the messages from individual probes are combined and aggregated at each beacon periodically. Thus, only these aggregates are sent to the TMC. The messages are sent from the vehicle to an average beacon at a rate of only 40 bps — an extremely low value. The highest expected load from vehicles to a beacon would come not from probe data, but from vehicles sending their routes to the TMC when there is partial coupling. Even for this message the load is only 70 bps.

Beacons appear to be a good method for implementing centralized route selection. Not only can an in-vehicle map database be omitted, but none of the communication loads is large; all are less than 100 bps to or from a vehicle. In addition, the limited analysis of storage loads indicates that strawman 4, with beacons and centralized route selection, would have lower storage requirements than the other architectures, because this combination does not require as much data to be processed or stored at the TMC. Instead, the storage and processing can be distributed to the beacon sites.

Beacons do appear to have a potential problem for in-vehicle routing, however, where the TMC must send link data to the vehicles. The link data must essentially be broadcast by the individual beacons at a rate fast enough to be received by passing vehicles. This requirement may not be critical when the vehicles are moving slowly, as in a dense CBD. But, at high speeds on an uncongested freeway, beacons may have a problem. At this time, we can not be certain about this issue, because of the aggregate way the analysis was carried out. An unfortunate aspect about this problem with beacons is that it is independent of the market penetration level of IVHS. In an area with only a few equipped vehicles, all link data would still have to be sent out at every beacon. On the other hand, beacons would appear to have no communication load problem when there are relatively few links, e.g., a small area, or when speeds are low. Hence, as mentioned in section 11.2.3, beacons could be used in a hybrid system with cellular radio, providing the service in the dense CBD areas.

11.3 INFLUENCE OF THE LOCATION OF ROUTE SELECTION AND LEVEL OF COUPLING

Independent of the communication technology that is used for vehicle-TMC data transmission, the other two key architecture attributes — location of route selection and the level of coupling — can have major effects on the size of the processing loads. In section 9, we have shown that centralized route selection has more complex processing requirements than does distributed route selection. In addition, this analysis indicates that coupling of route selection and traffic control would increase the processing complexity even further. Although these results are tentative because of the lack of quantitative information about the processing algorithms, they appear to be very important.

The location of the route selection function and the level of coupling also affect the size of the storage loads for communication data, as shown in section 8. However, these storage loads did not appear to present a problem in any of the architectures. We were unable to address the processing data needs and permanent data storage requirements of the architectures, which depend heavily on these two architecture attributes. However, these are important considerations that should be examined.

As discussed in (Cheslow et al., 1992b), the location of route selection and the level of coupling should not be decided in isolation from the type of communication system. The communication load analysis in this report reinforces this observation. The reason for this dependence is that the messages relating to route selection are the primary drivers (along with probe data) of the overall communication load in each architecture.

11.4 SYSTEM EVOLUTION CONSIDERATIONS

This section may repeat some of the observations presented in section 11.2. But, we think it is very important to bring all the conclusions that relate to system evolution together. Several issues relating to the evolutionary development of IVHS services were raised previously in Cheslow et al., 1992b. We have been able to draw conclusions on two of those evolutionary issues, based on the sensitivity analysis reported in section 10 of this report. The two issues are communication system start-up requirements and market growth impacts.

FM subcarrier is a relatively simple communication technology to implement. However, it does not provide any inbound channel, and therefore works only with in-vehicle route selection. Under this configuration, it does not have a market growth problem. That is, the communication load requirements are independent of the number of equipped vehicles operating.

Wide-area radio appears to be a good start-up communication system, when the number of equipped vehicles in the urban area is low. However, the communication load requirements for wide-area radio grow with the size of the market. This holds true for all potential architectures that were examined in section 10. Thus, with the communication system operational assumptions used in this report, the number of communication channels would have to be increased as the market grows.

An IVHS communication system based on cellular radio has advantages over one based on wide-area radio from an evolutionary perspective. Although the system-wide load requirements for cellular radio grow with the size of the market, as with wide-area radio, the number of cells can be increased to handle that load without increasing the number of IVHS channels per cell. There may be some limitations to this expandability related to the assumption that the IVHS service shares portions of the cellular system infrastructure with the phone service. On the other hand, integrating with the existing cellular infrastructure may provide more than enough capacity for IVHS communications.

A localized beacon communication system requires that an extensive beacon infrastructure be in place to begin providing IVHS services throughout a metropolitan area. Thus, it requires a significant start-up investment. Once installed, though, the system should have adequate capacity to handle market growth. This is because the relevant parameter is not the total number of equipped vehicles, but the number of vehicles in the coverage area of a beacon head at one instant. In specific cases where high vehicle speeds or traffic flow rates might stress the capacity of a beacon head, special designs, such as multiple beacon heads per direction, could be employed.

11.5 KEY FACTORS IN THE ANALYSIS

Many assumptions and estimates were made in order to quantify the load requirements in this analysis. The actual numerical results are not important; the value of this work is in identifying the potential communication load problems, or lack thereof, associated with various architecture combinations. Many factors throughout the methodology played a part in determining the overall communication loads. This subsection attempts to highlight the most important of these factors. These factors relate to the message length, message frequency, or the system-wide demand.

Several of the key factors vary by the type of communication system. For a wide-area radio system, the total number of equipped vehicles operating is a key parameter. All parameters that directly affect this number, then, including the assumed market penetration, are important. For cellular radio, the total number of equipped vehicles operating and the number of cells are key parameters. For beacon systems, distance between beacons, communication contact range, vehicle speed, and the flow rate of equipped vehicles (related to the total number of vehicles) are key factors.

Other key factors relate to the most important communication messages: dynamic link times, probe data, and recommended routes. Because these messages produce the majority of the total communication load, any factor influencing the associated message lengths and frequencies is important. For example, the size of the urban area, the size of the link ID data field, the TMC-vehicle update cycle period are all important factors in the determination of the total load.

It should be reiterated that the value assumed for market penetration (50 percent) was selected in order to model a mature rather than a start-up system. The M-IS market share is simply an input variable to the model. The reader can determine the effect of different market penetration values on the communication loads for the major messages by following the logic found in the sensitivity analysis in section 10.3.

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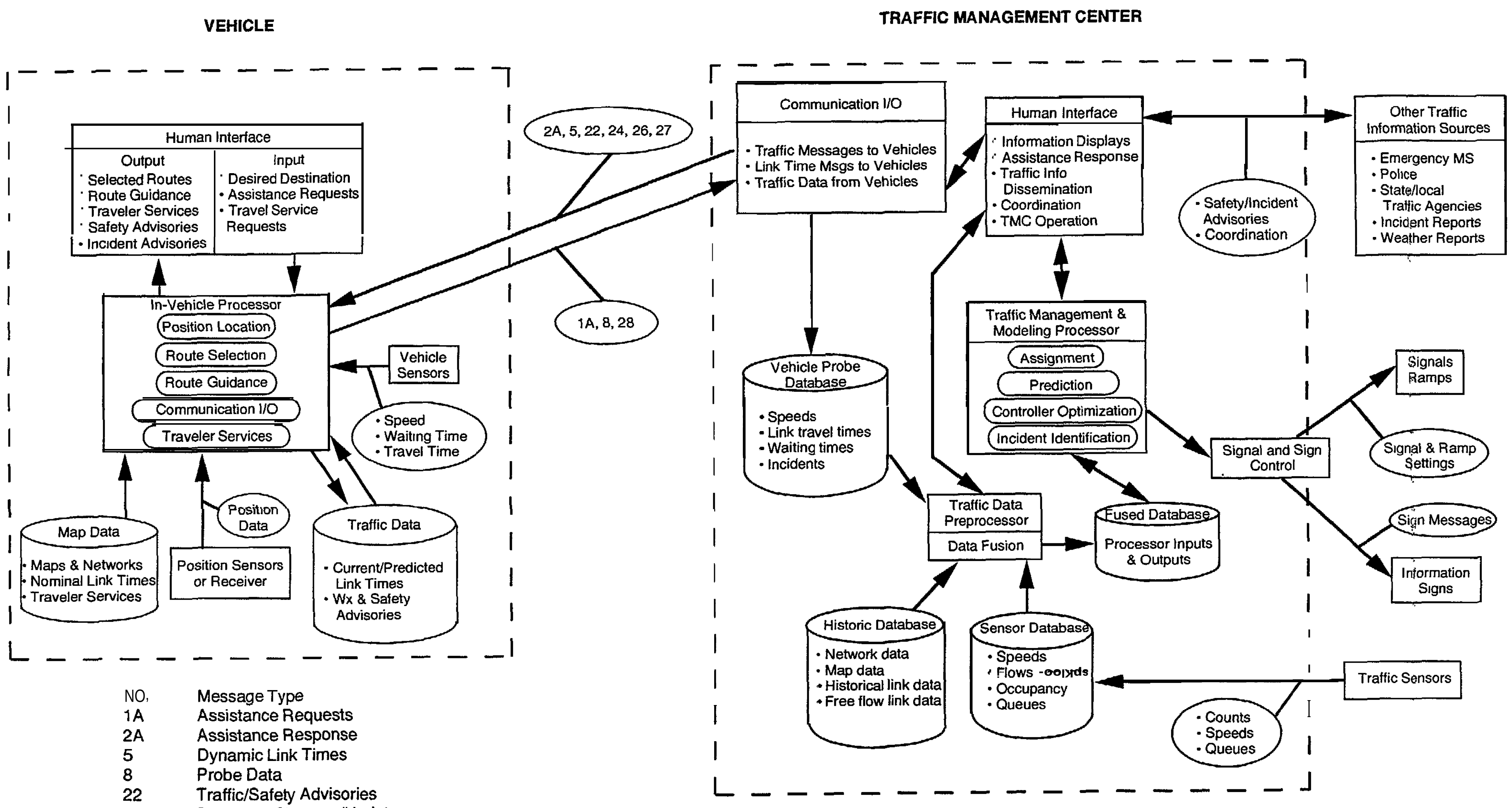
APPENDIX

STRAWMAN ARCHITECTURE FIGURES

Figures A-l through A-S highlight the processing functions, major databases, and information flows between the vehicle and the traffic management infrastructure for the five strawmen. The message ID numbers defined in this section have been inserted in place of the data elements that were included in previous reports. The messages defined here are more complete than those implied by the data flow diagrams shown for each architecture in previous reports (Cheslow et al., 1992 a, b), but are generally consistent with them. The names of the processing functions in the figures have also been slightly modified in order to maintain consistency with the current report.



NO.	Message Type
1A	Assistance Requests
2A	Assistance Response
5	Dynamic Link Times
8	Probe Data
22	Traffic/Safety Advisories
24	Database Changes/Updates
26	System Status/ Parameters
27	Exception Reporting Rules
28	Trip Completed

Figure A-1. Strawman Architecture 1

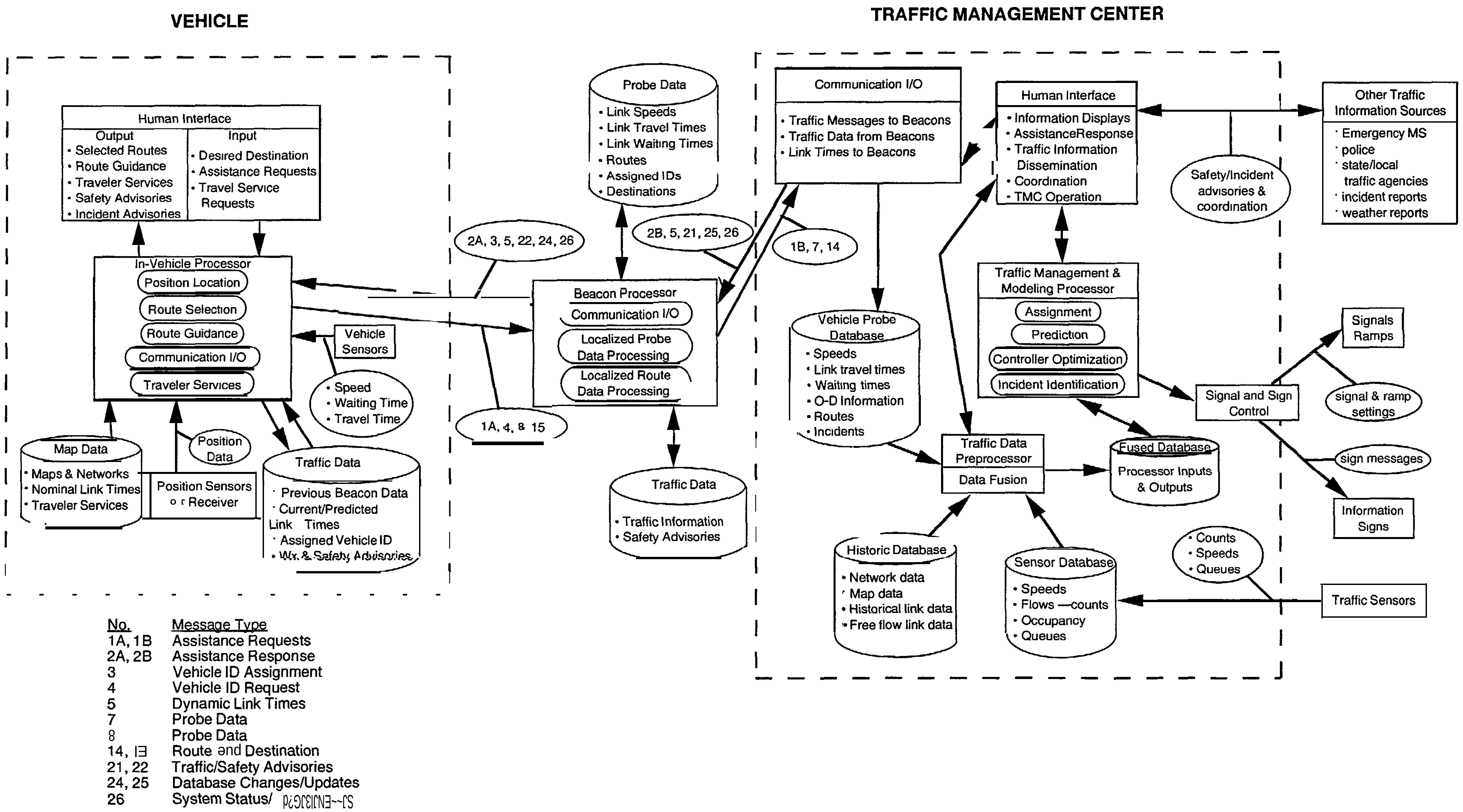
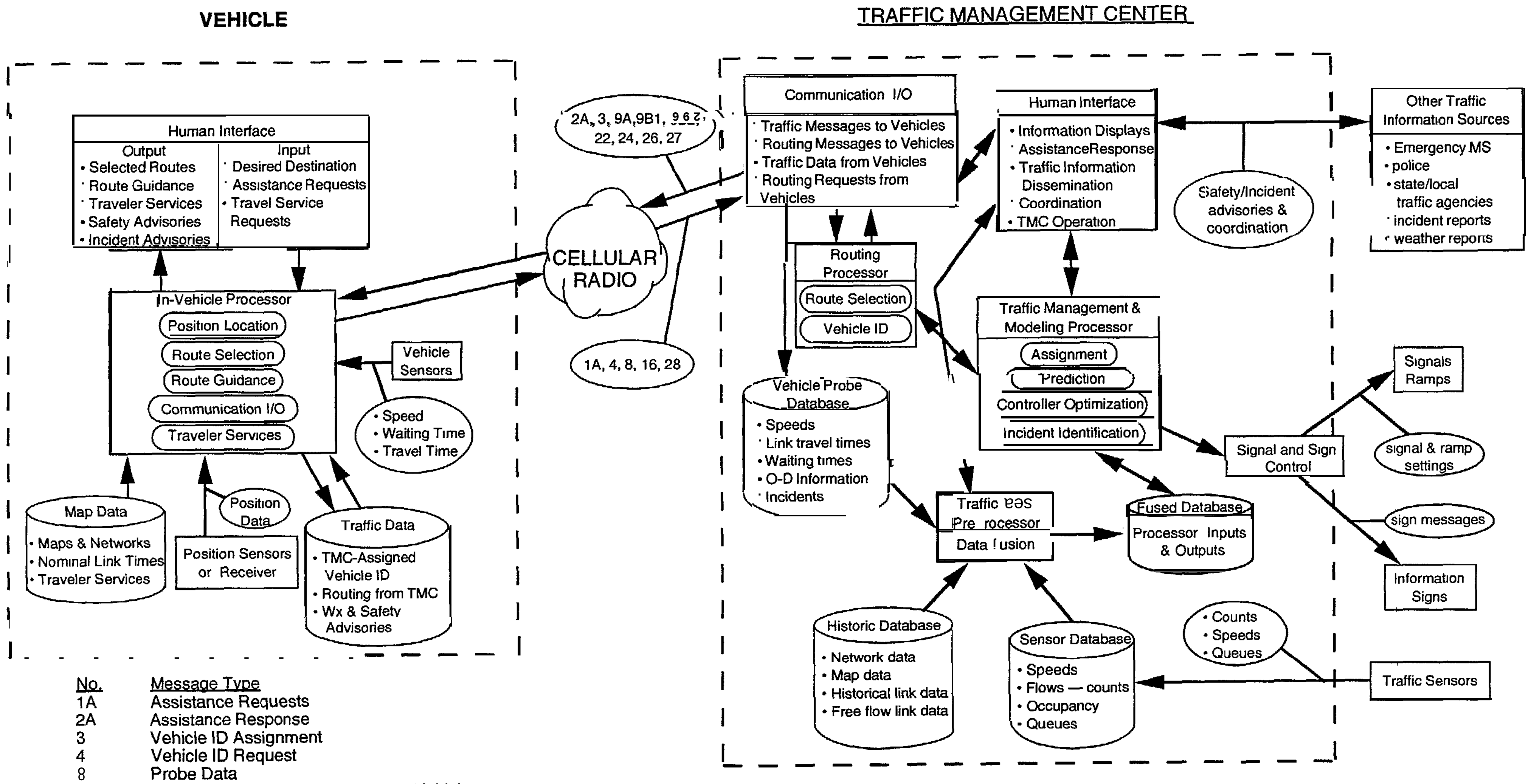
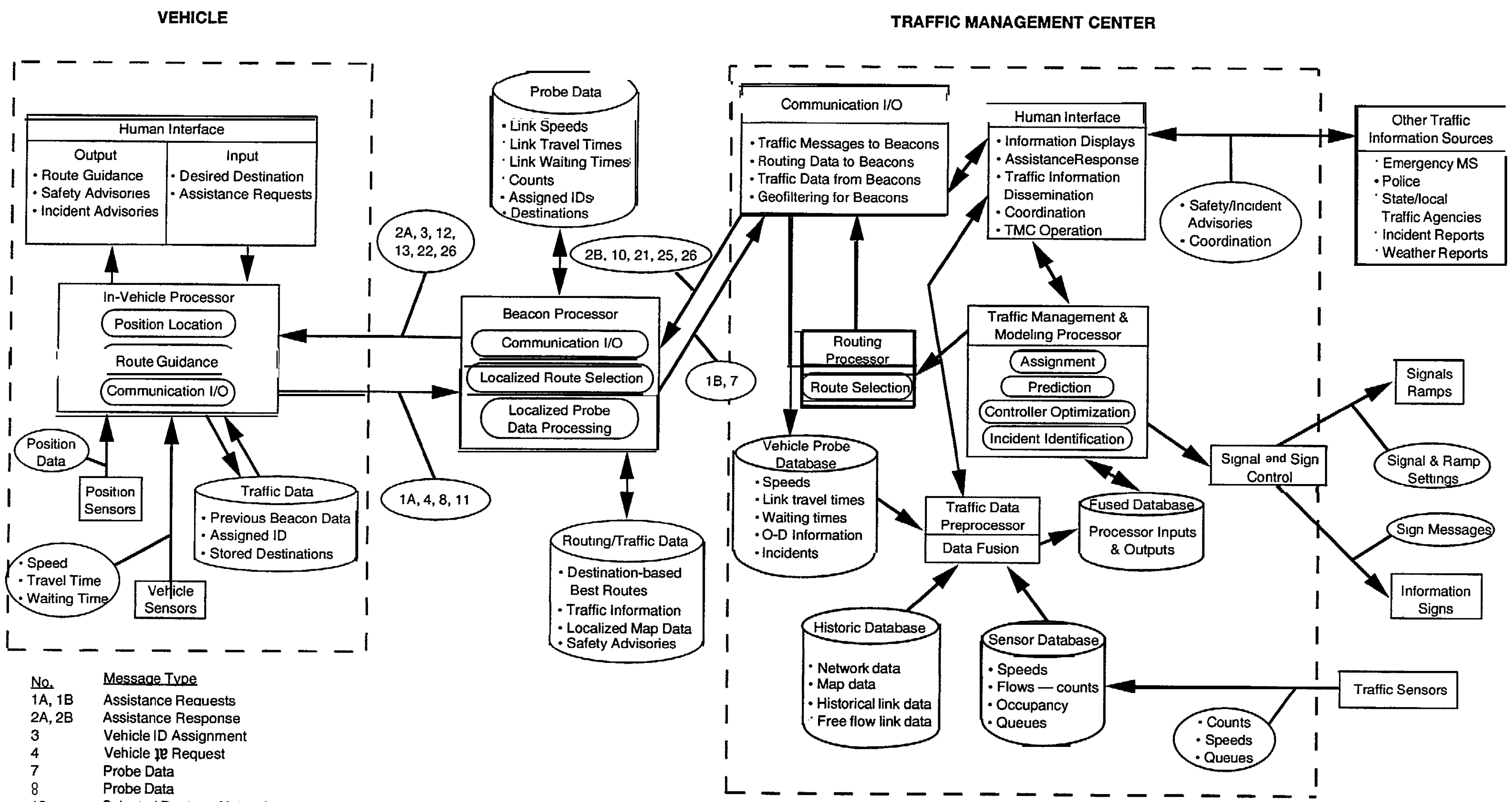


Figure A-2. Strawman Architecture 2



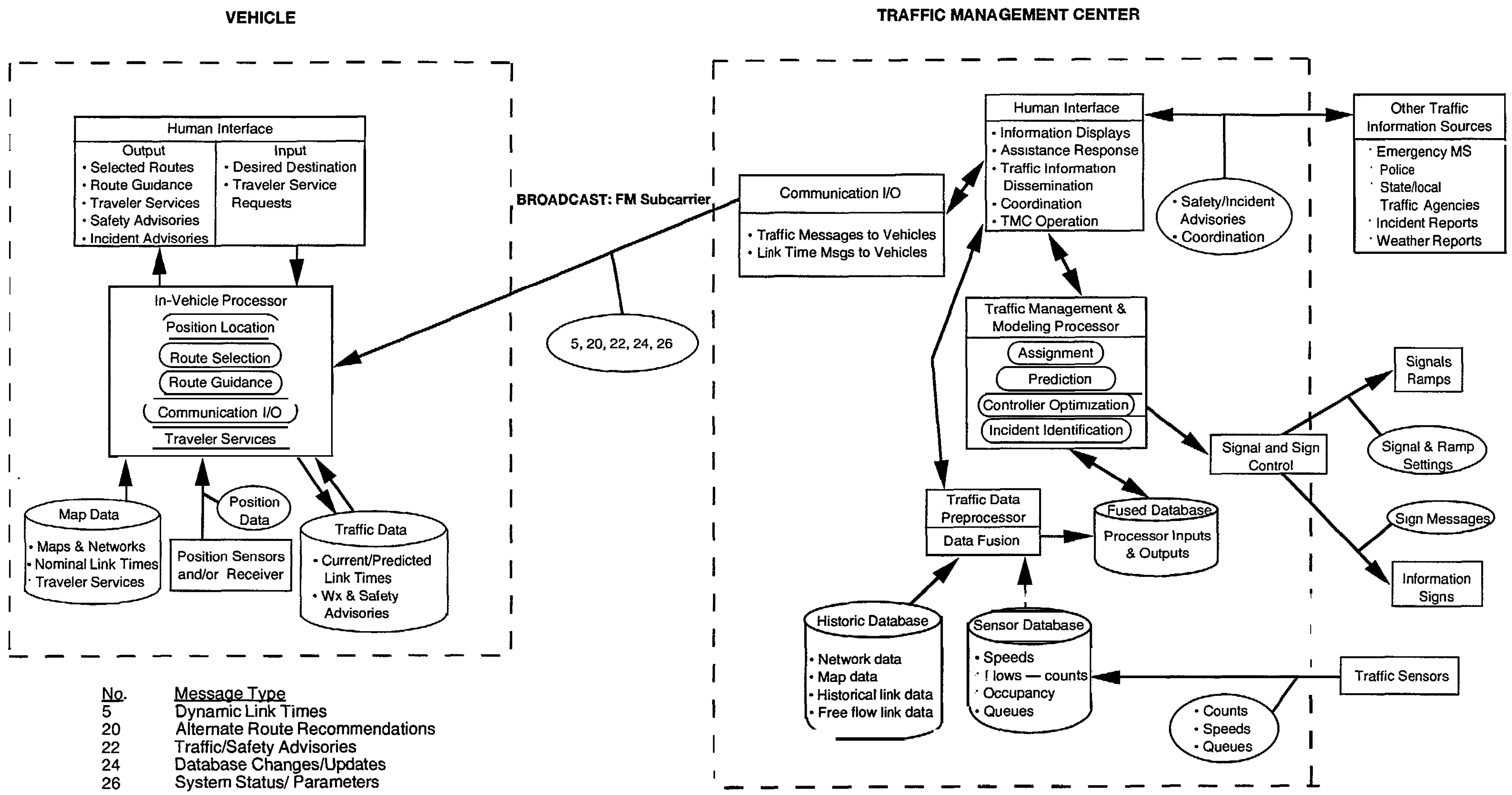
No.	Message Type
1A	Assistance Requests
2A	Assistance Response
3	Vehicle ID Assignment
4	Vehicle ID Request
8	Probe Data
9A, 9B1	Selected Routes Sent to Individual Vehicle
9B2	Route Status OU
16	Routing Request
22	Traffic/Safety Advisories
24	Database Changes/Updates
26	System Status/ Parameters
27	Exception Reporting Rules
28	Trip Completed

Figure A-3. Strawman Architecture 3



No.	Message Type
1A, 1B	Assistance Requests
2A, 2B	Assistance Response
3	Vehicle ID Assignment
4	Vehicle ID Request
7	Probe Data
8	Probe Data
10	Selected Routes - Network
11	Beacon Routing Request
12	Position Update
13	Localized Routing Data
21, 22	Traffic/Safety Advisories
25	Database Changes/Updates
26	System Status/ Parameters

Figure A-4. Strawman Architecture 4



No.	Message Type
5	Dynamic Link Times
20	Alternate Route Recommendations
22	Traffic/Safety Advisories
24	Database Changes/Updates
26	System Status/ Parameters

Figure A-5. Strawman Architecture

GLOSSARY

APTS	Advanced Public Transportation Systems
ARTS	Advanced Rural Transportation Systems
ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management Systems
AVCS	Advanced Vehicle Control Systems
CBD	Central Business District
c v o	Commercial Vehicle Operations
DOT	Department of Transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
ID	Identification
IVHS	Intelligent Vehicle Highway Systems
MPH	Miles Per Hour
MTSO	Mobile Telephone Switching Office
O-D	Origin-Destination
RDS	Radio Data System
RDS-TMC	Radio Data System-Traffic Message Channel
TMC	Traffic Management Center
VMT	Vehicle Miles Traveled