NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 437

Collection and Presentation of Roadway Inventory Data

Transportation Research Board
National Research Council

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Subject Areas

Planning and Administration
Highway and Facility Design
Pavement Design, Management and Performance
Bridges, Other Structures, and Hydraulics and Hydrology
Maintenance
Highway Operations, Capacity and Traffic Control
Safety and Human Performance

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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FOREWORD

By Staff
Transportation Research Board

This report contains the findings of a study to improve the collection and presentation of physical roadway inventory data through the application of existing, emerging, and transferable technology. Technical viability and cost-effectiveness for the most promising data collection technologies were verified, as were the processes for populating databases. Application of a linear indexing scheme to these databases permitted automation of straight-line diagram (SLD) production, proving the entire methodology feasible. The contents of this report, therefore, will be of immediate interest to highway professionals responsible for planning, administering, maintaining, and improving highway systems, as well as the many, varied transportation department units that currently input or use inventory data.

The North Carolina Supercomputing Center (NCSC) in Research Triangle Park, North Carolina, was awarded the contract to conduct NCHRP Project 15-15, "Collection and Presentation of Roadway Inventory Data." The research team, consisting of personnel from NCSC and the Department of Civil Engineering at North Carolina State University, conducted this research and wrote the report.

The report addresses several important aspects of collecting, processing, storing, and presenting highway inventory data, evaluating each aspect individually before proceeding to attempt to combine methodologies. This presentation format should be especially useful to state highway officials. Highway agencies currently have different requirements for inventory data (i.e., different collection methods for gathering that data, different processing activities for treating and/or storing the inventory data, and different distribution needs for the collected and recorded inventory data). No single solution for inventory data collection and presentation will meet every state's needs, nor will any one collection system accurately, rapidly and cheaply gather all possible inventory items. However, because different data collection technologies can be combined and because ongoing improvements in computer memory and data storage have substantially eliminated data capacity concerns, the question highway officials should now be asking is "what data do we need?" rather than "what data can we collect?"

This report emphasizes not only that information systems containing roadway inventory data should be needs-driven rather than technology-driven, but also that an understanding of the entire cycle of inventory data collection and use will allow state DOTs to avoid some of the common pitfalls others have experienced through the years. Because the objective of the research included "emerging technologies" (defined as being developed within 5 years of this research effort), some technologies may still not be completely finalized. Agencies also have different current inventory data needs and capabilities that may change over time. Rapid changes in technology result in a very short useful life for any current evaluation of new inventory data collection methods. This report recognizes the need for a testing protocol, not only to fully use the results of this research, but also to ensure that future evaluations are conducted consistently and accurately. The procedure followed in this research project for the evaluation of the different inventory data collection methods forms the basis for a testing protocol that could enable highway agencies and vendors to evaluate data collection methods in a standardized way. The report's Appendix E elaborates on the research agency's recommended standardized test protocol for evaluating improvements in inventory data collection systems as a result of the evolution of data collection technologies.

CONTENTS

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 15-15 by the North Carolina Supercomputing Center and the Department of Civil Engineering, North Carolina State University. The North Carolina Supercomputing Center was the contractor for this study. The work undertaken at North Carolina State University was under a subcontract with the North Carolina Supercomputing Center.

Dr. Hassan A. Karimi, Senior Research Scientist, North Carolina Supercomputing Center, was the principal investigator. The other authors of this report are Dr. Joseph E. Hummer, Associate Professor, Department of Civil Engineering, North Carolina State University, and Mr. Aemal J. Khattak, Ph.D. candidate, Department of Civil Engineering, North Carolina State University. The work was done under the general supervision of Dr. Hassan A. Karimi. Dr. Michael A. Chapman of the Department of Geomatics Engineering, The University of Calgary, Canada, and Mr. Durwood S. Pegram served as consultants. The work at North Carolina State University was done under the supervision of Dr. Joseph E. Hummer with the assistance of Dr. Dai Xialong, Mr. Aemal J. Khattak, and Mr. Craig R. Scheffler.

The authors wish to thank all state DOTs, companies, vendors, and individuals who helped in this research.

COLLECTION AND PRESENTATION OF ROADWAY INVENTORY DATA

SUMMARY

DOTs collect and maintain vast roadway inventories. Investigation of data collection and presentation methods and technologies was the focus of this research. The objectives included identification and evaluation of existing and emerging inventory data collection and presentation technologies. A 5-year future horizon was set for the emerging technologies.

In Phase I of the project, the research team identified the most promising data collection technologies (i.e., digital image capture—as an existing technology—and high-resolution satellite imagery—as an emerging technology) and the most promising data presentation technology (i.e., geographic information systems [GISs]—as the dominant presentation technology).

In Phase II of the project, these most promising technologies were evaluated, tested, and demonstrated. Evaluation of the digital image capture technology was by means of four experiments involving the use of different systems employing the technology. A comparison of descriptive data accuracy with manually collected descriptive data produced mixed results with no clear-cut winner. Compared with the manual method, the digital image capture technology requires less time in the field; however, in-office processing of the data collected by digital image capture technology requires more time than does the manual method. Collection of inventory data by digital image capture technology offers benefits such as a permanent visual record of the inventoried roadway, possible reduction in field trips, and reduced exposure of data collection crews to hazardous traffic conditions.

Evaluation of high-resolution satellite imagery indicated that some inventory elements can be extracted from images. Two major restrictions on the usefulness of images from satellites surfaced during this research. First, currently, images from satellites do not appear economically competitive for many state DOTs with sparse highway networks. Second, inventory units can collect only a handful of inventory data elements from satellite images. However, with the constant improvements in automated detection techniques for objects located in images, the research team anticipates that high-resolution satellite imagery holds significant promise for future inventory data collection.

The research team investigated presentation of collected inventory data by different technologies. The results of the investigation revealed that GISs are increasingly becoming the popular presentation tools for inventory data. In this respect, the research team evaluated the potential of presenting inventory data in SLD format within a GIS environment. The research team successfully produced SLDs within an off-the-shelf GIS environment using the data collected by one of the digital image capture systems.

The main question for state DOTs is which inventory technologies should they choose? Research conducted in this project indicates that no one technology can collect all of the desired inventory data. The research team recommends that the first step for state DOTs to select inventory technologies is to develop a mission for the inventory unit. Inventory units must articulate why they need to collect a particular type of data. Without a clear mission, inventory units face institutional problems (e.g., lack of adequate, consistent funding). The research team presents an inventory model that will help inventory units in developing a coherent mission. The second step in choosing appropriate technologies for inventory data collection is to select a proper means of transport for carrying the collection equipment. The default choice is a van, although other means (e.g., backpacks and satellites) are possible. The third step is to select a georeferencing technology. The Global Positioning System (GPS) offers considerable benefits compared with other georeferencing technologies. However, the use of a combination of different georeferencing technologies to avoid positional failures is recommended. The final step is to select appropriate descriptive data collection technologies. The research team recommends that the choice be based on two criteria: (1) the desire to have a permanent visual record of the inventoried roadway and (2) the possibility of collecting all of the desired inventory elements by the particular descriptive technology under consideration. It is likely that units may choose to collect inventory data using a combination of technologies (e.g., digital image capture and manual means).

Finally, the research team developed a test protocol for evaluating descriptive data obtained by different inventory data collection methods. This protocol will be of great value to state DOTs as it assists them in identifying the most suitable data collection method.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

All U.S. state DOTs maintain some type of roadway inventory database of physical features on the roadway. Common inventory data include roadway geometry, signs, signals, pavement markings, pavement quality, roadside objects, bridges, and driveways. The primary purpose behind collecting and processing roadway inventory data is to help make better decisions. State DOTs use inventory data to assist in planning, design, operations, and maintenance decisions. A secondary purpose for collecting and processing these data is to satisfy Federal requirements. State DOTs have cited Federal data requirements as an incentive for improving their roadway inventory data collection and processing efforts (Clark County Mapping Project, 1994; DeFrain et al., 1993).

The state DOTs collect and process many inventory data through labor-intensive methods such as the following:

- A DOT staff member drives along a roadway and stops at each traffic sign to record its location, size, message, and condition using paper and pencil. The collected data are later archived into a roadway inventory system.
- A DOT staff member reads as-built plans from a highway reconstruction project and then finds and edits the relevant lines in the computerized central highway geometrics file.

To reduce the time, effort, and funds spent on labor-intensive inventory data collection methods and presentation procedures, NCHRP-Project 15-15, *Collection and Presentation of Roadway Inventory Data* was initiated. A research team led by the North Carolina Supercomputing Center and North Carolina State University conducted research to identify and analyze existing and emerging technologies for efficiently collecting and presenting roadway inventory data. This document is the final report from that project, which was performed between June 1996 and March 1999.

RESEARCH PROBLEM STATEMENT

The need for this project is apparent from a survey of the available literature on roadway inventory data collection and presentation. The available literature is primarily old (Datta, 1986), focused on non-automated collection methods (ITE, 1994), or focused on technologies for collecting certain individual data elements. There is no current document that guides inventory unit personnel through the steps of choosing and using appropriate data collection and presentation technologies. There is a need for such guidance because of the significant changes in data collection and presentation technologies in the recent past.

RESEARCH OBJECTIVES AND SCOPE

To meet the overall objective of improving the collection and presentation of roadway inventory data through the application of existing, emerging, and transferable technologies, the research team fulfilled the following four objectives during the research:

- To identify and research technologies for automatic collection and presentation of roadway inventory data so that minimal labor is involved;
- To develop, evaluate, and demonstrate optimal automatic procedures for transferring collected data into a manipulable database on which queries can be performed;
- To develop, evaluate, and demonstrate optimal automatic procedures for using the most promising technologies to produce straight-line diagrams (SLDs); and
- To assess alternatives for moving the results of this research into practice.

The project scope was limited in several important ways. First, the researchers were focused on overall collection and presentation methods but did not have the resources or time to devote to investigating particular technologies that collect only one particular data element. These particular technologies include those used to collect pavement distress data, sign and marking retroreflectivity data, and underground structure data. The researchers did not pursue such particular technologies (although several such technologies are important to many agencies and could be improved with some research attention). During this project, the researchers concentrated on technologies that applied to the collection or presentation of sets of inventory elements.

The project scope also limited the number of technologies that the researchers could validate, test, and demonstrate. Although the researchers eventually chose three promising technologies to test, several others had obvious potential and could be the focus of future research.

There were two restrictions on the research effort. First, in keeping with NCHRP policy, the results do not include endorsements of specific brands of hardware, software, or equipment. When the text mentions specific company or brand names the purpose is purely illustrative and in no way should be interpreted as an endorsement. Second, although the researchers developed some new programming code to validate, test, and demonstrate new technologies, the code was intended for those limited purposes only. The researchers did not intend that their programs would be of production quality or would be immediately marketable.

RESEARCH APPROACH

The research consisted of two phases. During Phase I, the research team investigated a wide range of existing and emerging data collection and presentation technologies and then identified the most promising technologies for collecting and presenting roadway inventory data. The research team determined a 5-year horizon for emerging technologies. In Phase I, which was completed in July 1997 with a Final Interim Report (Karimi and Hummer, 1997), several promising technologies were described and three of them were recommended for evaluation and testing. In Phase II, which began in August 1997 and was completed in March 1999, the three most promising technologies were validated, tested, and demonstrated. This report provides the results of both phases of the project.

The Research Project Statement contained a list of 12 tasks necessary to accomplish the project objectives. The researchers were guided by this task list for the duration of the project. The 12 tasks were as follows:

- Task 1—Literature search;
- Task 2—Development of a list of representative data elements;
- Task 3—Survey of state DOTs;
- Task 4—Contacts with non-roadway organizations to collect information on the technologies they use for data collection purposes;
- Task 5—Technical, operational, and economic evaluation of the data collection technologies;
- Task 6—Technical, operational, and economic evaluation of the most promising data presentation systems;
- Task 7—Interim report for Phase I, including selection of technologies for detailed evaluation in Phase II;
- Task 8—Verification of the technical viability of the most promising data collection technologies;
- Task 9—Populating a database using the promising technologies;
- Task 10—A description of the method used to automate the production of SLDs using the most promising data presentation system;
- Task 11—Production of SLDs using the most promising data collection technologies; and
- Task 12—Final report.

REPORT CONTENTS

The remainder of this report is organized into seven chapters and five appendixes. Chapter 2 summarizes the research team's general findings on inventory data collection, while Chapter 3 summarizes the research team's general findings on data presentation. Chapter 4 presents the results of the research team's evaluation of photogrammetric digital imagery, while Chapter 5 presents the research team's evaluation of the use of data from satellites. Chapter 6 synthesizes much of this previous information into recommendations for selecting inventory technologies. Finally, Chapter 7 summarizes the conclusions of the study and presents recommendations for future research.

The appendixes present the results of the research in greater detail than the main text. Appendix A consists of the telephone survey questionnaire administered to DOTs nationwide. Appendix B presents the results of the telephone survey in a matrix format. The research team visited numerous agencies and inspected a variety of inventory data collection and presentation systems. Appendix C provides information on those visits and the inspected inventory data collection and presentation systems. Appendix D presents the adopted research methodology for evaluation of descriptive data accuracy and Appendix E presents details of a test protocol that agencies may adopt for future evaluations of different data collection methods. Appendixes A through D are not included herein. Copies are available for loan or purchase for a limited time on request to NCHRP, Transportation Research Board.

CHAPTER 2

INVENTORY DATA COLLECTION

This chapter discusses the results of the research team's findings on existing and emerging inventory data collection methods. The chapter is divided into several sections describing data collection system components, modes of transport, georeferencing technologies, and descriptive technologies. It also includes sections on non-roadway data collection technologies and state DOT inventory practices. In the first section, the data elements of a typical roadway inventory system are discussed.

DATA ELEMENTS

State DOTs are voracious collectors and users of data. One of the major categories of data state DOTs use is roadway inventory data. ITE (1994) defines an inventory as "a catalog, listing, accounting, record, or display of factual information that describes existing conditions." Roadway inventory data are distinct from other types of data handled by state DOTs in that (1) they are collected on each roadway or a large sample of roadways, rather than being collected for specific projects; (2) they pertain to the roadway and the right-of-way, but not to the surrounding buildings and areas; and (3) they pertain primarily to describing the identity, function, and physical features of the roadway and right-of-way.

Through a literature review, a telephone survey of state DOTs, and site visits, the research team assembled a list of representative data elements that are part of a typical roadway inventory. The first column of Table 1 shows these elements. No single list could hope to capture all types of inventory data being collected by all state DOTs, but Table 1 should contain all the major elements. The list has five major categories: (1) administrative characteristics, (2) roadway characteristics, (3) traffic characteristics, (4) collision records (see note 2 in Table 1), and (5) other characteristics.

The representative data elements can also be categorized by the primary user group within a typical DOT. By this method, the following categories of data elements emerge: (1) pavement (included in the "roadway" category above), (2) bridge (included in the "other" category above), (3) traffic (included in the "traffic" and "collision" categories above), and (4) basic or general use (included in the "other" category above). Some of the data called "inventory" data are actually collected in most state DOTs by units other than the roadway inventory unit, or even by agencies outside the state DOT. For example, traffic characteristic data are usually collected by a unit within traffic engineering or transportation planning; collision records are collected mostly by local police and compiled by state police or a department of motor vehicles; and data on utilities in the right-of-way are maintained by utility companies. The inventory unit within the state DOT thus typically collects some original data and combines them with these outside data to produce a larger data set.

The research team gained an in-depth understanding of the various elements in a typical roadway data inventory and of the state DOTs' requirements and current methods for collecting and presenting these data. The research team then used this information when considering the various automated technologies and approaches, both existing and emerging, that can be used to collect and present the data.

Each data set in a roadway inventory database may be collected using a different collection technology. Knowing what technology is used to collect any specific data set helps determine the characteristics of each data set. For example, one data set may be based on a linear-referencing system while another is based on the Global Positioning System (GPS). Obviously, these data sets would have different data, coordinate systems, and map projections. Users of roadway inventory databases must be made aware of such differences so they can perform proper transformations and conversions. Ideally, a roadway inventory database should have a common location referencing system in order to link event and inventory data for analysis purposes.

DATA COLLECTION SYSTEM COMPONENTS

The inventory data collection process consists of the use of an appropriate means of transport for data collection equipment, the use of appropriate technologies for collection of georeference data (i.e., locational information), and the use of appropriate technologies for collection of descriptive data (e.g., inventory element size and condition). In-office processing and archiving of the field data completes the inventory data collection process.

Common means of data collection transport include vans and backpacks. Satellites are another means of transporting data collection equipment. Georeference technologies include

TABLE 1 Inventory list and possible descriptive data accuracy

Key to Technologies
FP Paper and pencil in field, keystroke/scan in office
FC Computer keystroke in field
FV Computer voice recognition in field
IK Image in field, keystroke in office
IP Image in field, photogrammetric software in office
IA Image in field, automatic image processing in office
S Special study

Key to Accuracy
H High
M Medium
L Low

Inventory Category and Element	Descriptive data collection technology						
	FP	FC	FV	IK	IP	IA	S
Administrative Characteristics							
Names, route numbers	H	H	H	M		M	
Truck restrictions	M	M	M	L		M	
Roadway Characteristics							
Sign message	M	M	H	M		M	
Sign size, barrier height, fence height	L	L	L	L	H	H	
Sign support, signal displays	H	H	H	M		M	
Sign or marking condition, reflectivity	M	M	M				H
Number of signal phases	H	H	H	H			
Signal detectors	L	L	L				
Type of pavement, marking, barrier	H	H	H	H		H	
Pavement marking material	H	H	H	L			
Type of lighting	H	H	H	L		L	
Pole spacing	L	L	L	L	H	H	
Roadside object lateral placement	L	L	L	L	H	H	
Lighting quality	L	M	M				H
Number or type of lanes	H	H	H	H		M	
Lane or shoulder width	L	L	L	L	H	H	
Lane or shoulder cross slope					M		H
Shoulder material, barrier condition	H	H	H	H			
Sideslope percentage	L	L	L	M	M		M
Roadside hazard rating	M	M	M	M			
Pavement condition	L	L	L	L		M	H
Pavement friction, depth							H
Sight distances	L	L	L	L	M	M	M
Horizontal curve radius	L	L	L	L	M	M	H
Horizontal curve length, median width	L	L	L	L	M	M	
Percent grade, vertical curve length	L	L	L	L	M	M	H
Median type, landscaping	H	H	H	H		M	
Parking lane, gutter, or sidewalk width	M	M	M	M	H	M	
Parking restrictions	M	M	H	M			
Curb type	M	M	M	M		M	
Curb or sidewalk material	H	H	H	H		H	
Curb height	L	L	L	L	M	M	
Curb or sidewalk lateral placement	M	M	M	M	H	H	
Traffic Characteristics							
Hour, directional, or daily volume	L	M	L	M		M	H
Seasonal or monthly volume factors				L		M	H
Volume by weight							H
Volume by class	M	M	M	M		M	M
Posted speed limits	H	H	H	H			
Safe curve speeds							M
Mean, percentile, free-flow speeds	L	L	L	L		M	H
Other Characteristics							
Driveway, median opening width	M	M	M	M	H	H	
Driveway grade	M	M	M	M	H	M	
Adjacent land use	M	M	M	M		L	
Intersection, interchange crossroad name	M	M	M	M			
Interchange, median opening design	H	H	H	H			
Median nose design	H	H	H	H	M	M	
Railroad crossing: no. of tracks, control	H	H	H	H		H	
Railroad crossing angle	M	M	M	M	H	M	
Train volumes						H	
Belowground utility access points	M	M	M	L	M	M	
Utility wire clearance	L	L	L	L	H	H	
Bridge width, length, clearance	M	M	M	M	H	H	
Bridge design, fence type	H	H	H	M			
Feature crossed at bridge	M	M	M	L			
Structure quality	L	L	L	L			H
Type of drainage feature	H	H	H	H			
Billboard size	M	M	M	M	M	M	

Notes:
1. Location of each characteristic listed above is recorded by appropriate georeferencing technology and stored with descriptive data.
2. Additional characteristics of a roadway are typically collected separately and merged with inventory data. These additional characterisitics include administrative data like jurisdictions and Federal-Aid categories, design controls like design speed and maximum superelevation, traffic characteristics like forecast volumes and transit route information, reported collision data, and other characteristics like belowground utility locations and bridge weight imits.

the GPS, range- or distance-measuring instruments (DMI), and inertial navigation systems (INS). Some of the descriptive technologies include paper and pencil, keyboards, voice recognition, digital image capture systems, and automatic image processing systems. A brief discussion of the different means of transport, georeference technologies, and descriptive technologies used for collection of roadway inventory follows.

MODE OF TRANSPORT

Van

Many roadway agencies use suitably equipped vehicles (hereafter referred to as "vans") for inventory data collection transport. Data collection constitutes driving the van on the roads to be inventoried. The core component of these vans is a computer that synchronizes different operations during collection and stores the data for later processing. Different types of georeference and descriptive data collection technologies may be carried onboard. The GPS is a common georeferencing technology. However, other positioning technologies (e.g., a DMI or an INS) may also be carried. These two technologies may serve as backups for georeference data during GPS signal outage besides serving other purposes. The DMI may be used to trigger the data capture activities at regular distance intervals and the INS may be used to provide data on the vehicle body roll, pitch, and heading (i.e., orientation).

Descriptive data are collected by using several sensory technologies. Some of the more common sensory technologies include keyboards; pen-based computers; touch-sensitive screens; voice recognition systems; lasers; ground penetrating radar; and digital, video, or photo cameras. Multiple cameras mounted on the van pointed in different directions can record features such as right-of-way environment, traffic signs, pavement cracks, and utility poles. Photogrammetric software packages are available that allow users to make digital measurements on inventory elements captured in the images.

Costs for suitably equipped vans vary greatly depending on the data collection technologies. A DOT can equip a van with its choice of collection technologies in house, buy a van outfitted by a vendor, or rent a van outfitted by a vendor. The DOT can specify collection technologies in the two latter cases. The prices for equipped vans supplied by a vendor start at around $250,000 and may reach as much as one million dollars, depending on the collection technologies. Prices for photogrammetric software packages to extract inventory data elements from digital images range upward from $5,000. The cost of equipping a van in house may be lower than vendor-produced vans—in the range of $50,000 and up; however, an agency must have personnel with the adequate skills to properly install, configure, and maintain the different technologies.

Although a few DOTs have invested in data collection vans, the trend is toward hiring data collection services to minimize the large initial capital outlay. Many firms provide data collection services using vans on a per-kilometer basis, with costs ranging from $8/km to $20/km.

Generally, data collected by suitably equipped vans is of relatively high accuracy because the vans can carry multiple data collection technologies, with a high limit on the size or weight of the technologies. Employment of differential GPS can result in submeter georeferencing accuracy (Vaidya et al., 1994; El-Sheimy, 1996). Vendors providing data collection vans or van-based collection services usually guarantee georeferencing accuracy within 5 m. The accuracy of measurements on inventory elements using photogrammetric software packages varies depending on the particular package or sensors used. Table 2 presents some of the major advantages and disadvantages of vans relative to other means of data collection transport.

Backpack

Some agencies use their own staff members carrying equipment in backpacks to collect inventory data. The technologies used include lightweight, mobile equipment that can be handheld or carried on the back of a person in the field. During data collection, the crew usually drives to the study area and establishes a base station to provide a benchmark for accurate georeferencing. Crew members then approach each inventory element on foot, establish the element's georeference (more recently by using the GPS), and record the descriptive information (usually with an electronic device, such as a handheld computer or a pen-based input system). Employment of differential GPS to improve georeference accuracy is common practice, and attainment of submeter georeference accuracy is possible. Use of other georeference technologies, such as measuring wheels and laser rangefinders, is possible. Data collection via bicycle and golf cart is also possible and shares many of the features of collection via backpack.

Data collection by a backpack is time consuming because of the time involved in walking from one inventory element to another. Backpacks are useful in places that are inaccessible by other means of transport and are productive in locations where many of the required inventory elements are close to one another. The choice of data collection technologies is limited with the backpack because of size and weight restrictions. The trend is toward use of collection technologies that can weigh as little as 1 kg. Collection technologies must also operate on lightweight batteries and tolerate rugged handling.

The cost of data collection by means of the backpack usually consists of the cost of a GPS receiver and a pen-based computer. Prices for the type of GPS receivers adequate for backpacks start at about $2,000 per unit. Pen-based computers start at about $1,500 per unit. The equipment for data collection by means of a backpack is less expensive than a van because fewer technologies are used with a backpack. Table 2 presents the advantages and disadvantages of data collection by means of a backpack.

Satellite

Certain roadway inventory data can be extracted from analog or digital images captured through airborne sensors. Satellites offer a promising airborne approach because high-resolution digital imagery is becoming available for larger coverage areas, with more frequent revisit times, and at a lower cost. In particular, the emergence of 1-m-resolution satellite digital imagery (expected to be available to users sometime in 1999) should help improve the productivity of certain aspects of inventory data collection.

Compared with aerial photography, the satellite approach covers larger areas and provides frequent, systematic updates at low costs. Because the cost of covering large areas and providing frequent updates using aerial photography is very high, the use of the satellite approach in transportation inventories probably will increase.

Several steps are involved in collecting roadway inventory data using high-resolution satellite imagery (Figure 1). The first step is to acquire the images from a satellite platform. Users must determine whether the characteristics of the platform (e.g., coverage area, resolutions, and image capture schedule) meet their needs. The user then purchases images from the vendor. The next step is to georeference the image by determining the correspondence of individual pixels in the image with their respective ground locations. This step involves selecting and measuring ground control points and using a mathematical model to relate the two sets of measurements. Positional accuracy of 1.5 m is possible for features extracted from 1-m satellite digital images captured in raster formats. Software packages are available for conversion of the raster format to vector format, which is the preferred format of many GISs.

Inventory elements can be extracted from satellite imagery by employing a point-and-click (PAC) or an automated method. The PAC method requires the user to identify an inventory element in a high-resolution image (displayed on a computer monitor), position the element, obtain the georeference, and make measurements on it using software with image processing capabilities. The user may key-in relevant descriptive information and store the information in a database. A GIS software package, such as ArcView*, is one of the choices for the PAC method (Hutchinson and Daniel, 1995). The inventory elements can be stored as points, lines, or polygons.

The automated method relies on algorithms instead of human operators to understand and interpret high-resolution

* The use of a specific brand and/or company name is purely illustrative and not an NCHRP endorsement of the item mentioned.

TABLE 2 Advantages and disadvantages of major means of inventory data collection transport

Means of Transport	Relative Advantages	Relative Disadvantages
Van	Can collect at near highway speeds	Primarily uses crew of two collectors
	Much choice in technologies	If buying, requires large investment
	Can carry redundant systems	Slow data collection due to adverse weather
	High accuracy possible	Slow data collection due to traffic congestion
		Skilled crew required
Backpack	Efficient in areas with multiple elements	Slow collection process
	Lower initial cost	Little choice in technologies
		Physically demanding
		Collection stops in adverse weather
Satellite	Potential for high level of automation for inventory extraction	Cost depends on size of image, not on the size of roadway network
	No collection crew required	Cannot collect many inventory elements
	Covers large area inexpensively	Lack of fully automated extraction techniques
		Adverse weather affects image quality
		No control over collection schedule

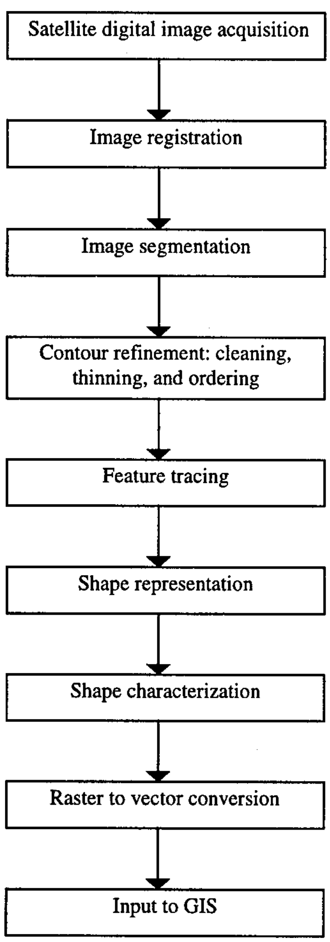

Figure 1. Steps in extracting data from satellite images.

imagery. Road network recognition and extraction from imagery has been investigated by several researchers (Fischler et al., 1981; Geman and Jedynak, 1996; Gruen and Li, 1997, Forlani et al., 1996, and Baumgartner et al., 1997). This method holds potential for real-time, large-area, inexpensive collection of roadway inventory elements (Firestone et al., 1996).

Table 3 presents 37 roadway inventory elements potentially extractable from 1-m satellite imagery. The availability of high-resolution satellite digital imagery allowing the collection of these inventory elements will serve an important niche. Agencies that inventory dense, highly developed highway networks or agencies that need frequent updates of basic elements in an inventory because of frequent changes in the road network may particularly benefit from high-resolution satellite imagery.

Table 2 provides the relative advantages and disadvantages of the satellite in comparison with the van and the backpack modes of transport. Collection of inventory data from satellite imagery is promising because of the possibility of automation. The roadway agency would not need to operate the satellite, and some of the image processing can be done automatically. More frequent update of some inventory data elements is possible than with the van or the backpack.

When transportation agencies first use satellite digital imagery for collecting roadway inventory data, they may have to hire consultants to assist them in georeferencing tasks. As the use of satellite digital imagery increases over time, the agencies probably will train existing personnel or hire new personnel with appropriate expertise.

TABLE 3 Potential elements recognizable from 1-m images and a comparison of extraction techniques

Roadway Feature Element	Point-and-Click		Automated Technique		
	DOR[1]	Comments	CTS[2]	EE[3]	Comments
Width of Lanes	Low	Image resolution is the main limitation to the detection of these individual features. High recognizability if these three features are combined. Individual features can be estimated from the combined estimation, i.e., Total Roadway Width (TRW).	2	n.e.d	If these features are combined into one representation, i.e., TRW, task of automation is much less challenging. Most-researched area; experimental algorithms are available, some of which operational.
Number of Lanes	Low		2	n.e.d	
Shoulder Width	Low		2	n.e.d	
Lane Type	Medium	Use roadway width changes indicator.	1	7-12	Road width and roadway width changes are indicators.
Shoulder Material	Medium	If shoulder is recognizable from the pavement.	5	1-3	Use gray level difference if different materials exist.
Roadside Fixed Objects	High	If object size is detectable with respect toimage resolution.	6	1-3	Object size and location. Knowledge needed for object identity.
Barrier: Lateral Placement	High	If barriers are detectable.	1	4-6	The key is to detect barriers first. Image resolution is a limitation.
Pavement: Materiel Type	Medium	If materials are spectrally different.	2	4-6	Cover type identification.
Sight Distances: Stopping	High	If terrain is flat and no obstacles exist.	2	1-3	Roadway network needed.
Sight Distances: Passing	High	If terrain is flat and no obstacles exist.	2	1-3	Roadway network needed.
Sight Distances: Intersection	Medium	If terrain is flat and no obstacles exist.	2	1-3	Roadway network needed.
Sight Distances:	Medium	If terrain is flat and no obstacles exist.	2	4-6	Roadway network needed.
Horizontal Curve: Radius	High	If terrain is flat and no obstacles exist.	2	4-6	Roadway network needed.
Horizontal Curve: Length	High	Arc length.	2	4-6	Roadway network needed.
Terrain Type	Medium	Visual check for flat, rolling, or mountainous terrain.	3	>12	Large neighborhood checking is needed.
Median Width	High	If median is sufficiently wide and distinctive.	5	1-3	Median is always distinctive from roadway.
Median Landscaping	High	Depends upon median land cover type.	6	1-3	Land cover classification
On Street Parking: Width	Low	If parked cars exist as indicators. It requires estimation of TRW.	1	n.e.d	Cars are the only indicator.
On Street Parking: Angle	Low	If parked cars can be used as indicators.	6	>12	Cars are only indicators.
Sidewalks: Width	Medium	If strips between roadway and sidewalk exist. Otherwise, it is included in TRW	5	1-3	If strips exist for differentiation.
Sidewalks: Lateral Placement	Medium	It depends on how the strips are identified.	5	1-3	If strips exist for differentiation.
Sidewalks: Materials	Medium	If it is different from roadway or strips exist.	5	1-3	If it is different from roadway or strips exist.
Driveway: Width	High	Bushes or trees may pose problems.	5	1-3	Bush or trees may pose problem.
Driveway: Land Use	Medium	Neighborhood checking required.	5	1-3	Land cover classification

TABLE 3 *(Continued)*

Roadway Feature Element	Point-and-Click		Automated Technique		
	DOR[1]	Comments	CTS[2]	EE[3]	Comments
Intersection: Turning Lanes	Medium	Use width change as the indicator.	1	7-12	Large neighborhood checking is needed.
Interchanges: Design	High	Requires visual check.	1	>12	Template matching problem for large neighborhood.
Median Openings: Width	High	High contrast is the key indicator	5	1-3	Median landscape is always distinctive.
Median Openings: one- or two-way	Medium	Depends upon the opening dimensions.	5	1-3	Decided by the width.
Median Opening: Nose Design	Low	Decided by the shape of the nose.	3	>12	Template matching problem for large neighborhood.
Median Opening: Turning Lanes	Low	Width change as indicator.	1	7-12	Width change checking in a large neighborhood.
Road Railway Crossing: #Tracks	Medium	Requires detection of the railroad width.	4	4-	Estimated by width.
Road Railway Crossing: Angle	High	General angle is always distinctive.	5	1-3	Angle determination after road network detection
Bridges: Length	High	Requires careful definition of starting and ending points.	3	4-6	Detection of the starting and ending points is essential
Bridges: Width	High	Readily distinctive in most cases.	5	1-3	Bridge surface is always distinctive from its surroundings
Bridges: Feature Crossed	High	Bridge surface is always distinctive from the features crossed.	5	1-3	This information can be extracted from land cover classification.
Drainage Type	Low	If drainage is distinctive from its surroundings.	3	n.e.d	Other data are needed.
Drainage Design	Low	Depends on the size and materials of drainage.	3	n.e.d	Other data are needed.

[1] Degree of Recognizability
[2] Current Technological Status
[3] Estimated Effort in Person Months to develop algorithms (n.e.d. – not enough data.)

The total cost of using satellite imagery consists of the cost of the image processing software and the cost of image acquisition. Currently, the cost of a satellite image processing software package ranges between $2,000 and $5,000. The cost of acquiring satellite digital imagery depends on the area of coverage and the resolution of the image. Generally, the cost of satellite digital imagery is about $5/km^2 for a single scene with 10-m resolution. The covered area of the image can vary from 50 km^2 to 500 km^2. For a 3- to 5-m-resolution panchromatic scene, the current price is about $40/km^2. For a 1-m-resolution scene, the expected price is about $60/km^2.

GEOREFERENCING TECHNOLOGIES

Global Positioning System

An increasingly popular georeferencing technology for roadway inventories is the satellite-based GPS established by the United States Department of Defense. There are 24 satellites (21 active and 3 spare) positioned 20,200 km above the Earth in six orbits that allow at least 4 satellites to be visible from almost anywhere in the world at any time (Hoffman-Wellenhof, 1992). The GPS is available 24 hours a day, in all weather conditions, anywhere on Earth. The GPS is an absolute positioning technology—it determines the coordinates of a receiver with respect to the Earth's reference frame by the intersection of the signals from four or more GPS satellites. GPS receivers receive GPS time and satellite position data. The receiver establishes its position by using the time differences in the transmission and reception of the GPS satellite signals and the position data of the satellites. The receiver provides the data to the user in vector format; the data are easily adapted for use in mapping software such as GIS packages. GPS receivers come with various features, and, with the help of special techniques, high locational accuracy is possible. Most GPS receivers are small and light enough to be carried in a backpack. In general, using standard GPS, an accuracy of 100 m or better is possible. The variation in accuracy results mainly from the errors caused by selective availability (SA), clock deviation, and changing radio propagation conditions in the ionosphere. Differential GPS (DGPS) techniques are commonly used to reduce these errors and obtain higher accuracy by the GPS.

DGPS techniques are based on relative positioning—the determination of the position of one point with respect to another point with known coordinates. A DGPS technique requires a GPS receiver at a base station that calculates the error in the GPS signal at any time by knowing the true geographic location of the base station. These corrections can be applied to the mobile GPS readings either in real time or in a post-processing mode. The real-time mode requires a radio communication link between the base station and the mobile GPS. Because of the radio-link requirement, the real-time mode is more expensive than the post-processing mode. In the post-processing mode, data from the base station and from the mobile GPS receiver are integrated at a later time. The post-processing algorithm must exactly match the times of the base station observations with the times of the mobile receiver observations. For roadway inventory data collection, post-processing is usually sufficient. Inventory units can hire companies to provide DGPS services.

The GPS has shortcomings when it is used as the sole georeferencing technique for collecting inventory data. The most notable difficulties stem from signal blockage in certain areas caused by thick tree canopies or bridges or multipath problems caused by signal deflection by high-rise buildings or other objects. To overcome these problems and to provide higher accuracy, the GPS technology is often integrated with an INS, a DMI, or both.

Depending on the accuracy and other features (e.g., durability and size), the prices of GPS receivers suitable for roadway inventory purposes start at about $2,000 per unit.

Distance Measuring Instrument

A DMI is an inexpensive georeferencing technology consisting of a mechanical device attached to one or more of the wheels of a van and connected to an in-vehicle recorder. The in-vehicle recorder, either a stand-alone display or a conversion device attached to a laptop computer, will record and display the distances (but not direction) the vehicle advances from a preset zero reference point based on wheel rotations. A DMI may cost only a few hundred dollars. A DMI provides only relative measurements and needs frequent calibration to minimize errors that accumulate as the result of travel.

Inertial Navigation System

An INS uses accelerometers and gyroscopes that provide pitch, roll, and heading information to derive a relative georeference for a point. An INS has high accuracy over small distances and is usually more accurate than the GPS but much more costly. An INS used in a van by the Michigan DOT to collect roadway curve and grade data, for example, cost $69,000 (DeFrain et al., 1993). The latest developments in INSs have resulted in compact (hand-held) devices and in a dramatic decline of INS costs to a range of $10,000 to $20,000.

Rangefinders

A rangefinder is a common and useful georeferencing device that typically uses the Doppler effect of a radar or laser beam to calculate a distance from the instrument to a target with a hard surface. It is small enough to be held by hand or easily mounted on a vehicle. Rangefinder prices range from $100 for optical binoculars to more than $5,000 for laser devices. Laser rangefinders display distance measurements from the device to an object up to 2 km away (if in the field of view) with an accuracy of 5 cm. Data collectors can use rangefinders to gather several relative georeferences without moving the GPS receiver, to gather georeferences for remote or unsafe points, or to obtain a georeference where the GPS cannot be used.

DESCRIPTIVE TECHNOLOGIES

Keyboard

Observers in the field can use standard computer keyboards, nonstandard keyboards or templates, and touchscreens for collection of descriptive information on an inventory element. Keyboards are usually employed during data collection by vans. For safety reasons, van drivers should not attempt to key data. Driver keying should be considered only for inventories with very few elements per kilometer and only if the driver can safely stop the vehicle to perform the keystrokes. Keying is faster and more accurate with categorical data elements than with continuous data elements. Bonsall et al. (1988) conducted extensive testing with various data collection equipment and concluded that keying data into a computer is more advantageous than writing on forms in the field when the data require an accurate time stamp. Bonsall et al. (1988), as well as several state DOTs and vendors, cited the ability to tie into an existing database while keying data into a computer as another advantage over paper and pencil recording.

Data collection productivity depends on the descriptive data. Collectors were able to key about 50 percent of the desired data elements during a typical inventory data collection effort in a rural Ohio county by using a van running at highway speeds and equipped with a customized PC keyboard (Clark County Mapping Project, 1994). Cost also varies widely depending on the complexity of the keyboards. Models can be found ranging from $30 to $4,000.

Voice Recognition

Voice recognition technology is available for inventory data collection. Voice recognition systems can be used to collect inventory data in the field or while viewing a video or photo log. The technology requires a headset microphone connected to a computer with a voice recognition software package. The software translates pre-defined speech phrases into a structured format and then places them into a database.

A major disadvantage in the past was that voice recognition systems were voice-dependent (i.e., they had to be customized for each data collector). Voice-dependent systems vary widely in price from $100 to $10,000 (Pawlovich et al, 1996). Voice-independent systems, while more desirable for their flexibility, were not as reliable and much more expensive. However, some systems are now entering the market that provide reliable voice-independent recognition at reasonable prices. One such system ranges in price from $8,000 to $14,000 and can reportedly recognize 95 to 98 percent of the words spoken into it.

The major advantage of the voice recognition technology is labor savings. A van driver can record many data elements while keeping his or her hands free to drive. Also, voice recognition technology is generally faster than keying or writing down descriptive information. Using one of the latest speaker-independent voice recognition systems, the City of Aurora, Colorado, reported that neighborhood code violation inspectors saved 1 to 2 hr per day using voice recognition systems over handwritten forms (Lawless and Bourgeois, 1995).

State DOTs and several vendors have expressed reservations about using voice-recognition technology for inventory data collection. Some cited voice fatigue over the course of a day's collection. Others cited background noise in the roadway environment as a problem, restricting collection to the inside of a vehicle with the windows up. The major criticism is that the range of speech phrases that the systems will recognize and code (and the number of phrases that a user can remember) is limited. Because of this, complex or continuous data elements are difficult to collect with voice recognition systems. However, the recently introduced systems mentioned above can recognize agency-specific and collector-specific terms and can incorporate ad hoc commentary into the database.

Digital Image Capture

Many roadway agencies collect and maintain roadway photologs and videologs collected by running suitably equipped vans on the roadways. Roadway imagery may be displayed on monitors by converting the photolog or videolog into digital images using appropriate software packages. Alternatively, roadway images may be captured by using digital cameras, with the images directly stored in a computer. In any case, users can key descriptive data into the computer while viewing the imagery on the computer monitor. Additionally, the use of photogrammetric software packages allows users to obtain georeference and descriptive measurements of inventory elements captured in the images. Obtaining these data requires users to point and click the computer mouse on an inventory element captured in two successive or simultaneous digital stereo images. The resulting data can be stored as attributes of the inventory element.

Acquiring inventory data from digital images requires a desktop computer costing about $1,500 and an appropriate photogrammetric software package, which costs upward of $5,000. The photogrammetric software requires georeference information (e.g., GPS or DGPS and orientation data) besides the digital imagery collected by the van. The costs reported here do not include the cost of the van equipped with appropriate data collection technologies.

Automatic Image Processing

Automatic image processing requires only a van driver to produce computerized inventory data files. Such systems rely on computer algorithms that detect and extract the required inventory data from roadway images. There are systems on the market for automatic processing of video images for pavement distress and for traffic monitoring (e.g., calculating volumes, flows, and speeds). The pavement distress system most widely recognized in the United States uses video from two downward-facing cameras on the back of a van traveling at highway speeds. After computations, the system estimates crack length, width, orientation, and location. In a test sponsored by the North Carolina DOT and FHWA, estimates from this system were compared with two manual systems and estimates from pavement experts walking along the test sections. The automatic system compared well with the expert evaluation and estimates provided by the manual systems, with a success rate of more than 90 percent in determining crack lengths (Roadware Corporation, 1994).

Automatic video image processing for traffic volumes and speeds has been available for about 10 years. Error rates of these are comparable with other leading automatic vehicle detection systems. Equipment costs begin at about $20,000 per intersection. The need for a central, elevated camera position makes system mobility difficult.

For other data elements, the only automatic image processing system available at the time the research team was investigating these systems is a prototype developed at FHWA to identify STOP signs from photologs. Although publications describing the details of this work have not been released, FHWA staff indicated that the system correctly identifies about 90 percent of all STOP signs. The FHWA hopes to field-test the prototype on a range of photologs and to extend the system to identify other signs. The ultimate objective for the system is to identify roadside obstacles automatically.

NON-ROADWAY DATA COLLECTION TECHNOLOGIES

In addition to addressing technologies specifically designed for roadway inventories, the research team searched for non-roadway data collection technologies that are potentially transferable to roadway practice. To find appropriate non-roadway technologies, the research team used a systematic approach to categorize current technological endeavors. The research team started with the best emerging technologies list found in the literature: a list of 20 categories from "trend watcher" Daniel Burrus (Burrus and Gittines, 1993). The extensive review of the literature, including on-line searches of the UnCover database and the Internet, provided other lists, but these all turned out to be subsets of the Burrus list.

The list of 20 technology categories contains 9 that the research team felt could not help in collecting roadway inventory data within the 5-year horizon defined for emerging technologies. These nine technology categories were genetic engineering, advanced biochemistry, photovoltaic cells, micromechanics, thin film deposition, molecular designing, new polymers, fiber-reinforced composites, and high-technology ceramics. Beyond the 5-year horizon, these technologies have potential for improving collection procedures; for example, data collection vehicles could be powered by photovoltaic cells. However, this speculation is beyond the scope of this project. The research team believed that the remaining 11 technologies may directly affect the inventory process within the next 5 years. In addition to this list, the research team found examples of specific products that could be integrated into the inventory data collection process. These were found in the literature and through contacts with government agencies (e.g., NASA) and private firms. The research team then split this combined list into technologies applicable to collection (Table 4) and presentation.

Non-roadway technologies applicable to inventory collection consist of collection platforms and sensors used to collect non-roadway data or are in the prototype stage and a specific use for them has not yet been determined. Table 4 lists these technologies along with the research team's ideas on how they could be used for roadway inventory data collection. As discussed previously, the research team recognized high-resolution satellite digital imagery as one non-roadway technology that has significant potential for automating inventory data collection.

STATE DOT INVENTORY PRACTICES

To determine general trends and practices in the use of existing and emerging technologies for roadway inventories, the research team contacted state DOTs by means of a standardized telephone survey (Appendix A). Officials in charge of roadway inventory data collection and presentation were questioned about their methods, equipment, and standards. Only one or two individuals from a particular DOT, usually from the branch associated with compiling and updating a roadway inventory, were contacted. The purpose was not to make an "inventory of all inventories," nor to contact everyone who was in charge of a particular inventory (e.g., signs, bridges, and pavements). A complete summary matrix of telephone survey responses is given in Appendix B. Although all 50 state DOTs were contacted, interviews were conducted with only 44. The other six DOTs either did not return the repeated telephone calls or did not have anyone willing to be interviewed on this topic.

On the basis of the trends identified from the telephone survey and the literature, the research team visited several state DOTs and other organizations involved with inventory data collection. Appendix C lists the organizations visited and the systems inspected at each site and contains brief remarks about the systems. The research team visited seven state DOTs: Connecticut, Maryland, Michigan, New Hampshire, North Carolina, Tennessee, and Colorado. Also, the team visited 16 companies and 1 university; all of these organizations have invented and/or market emerging technologies

TABLE 4 Emerging non-roadway technologies applicable to inventory data collection

Technology/product	Potential Application
Digital electronics	Can generate and process all information collected for an inventory and transfer it to storage seamlessly
Artificial intelligence	Could eliminate manual extraction of data through automatic image processing
Lasers	Already some applications; can be used for communicating information or measuring distance
Microwaves	Could be used in sensors for object identification and location
Advanced satellites	Satellites made of snap-together composite materials will provide low-cost data collection
Advanced computers	Could control more sensors, process more real-time data, and allow artificial intelligence applications
Remote control helicopters	Multisensory robotics equipped with GPS receivers and gyroscopes could be equipped and programmed to collect data
Automatic target recognition systems	U.S. Department of Defense project uses process similar to automatic image processing to detect aircraft by sensor data

TABLE 5 Summary of state DOT best practices

State DOT	Criterion	Practice	Data	Technologies	Improvements	Comments
Connecticut	Cost savings	Van-based photolog	Georeference, photolog, geometric	GPS, INS, DMI, CCD cameras, laser	Digital image	Savings of $800,000 every year
	Unique equipment	Digital cameras		CCD		Unit cost: $47,000 each camera
New Hampshire	Cost savings	Van-based	68 items	DGPS 93-5 m accuracy)		Unit cost: $68,000
Wisconsin	Access to inventory database	Van-based photo log	Roadway photolog	GPS, INS, DMI	Distribution on CD-ROM	
	Unique equipment	Digital cameras		Analog cameras with wide view		Reduction in processing time and cost with the new cameras
Michigan	Accuracy	Van-based data collection system	Depth of ruts in a pavement, highway horizontal and vertical alignment	Laser, INS	Improvement over traditional methods of measuring ruts, horizontal and vertical roadway alignment	Accurate measurement of ruts, horizontal and vertical alignment or roadways
Utah	Accuracy	Van-based data collection system	Pavement profile data	Laser		Unit cost: $172,000
Michigan	Unique equipment	Mobile Evaluation of Traffic Signs (METS)	Roadway sign data	Two video cameras: a flash tube and a laser rangefinder mounted on the roof		Faster and more accurate measurement of sign retroreflectivity compared to manual measurement

or relatively advanced roadway inventory products. In all visits, the research team members conducted discussions at length with people working on or with some of the more advanced roadway inventory systems in the United States. A wide variety of different data collection systems were inspected. In the DOTs, some of the systems were developed in house; others were purchased from private vendors. In the other organizations, most of the systems were developed in house.

State DOT Best Practices

In addition to the telephone survey and the site visits, the published literature provided some information on the current inventory practices of the state DOTs and revealed a few "best practices." The research team learned of the best practices in Louisiana (Smailus et al., 1996) and Michigan (Miller, 1993) from the literature. A presentation by Connecticut DOT personnel at the 1997 TRB Annual Meeting provided details about Connecticut's practices.

Low cost and high accuracy were the main criteria for selecting state DOT best practices to highlight in this report. Low cost and high accuracy were major emphasis areas throughout this project. Another criterion used to identify best practices involved the ability of an inventory data system to answer data queries; this included bringing inventory data to bear on various questions and providing data to customers quickly. Finally, the research team identified as best practices state DOT efforts that developed unique equipment.

Table 5 summarizes the best inventory practices by several DOTs according to the criteria discussed above. The best practices identified in this section are current activities of state DOTs. These activities have moved beyond the research stage into production and have been proven in the field. The best practices identified in this report should be transferable to other state DOTs to some extent, although different political and economic conditions will play a role in the transfer. There may be perfectly valid reasons for a state DOT to keep performing some inventory tasks the same way rather than switching to one of these best practices.

CHAPTER 3

INVENTORY DATA PRESENTATION

Technologies suitable for presenting inventory data are discussed in this chapter. Four presentation technologies are in widespread use: database management systems (DBMSs), straight-line diagram (SLD) technologies, GISs, and image processing software packages. The Internet and agency intranets are emerging with the potential to significantly affect inventory data presentation in the coming years. Two other technologies—automatic vehicle location systems and virtual reality—have potential for use in presenting roadway inventory data, but probably not within the 5-year time frame defined for emerging technologies in this project.

DATABASE MANAGEMENT SYSTEMS

DBMSs are software packages for storing, retrieving, managing, maintaining, and updating data. DBMSs store data in one of several formats and typically have their own specific data structures. Conventional DBMSs are based on hierarchical, network, or relational modeling (Everest, 1986). Of these, the relational DBMSs have gained popularity since the 1970s because of their simple data structuring; they are used in many applications, including managing and processing roadway inventory databases. To input inventory data into a relational DBMS (RDBMS), transportation agencies must (1) convert the format of the collected data (each data type collected may be in one of several formats) to that of the DBMS and (2) model the data in accordance with the procedures for relational data modeling. The first step is straightforward but time consuming; the second step requires special skills. Once data are in a DBMS, one can use a command language, a structured query language, or a graphical user interface to query an inventory database.

DBMSs can produce output in various ways, ranging from printouts to flat files to computer graphics. Today's DBMSs are equipped with presentation tools (e.g., bar charts), provide various import and export capabilities, and can be interfaced with other software packages. Thus, DBMSs allow presentation of roadway data in a multimedia environment. Smailus et al. (1996), for example, discuss a multimedia environment for the implementation of a highway sign database. Hughes (1996) discusses a multimedia environment for roadway applications that uses technologies such as audio, high-capacity mass storage, video, networking, a DBMS, and a GIS. DBMS software packages that can run on desktop computers cost more than $1,000.

SLD TECHNOLOGIES

An SLD is a one-dimensional graphical presentation of a roadway and the features that compose it. The centerline of the roadway is indicated by a straight line on the diagram—a single line for an undivided roadway and two parallel lines for a divided roadway. All lateral distance measurements are in reference to the roadway centerline. The inventory generally begins at mile point 0.00, accompanied by a description and a reference point (tie-in). Starting from the beginning mile point and proceeding along the road, the SLD shows point features (features with no significant longitudinal dimension, such as signs or accident locations) and locations where longitudinal features change. The dimensions, descriptions, and other pertinent data are indicated on or beside the road's centerline. A typical SLD may list the following types of information:

1. Heading: map number, name of the person who recorded the data, direction of travel, road name and number, county, and so on.
2. System data: data pertaining to the general, large-scale, administrative characteristics of the road, such as functional class, Federal aid type and number, and HPMS sample.
3. Traffic data: average daily traffic (ADT) estimate, information on traffic control (e.g., traffic signals and stop signs), access control, and parking restrictions.
4. Pavement data: widths of traveled way, shoulder, and median; type of surface of traveled way, shoulder, and median.
5. The line diagram: indicates mile point, state line, corporate limits, locations of bridges and culverts, intersections, and locations of prominent features (e.g., guard rails, buildings, accident locations, and so on).

Presentation of data using SLDs is well established and is popular with some roadway agencies. SLDs are easy to understand and provide the information necessary for many operation and maintenance purposes. However, presentation of information on an SLD is one-dimensional and the data do not lend themselves readily to spatial queries.

SLDs can be produced manually by recording the features on printed forms or can be prepared from existing data using computer software packages. Collection and display of roadway feature data on SLDs in real time is possible when specially equipped vans are employed during data collection (*LRS Technical Manual,* 1995). These systems can also accept previously collected data (in computerized formats) as input and then use them to produce SLDs that display upcoming roadway features on computer screens for verification purposes as the van drives along a road.

SLD Production*

The research team produced example SLDs using the data collected by a van system for Chapter 4. Given that most DOTs produce SLDs using in-house SLD production software, the research team had difficulty finding a commercial software package to produce an SLD automatically from the collected data. The research team finally located a newly available software package (GeoDynSeg from Bentley Systems, Inc.) specifically designed for production of SLDs in a GIS environment. This software package was used to demonstrate the production of SLDs using the data collected in this project. Figure 2 shows the procedure the research team followed to produce SLDs. Data obtained by the van system were transferred to a relational DBMS after creation of points, lines, and polygons. GeoDynSeg required the use of the Oracle DBMS (from Oracle Corp.) for storing the data in tabular forms. Oracle is a popular DBMS that allows presentation of the stored data in a GIS (e.g., MicroStation-SE and ArcView). GeoDynSeg operates as an extension of the MicroStation-SE GIS software package (Bentley Systems, Inc.) and users need to install MicroStation-SE before operating GeoDynSeg (*GeoDynSeg User's Manual,* 1998). GeoDynSeg allows users to display and analyze linear graphic elements such as roads and pipelines using a dynamic segmentation approach. Dynamic segmentation is the process of dividing a section of roadway (or any other linear feature) into segments based on criteria such as the number of lanes. The software package allows boolean analysis so that creation of a new attribute combining two or more existing data attributes is possible (*GeoDynSeg User's Manual,* 1998). For example, it is possible to automatically create a diagram that combines the number of accidents with the number of lanes. The resulting diagram indicates changes in either attribute on the diagram.

GeoDynSeg setup requires the user (or computer system administrator) to have a good working knowledge of MicroStation-SE and Oracle DBMS and be familiar with the process of setting up Oracle databases and computer applications. The computer storage requirement for the setup (GeoDynSeg, MicroStation-SE, and Oracle) is of the order of 1.5 GB. The inventory database will require additional computer storage space. Once the software package is correctly set up and data are appropriately stored in the DBMS, the operation to display the data in SLD format is relatively straightforward. Users can learn basic SLD production in 1 day. Operation of sophisticated queries on the stored data and production of customized SLDs for special purposes may take additional time.

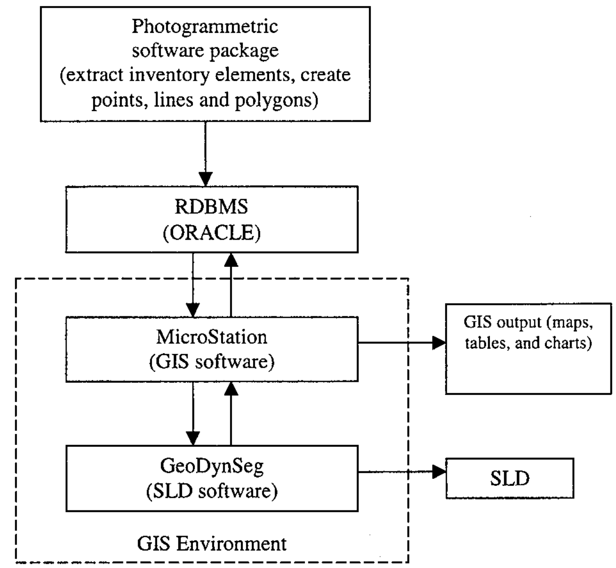

Figure 2. SLD production procedure.

SLDs comparable to typical DOT SLDs were created to verify the viability of SLD production from the data acquired by the Lambda method. Sample SLDs for three different roadway environments are shown in Figures 3 through 5. These sample SLDs depict some of the commonly found information on SLDs. Inclusion of other types of information (e.g., system data and pavement data) is possible.

Cost and Setup Information*

The cost of using GeoDynSeg for producing SLDs includes the cost of the GeoDynSeg, MicroStation-SE, and Oracle DBMS. The combined cost for GeoDynSeg and MicroStation-SE is $1,500 to $7,100—depending on the functionalities included in the package. The cost for the Oracle DBMS is $1,500 or more, again depending on the software functionality.

Labor time for production of SLDs includes first-time software package setup and configuration time that can be significant for the novice. However, support from the vendors is available, and vendors can set up the software. Labor time for

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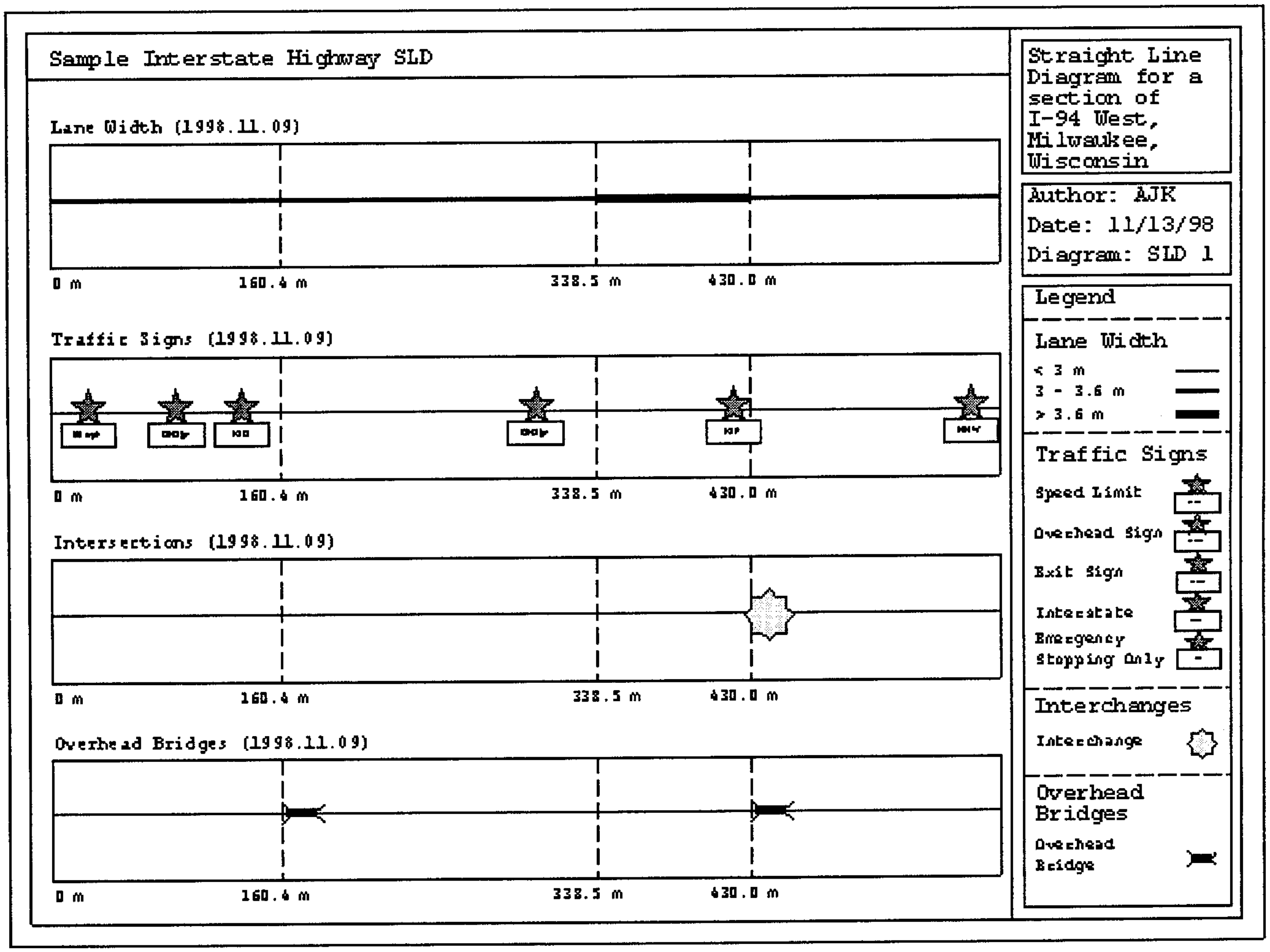

Figure 3. Sample SLD for interstate environment.

creation of the database (i.e., creation of points, lines, and polygons) depends on the database size. It took the research team 20 working days (one person working full time) to set up the system, input the data for about 20 km of roadways into the DBMS, and produce the first set of SLDs. Because of the significant learning curve involved with the setup process, the research team recommends that the system setup and configuration be undertaken by the vendors (at least the first time) and that DOT personnel be trained in administration and use of the database.

GEOGRAPHIC INFORMATION SYSTEMS

GISs excel at the storage, retrieval, management, and processing of spatial data—they are rapidly becoming the technology of choice for managing and presenting roadway inventory data. GISs have extensive visualization capabilities that can be used to present roadway inventory data in various forms. Other components of a GIS, providing benefits to roadway inventory data operations, are the DBMS, data layering, and spatial analysis (Karimi and Blais, 1996). The DBMS component can be used to organize and manage the collected data and provide common approaches for querying data from inventory databases. The data layering component can be used to group data into several layers (based on their types and characteristics) and to provide composite maps using the inventory data layers and other data such as road network data. The spatial analysis component can be used to analyze many spatially oriented problems such as cut-and-fill calculations, determining the shortest path along the network, route allocation, and address matching.

Despite the use of GISs for solving problems in many diverse applications, their use to solve real-world 3-D applications has been limited. This limitation has been caused by the lack of appropriate 3-D topological data models in commercial GISs. Current GIS packages are often based on 2-D data models. A data structure constitutes the basis for building data models in GISs. Three-dimensional data structures are critical for solving real-world applications, especially 3-D modeling and simulation. Currently, the standard approach for GIS applications that require 3-D information is to simplify, project and/or represent 3-D objects in 2-D surfaces

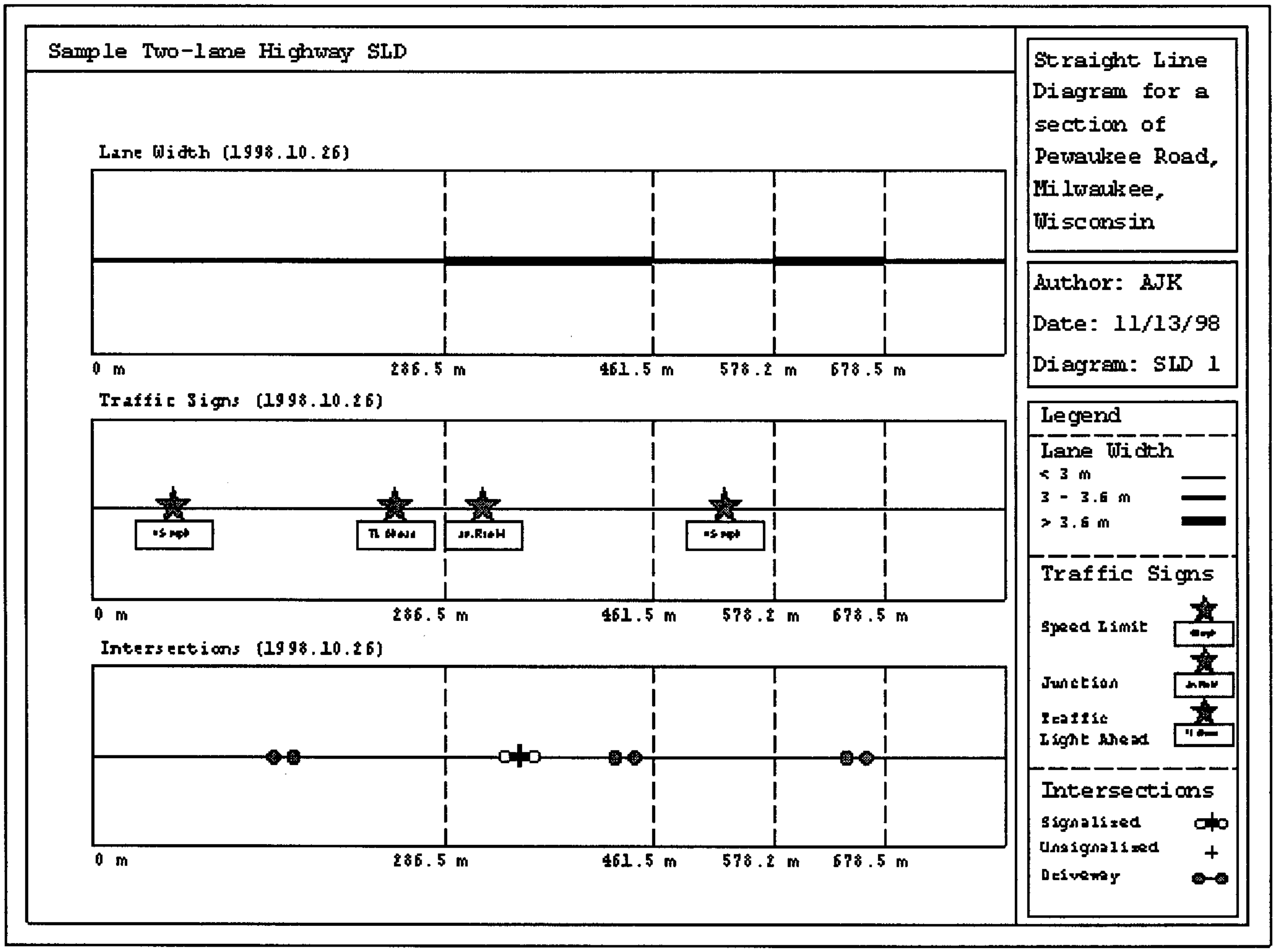

Figure 4. Sample SLD for two-lane environment

using vector or raster data structures defined on points, lines, and polygons. This approach does not provide optimal solutions to 3-D problems and does not support certain functionalities; in particular, it does not provide initial data and final analysis for 3-D numerical solutions obtained from modeling and simulation. For this reason, there is a need for 3-D data structures to solve, efficiently and effectively, real-world 3-D applications.

To date, attempts at building spatial 3-D data structures have resulted in impractical and complex solutions. These methods fall short in handling topological information and/or numerical solutions to 3-D modeling and simulation. They also typically require a large amount of storage and computing resources. Despite claims by some GIS vendors, existing commercial GIS software packages are not based on true 3-D data structures. Some GIS software packages provide 3-D graphics for representation of data that have the third dimension (elevation), but they are far from true 3-D GISs because they are not based on 3-D data structures and support very limited 3-D functionality. However, research on building a proper foundation for 3-D GISs is underway, and true 3-D GISs, when available, will be beneficial to many transportation activities, including the presentation of roadway inventory data.

GISs can provide state DOTs with advantageous ways to present roadway inventory data and can perform various other analyses. Figure 6 shows the general procedure to produce SLDs using GISs. The research team developed this procedure by analyzing the current methods of producing SLDs in different state DOTs and by analyzing the working of current GISs. Without a GIS, users generally have to rely on several independent, nonstandard software tools to update and maintain roadway inventory data, which makes those tasks very difficult. Some GISs, called GIS-Ts, are designed specifically for transportation problem-solving. Many GIS-Ts provide the means for simple integration with off-the-shelf CADs (e.g., for producing detailed SLDs). GIS software packages are increasingly becoming available for use on desktop computers, which continue to become more powerful, less expensive, and easier to use. The prices for desktop GIS packages suitable for roadway inventory purposes start at around $1,000.

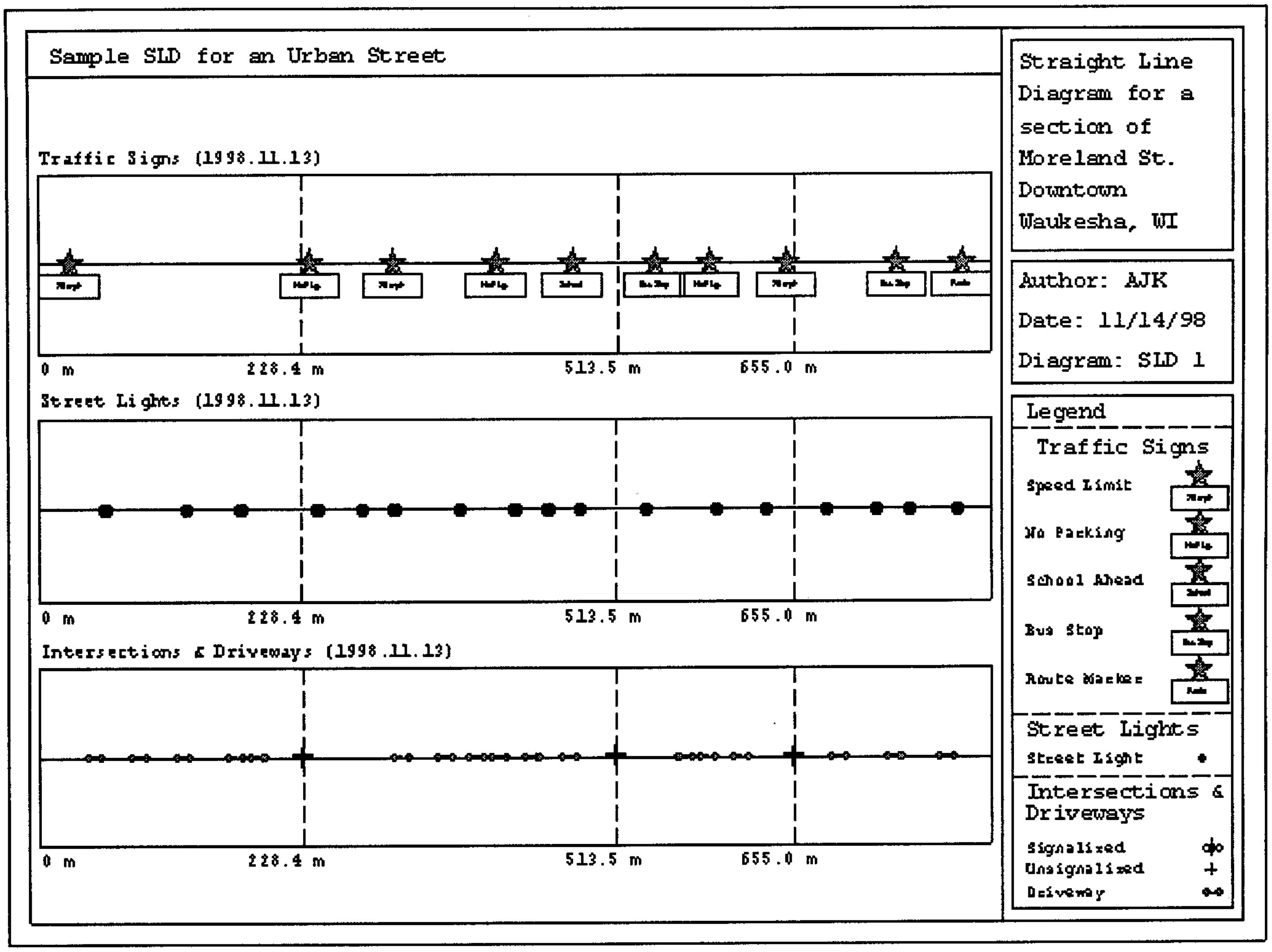

Figure 5. Sample SLD for urban environment.

PHOTOGRAMMETRIC IMAGE PROCESSING SOFTWARE PACKAGES

Photo, video, and digital images are attractive methods for collecting roadway inventory data, and viewing the images is an effective presentation technique. Each image is georeferenced and is tagged with other information such as the date and time of collection. Once the required images are recorded and digitized, photogrammetric software packages can be used in the office to present the georeferenced images. Some photogrammetric software packages allow users to extract georeference and descriptive data by pointing and clicking the computer mouse on two (or more) successive or simultaneous digital images.

THE INTERNET AND INTRANETS

The Internet is an emerging technology for the presentation of roadway inventory data. Within transportation agencies, the use of the Internet and, more recently, in-house intranets is increasing. In addition to establishing communication (e.g., email) among different users and divisions in the state DOTs, the Internet can also be used as a backbone for providing on-line solutions to many transportation problems. The Internet is particularly well suited for the presentation of roadway inventory data because it can facilitate widespread access to the data at a lower cost. One state DOT, Kentucky, indicated during an interview that the DOT used the Internet to distribute roadway inventory data to users.

Using the Internet, it is possible to either centralize (Figure 7) or distribute (Figure 8) the inventory database. When the database is centralized, all of the DOT divisions responsible for collecting the various types of data store all updates in one centralized database that every division can access. With a distributed database, each division maintains and updates a database subset containing the data for which they are responsible; they can share all of the data in the other divisions' database subsets. Each of these strategies has advantages and disadvantages, from the technical and administrative points of view. A primary advantage of the centralized strategy is the required coordination and conformity in the use of the data. A disadvantage is the complex process involved in handling

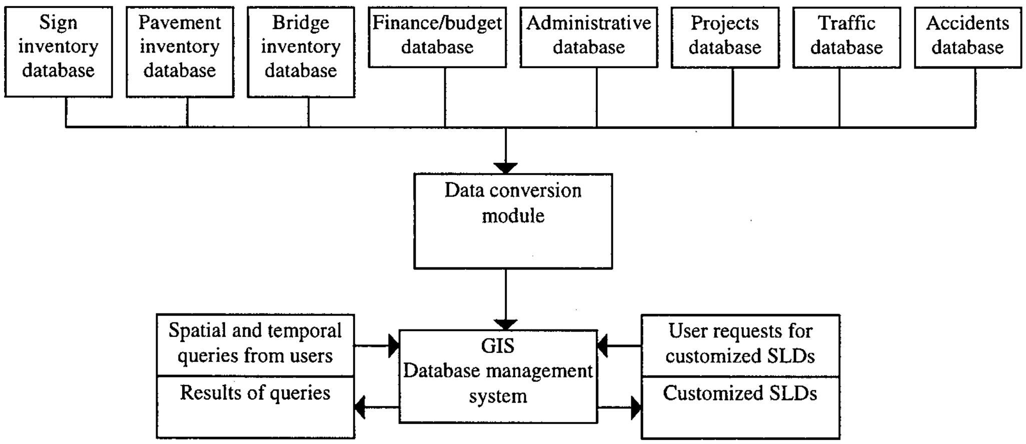

Figure 6. General procedure for production of SLDs from GISs.

simultaneous database access by many users. One advantage of distributing the inventory database is that each division maintains and updates a subset of the inventory database, which simplifies the overall operation. A disadvantage is the required coordination to standardize across divisions.

Providing the roadway inventory data in a centralized or distributed database and allowing users to access the database through the Internet should improve the individual and coordinated activities of different divisions and users who work with roadway inventory data. A user will be able to query the database for the required data and do one or more of the following:

- Download the data via file transfer protocol (FTP) procedures to the user's site and then present them using SLD, GIS, or visualization software,
- Perform remote visualizations, in which presentation processing tasks are done remotely and the final results are transmitted back to the user's site, or
- Present the data using World Wide Web visualization and GIS resources (Web-based GIS software is becoming more common).

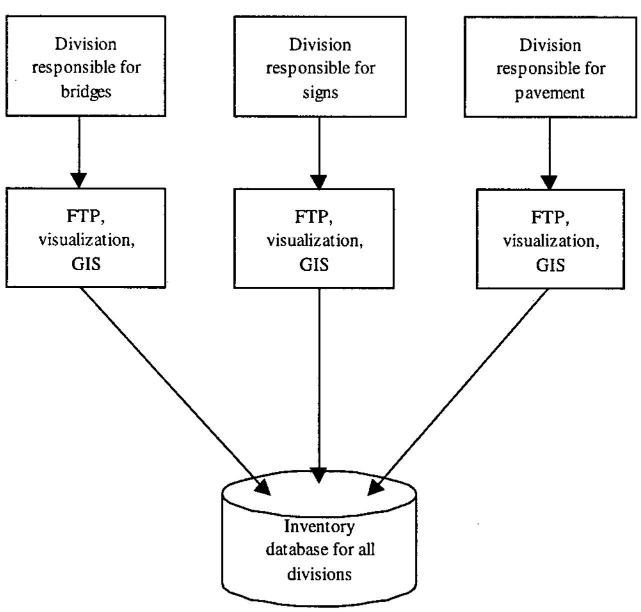

Figure 7. Centralized inventory database.

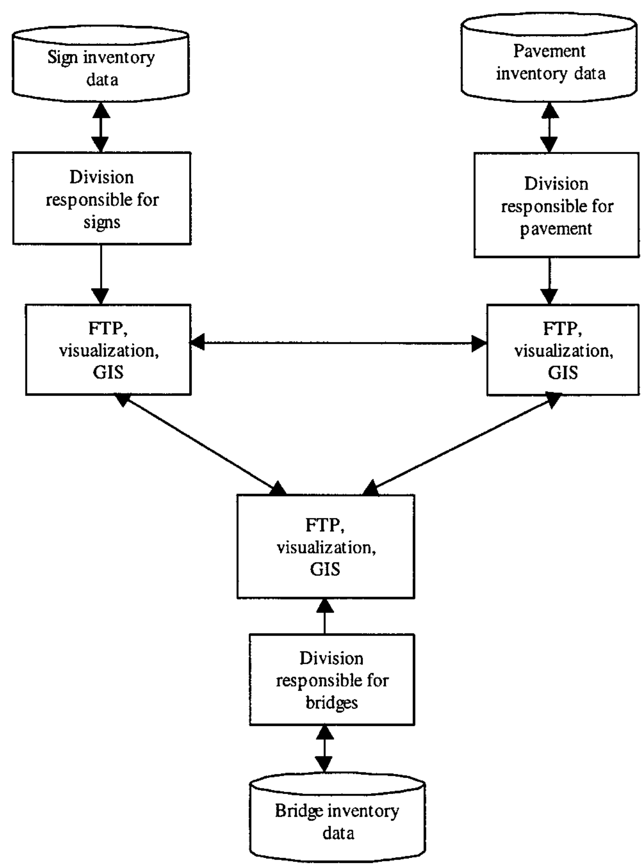

Figure 8. Distributed inventory database.

With advances in GIS and networking technologies, new GIS capabilities are becoming available on the Internet and through PC- and workstation-based GIS access to supercomputers (Karimi, 1996). Figures 9 and 10 show the transfer rates and times supported by available communication systems that are used to transfer roadway inventory data so they can be used for presentation. Figure 9 presents the bytes-per-second transfer rate of various systems, from slow modem (the slowest rate) through asynchronous transfer mode (ATM), the fastest rate. The difference between the slowest system and the fastest one is dramatic. Figure 10 presents the transfer times for some vector and raster files using various communication systems and bandwidths. GIS databases, such as the TIGER database produced by the U.S. Census Bureau*, are stored in vector format. Satellite images are stored in raster formats. The GISs available today are primarily vector-based but they are being improved to work with raster data as well. Figure 10 illustrates that it is not practical to use a modem for transferring GIS data because it takes an excessive amount of time to transfer both vector and raster data.

Despite the growing trend toward desktop computing (especially microcomputers) in public and private agencies, some state DOTs use mainframe computers and intend to continue providing inventory databases on them. Because of the large investments in mainframe computers by these DOTs, it is not financially feasible to replace them with desktop machines in a short time. Therefore, some state DOTs need to present roadway inventory data using mainframe computers. The Internet approach allows each division to use its own computing facility while having connectivity to other divisions' computing resources. For example, the mainframe in a state DOT could be used as the central storage for the inventory database, and divisions that have desktop or other computing machines could connect through the Internet to the mainframe. The available computing platforms must be taken into account when deciding to centralize or to distribute an inventory database.

The Internet approach for presenting roadway inventory data provides users with extended capabilities and a more flexible environment to work in. This approach allows users to present roadway inventory data using off-the-shelf or in-house SLD, visualization, or GIS tools. Also, users can have both local and remote access to the inventory database through the Internet or an intranet, and the database can be either centralized or distributed, depending on the agency's needs.

AUTOMATIC VEHICLE LOCATION SYSTEMS

Automatic vehicle location (AVL) systems provide navigation and route guidance information (Zaho, 1997; Karimi and Krakiwsky, 1988). These systems, particularly the GIS components of standalone AVL systems, may be adaptable for presenting roadway inventory data. Standalone AVL systems are used primarily in passenger cars for navigating in unfamiliar geographic areas or for finding optimal routes and include in-vehicle GISs. These GISs differ from off-the-shelf GISs in that they are used in custom computer hardware suitable for in-vehicle operation and that they need to operate in real time. In-vehicle AVL GISs provide limited, specialized functions but have fast algorithms that allow real-time operations. The displays are similar to those of SLDs and could easily be customized with inventory data. Because AVL systems are based on one or more positioning techniques (current systems are mostly based on the GPS) and use road network databases, they can be used for building inventory data collectors. Together with advances such as touch screens and voice synthesizers, an adapted AVL system could be a powerful way to present roadway inventory data in a vehicle in real time.

VIRTUAL REALITY

Virtual reality has been defined many ways as the technology has developed during the last few years. Landphair and Larsen (1996) offered a strict definition of virtual reality in their recent NCHRP synthesis on applications of 3-D and 4-D: "a suite of technologies which integrate real-time, full-motion, or stereographic imagery with other input/output devices that control all stimuli to the user." This strict definition implies input to the user and output from the user through seeing, hearing, and feeling. Helmets, gloves, and entire rooms with surrounding displays may allow this full immersion input and output.

One could use inventory data to help create this type of virtual reality presentation, but the hardware and scenario production would be costly and much other data would be needed. The research team has witnessed transportation applications in this type of virtual reality, including virtual neighborhoods and virtual airports. The hardware costs for immersion-type virtual reality presentations start at $100,000. The research team visited a company marketing a virtual reality dome within which 10 or more people could view 360-deg presentations (without helmets or gloves and with one operator controlling the view for all). The purchase cost for such a dome starts at $250,000. The production cost is primarily for the labor to create the scenes and sounds. Typical inventory data—from the list of representative data elements in Table 1 for example—would need to be supplemented by textures and colors for the entire highway and background and by many details not available in the inventory database. Even though production software has improved greatly in recent years, the creation of scenes from these data could take significant time per minute of presentation to the user.

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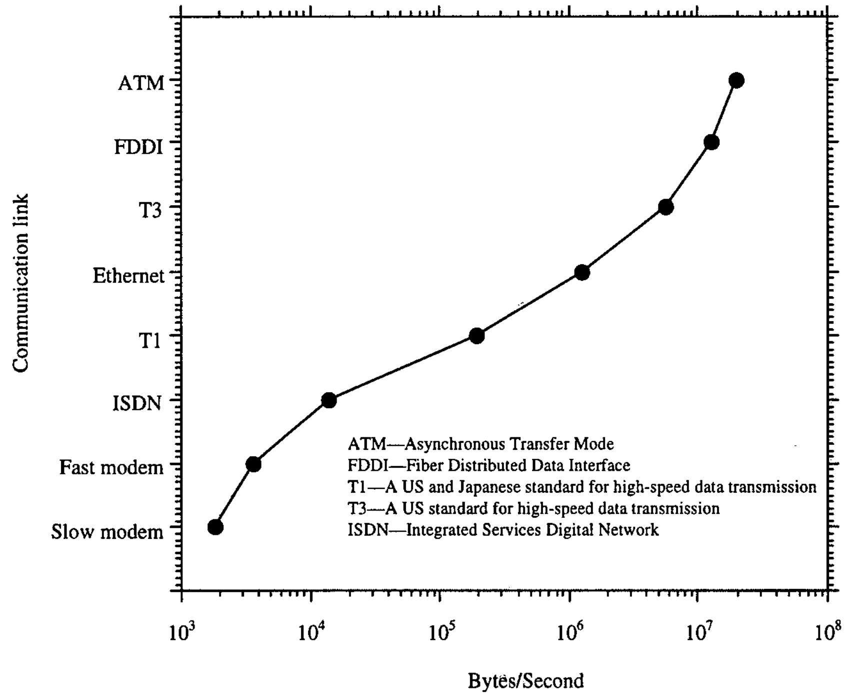


Figure 9. Data transfer rate for various communication systems.

In light of the high hardware and production costs, total-immersion virtual reality is unlikely to play a role in inventory data presentation any time soon. Landphair and Larsen (1996) state that "there is no evidence of any emerging use of virtual reality in transportation other than in the area of flight simulation and pilot training." Based on the literature review, contacts with state DOTs, and contacts with contractors in the inventory business, the research team agrees. Particularly for the presentation of roadway inventory at the network level (i.e., long stretches of basic highway data presented quickly), virtual reality as strictly defined is years away. At the project level (i.e., a detailed look at a single highway segment), agencies could use inventory data to begin to put together virtual reality presentations, but the high costs of doing so will discourage most agencies.

Some professionals use a less strict definition of virtual reality, which incorporates interactive scenes but does not necessarily present sound or touch and does not necessarily present realistic views. Some refer to this scaled-down virtual reality as a 4-D presentation. The hardware and production costs for this form of virtual reality are much lower. The hardware needed for many such presentations are simply good modern personal computers at $2,000 or so each. The software to create these types of presentations for small projects (i.e., no more than several city blocks) can cost as little as $100. The production time for such limited virtual reality is dramatically less than for full virtual reality, with useful scenarios for small projects sometimes requiring less than 1 hr.

Landphair and Larsen (1996) surveyed the state DOTs and a few other transportation agencies during preparation of their recent NCHRP synthesis. The survey yielded some interesting results on the uses of 3-D and 4-D presentations. All applications listed in their survey responses were at the project level rather than the network level. Assessing environmental impacts, assessing aesthetic impacts, and bridge design were the most common applications cited by the respondents. The respondents predominantly used 4-D rather than 3-D in those applications. Among the many qualities of 3-D and 4-D presentations judged about equally important were "high level of detail" and "ease of modeling alternatives" but judged less important were "realistic motion" and "control of the motion of other objects."

The low hardware and production costs for scaled-down virtual reality has allowed many transportation agencies to use these presentations. At the past few TRB Annual Meetings, and during TRB-sponsored conferences in 1995 and 1997, dozens of agencies have displayed such presentations. The Landphair and Larsen survey showed almost 50 percent of respondents using animation to some extent. (There may be some self-selection bias in this percentage, because agencies more interested in the topic would be more likely to return the survey form).

FHWA has been experimenting with limited virtual reality recently. The Advanced Research Unit of FHWA is conducting a project to create limited virtual reality presentations of the output of a traffic simulation program for two-lane rural roads. The FHWA staff members guiding the project believe

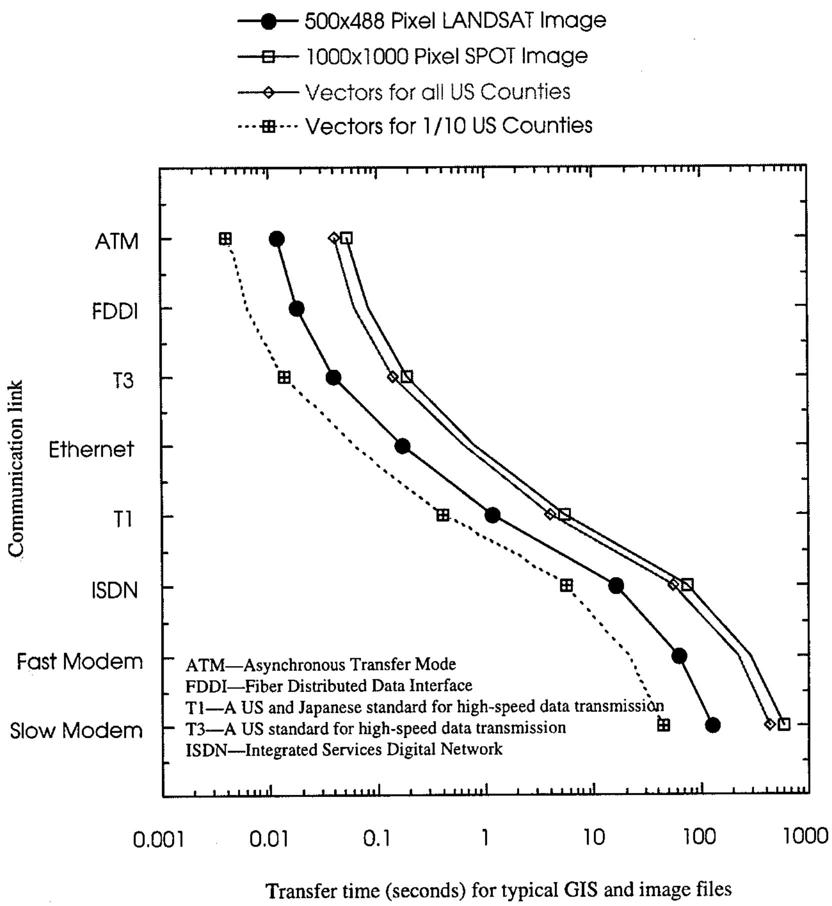


Figure 10. Transfer time for typical GIS and image files via various communication systems.

the ability to view fairly realistic scenes of traffic operations would help engineers spot and correct problems. The presentation to this point has been successful enough for this purpose, in the opinion of the FHWA staff, although the simulation program developers feel the presentation does not do their program justice. In fact, FHWA staff members interviewed by the research team emphasized that virtual reality presentations do not have to be totally realistic to be helpful to engineers and designers. The virtual reality presentation for the traffic simulation model used the model's built-in highway alignment but could have easily used standard highway inventory data. FHWA staff members expressed the opinion that standard inventory data could provide a useful backbone for limited virtual reality presentations but that the data would have to be supplemented for most projects by stereographic image displays or by detailed as-built plans in computer-aided design (CAD) files.

NON-ROADWAY DATA PRESENTATION

Non-roadway technologies applicable to the inventory presentation process center on ways to transmit, store, and display data more efficiently. Table 6 lists these technologies and briefly explains how each might be used in the data presentation process.

The research team's literature review and visits indicated that non-transportation agencies such as utilities inventory their systems much like highway agencies. For more details on specific non-roadway technologies used by various agencies the reader is referred to Vaidya et al., (1994), Fletcher (1996), Bourguignon et al., (1994), and Meehan (1994).

STATE DOT INVENTORY PRACTICES

Based on the trends that emerged from the telephone survey and the literature, the research team visited several state DOTs and other organizations involved with inventory data collection and presentation. Appendix C lists the organizations visited and the systems inspected at each site and provides brief remarks about the systems. Various data presentation systems were inspected. In the DOTs, some of the systems were developed in house; others were purchased from private vendors. In the other organizations, most of the systems were developed in house.

TABLE 6 Emerging non-roadway technologies applicable to inventory data presentation

Technology/product	Potential Application
Fiber optics	A reliable way to transmit information quickly; can efficiently link users across a wide network
Superconductors	Could allow extremely efficient data, processing, storage, and presentation when fully developed
Distributed computing	Further developments will allow better integration of databases and provide powerful computing capabilities to remote users
Advanced computers	Faster, more flexible processing and storage will allow real-time computing and computationally intensive operations like virtual reality
Optical data storage	Provides ability to store a large amount of inventory information in a small space; can store data, images, text and sound
Advanced video displays	High-definition video will allow for more accurate graphical interpretation and presentation of data; can aid in developing virtual reality presentations
VisionDome	180° visualization of surrounding roadway environment would allow groups of inventory users to see and evaluate data features together all at one time and in one place

State DOT Best Practices

The criteria for selecting state DOT best practices to highlight in this report included low cost, the ability of a system to answer a wide variety of queries, providing data to customers quickly, and unique equipment. The best practices identified in this section are current activities of state DOTs. These activities have moved beyond the research stage into production and have been proven in the field.

Table 7 summarizes the best DOT inventory presentation practices identified according to the criteria discussed above. Table 8 summarizes different DOT SLD productions. All of

TABLE 7 Summary of state DOT best practices

State DOT	Criterion	Practice	Data	Technologies	Improvements	Comments
New Jersey	Access to inventory data	SLD on a CD-ROM	Statewide roadway database	Object linking and Embedding (OLE) technology	Distribution on CD-ROM and integration with videolog imagery	On-line availability to users within the department who meet system requirements
Minnesota	Access to inventory data	GIS base map on a CD-ROM	GIS basemap	Workstation GIS	Distribution on CD-ROM	Basemap allows users to display and analyze data from different sources and in several location-reference systems
Washington	Access to inventory database	Image and georeference database	Image and State Highway Log data	DBMS with in-house developed software	Distribution on CD-ROM	On-line availability to users within the department
Colorado	System flexibility	A SLD program that incorporates traffic and accident data with roadway inventory data	Speed, no-passing zones, accident, roadway inventory	DBMS with in-house developed software	Accident diagrams for different locations	Integrating inventory data with an inventory of roadside obstacles and a database of accident reduction factors is its most unique feature
Louisiana	System flexibility	Multimedia highway sign database	Gas, food, lodging, and camping signs (logo signs) on interstate highways	Relational DBMS		Different types of reports may be generated by the system
Pennsylvania	Time required	Updating SLDs in real time	Existing roadway SLD database			Collection, update, and display in realtime

TABLE 8 Summary of state DOT SLD production information

State Highway Agency	Unit Responsible for SLDs	SLD Software	Databases Used	Remarks
Colorado DOT	Transportation Safety and Traffic Engineering	Developed in house	Roadway inventory, traffic, collision, special studies	Major characteristic is roadway safety
New Jersey DOT	Bureau of Transportation Data Development	Custom developed for NJ DOT by consultant	Roadway inventory data including GIS data	Based on client-server technology including a GIS
Pennsylvania DOT		Developed in house	State route, intersection and railroad, bridge maintenance	SLD database updated daily
Hawaii DOT	Planning Survey Section	Manual production	Highway photolog	SLD production is manual; update is based on information from a highway photolog

TABLE 9 Summary of state DOT GIS best practices

State Highway Agency	Unit Responsible for GIS	GIS Software	Databases Used	Remarks
Minnesota DOT	Cartographic Unit	Commercial	USGS 7.5 min. Quadrangles	Base map with several themes completed
New York DOT	Mapping and GIS section	Commercial	Flat roadway inventory files, traffic and crash data in DBMS	The DOT working toward enterprise wide GIS
Maryland State Highway Administration	GIS Team	Commercial	Highway inventory, traffic, crash, pavement and bridge management	The agency working toward adoption of enterprise wide GIS
Florida DOT	Central Office	Commercial	Five-year work program	Eight districts perform various GIS-related operations

the SLDs are produced by methods developed in house and the production complexity varies among the agencies. Table 9 summarizes some of the best GIS practices among the DOTs. All DOTs mentioned in Table 9 use commercially available GIS packages. The best practices identified in this report should be transferable to other state DOTs to some extent, although different political and economic conditions will play a role in the transfer. There may be perfectly valid reasons for a state DOT to keep performing some inventory tasks the same way, rather than switching to one of these best practices.

CHAPTER 4

EVALUATION OF PHOTOGRAMMETRIC DIGITAL IMAGERY

This chapter describes the methods used for and the results obtained in evaluating photogrammetric digital imagery. It contains sections describing the criteria used for selecting emerging technologies, the accuracy performance of digital image capture systems reported in the literature, the methodology employed to evaluate systems during this project, and the results of the evaluation. The chapter ends with description of a protocol for future use by state DOTs and companies in evaluating photogrammetric digital imagery.

CRITERIA TO SELECT EMERGING TECHNOLOGIES

The research team used six criteria to select emerging technologies for in-depth investigation:

1. The technology must have advanced to the point where it can be field-tested. There must be an existing prototype to test. Although the research team expected to make small method or process improvements for testing, it was not within the project scope to fabricate complete new devices, write significant sections of computer code, or otherwise make major improvements.
2. The improvement must be currently unavailable to the general state DOT market.
3. The improvement must have a reasonable chance to reach the general state DOT market in the next 5 years. This time frame is consistent with the previous definition of an "emerging" technology. Beyond 5 years, new generations of computing equipment, new political and institutional climates, new vehicle technologies, or other "megatrends" could drastically change the roadway inventory process as it is now known.
4. The technology should be able to address a wide range of inventory data elements.
5. The improvement should have the potential for significant cost savings over current methods of delivering data to decisionmakers.
6. The improvement should have the potential for significant enhancement of the accuracy of information delivered to decisionmakers. The accuracy of the information being delivered, not simply collected, is what matters here.

Table 10 shows the matrix used for choosing which emerging technologies to evaluate in depth during the project. The first column on the left side of the table shows the collection and presentation technologies, most of which were addressed previously. The top row of the table contains the six criteria given above. This table does not include any non-roadway technologies because the research team believes that such technologies will cause incremental improvements in inventory collection and presentation but will not result in entirely new products. After considering all applicable existing and emerging technologies for state DOTs, the research team identified four as the most promising technologies and investigated them (item 2 below combines two of them):

1. Data collection: digital image capture (onboard a van);
2. Data collection: satellite technology, including satellite digital image processing; and
3. Data presentation: using a GIS for presentation and analysis of roadway inventory data, especially for SLD production.

Figure 11 shows where the technologies selected for in-depth investigation fit within the general inventory process.

A fifth strong possibility for in-depth investigation, AVL systems, was rejected because a field test was not possible within the time frame of this project. A sixth, virtual reality systems, was not chosen because it will probably be viable only beyond the 5-year horizon. Virtual reality is in use at FHWA and in some state DOTs, but primarily at the project level. The seventh strong possibility, automatic image processing, was eliminated because (1) it might not be marketable within 5 years and (2) it lacks a prototype for most common inventory data elements, so a field test was not possible.

In the rest of this chapter, evaluation of photogrammetric digital imagery and the results of tests conducted on this technology are discussed. The other items, from the above list, are discussed in subsequent chapters.

TABLE 10 Potential technologies for in-depth investigation

	Phase 2 selection criteria					
Collection or presentation technology	Is field test possible?	Currently available?	Marketable within five years?	Able to address how many data elements?	Potential cost savings?	Potential accuracy improvements?
Data Collection						
Mode of Transport						
Backpack	Yes	Yes	Yes	Some	Medium	Medium
Van	Yes	Yes	Yes	Many	High	High
Satellite	Yes, limited	Improved version, no	Yes	Some	High	High
Georeferencing technologies						
GPS	Yes	Yes	Yes	Many	High	Medium
DGPS	Yes	Yes	Yes	Many	Medium	High
INS	Yes	Yes	Yes	Many	Medium	High
Map matching	Yes	Yes	Yes	Some	Medium	Medium
Laser range finders	Yes	Yes	Yes	Some	Medium	Medium
Descriptive technologies						
Voice recognition	Yes	Yes	Yes	Many	Medium	Medium
Digital image capture	Yes	Improved versions, no	Yes	Many	Medium	Medium
Image point-and-click	Yes	Yes	Yes	Some	Medium	High
Satellite digital image processing	Yes, but may be limited	Improved versions, no	Yes	Some	High	High
Scanning forms (optical character recognition)	Yes	Yes	Yes	Many	Medium	Medium
Keying data using hand-held computers	Yes	Yes	Yes	Many	Medium	Medium
Bar code reader	Yes	Yes	Yes	Some	Medium	High
Radio frequency identification	Yes	Yes	Yes	Some	Medium	High
Data Presentation						
GISs	Yes	Yes	Yes	All	High	High
Database management systems	Yes	Yes	Yes	All	High	High
Intranet/Internets	Yes	No	Yes	All	High	High
Collection or presentation technology	Is field test possible?	Currently available?	Marketable within five years?	Able to address how many data elements?	Potential cost savings?	Potential accuracy improvements?
Virtual reality	Yes	No	Possibly	Many	Medium	Medium
Real-time SLD generation	Yes	Yes	Yes	Many	Medium	Medium
Video log software	Yes	Yes	Yes	Some	Medium	Medium
Automatic vehicle location systems	No	No	Yes	Many	Medium	Medium

DIGITAL IMAGE CAPTURE—ACCURACY PERFORMANCE*

This section presents a review of the accuracy performance of inventory obtained from various digital image capture technologies (usually on board a van). Existing literature provides information on several tests of the georeference accuracy of such data. Table 11 summarizes those tests. Using a van system developed at the Ohio State University Mapping Center, Coetsee et al. (1994) simulated the loss and reacquisition of the GPS signal and reported the georeference accuracy of data obtained from digital images between 1 and 3 m. In another research effort, researchers at the Ohio State University Mapping Center reported georeference accuracy of 1.50 m (Clark County Mapping Project, 1994). Vaidya et al. (1994) reported on the use of a van system for collection of railroad track data. The authors of all these studies reported sub-meter georeference accuracy for the track centerlines.

In a test sponsored by the FHWA, Whited and Kadolph (1995) reported accuracy of georeference data obtained by a van system within 1.50 m of the true value. They also reported gathering 75 percent of the data elements needed for a sign inventory by viewing high-resolution images. According to Shaw and Guthrie (1997), locational data obtained by a van system were of sufficient accuracy for the Michigan DOT inventory. Schwarz and El-Sheimy (1997) reported sub-meter georeference accuracy when they compared data obtained by a van system to ground truth data. Finally, Novak and Nimz (1997) reported on the georeference accuracy of data obtained by a van system—according to the authors, the accuracy of measurements made on different objects was 0.30 to 0.60 m. This accuracy varied with the distance of the object from the

* The use of a specific brand and/or company name is purely illustrative and not an NCHRP endorsement of the item mentioned.

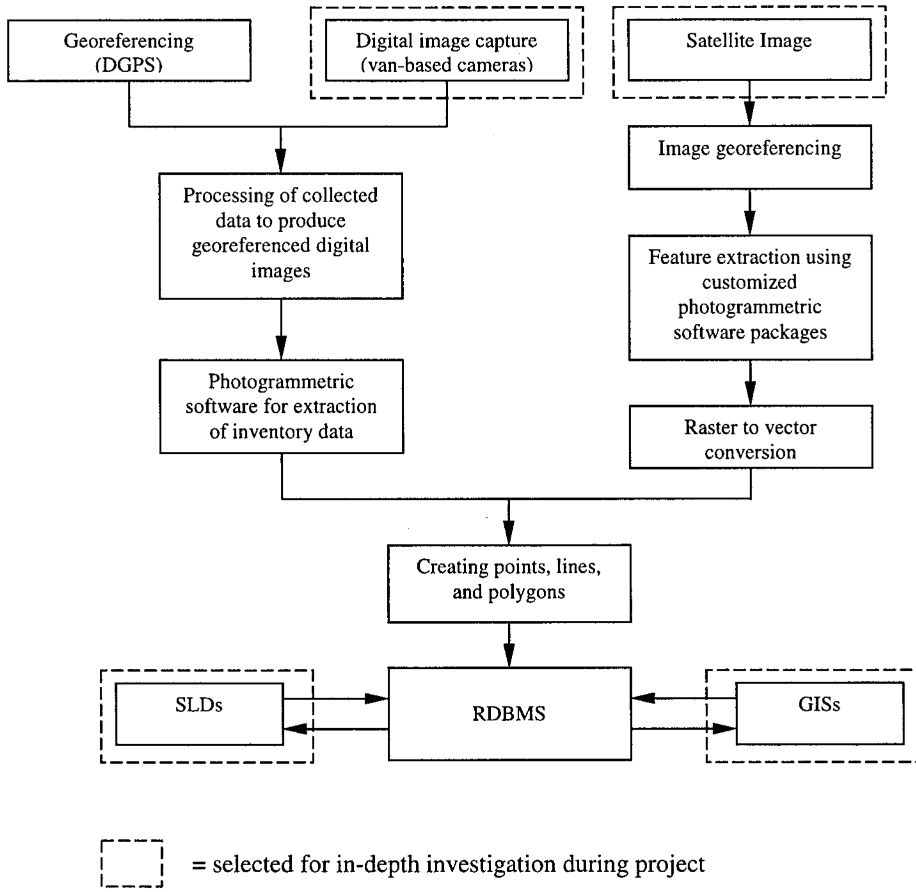


Figure 11. Technologies identified for in-depth investigation within the general inventory process.

camera. They did not provide any information on inventory elements measured or the data collection methodology.

Different researchers reported on accuracy tests of curve and grade data. Using a van system developed by the Michigan DOT featuring an INS, Miller (1993) reported that the curve and grade data accuracy satisfied the FHWA's inventory data reporting requirements. Roadware Corporation, using the ARAN van system, reported on the accuracy of cross slope data by comparing them with manually obtained data (Roadware Corp., 1995). Roadware's results indicate highly accurate cross slope data for both the right and left lanes of a two-lane roadway.

TABLE 11 Summary of georeference accuracy tests on data collected by van systems

Author	Van System	Methodology	Findings
Coetsee et al., 1994	Ohio State University Mapping Center van	Simulation testing	Georeference accuracy 1 - 3 meters
Clark County Project, 1994	Transmap van	Unreported	Georeference accuracy within 1.5 meters
Vaidya et al., 1994	Transmap van	Evaluation of railroad track centerline by using DOD Track and Garrison data	Georeference accuracy within 3 meters
Whited & Kadolph, 1995	Iowa DOT van supplied by Mandli Communications	Comparison of van geodata with USGS 7.5 min. quad maps	Georeference accuracy within 1.5 meters
Shaw & Guthrie, 1997	GeoResearch van	Comparison with Michigan High Accuracy Reference Network (HARN)	Georeference accuracy within 3.9 meters
Schwarz and El-Sheimy, 1997	VISAT van	Comparison with ground truth	Sub-meter georeference accuracy
Novak and Nimz, 1997	Transmap van	Unreported	Georeference accuracy 0.3 - 0.6 meters

The Highway Safety Research Center (HSRC) at the University of North Carolina at Chapel Hill conducted a comparative study of horizontal curve data obtained from the ARAN van system (Harkey, 1997). The comparison was of horizontal curve data obtained by the van system with data obtained from as-built drawings. According to the study report, the horizontal curve data obtained from the van system were neither accurate nor consistent with data from as-built drawings. A limitation of the study, recognized by Harkey, was reliance on data from as-built drawings for the comparison. This was a limitation because of the possibility of discrepancies between as-built drawings and ground truth. Furthermore, Harkey indicated that the problem of inaccuracy and non-consistency stemmed from the algorithm used for calculations of the curve and grade data and not from the raw data.

Finally, Drakopoulos and Ornek (1999) reported on the collection of curve length and radius data using the Wisconsin DOT's van system. Their results indicate reliable measurements for curves with lengths greater than 300 m. The reliability of measurements of shorter curves was affected by the distance between successive data collection points by the van system, however. The study relied on as-built drawings for verification of the van data accuracy, which was a limitation as noted above.

The literature provides relatively little information on the accuracy of descriptive data elements obtained from digital images. Table 12 summarizes the studies on extraction of measurements from digital images. In a comparative study of data obtained by a van system and ground truth observations, Lee et al. (1991) concluded that the data obtained by the van system was of "reasonable" accuracy. Table 13 shows the results reported by Lee et al. The conclusion of Lee et al. was not based on any statistical analysis of the data (perhaps because of the limited number of observations) and they did not define "reasonable" accuracy. The photogrammetric software package (Microscience SIS) used in the study is no longer available.

Mastandrea et al. (1995) reported on a test of descriptive data accuracy using the Surveyor™ photogrammetric software package (from the Roadware Corporation). According to Mastandrea et al., the accuracy of measurements on offsets, widths, and heights of inventory elements was between 5 to 10 cm. They did not report on the data elements used in the evaluation or the evaluation methodology used in the study and did not provide any details on the evaluation test, sample data, or statistical analysis.

El-Sheimy (1996) reported on the accuracy of data obtained by the VISAT van system by comparing lengths of inventory elements with ground truth. According to El-Sheimy, errors in digital measurements increased with increasing distance between the object and the van. The error reached a magnitude of 5 to 15 cm for objects 33 m directly in front of the camera. The test areas included rural areas, urban centers with narrow roads, and minor and major highways. However, there is no information on the identity and size of the measured inventory elements or on the number of observations made on the elements. Without such information, it is not possible to judge if the accuracy of the digital measurements varies with the type and size of the inventory element.

Roadware Corporation reported on the accuracy of crack identification and classification (Roadware Corp., 1994) using the ARAN van. The test indicated comparable crack identification with the long-term pavement performance (LTPP) procedure developed by the Strategic Highway Research Program (SHRP). However, there was no similarity in crack classification (e.g., block, fatigue, transverse, longitudinal wheelpath, and edge) between the two methods. In another test, Roadware Corporation showed that their system was able to automatically classify collected data on pavement cracks into the LTPP categories (Roadware Corp., 1996). However, there was no information on whether or not the classification was correct.

EVALUATION METHODOLOGY FOR DESCRIPTIVE DATA

Accuracy Assessment*

The research team focused on the accuracy of descriptive data obtained from digital image capture technologies because the literature indicated that the georeference accuracy from such systems was sufficiently high for roadway inventory purposes. The descriptive data accuracy assessment involved comparing descriptive data obtained from various digital image capture technologies with data collected by a commonly used method. This section presents an overview of the research hypotheses and the research methodology for the descriptive data accuracy assessments. A detailed description of the research methodology is provided in Appendix D.

In this research, the different methods of data collection investigated included the following:

- The manual method—the method commonly used by many DOTs, in which a staff person riding in a van records estimates on paper, with a DMI displaying georeferences.
- The Lambda method—a van system from Lambda Technologies, International, employing a combination of DGPS, INS, DMI, and digital image capture technologies.
- The MSI method—a van system from Measurement Science, Inc., using a combination of DGPS, INS, DMI, and digital image capture technologies.
- The Mandli method—a van system from Mandli Communications, Inc., equipped with DGPS, INS, DMI, and digital image capture technologies.

* The use of a specific brand and/or company name is purely illustrative and not an NCHRP endorsement of the item mentioned.

TABLE 12 Summary of tests on accuracy of extracted descriptive data from digital images

Author	Photogrammetric Software	Inventory Element	Roadway Environment	Reported Accuracy
Lee et al., 1991	Pavedex / Microscience SIS	Sign size and height	Unreported	"Reasonable"
Mastandrea et al., 1995	Roadware / Surveyor	Offset, width, and height of various objects	Unreported	5 - 10 cms
El-Sheimy, 1996	VISAT station	Unreported	Rural and urban	10 – 15 cms

- The ConnDOT method—a van system (developed by Roadware Corporation and owned by the Connecticut DOT) equipped with DGPS, INS, DMI, and digital image capture technologies.

Although the latter four methods employ similar technologies, differences in integration of those technologies, software routines, input requirements, and other characteristics preclude treating them as one method of data collection. Thus, these four represent four different data collection methods each using digital image capture technologies. A technical overview of each of the four data collection methods employing digital image capture technologies is included in Appendix D. Four comparisons were designed; in each comparison, one of the data collection methods employing digital image capture technology was compared with the manual data collection method. The comparisons required collection of ground truth data to assess the accuracy of each collection method. The ground truth represents the true dimensions of an inventory element. Thus, comparing data collected by a particular method with the ground truth data reveals the accuracy of that collection method. During each experiment, data were collected in three different roadway environments: two-lane rural, interstate, and urban. Appendix D provides details on why these choices were made.

Because of the rapid change in technology, it is expected that van systems employing digital image capture technologies will change in the near future and that the usefulness of any evaluation will be short-lived. Roadway agencies may need to evaluate new data collection methods or re-evaluate previously tested data collection methods because of changes in the technologies employed in those methods. A testing protocol is therefore needed to ensure that future evaluations are conducted consistently and accurately. The procedure followed in this project for the evaluation of the different data collection methods forms the base for the testing protocol that will enable roadway agencies and vendors to evaluate data collection methods in a standardized way.

DATA ANALYSIS

The research team collected inventory data by the different methods on three different types of roadways at four different locations. Using the Lambda and the manual methods, data were collected in Milwaukee, Wisconsin. Using the MSI and the manual methods, data were collected in Denver, Colorado. Using the Mandli and the manual methods, data were collected in Madison, Wisconsin. Data were collected in Rocky Hill, Connecticut, using the ConnDOT and the manual methods.

The research team defined percent measurement error (PME) as the main measure of effectiveness for the accuracy of digital and manual data. The PME for a data element collected by a digital image capture system is given by

$$\text{PME} = [(\text{Digital observation} - \text{Ground truth})/\text{Ground truth}] * 100$$

where:

Digital observation = data collected by the digital image capture system, and

TABLE 13 Other tests on data collected by van systems

Author	Van System	Research Issue	Methodology	Findings
Miller, 1993	Michigan DOT van	Curve and grade data accuracy	Field data collection using the van	Curve and grade data satisfies FHWA's reporting requirements
Harkey, 1997	Roadware ARAN van	Horizontal curve data	Comparison with as-built drawings	Horizontal curve data neither accurate nor consistent
Roadware Corp., 1995	Roadware ARAN van	Cross slope	Comparison with manual observations	Mean difference of 0.189 % and 0.143% for left and right lanes
Roadware Corp., 1994	Roadware ARAN van	Pavement crack detection	Comparison with manual observations	Comparable crack identification with manual observations
Roadware Corp., 1996	Roadware ARAN van	Pavement distress classification	Field data collection using the van	Distress classification according to the LTPP criteria possible

Ground truth = direct observation of the inventory element using measuring tape, measuring wheel, or slope meter.

The PME for the manual method can be calculated by substituting the manual observation in place of the digital observation in the above equation.

Analysis of Milwaukee Data

Figure 12 shows a sample digital image captured by the Lambda method. Tables 14 and 15 summarize the data collected in Milwaukee, Wisconsin. Table 15 shows that, overall, the manual method was slightly more accurate than the Lambda method. The manual method also provided data that were slightly less scattered, as measured by the standard error, than the Lambda method (about 95 percent of all PME values fall within two standard errors of the mean PME). Investigation of the main effects (i.e., measurement method, roadway environment, and inventory element type) and their interactions was undertaken by using analysis of variance (ANOVA). The research team decided to use the ANOVA because it provides information on the interactions between various methods. Because ANOVA is based on comparison of means of the different levels of main effects, empty data cells such as those in Table 15 result in erroneous calculations (Neter et al., 1990; Devore, 1991). A statistically appropriate approach to correct such a problem is to drop the factors with missing levels from the ANOVA. These elements were sideslope, barrier height, driveway width, and street light spacing. A discussion of the ANOVA results follows.

Main Effects

Table 16 presents the ANOVA results for the Lambda and the manual data collection methods. All three main effects were statistically significant (at the 0.05 level). However, a conclusion regarding significant differences in the means cannot be reached because of the significance of the interaction effects (see below).

Interaction Effects

Table 16 shows the results pertaining to the interactions among the three main factors. All three two-way interactions were statistically significant. The significance of the three-way interactions among method of data collection, roadway environment, and inventory element type indicates that one should look at the individual levels of each of the three main effects for differences in the means.

Figure 13 compares PME for the Lambda and manual methods on the two-lane rural environment for the different

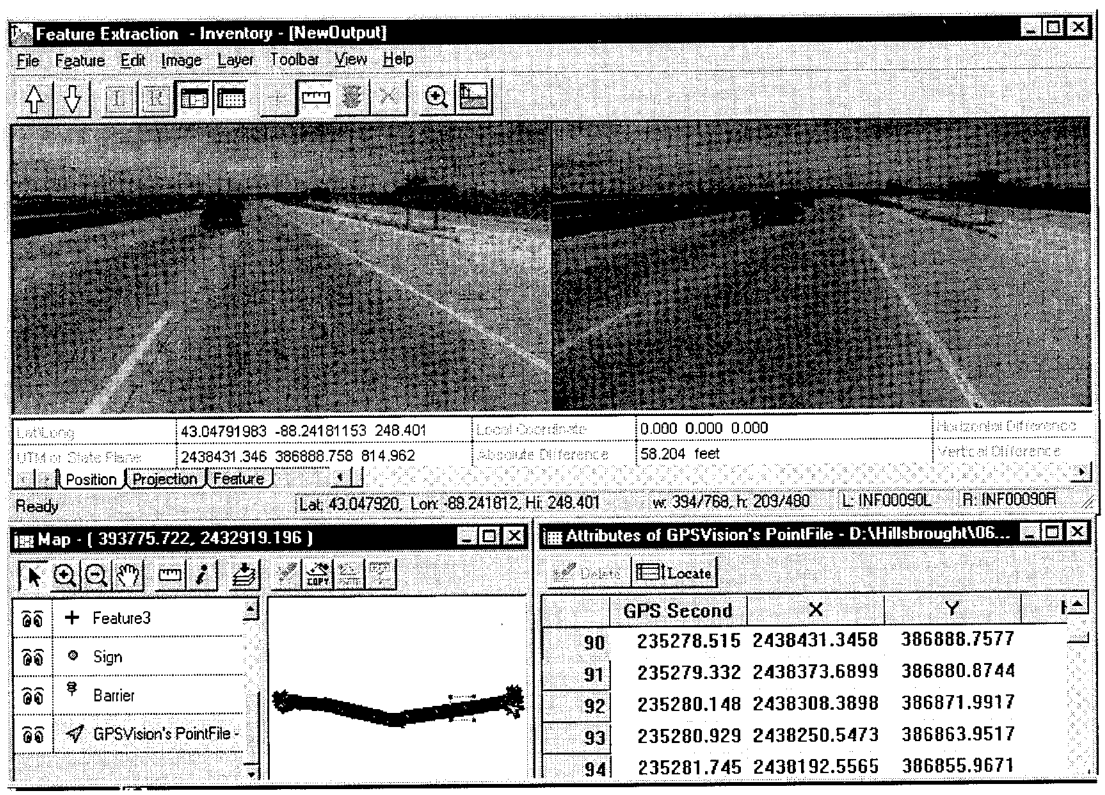


Figure 12. Extraction of data from digital images collected by the Lambda van.

TABLE 14 A summary of data collected in Milwaukee, Wisconsin

Roadway	Roadway Environment	Test Section Length (km)	Data Detail	Inventory Element: Lane width (m)	Sideslope (degrees)	Barrier height (m)	Driveway width (m)	St. light spacing (m)	Traffic sign: Width (m)	Traffic sign: Height (m)	Traffic sign: Support height (m)	Traffic sign: Lateral placement (m)	Total Number of Obs. by Each Method
Pewaukee Road	Two-lane rural	8.0	No. of obs. by each method	17	16	6	9	-	6	6	16	17	93
			Manual method mean	3.35	9.25	0.76	22.69	-	0.49	1.01	1.94	4.41	
			Lambda method mean	3.65	10.83	0.73	18.01	-	0.67	0.90	1.62	3.90	
			Ground truth mean	3.64	12.18	0.71	19.84	-	0.45	0.91	1.66	3.58	
I-94 and US Route 16	Rural interstate	31.4	No. of obs. by each method	35	27	15	-	-	10	7	31	31	156
			Manual method mean	3.70	8.48	0.84	-	-	2.07	1.39	2.24	5.36	
			Lambda method mean	3.58	7.70	0.82	-	-	2.88	1.40	2.42	6.60	
			Ground truth mean	3.60	9.90	0.89	-	-	2.79	1.48	2.16	6.12	
Moreland Street	Urban	7.2	No. of obs. by each method	18	-	-	14	13	6	6	20	17	94
			Manual method mean	5.06	-	-	9.47	39.39	0.58	0.99	2.0	0.60	
			Lambda method mean	6.42	-	-	8.54	28.38	0.65	1.04	2.11	0.96	
			Ground truth mean	6.48	-	-	8.78	28.81	0.56	1.02	2.16	0.81	
Total Number of Obs. by Each Method				70	43	21	23	13	22	19	67	65	**343**

Note: Measurements reported in meters were originally recorded in feet/inches

- indicates not applicable

inventory elements. Paired t-tests (at the 0.05 level) among the different inventory elements indicate that the Lambda method of data collection provided more accurate data for lane width, sign support height, and driveway width. The differences in the measurement of other inventory elements were statistically not significant.

Figure 14 compares PME for the Lambda and manual methods on the interstate environment for the different inventory elements. Paired t-tests indicate that, in comparison with the manual method of data collection, the Lambda method provided statistically more accurate data for lane width and sign width (at 0.05 level). The manual method

TABLE 15 A summary of PME values for data collected in Milwaukee, Wisconsin

Roadway	Roadway Environment	Data Collection Method	Inventory Element Mean PME (Standard Error of the PME Mean): Lane Width	Sideslope	Barrier Height	Driveway Width	St. light spacing	Traffic Sign: Width	Traffic Sign: Height	Traffic Sign: Support height	Traffic Sign: Lateral placement	Total
Pewaukee Road	Two-lane rural	Manual	-5.71 (2.80)	-15.23 (8.04)	18.96 (21.29)	15.48 (8.58)	-	12.50 (5.59)	12.99 (11.27)	17.36 (3.21)	38.85 (23.05)	10.78 (5.05)
		Lambda	0.75 (1.54)	-13.83 (28.47)	5.02 (8.84)	-10.41 (5.20)	-	38.58 (16.70)	-1.51 (1.77)	-1.95 (1.96)	10.35 (3.4)	1.02 (5.15)
I-94 and Route 16	Rural interstate	Manual	2.98 (0.98)	-6.89 (6.82)	-2.66 (2.24)	-	-	-22.33 (4.30)	-5.71 (4.41)	5.61 (2.91)	-5.56 (4.70)	-2.45 (1.74)
		Lambda	-0.30 (1.12)	-19.90 (5.46)	-1.17 (6.03)	-	-	8.49 (4.19)	-4.95 (4.10)	8.85 (9.69)	6.97 (1.58)	-0.15 (2.38)
Moreland Street	Urban	Manual	-18.92 (2.37)	-	-	16.80 (8.50)	36.22 ()	4.16 (4.16)	-1.71 (6.66)	-5.28 (4.31)	-15.84 (10.09)	0.05 (3.12)
		Lambda	-1.32 (1.69)	-	-	-2.40 (2.82)	-0.47 (3.63)	16.87 (5.30)	2.43 (2.53)	-2.17 (1.47)	38.18 (18.14)	6.99 (3.67)
Total Manual			-4.76	-9.93	3.51	16.29	36.22	-5.60	1.45	5.16	3.36	1.82
Total Lambda			-0.31	-17.64	0.59	-5.54	-0.47	18.98	-1.53	2.98	16.01	2.12

Note: - indicates not applicable

TABLE 16 ANOVA results for data collected in Milwaukee, Wisconsin

Dependent Variable: PME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	29	87918.27662570	3031.66471123	3.27	0.0001
Error	456	423337.12913830	928.37089723		
Corrected Total	485	511255.40576399			

R-Square	C.V.	Root MSE	PME Mean
0.171965	849.1958	30.46917946	3.58800412

Source	DF	Type III SS	Mean Square	F Value	Pr > F
METHOD	1	4163.26834799	4163.26834799	4.48	0.0347
ENVIRON	2	10241.47404018	5120.73702009	5.52	0.0043
METHOD*ENVIRON	2	7409.51090688	3704.75545344	3.99	0.0191
ELEMENT	4	17451.37797549	4362.84449387	4.70	0.0010
METHOD*ELEMENT	4	8555.79431646	2138.94857911	2.30	0.0576
ENVIRON*ELEMENT	8	18747.36348352	2343.42043544	2.52	0.0108
METHOD*ENVIRON*ELEMENT	8	20087.54868583	2510.94358573	2.70	0.0064

Class Level Information

Class	Levels	Values
METHOD	2	DIGITAL MANUAL
ENVIRON	3	URBAN INTERST TWOLANE
ELEMENT	5	LANEWID LAT_PLAC SUP_LENG S_HEIGHT S_WIDTH

Number of observations in data set = 486

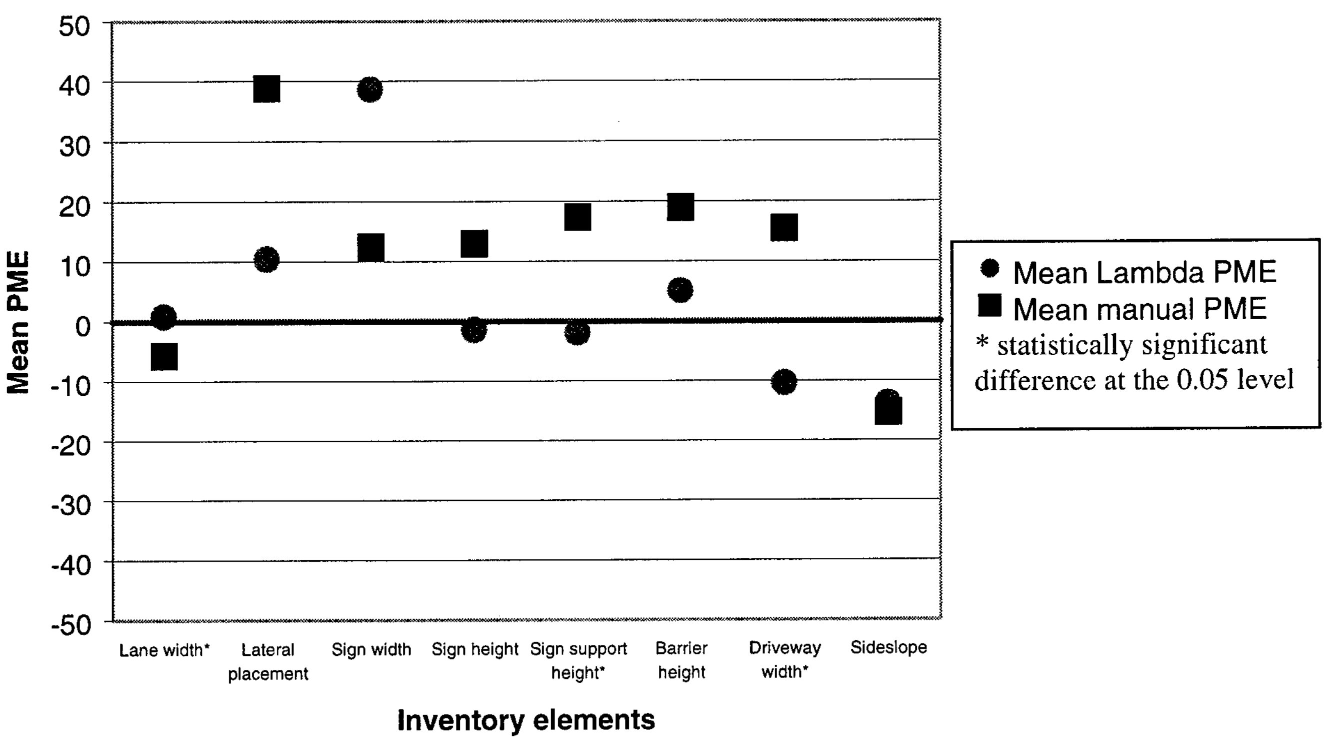


Figure 13. Comparison of mean PME values, two-lane environment, Milwaukee, Wisconsin.

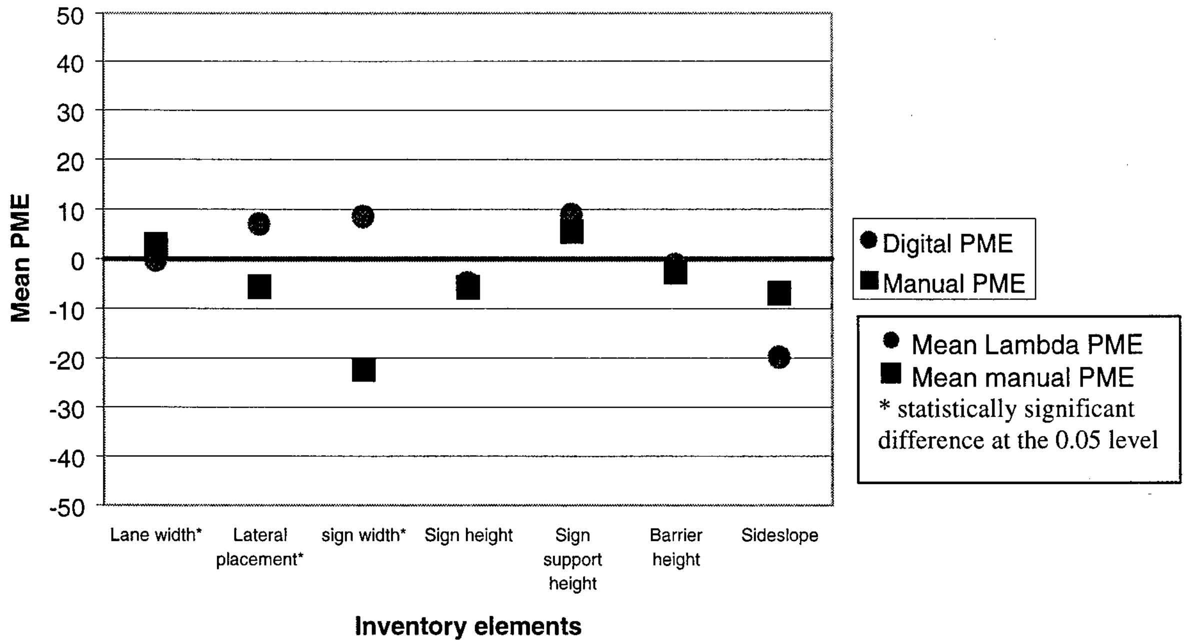


Figure 14. Comparison of mean PME values, interstate environment, Milwaukee, Wisconsin.

provided statistically more accurate data for the lateral placement of signs. Differences across data collection method for the other elements were statistically not significant.

Figure 15 indicates that in urban conditions the Lambda method outperformed the manual method in the measurement of lane width, streetlight spacing, and driveway width. The manual method performed better for sign width and sign support height.

Overall Findings from Milwaukee Data

The data collected in Milwaukee, Wisconsin, showed that the Lambda and the manual methods of data collection varied in accuracy across different roadway environments and across different inventory elements. The Lambda method of data collection provided data that were more accurate for a greater number of inventory elements under all roadway

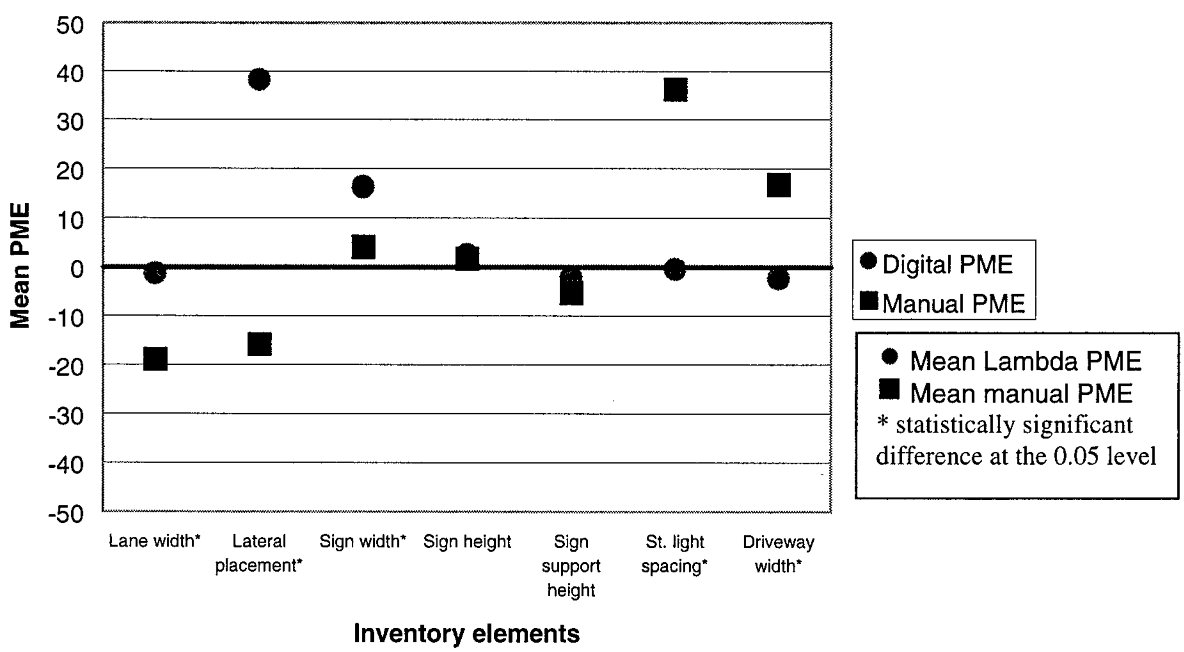


Figure 15. Comparison of mean PME values, urban environment, Milwaukee, Wisconsin.

environments. This method of data collection provided more accurate results for lane width, sign support height, and driveway width in the two-lane rural environment, for lane width and sign width in the interstate environment, and for lane width, driveway width, and streetlight spacing in the urban environment. The manual method of data collection provided more accurate results for lateral placement of signs in both the interstate and the urban environments and for sign width in the urban environment. Overall, the Lambda data collection method performed better than the manual method for a greater number of inventory elements.

Analysis of Denver Data

Figure 16 shows a sample digital image captured by the MSI method. Tables 17 and 18 summarize the data collected in Denver. Table 18 reveals that, overall, the manual method was slightly more accurate than the MSI method and that there was very little difference in the scatter of the data between the two methods as measured by the standard errors. Table 19 presents the ANOVA results for these data. Factors with empty cells were again excluded from the ANOVA.

Main Effects

The three main effects and their interactions were tested for their effects on the accuracy of the two methods. The type of inventory element was statistically significant, indicating that the accuracy of measurements depended on the type of inventory element collected. The method of data collection was also statistically significant. However, because of the significance of the interaction between the method of collection and the environment, nothing can be conclusively said about its effect on PME.

Interaction Effects

Only the interaction between the method of data collection and roadway environment was statistically significant, indicating the need to examine these two factors closely. Figure 17 presents the variation in mean values of PME between the MSI and manual methods across the three roadway environments. Data collected by the MSI method in the two-lane and the interstate environments were more accurate whereas the manual method produced more accurate data in the urban

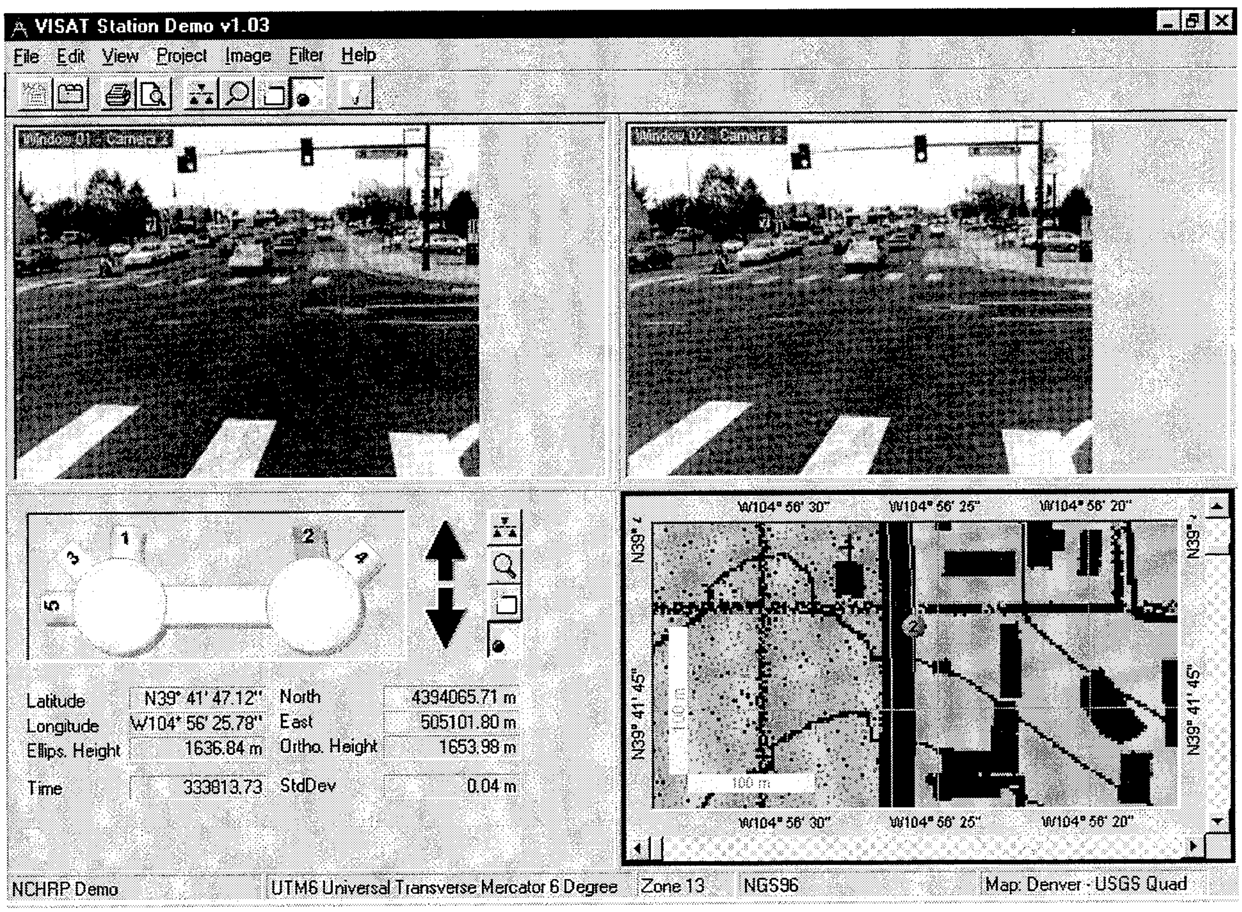


Figure 16. Extraction of data from digital images captured by the MSI van.

TABLE 17 A summary of data collected in Denver, Colorado

Roadway	Roadway Environment	Test Section Length (km)	Data Detail	Inventory Element									Total Number of Obs. by Each Method
									Traffic sign				
				Lane width (m)	Sideslope (degrees)	Barrier height (m)	Driveway width (m)	St. light spacing (m)	Width (m)	Height (m)	Support height (m)	Lateral placement (m)	
Colorado Route 86	Two-lane rural	17.4	No. of Obs. by each method	13	7	6	10	-	7	7	13	10	73
			Manual method mean	3.47	6.0	0.71	11.43	-	1.52	1.05	2.24	6.12	
			MSI method mean	3.54	7.83	0.73	16.51	-	1.47	1.02	2.05	6.41	
			Ground truth mean	3.61	8.85	0.65	16.47	-	1.52	0.92	2.04	5.70	
I-25	Rural interstate	25.0	No. of Obs. by each method	16	12	9	-	-	11	11	18	18	95
			Manual method mean	3.66	11.66	0.68	-	-	2.30	2.31	2.04	7.36	
			MSI method mean	3.60	7.81	0.70	-	-	2.34	2.23	2.12	7.87	
			Ground truth mean	3.70	9.41	0.68	-	-	2.29	2.19	2.03	7.27	
Colorado Blvd.	Urban	8.5	No. of obs. by each method	12	-	-	15	11	8	7	14	12	79
			Manual method mean	4.67	-	-	13.71	63.74	0.83	1.17	2.10	1.54	
			MSI method mean	4.80	-	-	11.10	60.12	0.93	1.33	2.46	1.77	
			Ground truth mean	4.73	-	-	12.06	58.85	0.86	1.18	2.46	1.54	
Total Number of Obs. by Each Method				41	19	15	25	11	26	25	45	40	**247**

Note: Measurements reported in meters were originally recorded in feet/inches

- indicates not applicable

TABLE 18 A summary of PME values in Denver, Colorado

Roadway	Roadway Environment	Data Collection Method	Inventory Element Mean PME (Standard Error of the PME Mean)									Total
								Traffic Sign				
			Lane Width	Sideslope	Barrier Height	Driveway Width	St. light spacing	Width	Height	Support height	Lateral placement	
Route 86	Two-lane rural	Manual	-3.53 (2.05)	-30.94 (9.03)	8.74 (1.91)	-32.10 (5.34)	-	-4.13 (5.68)	12.85 (12.00)	10.80 (3.43)	9.51 (7.26)	-3.19 (2.80)
		MSI	-1.82 (2.16)	-16.53 (16.00)	12.54 (23.13)	-0.73 (1.95)	-	0.61 (6.39)	13.11 (10.74)	1.80 (6.29)	15.41 (8.76)	2.76 (3.19)
I-25	Rural interstate	Manual	-0.68 (1.43)	30.40 (8.29)	0.46 (0.46)	-	-	1.20 (4.10)	1.95 (3.41)	0.52 (2.26)	5.10 (3.86)	5.19 (1.76)
		MSI	-2.76 (1.20)	-10.26 (16.63)	3.79 (5.56)	-	-	3.51 (1.05)	3.59 (2.94)	4.53 (4.58)	8.40 (2.96)	1.86 (2.43)
Colorado Blvd.	Urban	Manual	-2.0 (2.47)	-	-	17.03 (9.16)	14.24 (9.44)	-2.94 (4.419)	-0.84 (4.44)	-13.36 (2.34)	4.48 (4.19)	2.70 (2.57)
		MSI	0.09 (3.51)	-	-	3.97 (2.18)	-6.95 (4.46)	10.49 (7.66)	15.94 (10.20)	0.07 (1.64)	18.04 (7.77)	4.47 (2.10)
Total Manual			-1.62	7.80	3.77	-4.29	17.03	-1.50	4.21	-0.80	6.01	1.92
Total MSI			-1.98	-12.77	7.28	-4.46	3.96	4.87	9.71	2.35	13.04	2.96

Note: - indicates not applicable

TABLE 19 ANOVA results for data collected in Denver, Colorado

Dependent Variable: PME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	29	16009.19285293	552.04113286	2.25	0.0004
Error	324	79586.07149509	245.63602313		
Corrected Total	353	95595.26434802			

R-Square	C.V.	Root MSE	PME Mean
0.167468	495.2745	15.67277969	3.16446328

Source	DF	Type III SS	Mean Square	F Value	Pr > F
METHOD	1	1850.21141857	1850.21141857	7.53	0.0064
ENVIRON	2	516.35931976	258.17965988	1.05	0.3508
ELEMENT	4	7337.39645100	1834.34911275	7.47	0.0001
METHOD*ENVIRON	2	1922.94898428	961.47449214	3.91	0.0209
METHOD*ELEMENT	4	656.30126707	164.07531677	0.67	0.6146
ENVIRON*ELEMENT	8	3502.18963959	437.77370495	1.78	0.0797
METHOD*ENVIRON*ELEMENT	8	1137.07946848	142.13493356	0.58	0.7954

Class	Levels	Values
METHOD	2	DIGITAL MANUAL
ENVIRON	3	URBAN INTERST TWOLANE
ELEMENT	5	LANEWID LAT_PLAC SUP_LENG S_HEIGHT S_WIDTH

Number of observations in data set = 354

environment. However, none of the differences between the MSI and the manual methods were statistically significant at the 0.05 level for the different environments.

Overall Findings from Denver Data

The data collected in Denver, Colorado, indicated that the accuracy of inventory data depended on the type of data element measured. The significance of the interaction between the other two main effects shows that the accuracy of inventory data depended on the method of data collection under different roadway environments. Overall, the MSI method performed better in the two-lane and the interstate environments. The manual method performed better in the urban environment.

Analysis of Madison Data

Figure 18 shows a sample digital image captured by the Mandli method. Tables 20 and 21 provide the data collected in Madison. Table 21 shows that, overall, data from the manual method were slightly more accurate than data from the Mandli method. Table 21 also shows that, overall, there was very little difference in the scatter of the data between the methods as measured by the standard errors. ANOVA on the data collected by the Mandli and manual methods tested

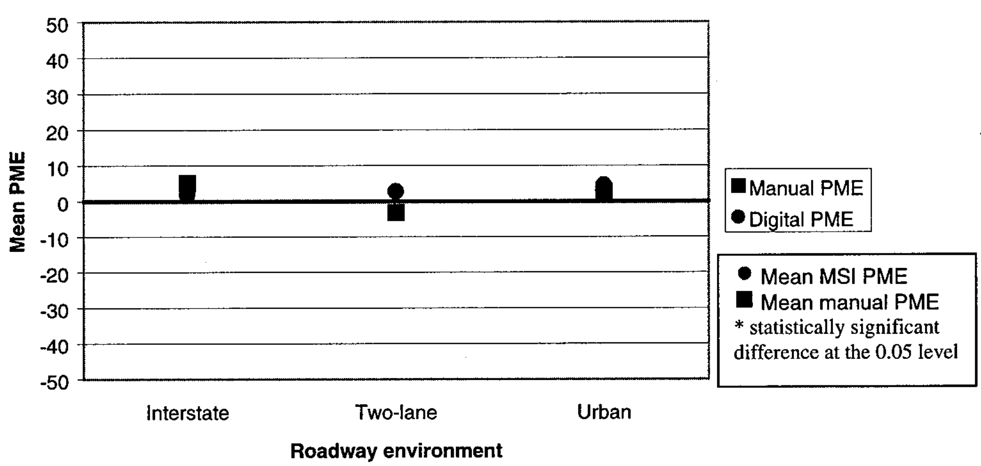


Figure 17. Comparison of mean PME values, Denver, Colorado.

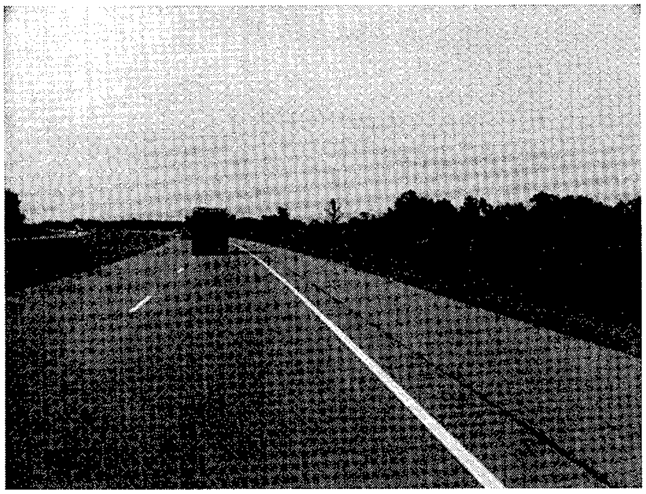


Figure 18. A digital image of an interstate highway captured by the Mandli method, Madison, Wisconsin.

the effects of the main factors and their interactions on data accuracy. There was no problem of empty cells in the data collected in Madison, Wisconsin. This was because no measurements were made on street light spacing, driveway width, and road sideslope by the Mandli method because of the limitations of the software package used on the digital images.

Main Effects

Table 22 presents the ANOVA results. The F-statistic for the method of data collection was not statistically significant (at the 0.05 level). The environment variable was also not statistically significant. The inventory element type was statistically significant indicating that the type of inventory element affected the measurement accuracy.

Interaction Effects

Interaction effects among the three main effects were explored. None of the two-way or three-way interactions among the main effects were statistically significant at the 0.05 level.

Overall Findings from Madison Data

The analysis of data collected in Madison, Wisconsin, indicates that the accuracy of inventory elements depended on the type of inventory element under consideration. The analysis did not reveal any significant difference in the accuracy of data collected by the two collection methods.

Analysis of Rocky Hill Data

Figure 19 shows a sample digital image captured by the ConnDOT method. Tables 23 and 24 summarize the Rocky Hill data. Table 24 shows that, overall, the manual method had slightly greater accuracy than the ConnDOT method. The manual method also had slightly less scatter in its data overall compared with the ConnDOT method, based on the standard errors. Because driveway width and street light spacing are not common across the three roadway environments, these two elements presented the empty cell problem

TABLE 20 A summary of data collected in Madison, Wisconsin

Roadway	Roadway Environment	Test Section Length (km)	Data Detail	Inventory Element					Total Number of Obs. by Each Method
					Traffic sign				
				Lane width (m)	Width (m)	Height (m)	Support height (m)	Lateral placement (m)	
County MM	Two-lane rural	13.0	No. of obs. by each method	13	4	4	13	13	47
			Manual method mean	3.37	0.99	1.21	1.95	4.33	
			Mandli method mean	3.45	1.02	1.14	1.72	3.88	
			Ground truth mean	3.48	1.10	1.31	1.96	3.76	
I-90	Rural interstate	16.2	No. of obs. by each method	16	9	9	13	16	66
			Manual method mean	3.65	2.57	1.35	2.05	5.71	
			Mandli method mean	3.67	2.62	1.31	2.11	5.64	
			Ground truth mean	3.71	3.01	1.59	2.30	5.96	
Main Street	Urban	13.5	No. of obs. by each method	13	4	4	13	13	47
			Manual method mean	4.05	0.59	0.80	2.08	0.72	
			Mandli method mean	5.03	0.57	0.67	2.09	0.81	
			Ground truth mean	5.05	0.57	0.78	2.05	0.77	
Total Number of Obs. by Each Method				42	17	17	42	42	**160**

Note: Measurements reported in meters were originally recorded in feet/inches

TABLE 21 A summary of PME values in Madison, Wisconsin

Roadway	Roadway Environment	Data Collection Method	Inventory Element Mean PME (Standard Error of the PME Mean)					Total
			Lane Width	Traffic Sign				
				Width	Height	Support height	Lateral placement	
County MM	Two-lane rural	Manual	-1.73 (2.58)	-7.29 (4.29)	-2.82 (11.06)	-0.67 (1.73)	16.66 (5.42)	3.08 (2.27)
		Mandli	-0.78 (0.67)	-8.15 (9.67)	-12.44 (15.69)	-12.43 (1.48)	3.68 (5.66)	-4.38 (2.32)
I-90	Rural interstate	Manual	-1.48 (0.36)	-7.21 (9.42)	-7.67 (11.13)	-10.14 (1.78)	2.15 (5.56)	-4.32 (2.40)
		Mandli	-1.17 (0.45)	-0.45 (18.11)	-9.67 (8.15)	-8.85 (3.09)	-1.33 (3.92)	-4.13 (2.85)
Main St.	Urban	Manual	-19.81 (1.02)	3.12 (7.86)	6.41 (10.88)	7.34 (9.32)	3.36 (9.71)	-1.70 (4.11)
		Mandli	-0.67 (1.15)	1.73 (5.02)	-11.35 (9.79)	6.56 (7.89)	10.45 (7.76)	3.70 (3.23)
Total Manual			-7.22	-4.79	-3.21	-1.79	7.01	-1.37
Total Mandli			-0.89	-1.74	-10.71	-5.19	3.86	-1.90

and were dropped from the ANOVA. Table 25 shows the ANOVA results for the Rocky Hill data.

Main Effects

The three main effects under investigation were all statistically significant. However, a conclusion regarding their effect on data accuracy cannot be reached because of the significance of the interaction terms (see below).

Interaction Effects

The two-way interactions between method of data collection and roadway environment and between method of data collection and type of inventory element were statistically significant. Furthermore, the three-way interaction among the three main effects was also statistically significant (at the 0.05 level). This indicated that the mean PME values for each inventory element on each roadway environment and across each method of data collection should be studied separately.

TABLE 22 ANOVA results for data collected in Madison, Wisconsin

```
Dependent Variable: PME
Source                    DF     Sum of Squares          Mean Square   F Value      Pr > F
Model                     29     19677.50643192         678.53470455      1.56      0.0371
Error                    290    126160.48412308         435.03615215
Corrected Total          319    145837.99055500

                    R-Square               C.V.             Root MSE              PME Mean
                    0.134927          -1269.574          20.85752028           -1.64287500

Source                    DF        Type III SS          Mean Square   F Value      Pr > F
METHOD                     1       168.34812917         168.34812917      0.39      0.5344
ENVIRON                    2      1230.38987205         615.19493602      1.41      0.2448
METHOD*ENVIRON             2       747.10817211         373.55408605      0.86      0.4248
ELEMENT                    4      6026.23898020        1506.55974505      3.46      0.0088
METHOD*ELEMENT             4      2129.26260295         532.31565074      1.22      0.3009
ENVIRON*ELEMENT            8      6404.81915155         800.60239394      1.84      0.0694
METHOD*ENVIRON*ELEMENT     8      2026.54641104         253.31830138      0.58      0.7923

Class      Levels    Values
METHOD          2    DIGITAL MANUAL
ENVIRON         3    URBAN INTERST TWOLANE
ELEMENT         5    LANEWID LAT_PLAC SUP_LENG S_HEIGHT S_WIDTH

Number of observations in data set = 320
```

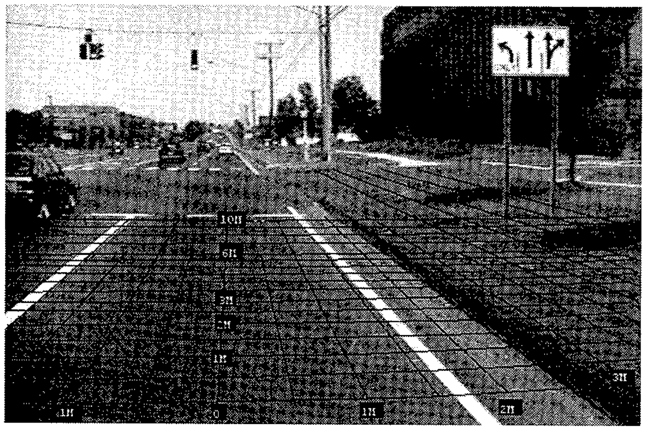


Figure 19. A digital image with overlaid calibrated grid for measuring inventory data by the ConnDOT method.

Figure 20 compares mean values of PME for the ConnDOT and manual methods in the two-lane rural environment. Lane width was more accurately measured by the ConnDOT method whereas lateral placement of signs and driveway width was more accurately measured by the manual method. All differences were statistically significant at the 0.05 level.

Figure 21 compares mean values of PME for the ConnDOT and the manual methods in the interstate environment. The lateral placement of signs was measured more accurately by the manual method and the difference between the methods for this inventory element was statistically significant at the 0.05 level. Lane widths were also measured with higher accuracy by the manual method, but the difference was not statistically significant.

Figure 22 compares the mean values of PME for the ConnDOT and the manual methods in the urban environment. The ConnDOT method outperformed the manual method in measuring lane width, driveway width, and street light spacing. The manual method produced more accurate results for the lateral placement of traffic signs. All differences were statistically significant at the 0.05 level.

Overall Findings from Rocky Hill Data

The Rocky Hill data set was the most limited because the ConnDOT method did not measure vertical or sloped elements. For lateral and longitudinal measurements, the ConnDOT method outperformed the manual method in the urban environment while the manual method produced better results in the two-lane and the interstate environments.

Information on Time and Cost of Data Collection and Presentation

Information on time and cost of data collection and subsequent presentation was collected during the experiments. Table 26 summarizes the information on the manual method and the methods employing image capture technologies. Overall, data collection by the manual method was more time consuming in the field on all three-roadway environments

TABLE 23 A summary of data collected in Rocky Hill, Connecticut

Roadway	Roadway Environment	Test Roadway Section Length (km)	Data Detail	Inventory Element: Lane width (m)	Inventory Element: Driveway width (m)	Inventory Element: Street light spacing (m)	Inventory Element: Traffic sign lateral placement	Total Number of Obs. by Each Method
Connecticut Route 74 W and Connecticut Route 85 N	Two-lane rural	21.2	No. of obs. by each method	23	23	-	22	68
			Manual method mean	3.35	9.34	-	2.03	
			ConnDOT method mean	3.51	11.09	-	2.90	
			Ground truth mean	3.53	10.45	-	2.26	
I-84	Rural interstate	17.7	No. of obs. by each method	25	-	-	20	45
			Manual method mean	* 3.67	-	-	6.05	
			ConnDOT method mean	* 3.65	-	-	4.97	
			Ground truth mean	* 4.30	-	-	6.26	
Connecticut Route 99 N	Urban	5.1	No. of obs. by each method	19	27	6	21	73
			Manual method mean	3.35	12.47	20.83	1.71	
			ConnDOT method mean	3.49	14.95	26.25	2.80	
			Ground truth mean	3.52	14.94	27.02	1.96	
Total Number of Obs. by Each Method				67	50	6	63	**186**

Note: - indicates not applicable; measurements reported in meters were originally recorded in feet/inches

* indicates shoulder width measured in place of lane width

TABLE 24 A summary of PME values in Rocky Hill, Connecticut

Roadway	Roadway Environment	Data Collection Method	Inventory Element Mean PME (Standard Error of the PME Mean)				Total
			Lane Width	Driveway Width	Street Light Spacing	Traffic Sign Lateral placement	
Route 74 W & Route 85 N	Two-lane rural	Manual	-4.83 (1.02)	-1.71 (10.58)	-	-5.12 (4.63)	-3.86 (3.84)
		ConnDOT	-0.32 (1.54)	18.77 (16.04)	-	30.05 (6.39)	15.96 (5.94)
I-84	Rural interstate	Manual	* -14.41 (1.58)	-	-	6.67 (12.89)	-5.03 (5.92)
		ConnDOT	* -14.81 (1.73)	-	-	-12.44 (7.66)	-13.75 (3.49)
Route 99 N	Urban	Manual	-4.32 (1.71)	-14.38 (4.11)	-18.22 (7.65)	-10.66 (3.29)	-11.00 (1.98)
		ConnDOT	-0.78 (0.89)	0.06 (3.21)	3.14 (13.02)	42.33 (4.65)	12.20 (30.3)
Total Manual			-8.25	-8.55	-18.22	-3.22	-5.80
Total ConnDOT			-5.85	8.60	3.14	20.65	6.99

Note: * indicates measurement of shoulder width in place of lane width

- indicates not applicable

TABLE 25 ANOVA results for data collected in Rocky Hill, Connecticut

Dependent Variable: PME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	75927.12911131	6902.46628285	12.74	0.0001
Error	248	134338.44894215	541.68729412		
Corrected Total	259	210265.57805346			

R-Square	C.V.	Root MSE	PME Mean
0.361101	3967.796	23.27417655	0.58657692

Source	DF	Type III SS	Mean Square	F Value	Pr > F
METHOD	1	10531.41611704	10531.41611704	19.44	0.0001
ENVIRON	2	12369.97956001	6184.98978000	11.42	0.0001
METHOD*ENVIRON	2	17175.05419696	8587.52709848	15.85	0.0001
ELEMENT	1	14603.78363964	14603.78363964	26.96	0.0001
METHOD*ELEMENT	1	6750.33014968	6750.33014968	12.46	0.0005
ENVIRON*ELEMENT	2	466.89526395	233.44763197	0.43	0.6504
METHOD*ENVIRO*ELEMEN	2	13284.96226520	6642.48113260	12.26	0.0001

Class Level Information

Class	Levels	Values
METHOD	2	DIGITAL MANUAL
ENVIRON	3	URBAN INTERST TWOLANE
ELEMENT	2	LANEWID LAT_PLAC

Number of observations in data set = 260

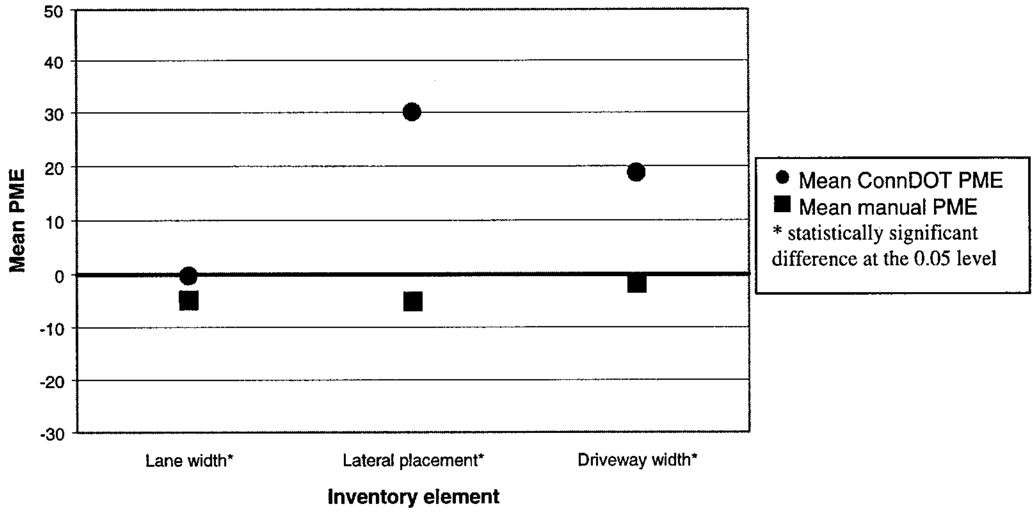


Figure 20. Comparison of PME means, two-lane environment, Rocky Hill, Connecticut.

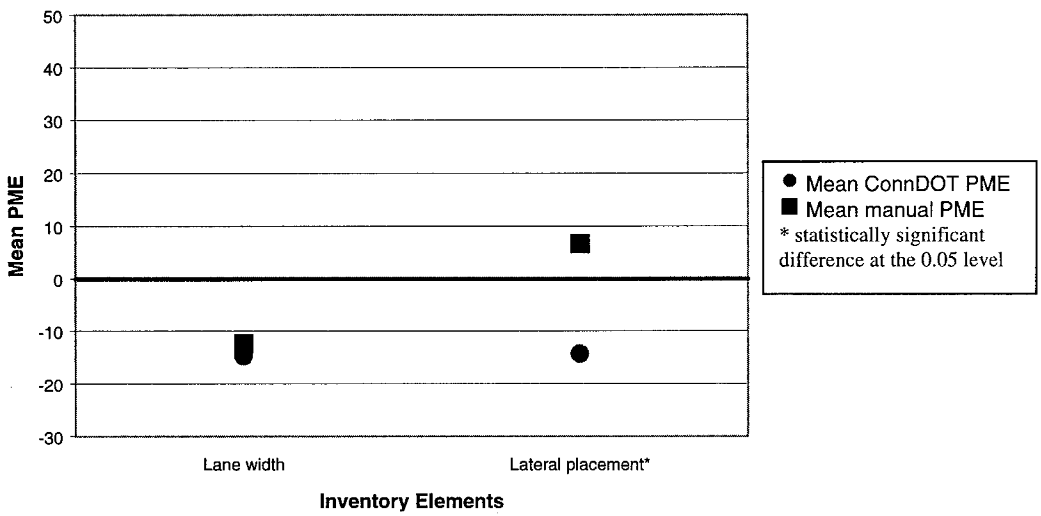


Figure 21. Comparison of PME means, interstate environment, Rocky Hill, Connecticut.

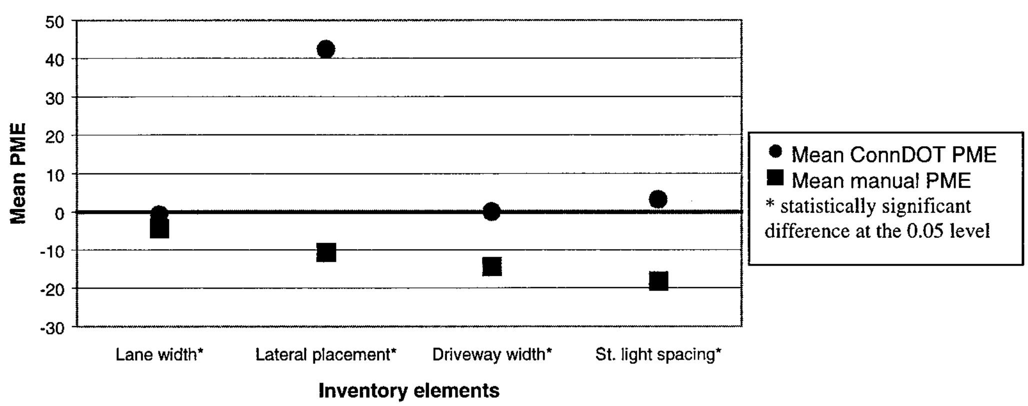


Figure 22. Comparison of PME means, urban environment, Rocky Hill, Connecticut.

TABLE 26 Summary of time and cost of data collection by different methods

	Manual Method			Method Employing Digital Image Capture Technology		
Environment / **Item**	Urban	Two-lane rural	Interstate	Urban	Two-lane rural	Interstate
Collection time for 100 inventory elements in the field including equipment setup (min.)	35.5	47.2	50.3	8.5	5.2	7.0
In-office processing time for 100 inventory elements (min.)	-	-	-	2.5	2.5	2.5
Feature extraction time for 100 inventory elements, input to computer and creation of inventory database including transfer to GIS (min.)	45.0	45.0	45.0	75.0	75.0	75.0
One time purchase of equipment (hardware, software, and peripherals; $)	30,000*			250,000 and above**		

* Manual method cost includes purchase of van and a single workstation.
** The costs of the methods employing digital image capture technology depend upon the number and type of sensors installed in the van and vary significantly.

because the observer had to make frequent stops during data collection. The data collection methods using digital image capture technologies required processing in the office, which consisted of downloading the data from the van, DGPS processing, and aggregation of the data from the different collection sensors (e.g., DGPS, INS, DMI, and digital cameras). This time was not required when collecting data by the manual method.

Feature extraction and creation of a database in the case of the manual method included coding the data from paper forms into a computer spreadsheet and then transferring the data to a GIS. For the other methods (using van systems), feature extraction and database creation involved making digital measurements by using photogrammetric software packages and then transferring the data to a GIS. Overall, these other methods were more time consuming because the data collector had to carefully execute multiple points-and-clicks using the computer mouse on inventory elements in the digital images.

One-time purchase costs of equipment for collection and processing are also reported. The cost of the manual method is based on purchase of a van and a single computer. There is significant variation in the cost of purchase of a van system equipped with digital image capture technologies because it depends on the type and number of sensors installed in the van. This evaluation did not consider training costs or costs resulting from software incompatibility issues because of the wide variation in these factors. Overall, the one-time purchase cost for the van systems employing digital image capture technologies is significantly higher than the one-time purchase cost for the manual method.

EVALUATING PROTOCOL

An agency desiring to evaluate a data collection method must examine the method's accuracy as well as the time required, cost, training requirements, software compatibility, and other issues. Based on the four experiments evaluating the accuracy of digital image systems described in this chapter, the research team constructed a test protocol, described in Appendix E, that shows agencies and/or companies should fairly and efficiently evaluate the accuracy of descriptive data obtained from digital image systems. At the heart of the protocol lies the PME measure of effectiveness for accuracy.

In brief, the protocol requires an evaluator to define data collection methods and identify the factors that affect the accuracy of inventory data (e.g., method of collection, roadway environment, and inventory element type were identified during the four experiments). The evaluator should control for other factors that may affect accuracy to the extent possible (e.g., weather and light conditions and terrain). The evaluator should collect enough observations to conduct a statistically valid experiment. Guidance on sample sizes for some inventory elements is provided in Appendix E. Inventory data should be collected by the specified methods in the field. Ground truth observations must also be collected for accuracy assessment. Finally, after processing, the evaluator will conduct appropriate statistical analysis and interpret the results of the findings. Use of the suggested test protocol will build confidence in promising new systems and allow unbiased comparisons of new systems to existing systems without having to obtain and re-run the existing systems.

CHAPTER 5

EVALUATION OF SATELLITE DATA PRESENTATION

Collection of roadway inventory data through high-resolution satellite digital imagery is promising because it can be used for both small and large roadway systems, it provides systematic updates, its operation is automatic (it does not require personnel in the field), and its cost is expected to be lower than aerial photography. The launch of satellites capable of collecting high (1-m) resolution images is expected sometime in the year 1999.

The research team investigated the potential usefulness of these images for collecting roadway inventory data. In its experiments on high-resolution images, the research team used 1-m aerial photographs to simulate satellite imagery with 1-m resolution. The dataset used in some of the experiments was a portion of an urban area in San Francisco, California (Figure 23), extracted from Space Imaging EOSAT's Carterra public products. This aerial photograph was in digital form and was color enhanced. It had three visible bands with ground resolution of $1m^2$, which closely resembles the characteristics of 1-m resolution panchromatic satellite images that will be provided in the near future by Space Imaging EOSAT.

In this project, the research team experimented with extraction of roadway inventory data from high-resolution satellite imagery (simulated 1-m aerial photographs) using point-and-click (PAC) and several automated methods. The objectives of these experiments were (1) to investigate the types of inventory data elements that could be collected from high-resolution satellite images by various methods and (2) to determine the specific advances in image processing that are needed to enable collection of additional inventory elements in the near future.

POINT-AND-CLICK METHOD

The focus of this experiment was to use commercially available software tools to extract roadway inventory elements from 1-m resolution imagery. Inventory data collection by the PAC method requires on-screen manual extraction from the digital image. Most commercially available GIS packages accommodate on-screen extraction functions. The commercial GIS package used in this experiment was ArcView (from Environmental Systems Research Institute, Inc.) because of its popularity in the transportation industry.* Figure 24 shows an example of the roadway network extracted from the image in Figure 23 using the PAC method; its overlay on the original image is in Figure 25. Because the image was registered to a map projection, each pixel had known coordinates. The location and characteristics of each point can be displayed on the computer monitor. Location of points may be in any one of the standard coordinate systems (e.g., UTM, state plane, or latitude and longitude). The characteristics that may be displayed include point measurements, segment measurements, and polygon measurements. Those include areas, lengths, angles, perimeters of polygons, width of roads, and distances between points. Because this procedure uses a GIS software package (e.g., ArcView), the attributes of the road network are readily stored in a database after extraction as shown in Figure 26, which lists a series of attributes of polylines. By querying each polyline of interest, a list of attributes for that polyline can be produced.

The PAC method of roadway inventory data extraction requires a computer and the GIS software package. The detected elements along with their characteristics may be input to suitable database management systems. The PAC method is simple and straightforward. It can be performed by operators with training in one of the commercially available GIS packages. In essence, the feature extraction process within a GIS software is equivalent to on-screen digitizing. Images are displayed in a window and features are visually identified by the operator. Features of interest are digitized and recorded by pointing and clicking the computer mouse. Most features listed in Table 3 can be extracted this way if the conditions specified are satisfied. The PAC method is feasible only when the study area is small, but this method is always an alternative when other methods of inventory data extraction are not available or fail. The disadvantages of this method are its (1) non-constant positional accuracy (i.e., it is dependent on human correspondence of features during pointing and clicking), (2) inconsistency caused by the operator, and (3) its impracticality for large areas.

* The use of a specific brand and/or company name is purely illustrative and not an NCHRP endorsement of the item mentioned.

Figure 23. An urban area in San Francisco, California (extracted from the Space Imaging EOSTAT's Carterra Public Products).

Figure 25. Overlay of the road network on the original image.

AUTOMATED METHODS

The research team performed experiments to detect cover, shape, and measurement type features by using an automated method of data extraction. The cover type features included roadway network, shoulder material, pavement material, median landscaping, sidewalk material, and driveway land use. All of these features are related to land surface cover type and can be detected by land cover classification. Classification is the process of determining a category (e.g., roadway network and pavement material) for each pixel in an image and can be performed either supervised or unsupervised. In supervised classification, the image analyst supervises the pixel categorization process by specifying numerical descriptors of the various land cover types present in an image. In unsupervised classification the process of pixel categorization is performed automatically with minimum intervention by the image analyst.

A surface material classification scheme (Table 27) was developed for roadway inventory extraction (Karimi et al., 1998). This classification scheme consisted of four levels. Level I included background, natural features, man-made features, and shadows. At Level II, natural features were divided into bare soil, vegetation, and water, while man-made features were grouped into asphalt, concrete, and tile. Vegetation was further divided into grass and tree at Level III. At Level IV, conifer and deciduous were identified from the tree category.

Figure 27(a) shows an example of an original image captured through airborne sensors (aerial photograph in this case), Figure 27(b) shows the image after it was processed for cover-type feature detection (classification), and Figure 27(c)

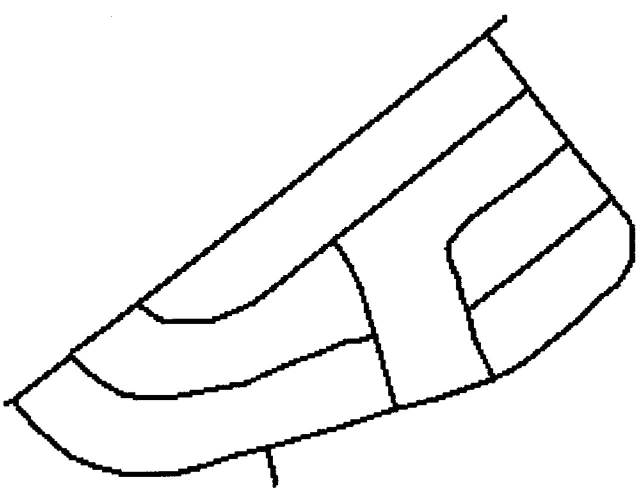
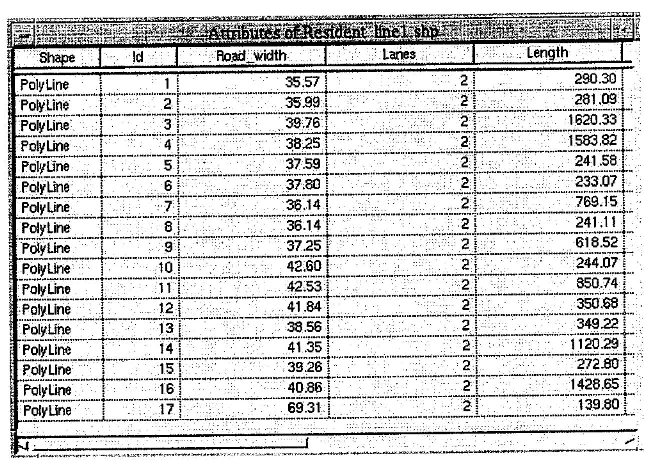


Figure 24. The roadway network extracted from the image in Figure 23.



Attributes of Resident_line1.shp

Shape	Id	Road_width	Lanes	Length
PolyLine	1	35.57	2	290.30
PolyLine	2	35.99	2	281.09
PolyLine	3	39.76	2	1620.33
PolyLine	4	38.25	2	1583.82
PolyLine	5	37.59	2	241.58
PolyLine	6	37.80	2	233.07
PolyLine	7	36.14	2	769.15
PolyLine	8	36.14	2	241.11
PolyLine	9	37.25	2	618.52
PolyLine	10	42.60	2	244.07
PolyLine	11	42.53	2	850.74
PolyLine	12	41.84	2	350.68
PolyLine	13	38.56	2	349.22
PolyLine	14	41.35	2	1120.29
PolyLine	15	39.26	2	272.80
PolyLine	16	40.86	2	1428.65
PolyLine	17	69.31	2	139.80

Figure 26. Storage of road network attributes in a database after extraction.

TABLE 27 Classification scheme for cover-type features

Level I	Level II	Level III	Level IV
Background	Background	Background	Background
Natural Features	Bare Soil	Bare Soil	Bare Soil
	Vegetation	Grass	Grass
		Tree	Conifer
			Deciduous
	Water	Water	Water
Man-made Features	Asphalt	Asphalt	Asphalt
	Concrete	Concrete	Concrete
	Tile	Tile	Tile
Shadow	Shadow	Shadow	Shadow

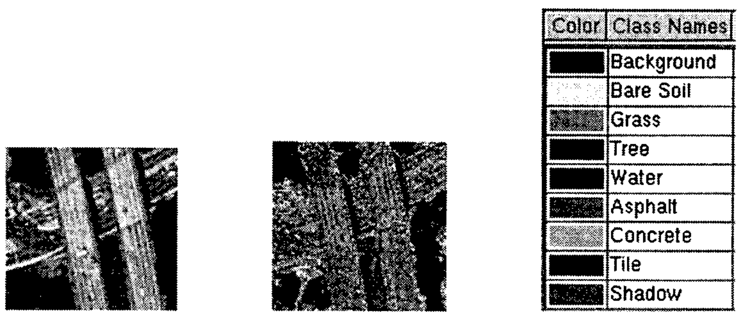


Figure 27(a,b,c). An example for cover-type feature detection.

shows the result of classification of features in the original image. The Iterative Self-Organizing Data Analysis Technique (ISODATA) unsupervised classifier was used in land cover classification. Fifty clusters were initially obtained, and operator interpretation was used to label those clusters. Several remote sensing software packages have the capability for image classification. The time required to classify an image largely depends on the machine, image size, and the problem at hand (e.g., number of clusters). For classifying a 512 × 512 pixel image with three bands, it takes less than 1 min to classify the image into 50 clusters using the Erdas Imagine software package (Erdas Field Guide, 1991).* The interpretation time ranges from hours to days, depending on the operator's experience and reference data for interpretation.

For shape and measurement type feature extraction, the research team used a seeded region growing method (Pavlidis and Liow, 1990; Chang and Li, 1994), which might be used as a semi-automated aid in computer feature extraction in combination with other methods. The results from a test of the seeded region growing method for extracting roadway inventory elements are given in Figure 28.

Application of this method has the following advantages: (1) it is easy to use and is user-interactive; (2) it is robust and powerful in handling image noise; (3) it operates in real time; (4) it requires neither tuning parameters nor training sets; and (5) it excludes undesired features. Disadvantages of this method include (1) it is subject to problems when there are low contrasts in the images, and (2) it is hard to fully automate.

AUTOMATED ROADWAY CENTERLINE EXTRACTION SYSTEM (ARCES)

The research team developed a new procedure to automatically collect information on two common components of roadway inventories—roadway centerline location and roadway width—from simulated satellite images. A flowchart of this automated roadway centerline extraction procedure is shown in Figure 29. The procedure was based on the Thin and Robust Zero-Crossing algorithm (Dai and Khorram, 1997). ARCES takes images as input and outputs three roadway parameters: roadway edges, roadway centerline, and

* The use of a specific brand and/or company name is purely illustrative and not an NCHRP endorsement of the item mentioned.

Figure 28. Extracted roadway features using the seeded region growing method.

roadway width. The entire procedure is coded and implemented in Matlab and fully automated.

A sample window of 512 by 512 pixels was used to test the performance of this procedure. The image was a 1-m resolution panchromatic image as shown in Figure 30. The edges detected by the improved LoG operator are shown in Figure 31, where weak edge points exist. The edge points were first refined by an algorithm called edge strength array, as displayed in Figure 32. The refined edge points are shown in Figure 33. These edge points were presented to the edge search and sorting program. Short contours were discarded after this program, as shown in Figure 34. Based on their parallel characteristics, roadway edges were detected by the roadway edge extraction program, as shown in Figure 35. An example of a highway with the detected edges is shown in Figure 36. For each pair of roadway contours, the centerline extraction subroutine was called to extract the roadway centerline. The centerline extracted by the program is shown in Figure 37.

Further processing was needed to remove the "zigzag" effects along the detected centerline. After detection of roadway centerline from the image, presentation of roadway parameters was relatively straightforward. For example, the total roadway width at each point along the centerline was easily computed by finding the corresponding points along

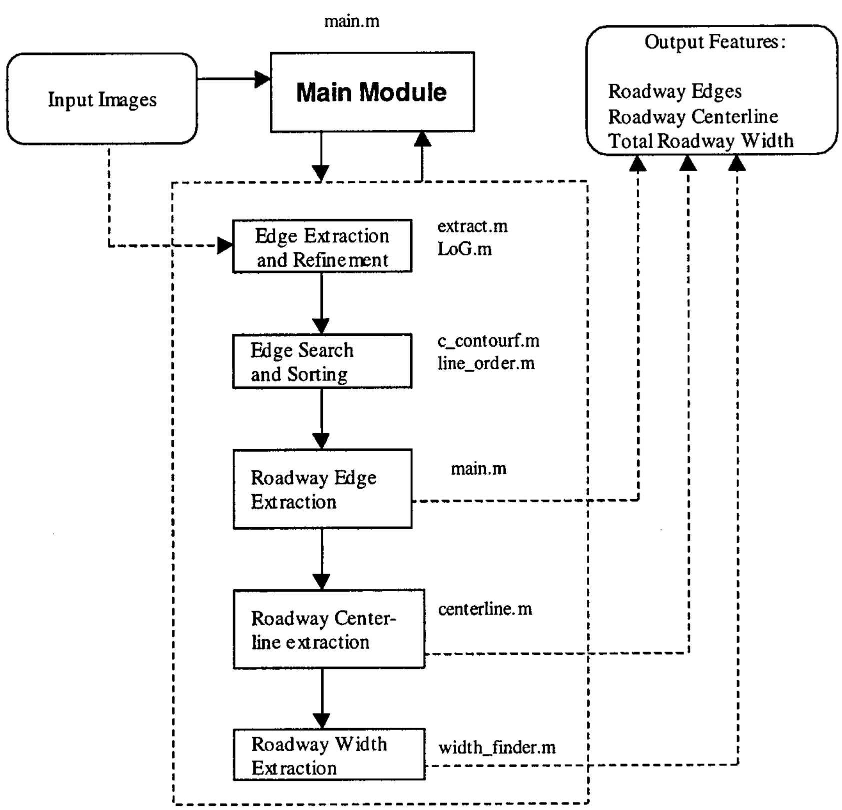


Figure 29. A flowchart of the automated roadway centerline extraction system.

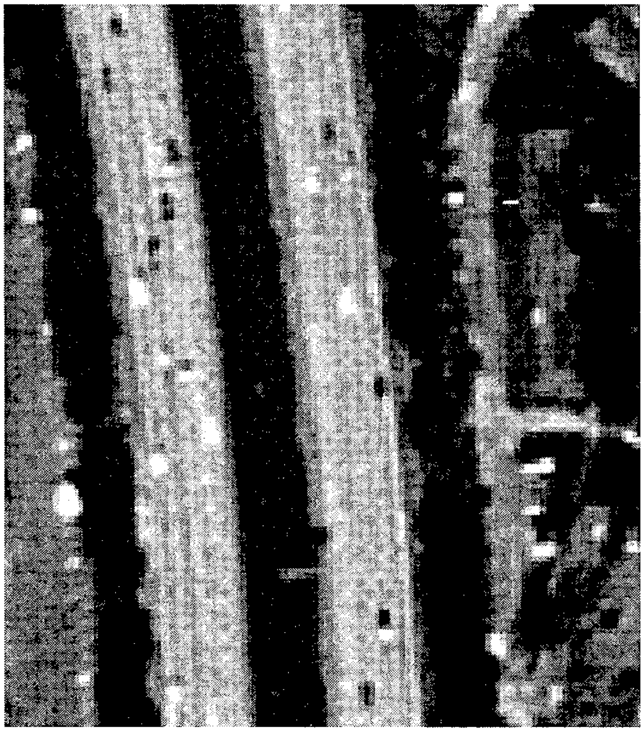


Figure 30. One-meter resolution panchromatic image.

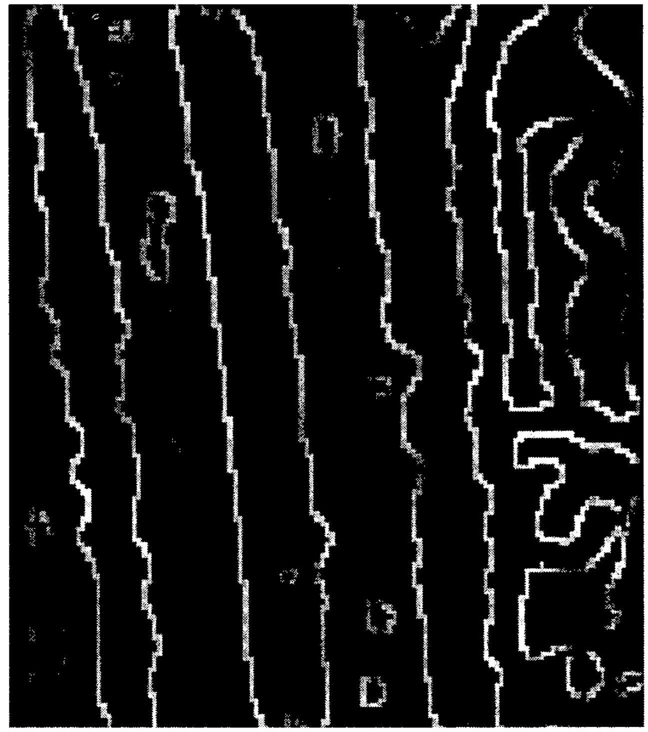


Figure 32. Refinement by the edge strength array.

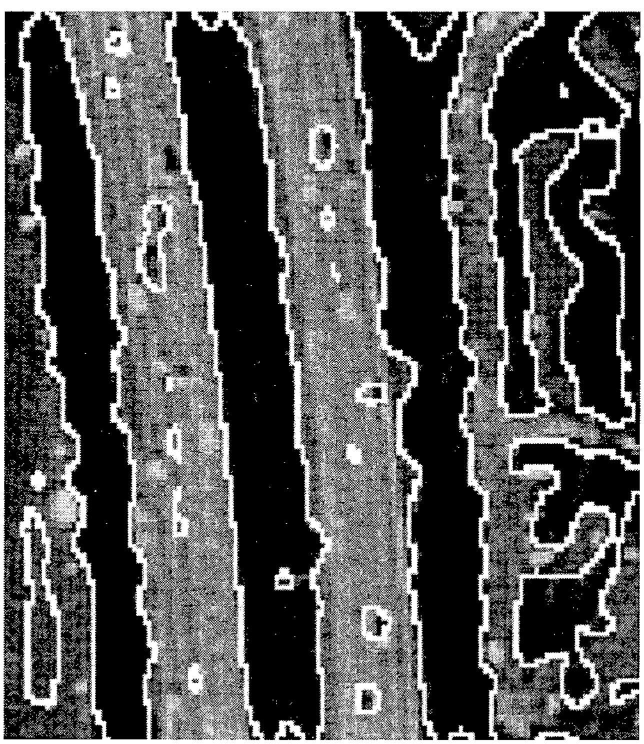


Figure 31. Edges detected by the improved LoG Operator.

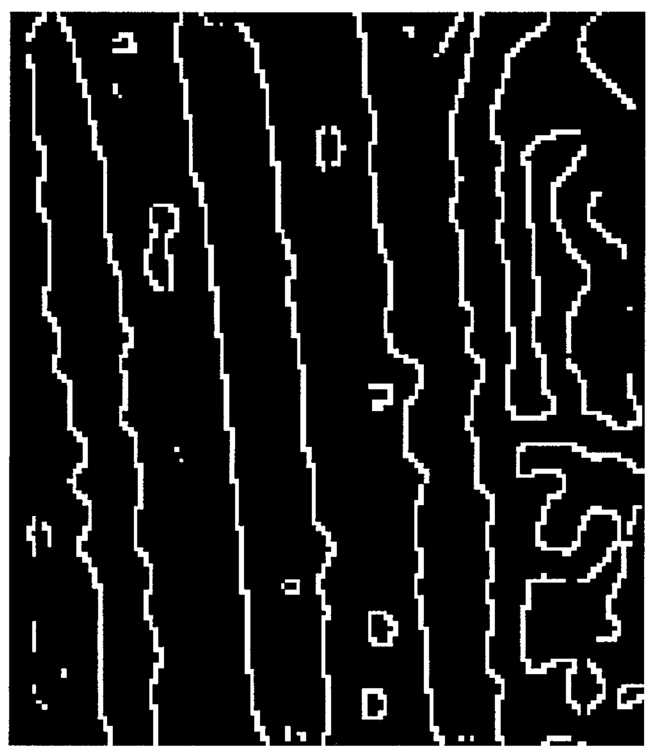


Figure 33. The refined edge points.

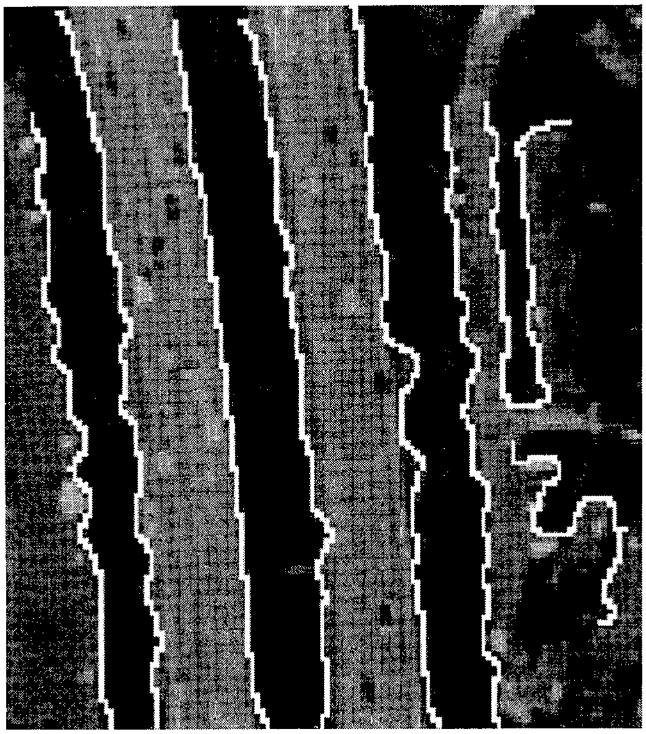


Figure 34. Discarded short contours.

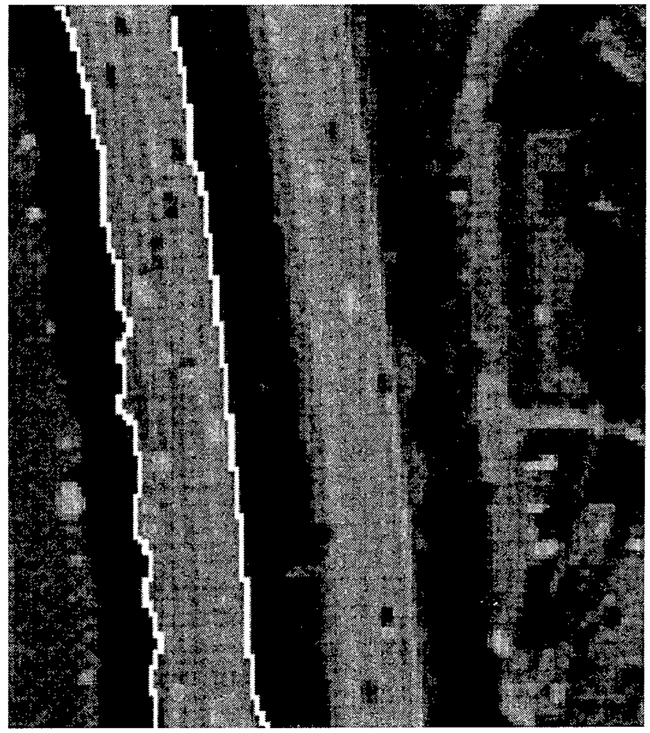


Figure 36. An example of a highway with detected edges.

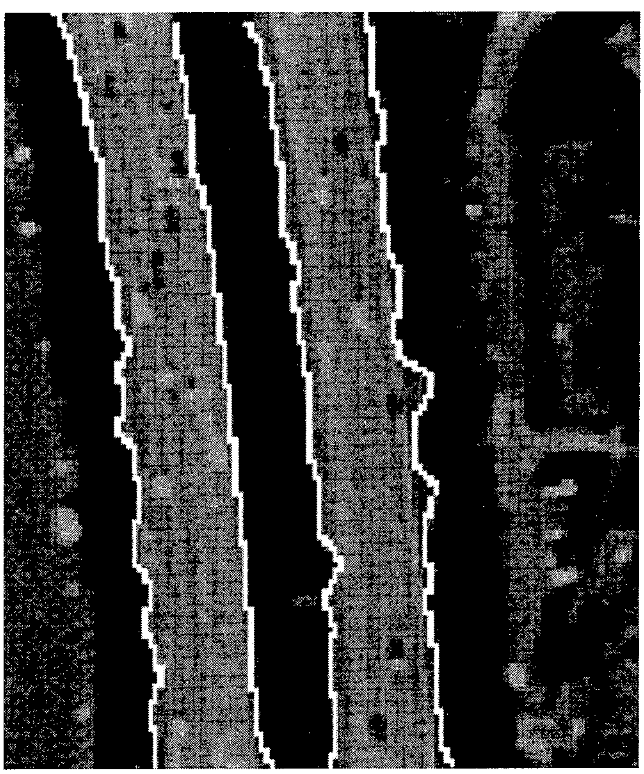


Figure 35. Detection by the roadway edge extraction program.

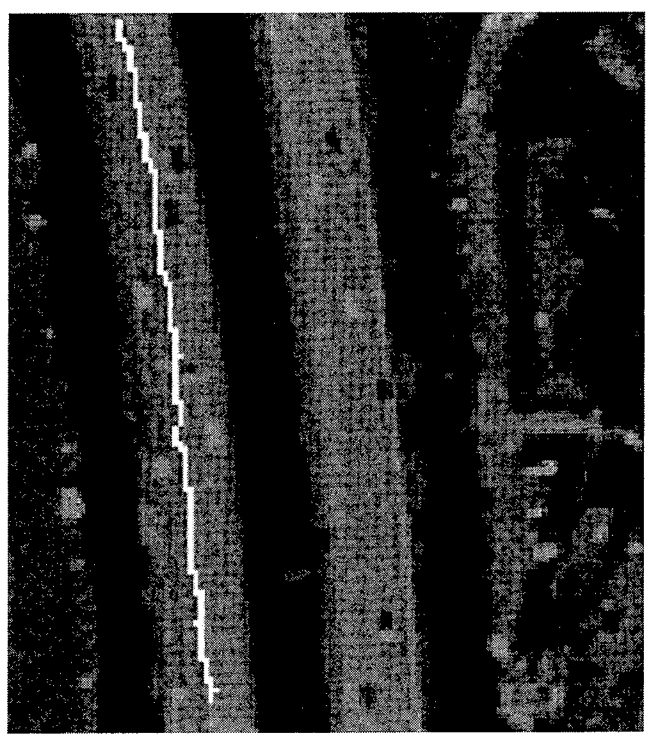


Figure 37. Centerline extracted by the program.

the roadway edges. Because the image was registered to a map projection, each centerline pixel had known coordinates. The location of the centerline and the roadway width were determined at the same time. Other segment measurements including lengths, angles, and distances between pairs of points can then be derived from the image automatically.

VALIDATION AND ACCURACY ASSESSMENT

Experimentation with satellite imagery included validating the accuracy of image georeferencing and assessing the descriptive accuracy of certain roadway cover-type materials.

The image data source used for georeferencing was United States Geological Survey (USGS) Digital Orthophoto Quarter Quads (DOQQs), a quarter-quad portion of the 7.5-minute quadrangles. Digital orthophotos are digital images that have the properties of an orthographic projection and are derived from scanned aerial photographs differentially rectified so that image displacements caused by camera tilt and terrain relief are removed. The current production of DOQQs is based on 1:40,000 scale black-and-white photography scanned with a 25-micron aperture resulting in a ground resolution of 1 m. A black-and-white quarter-quadrangle digital orthophoto generated and cropped from a 9-in.-by-9-in. photograph, scanned at 25 microns, with the requisite over-edge and header records produces a rectified file of approximately 55 megabytes. The digital orthophoto is cast on the UTM projection on either the North American Datum of 1927 (NAD 27) or North American Datum of 1983 (NAD 83).

To validate the results of registration using DOQQs, a DGPS technique was employed to ground truth a selected number of points. A handheld GPS unit (from Trimble, Inc.)* was first used in the field and the measurements were then differentially corrected using base station data. The study area used was the northern campus of Meredith College, in Raleigh, North Carolina.

It is generally appropriate to assume that the registration error is uniformly distributed throughout the image. Therefore, approximately 10 to 15 locations in a 512 × 512 pixel image window were enough to draw a conclusion on its georeference accuracy. Thirteen points were selected for GPS measurements. At each point in the field, the UTM coordinates were measured using the GPS unit (over 100 samples per point) and the ground cover type was recorded. Table 28 summarizes the data recorded in the field.

The GPS measurements were downloaded from the unit into a computer. An up-to-the-hour base station file was used for differential corrections. For each point, there were more

* The use of a specific brand and/or company name is purely illustrative and not an NCHRP endorsement of the item mentioned.

TABLE 28 Ground measurements by GPS

ID on Photo	ID by GPS	Time (16 June 1998)	Cover Type
1	R061616A	12:05 p.m. EST	Concrete
2	R061616F	12:09 p.m. EST	Concrete
3	R061616G	12:15 p.m. EST	Concrete
4	R061616H	12:26 p.m. EST	Concrete
5	R061616I	12:30 p.m. EST	Concrete
6	R061616J	12:42 p.m. EST	Concrete
7	R061616K	12:52 p.m. EST	Concrete
8	R061616L	12:59 p.m. EST	Concrete
9	R061617A	2:00 p.m. EST	Concrete
10	R061618A	2:07 p.m. EST	Asphalt
11	R061618B	2:10 p.m. EST	Concrete
12	R061618C	2:22 p.m. EST	Asphalt
13	R061618D	2:39 p.m. EST	Asphalt

than 100 corrected observations. These data were transferred into Matlab for further processing. A typical distribution of the samples taken at each measurement point is shown in Figure 38. These samples are scattered with standard deviations shown in Table 29. The mean of the samples for each measurement point was used as the position of that point recorded in UTM coordinates in meters. A 6-m positional accuracy was obtained after implementing the DGPS technique.

Positional Accuracy Analysis

The differentially corrected data are shown in Table 30. The root mean square error (RMSE) at the measurement

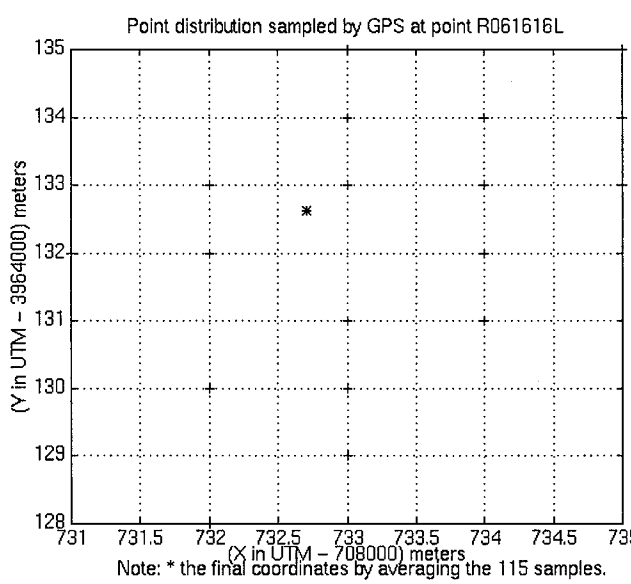


Figure 38. A typical distribution of the samples taken at each measurement point.

TABLE 29 Standard deviations of the sample observations (m)

Points	1	2	3	4	5	6	7	8	9	10	11	12	13
Std in X	0.59	2.23	1.25	3.32	1.73	1.89	1.35	1.36	0.45	1.91	0.44	1.96	5.91
Std in Y	1.80	1.29	1.23	1.79	1.20	1.49	6.33	1.37	0.81	1.18	5.51	3.28	5.91

TABLE 30 Differentially corrected data

Points	GPS Measurements		Image Registration (m)		Differences (b-a) (m)		
	X	Y	X'	Y'	ΔX	ΔY	Root square error
1	708605.9027	3964301.0708	708608.4549	3964303.4256	2.5522	2.3548	3.4726
2	708598.6891	3964288.8067	708607.5975	3964291.3939	8.9084	2.5872	9.2765
3	708609.0163	3964278.7886	708617.5648	3964278.5028	8.5485	-0.2858	8.5533
4	708613.1739	3964317.5217	708619.6011	3964316.4241	6.4272	-1.0976	6.5202
5	708681.6396	3964199.0721	708685.0000	3964194.0000	3.3604	-5.0721	5.6284
6	708673.4587	3964125.0275	708678.9765	3964123.9170	5.5178	-1.1105	5.6284
7	708675.4771	3964054.2661	708681.3344	3964055.5942	4.8573	1.3281	5.0356
8	708732.7130	3964132.6348	708732.3500	3964133.5853	-0.3630	0.9505	1.0175
9	708430.9016	3964211.9016	708431.2934	3964208.2463	0.3918	-3.6553	3.6762
10	708429.9725	3964501.5413	708432.0436	3964498.9406	2.0711	-2.6007	3.3246
11	708406.9823	3964614.4159	708409.0150	3964609.3638	2.0327	-5.0521	5.4457
12	708358.3333	3964500.3063	708364.9940	3964500.0299	6.6607	-0.2764	6.6664
13	708368.7232	3964378.3661	708373.9474	3964379.0383	5.2242	0.6722	5.2673
Means					4.3223	-0.8660	5.7865

points is commonly used to evaluate the performance of the accuracy of the image registration, which is usually defined as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - x_i')^2 + (y_i - y_i')^2}{N}}$$

where:

x and y are coordinates measured by the GPS

x' and y' are coordinates obtained by registration using DOQQs, and

N is the number of the measurement points.

Using the GPS measurements as ground truth, the RMSE at the 13 points measured computed to be 5.7865 pixels (1 pixel = 1 m × 1 m). The cover types resulting from image classification at these 13 points (10 concrete sites and 3 asphalt sites) completely matched the ground truth. For extensive investigation of other cover types, including non-roadway-related land cover types, additional ground truth data are needed.

CHAPTER 6

SELECTING COLLECTION AND PRESENTATION TECHNOLOGIES

Chapters 2 through 5 presented considerable data on technologies for inventory data collection and presentation. After viewing all those data, the main question for state DOTs still remains: which data collection and presentation technologies should they choose? This chapter addresses that question. This chapter first provides suggestions regarding confronting institutional issues and then discusses factors in choosing data collection technologies. The chapter then provides suggestions on choosing presentation technologies. The chapter concludes with a look at how a DOT might work through these collection and presentation technology selection issues.

INSTITUTIONAL CONTEXT

Before state DOTs choose data collection and presentation technologies for their inventory data, the research team recommends that they consider data collection and presentation in its broad institutional context. Inventory units can select the most up-to-date technologies and still fail if they are collecting the wrong types of data. Alternately, inventory units failing to articulate a coherent vision for data collection could be shut out of funding for the equipment and personnel they desire.

The research team recommends that the first step for state DOTs to select inventory technologies is to develop a mission for the inventory unit. Inventory units must articulate why they need to collect a particular type of data. Successful inventory data collection in the past has focused on providing timely information to solve problems, so data collectors must look for problems to help solve. Also, units should consider data collection to be cyclical; providing information to solve one problem will likely churn up other opportunities, so units should think ahead to maintain and build on their databases.

Without a clear mission, inventory units face a host of institutional challenges. State DOT personnel and technology vendors expressed the various institutional constraints to efficient data collection during interviews and site visits. Many professionals mentioned that certain institutional constraints could be more serious threats to efficient road inventorying than are technical challenges. The major institutional problem cited was lack of adequate and consistent funding. It appears that investments in data collection and presentation are difficult to sell to DOT policy makers. "You cannot cut a ribbon for a database" was a theme stated by several professionals. Spending money to simply maintain existing databases was a problem for others. Another problem cited by several agency personnel was that, in some cases, several units of a DOT collect virtually the same data over the same roadways. Others noted that potential "customers" for collected data, both inside and outside of a DOT, rarely knew what was available or how to get it. Some DOT personnel cited a lack of incentive to collect more data than the minimum needed to satisfy Federal requirements. Finally, inventory officials mentioned the fear of providing data to plaintiffs' attorneys in lawsuits against the DOT as a reason for not investing in new technologies.

Developing a coherent mission can help an inventory unit avoid these problems. Based on the comments of professionals interviewed during this project, Figure 39 presents an idealized agency inventory collection and presentation model which could serve as the main component of a unit's mission. The primary purpose of data collection in engineering is to provide better information to decision makers. Thus, the inventory model in Figure 39 begins with a list of problems to solve. This cannot be a list of all the problems that face the DOT—it should be a limited list of problems that have arisen as a result of a lack of inventory data. Communication between the inventory unit and all other units of the agency that might require inventory data is critical here to ensure that all major problems are included and a duplication of effort is avoided.

Several of the best current inventory efforts at state DOTs began with the articulation of problems important to policy makers. For example, the Connecticut DOT's photo log and video log efforts sprang in part from the need for better bridge data after a tragic freeway bridge collapse in 1984 (Hudson, 1997). Also, policy makers began backing the Tennessee DOT's inventory program when the possibilities for better, faster answers to constituents' transportation information requests became clear.

In the second part of the model inventory system, the consolidated list of problems to be solved is used to create a list of inventory data to be collected. Units then use this second list to develop an information system plan. This document details which units will collect what data, which units will need what data, which units will process data, which units

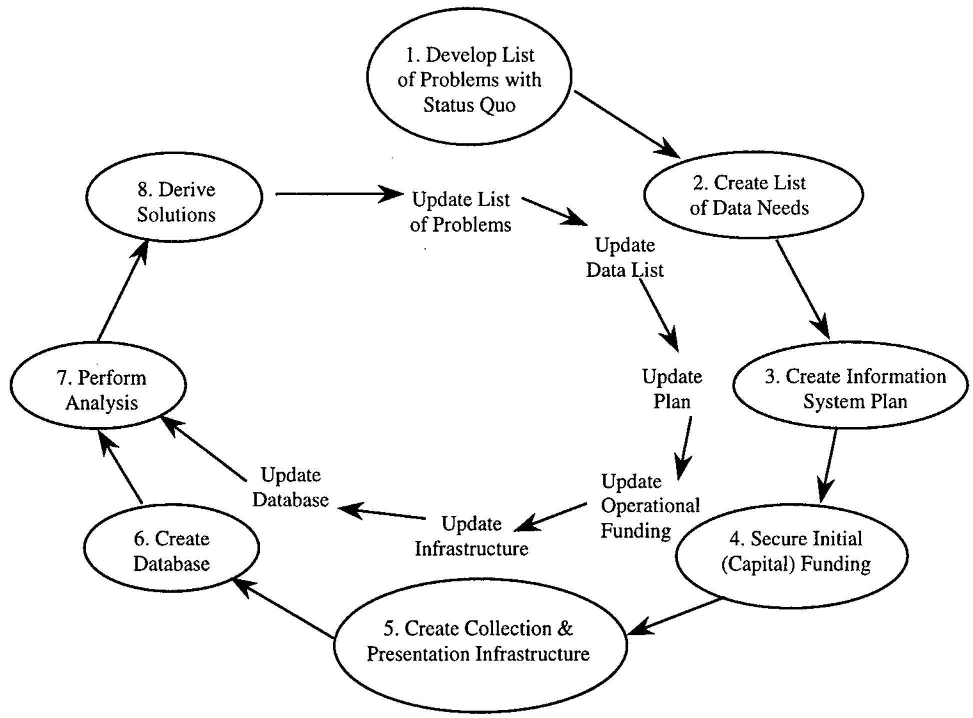


Figure 39. The roadway inventory model.

will store data, and how the data will be communicated among units. The information system plan should provide as many specifications as possible and detail update rates. The plan helps avoid duplicate efforts and shows where bottlenecks are likely to develop if the agency uses insufficient staff, hardware, software, or communications. The final products of the plan are lists of equipment, software, and personnel needed to execute the plan, including new resources that must be acquired.

The model continues with acquiring funding, creating an inventory infrastructure, collecting data, analyzing data, and deriving solutions for the problems listed in the first step. Performing analyses and finding solutions are often the business of units outside the inventory unit; however, after solutions have been derived, the inventory unit must document some successes and estimate the money saved. The Connecticut DOT is an example of a leader in the inventory field and has achieved that status by documenting savings attributable to better inventory data (Hudson, 1997).

The final major point about the inventory model is that it is cyclical. The main forces behind the cycle are new problems that arise and changes in the road system. One of the major criticisms of roadway inventory systems of the 1970s and 1980s was that they were quickly obsolete. The need to continually reassess performance (i.e., total quality management) and opportunities for greater efficiency with new technologies also make the case for a cyclical system. Agencies making information system plans must realize the long-term commitment required for success.

In sum, before selecting technologies, inventory units must determine what they need to collect. It is recommended that units move beyond that simple idea to development of an information system plan. The inventory unit should understand who will use the data, how the data will be used, and what quality of data is needed. Excellent starting points for the DOTs in making information system plans are the products of NCHRP Projects 20-27 and 20-27(2). In particular, *NCHRP Report 359* recommends ideal arrangements of hardware and software to allow the best possible use of existing data (Vonderohe et al., 1994). These previous NCHRP projects also emphasized that information systems should be needs-driven rather than technology-driven. Understanding the entire cycle of inventory data collection and use will allow units to avoid some of the common pitfalls others have experienced through the years.

SELECT MEANS OF TRANSPORT

After considering the institutional context, inventory units must select the proper mode of transport for data collection. Vans are a popular choice but by no means an automatic choice. Units can also collect certain inventory data using satellites at one extreme and backpacks at the other extreme. This section describes the factors that inventory units should consider when making a choice, including the number of inventory elements needed and the extent of urban highways to be inventoried.

Backpacks

Data collectors carrying backpacks on foot, on bicycles, or in golf carts can collect some roadway inventory data; however, the conditions under which this option is cost-effective are very limited, and most units will not choose this method. Units should consider three factors when choosing backpack and related means of transport:

1. Units should consider the degree of urbanization. Because data collectors with backpacks move slowly along the highway, this method is much more effective in urban centers where the use of a van is cumbersome because of heavy traffic (traffic may also obstruct the field of view of image capture technologies on board the van). Thus, the backpack means of transport is feasible only where there is a dense set of data elements per kilometer to be collected.
2. Units should consider whether there is any off-road data collection needed. People on foot, on bicycles, or in golf carts can get near objects off the roadway that vans cannot.
3. Units should consider that people with backpacks can carry limited equipment. Most backpack units on the market consist of a DGPS unit and a notebook or handheld computer. If the data elements desired require additional or different sensors, the backpack means of transport is not suitable.

Satellites

As demonstrated in Chapter 5, inventory units can collect some inventory data from satellite images. There are two major restrictions on the usefulness of images from satellites. First, images from satellites do not appear economically competitive for many state DOTs with sparse highway networks. Second, Chapter 5 showed that units can collect only a handful of inventory data elements from satellite images.

The density of highways per square kilometer should be high to justify the cost of satellite images. Chapter 2 reported average prices of $40 to $60 per square kilometer for satellite images suitable for inventory data collection (1- to 5-m resolution) and $8 to $20 per km per direction for van systems with digital image capture systems. Assuming that most highway mileage needs two-way data collection, the van price doubles to about $16 to $40 per centerline km. Using mid-range prices of $50/sq. km and $28/centerline km for satellites and vans, respectively, and assuming that processing costs are roughly equivalent (a reasonable assumption until automatic image processing algorithms are on the market), an inventory unit would need 1.79 centerline km per square km or greater to justify satellite images based on cost. Table 31 shows that only the District of Columbia, Delaware, North Carolina, and Virginia DOTs meet this threshold. It appears that at current costs, satellite data collection may be economically advantageous for a few state DOTs with denser highway networks but not for most state DOTs. Satellite data collection is likely economically competitive for many metropolitan planning organizations, urban county, and city highway agencies.

The limited number of inventory elements that inventory units can extract from satellite images is the second restriction on the widespread use of this method. Table 3 conveyed the researchers' estimate that inventory unit personnel could extract 37 representative data elements (about one-third of the total list of representative elements in Table 1), using point-and-click techniques on 1-m resolution images). Furthermore, the research team judged 9 of those 37 to have a low degree of recognizability. Automatic image processing algorithms are available for only a handful of elements, and none of those algorithms is currently available in off-the-shelf software packages. Inventory units desiring to collect a wider range of data elements than those 37 listed in Table 3 must supplement the satellite images with data from backpacks or vans or should not rely on satellite images.

Vans

Vans are the default choice currently for transporting data collection crews and their equipment. Vans overcome most of the restrictions of backpack and satellite modes of transport because they are much more flexible. Inventory units can equip vans with any number of sensors that can collect data simultaneously during a single pass on the roadway. Data collection can typically occur at highway speeds. Together with the fact that a van crew rarely needs to exceed two technicians, the high speed of vans results in less time spent in the field. Vans are restricted to the highway, but this is not a serious limitation for most state DOT inventory units. Overall, most inventory units will choose vans to convey their data collectors and equipment most of the time.

Having made the decision to use vans in data collection, inventory units face difficult choices in how to obtain and operate the vehicle. In particular, an inventory unit could

1. Equip its own van and use staff to operate it,
2. Buy an equipped van and use staff to operate it,
3. Rent an equipped van and use staff to operate it, or
4. Contract with a company to collect the data using the company's van and crew.

Other options are possible but unlikely in practice.

Several state DOTs have equipped their own data collection vans. For example, the Michigan DOT developed a data collection van at a cost of $125,000 (Miller, 1993) and the New Hampshire DOT developed a van system for $68,000. These DOTs reported substantial cost savings resulting from in-house fabrication (Miller, 1993). However, in-house development and production requires staff highly skilled in

TABLE 31 State roadway density

State	Rural roadway length under state control (km)	Urban roadway length under state control (km)	Total roadway length under state control (km)	Land area (sq. km)	Total roadway km/sq. km
AK	17,781	1,591	19,372	1,478,457	0.01
AL	29,792	6,199	35,991	131,487	0.27
AR	49,289	4,025	53,314	134,882	0.40
AZ	17,988	2,148	20,136	293,986	0.07
CA	47,137	12,726	59,863	404,814	0.15
CO	26,965	3,375	30,340	268,311	0.11
CT	7,019	6,025	13,044	12,618	1.03
DC	0	4,441	4,441	163	27.25
DE	11,359	4,920	16,279	5,004	3.25
FL	22,881	16,220	39,101	140,256	0.28
GA	48,970	9,784	58,754	150,365	0.39
HI	2,772	1,171	3,943	17,211	0.23
IA	29,999	3,277	33,276	144,949	0.23
ID	15,908	892	16,800	213,447	0.08
IL	40,728	15,655	56,383	144,121	0.39
IN	31,386	5,714	37,100	93,064	0.40
KS	32,830	2,204	35,034	211,805	0.17
KY	82,174	7,970	90,144	102,743	0.88
LA	48,088	6,550	54,638	115,309	0.47
MA	5,392	6,524	11,916	20,264	0.59
MD	12,287	5,458	17,745	25,478	0.70
ME	25,368	2,663	28,031	80,277	0.35
MI	25,066	6,560	31,626	147,511	0.21
MN	39,767	3,870	43,637	206,029	0.21
MO	100,539	5,635	106,174	178,568	0.59
MS	32,013	2,795	34,808	122,333	0.28
MT	26,191	554	26,745	376,555	0.07
NC	226,543	30,396	256,939	126,503	2.03
ND	23,600	672	24,272	179,487	0.14
NE	32,584	1,112	33,696	198,508	0.17
NH	11,854	1,332	13,186	23,292	0.57
NJ	4,851	5,920	10,771	19,342	0.56
NM	35,683	2,001	37,684	314,258	0.12
NV	15,560	1,738	17,298	284,625	0.06
NY	38,110	15,400	53,510	122,706	0.44
OH	53,858	13,392	67,250	106,200	0.63
OK	39,724	3,293	43,017	177,816	0.24
OR	33,771	2,686	36,457	249,117	0.15
PA	118,526	26,545	145,071	116,260	1.25
RI	1,063	2,657	3,720	2,732	1.36
SC	114,085	22,665	136,750	78,226	1.75
SD	25,200	620	25,820	196,716	0.13
TN	38,186	7,856	46,042	106,591	0.43
TX	223,132	34,279	257,411	678,624	0.38
UT	16,498	2,499	18,997	212,569	0.09
VA	159,237	27,680	186,917	102,833	1.82
VT	8,731	577	9,308	24,017	0.39
WA	58,259	3,831	62,090	172,263	0.36
WI	35,968	4,812	40,780	140,963	0.29
WV	100,568	4,438	105,006	62,468	1.68
WY	21,044	1,292	22,336	251,202	0.09
Total US	2,266,323	366,642	2,632,965	9,167,328	0.29

technologies such as computer programming, GIS, GPS, and fabrication, besides requiring extensive research and fabrication facilities.

When buying a van from a vendor, costs are obviously relative to the particular packages offered. Some companies sell vans with modular systems that allow more flexibility in the selection of particular sensors. Other companies prefer to sell vans equipped with everything needed to do comprehensive data collection. The resulting costs need to be factored against what an agency can afford for its inventory. Again, decision makers must consider what data elements they need to collect.

If buying a van is too great a capital outlay, agencies can and should consider renting vans from vendors. Vendors have been successful in offering packages suitable to the type of data collection an agency wants to accomplish. Renting a van requires an agency to decide if it wants to use its own personnel to operate the van and collect the data or let the vendor do the entire job. In the vendor-staffed case, the agency must outline exact specifications for data collection so the collected data fit within the standards of the agency's inventory. If the agency wants to use its own personnel, usually the field crews will need training (up to a week, in some cases) and this factor must be added to the base rental cost.

Renting a van-based system still offers an agency the flexibility of when it chooses to do its inventory collection. For cost-effectiveness, an agency should make best use of its rented van by doing most of its road network at a time. There is additional cost every time a vendor must mobilize a van and send it to the agency's location.

SELECT GEOREFERENCING TECHNOLOGIES

An increasingly popular georeferencing technology is the GPS, primarily because of its wide availability and low price. It may be transported on board the van or carried in a backpack. Its accuracy ranges from 100 m to 1 m with differential correction techniques. However, the GPS has shortcomings when it is used as the sole georeferencing technology for collection of inventory data. The most notable difficulties stem from signal blockage in certain areas.

Inventory units can choose a combination of technologies for georeferencing to compensate for lack of performance of a particular technology under certain conditions. Other technologies for georeferencing include DMI, INS, and rangefinders. These technologies provide relative positioning, whereas the GPS results in absolute positioning.

SELECT DESCRIPTIVE DATA COLLECTION TECHNOLOGIES

After selecting a mode of transport for collecting inventory data, agencies must choose the technologies with which to collect descriptive data elements. For the satellite and backpack modes of transport, the choices of descriptive data collection technologies are very limited. Satellites will rely on imagery for the foreseeable future. The backpack mode will rely on observations recorded in a notebook or handheld computer by the data collector. Data collectors on foot may also be able to record their utterances for later playback in a voice recognition system, but such a system has yet to be tested.

The van mode of transport provides many more choices in descriptive data collection technologies. For the collection of multiple inventory elements using a van, Chapter 2 discussed observations recorded with the help of a keyboard, recording of digital images using digital image capture technologies, the automatic processing of digital images, and voice recognition systems. Recording observations with pencil and paper is of course possible from a van. The automatic processing of digital images from a van will not be developed for several years. Chapter 4 presented the results of four experiments that the research team conducted to compare manual observations and digital images. Many other data collection technologies are available for vans for specific elements, such as retroreflectometers for sign quality, ground-penetrating radar for locations of underground features, and lasers for pavement-related measurements.

When choosing data collection technologies for vans, with a set of desired data elements in mind, the research team recommends that agencies examine

1. The georeference and descriptive data accuracy desired for each element,
2. The budget and staff available, and
3. The desire for a recorded image that the agency may consult later.

Other decision factors mentioned in the literature or by professional contacts during the project typically were subsets of one of the above. The third factor listed, the desire for a recorded image, is generally much less important than the other two factors but is a relative advantage of the digital image technology.

Vendors of van systems can integrate almost any combination of data collection technologies into a van. This flexibility is because computer memory and data storage have improved significantly in recent years. This places the emphasis for agencies even more squarely on the question "What do you want to collect?" rather than on the old question "What is possible to collect?" In other words, the more flexible van systems available today make inventory data collection more driven by problem-solving than by available technologies.

For many data elements, data collection technologies include manual observation, photogrammetric software digital measurements, and voice recognition technology. This research did not add to the body of knowledge regarding voice recognition. Voice recognition technology appears promising, in large part because of the labor savings allowed by the van driver doing the talking. However, the available evidence on the accuracy and speed (labor needed) provided by voice recognition systems is thin. The results available to this point are from uncontrolled studies outside the roadway inventory field that have not been well documented. The accuracy of voice recognition systems will likely be no better than manual observation recorded with paper and pencil or on computer, because manual decisions are still needed. The additional error probable with voice recognition over those currently common manual systems is in the software that decodes the speaker's utterances. Agencies considering voice recognition technology for their inventory should conduct thorough tests of its accuracy and speed before committing to it. As an alternative, those with a stake in better inventory data collection should collectively fund a rigorous scientific test of the accuracy of voice recognition systems.

Manual Observation or Digital Image Capture Technology?

The four experiments described in Chapter 4 should be a considerable help to agencies choosing between manual observations and digital image capture technologies for their vans. Table 32 shows a summary of t-tests on the overall data collected at the four locations. The research team conducted the experiment on nine representative elements in three highway environments at four different locations. Table 32 shows that, overall, manual observations were slightly, but not significantly, more accurate than digital. There was a trend in the results that the more sophisticated the digital system, the better its performance relative to the manual observations. Digital was clearly more accurate than manual on lane width, a short measurement near the camera(s), and less accurate than manual on sign lateral placement, a longer measurement further from the camera. Digital also proved more accurate (in most cases) than manual for the longitudinal elements: driveway width and street light spacing. The experiment showed very little difference between manual and digital for vertical measurements or the estimation of the sideslope. By roadway environment, the more sophisticated digital systems proved more accurate on two-lane and interstate highways, while manual observation was more accurate than all four digital systems on urban streets.

The research also clarified the amount of staff time and, ultimately, budget required for manual observation and photogrammetric software digital measurements for typical data elements. Manual observation requires relatively more time in the field because the data collector makes several stops for collection of data if the required data elements are somewhat dense. Digital systems, by contrast, require more processing time in the office.

Because there is no clear leader in accuracy or staff requirements between manual observation and digital measurement, the best choice for many agencies will be a combination of the two technologies. The research team recommends that agencies trying to decide between, or on a combination of, manual observation and digital image data collection consult Figure 40. The flowchart in Figure 40 relies on three questions to point agencies to one of three outcomes—manual only, a combination of manual and digital images, or digital images only. If the combination is recommended (i.e., if a second crew member is needed in the van to do manual observations), it will usually be most efficient to have the non-driver data collector collect as much data as possible.

TABLE 32 Summary of manual versus digital image data accuracy tests

Location	Environment	Element									For all elements	Overall
		Lane width	Sign width	Sign lateral placement	Driveway width	St. light spacing	Barrier height	Sign height	Sign support height	Side slope		
Milwaukee, Wisconsin	Two-lane	V_{Lambda}	–	–	V_{Lambda}	X	–	–	V_{Lambda}	–	V_{Lambda}	M**
	Interstate	V_{Lambda}	V_{Lambda}	M	X	X	–	–	–	–	V_{Lambda} **	
	Urban	V_{Lambda}	M	M	V_{Lambda}	V_{Lambda}	X	–	–	X	M**	
Denver, Colorado	Two-lane	–	–	–	–	X	–	–	–	–	V_{MSI}**	M**
	Interstate	–	–	–	X	X	–	–	–	–	V_{MSI}**	
	Urban	–	–	–	–	–	X	–	–	X	M**	
Madison, Wisconsin	Two-lane	–	–	–	X	X	X	–	–	X	M	M**
	Interstate	–	–	–	X	X	X	–	–	X	V_{Mandli}**	
	Urban	–	–	–	X	X	X	–	–	X	M**	
Rocky Hill, Connecticut	Two-lane	$V_{ConnDOT}$	X	M	M	X	X	X	X	X	M**	M**
	Interstate	–*	X	M	X	X	X	X	X	X	M**	
	Urban	$V_{ConnDOT}$	X	M	$V_{ConnDOT}$	$V_{ConnDOT}$	X	X	X	X	M	

Legend
X = Not Tested
– = Not statistically different at the 0.05 level
M = Data collected by the manual method is statistically more accurate at the 0.05 level
V_{Lambda}, V_{MSI}, V_{Mandli}, $V_{ConnDOT}$ = Data collected by the particular digital image method is statistically more accurate at the 0.05 level
* Shoulder width measured in place of lane width
** Statistically not different at the 0.05 level

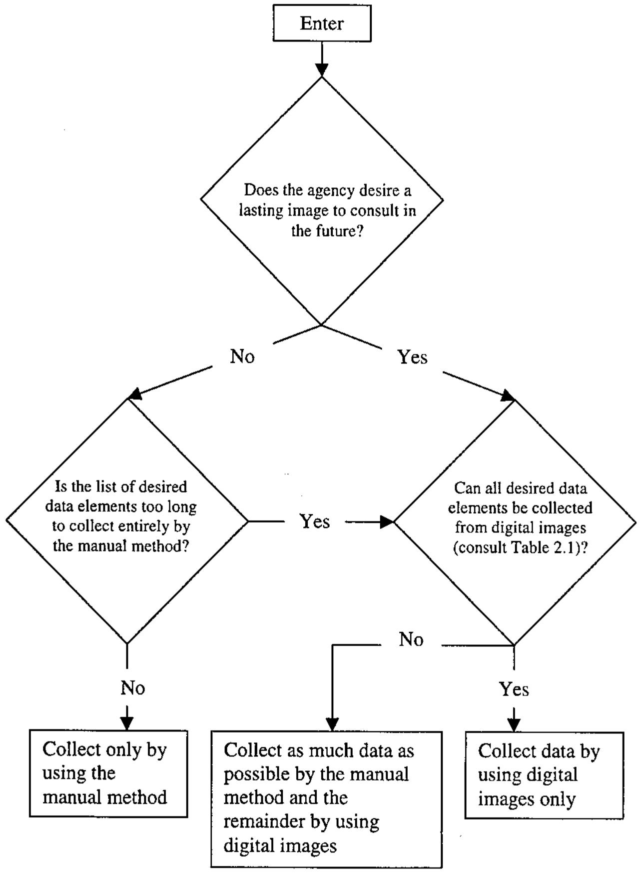


Figure 40. Guidance on selecting between, or a combination of, manual and digital image data collection technologies.

SELECT PRESENTATION TECHNOLOGY

Figure 41 provides a decision tree on how an agency should set up an inventory data presentation system. This presentation system selection process has more decisions than the data collection selection process because the way an agency will present and use inventory data is more closely related to the way that the agency as a whole shares information. There are 12 distinct paths through the decision tree for inventory data presentation.

The first decision in Figure 41—whether or not an agency should have a computerized database—will either limit an agency to manual methods or allow it to use automated methods. The benefits of computerization are well known, and agencies will almost universally say "yes" at this decision point.

The second decision is a choice between mainframe and personal computing. This is a huge decision, typically made by decision-makers outside the inventory unit, and generally outside the scope of this project. The research team will only point out a few of the most important facets of the decision here. First, a mainframe is currently the standard computing platform in many highway agencies. This implies that a switch to PCs may be costly initially and that the institutional culture and expertise are in mainframes. Of course, the costs of new PCs may be spread over several functions besides the presentation of inventory data. Second, mainframes restrict an agency from using GISs that run on PCs and workstations. Third, PCs these days feature increasing speed, increasing memory, expanding ranges of available software, and decreasing costs. Fourth, many institutions take advantage of vastly expanded communications capabilities to network their PCs and provide the capabilities for distributed systems. Researchers from the University of Wisconsin provided an excellent summary of these issues a few years ago for NCHRP (Vonderohe et al., 1994) that agencies should turn to for help on this question.

The third decision in the tree is whether to use a GIS to present the inventory data. As described earlier in the report, GISs have many functions that agencies may find desirable to aid data presentation, including 2-D and 2.5-D visualization, querying, data layering, and various built-in spatial analysis tools. If the highway agency is interested in one or more of these functions, a GIS is encouraged.

Of course, choosing a GIS is a huge decision with many options. For example, a survey of 50 transportation agencies at a recent GIS conference showed a wide range in GIS-related operations (Moyer and Pierzinski, 1997). There was a sizable variation in hardware (7 different systems) and software (13 different systems or packages) among the agencies responding. The number of PCs or workstations used varied from 3 to 300, budgets ranged from $75,000 to $2.5 million, and staff sizes varied from 1 to 30. Organizationally, GIS-related staff were located in the planning, information, GIS, cartography/mapping or engineering units. (Decisions 6 through 9 in the tree help agencies choose a GIS, and there are many references available to help as well.)

The fourth decision in the tree is whether the agency plans to present videologs without a GIS, in which case it will need software for that purpose.

With or without videologs, the agency must determine whether it needs SLDs. This is the fifth decision in the tree and the last pertaining to presentation without a GIS. Several agencies have developed their own software for producing SLDs outside of a GIS. Outside of a GIS, most agencies would use standard PC software, such as spreadsheets, to produce reports from inventory data, so this activity terminates this branch of the tree.

Decision 6 in the tree concerns how an agency will use its GIS. Off-line information flow—sharing data by diskette or tape, or sending a report on paper—is currently a common practice. However, on line, via the Internet or an intranet, is a vastly superior way to share inventory information in a GIS database. If the highway agency has outfitted many of its units with sufficient Internet or intranet connections, it will likely choose on-line data sharing.

If the agency will share data in a GIS on line, it has two more basic organizational decisions to make before choosing a particular GIS package. Decision 7 is whether the agency

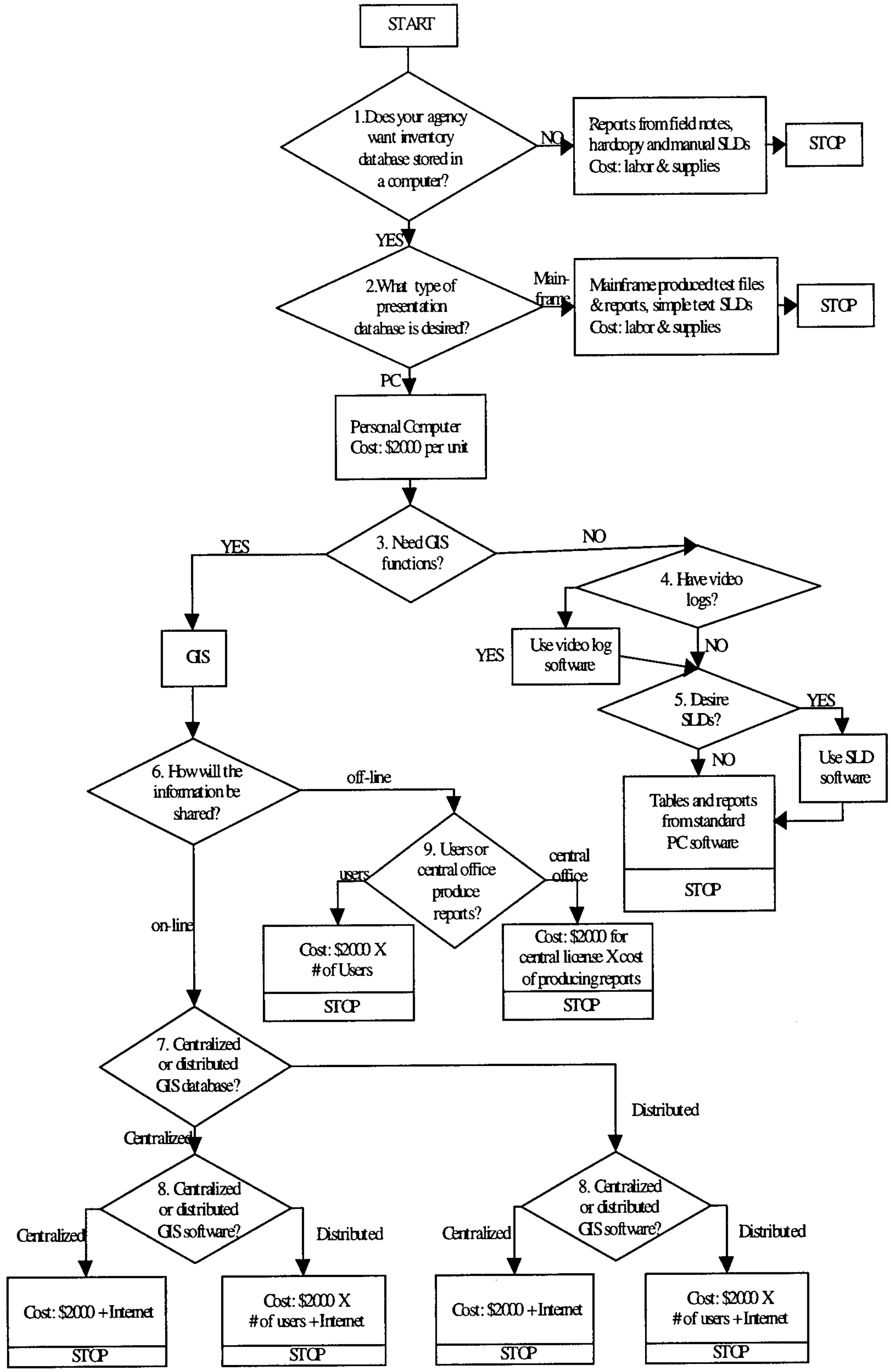


Figure 41. Decision tree for data presentation.

desires a centralized or distributed GIS database. A centralized database is maintained by a single unit. Users request data from the central unit, and the central unit supplies a "read-only" copy. With a distributed system, several units within the highway agency collect and maintain inventory data, usually meeting some common specifications. Users receive data over the Internet from the maintaining unit.

Centralized and distributed databases each provide several advantages over the other. Users in an agency with centralized databases know where to go for information. In addition, the inventory professionals in the central agency will likely be more efficient in data processing than people in a variety of units maintaining separate databases. A central unit may be more successful establishing and keeping common specifications across several databases. A central unit exclusively in the inventory data "business" may also be able to find more "customers" for its data. With distributed data, however, the maintaining unit has more of a stake in its own data. Distributed databases allow one fewer step between collection and presentation.

Decision 8 is whether the agency desires the GIS software to be centralized or distributed. Centralized software means that users scattered throughout the agency would load up a single software package maintained by a central unit when they wanted to make an analysis. Centralization leads to great efficiencies in licensing, loading, and maintaining software. Training users in the same software is also likely more efficient than training in many different packages. Distributed software, on the other hand, allows users to purchase and customize their own software.

The ninth and final decision in the tree is, in the case of off-line information sharing, whether analyses will be made by central unit staff or by personnel in units scattered throughout the agency. Central unit staff would be GIS experts, highly familiar with the chosen software. Analysts scattered through the agency would need a great deal of training to be effective with today's GIS packages. However, if the central unit staff is underfunded or receives a flood of requests, turnaround time for results may be high. Also, analyses by a central unit staff would deprive the scattered units of the ability to interact with the data and quickly follow up promising leads.

AN EXAMPLE APPLICATION OF THE SELECTION METHODOLOGIES

To illustrate how a state DOT might use the collection and presentation selection methodologies presented above, the research team offers the following case of the Connecticut DOT. The research team chose the Connecticut DOT because it has a relatively advanced state DOT inventory unit that has thought through most of the steps in the selection methodologies already.

The research team's knowledge of the Connecticut DOT inventory system is incomplete. In instances during the example where the research team recommends some action that is different from the current procedures of the Connecticut DOT, it is a strong probability that the difference results from incomplete knowledge rather than some shortcoming of the inventory unit. The example is for illustrative purposes only.

The process to select data collection technology is discussed in the following paragraphs.

Consider the Institutional Context

The Connecticut DOT has a fine understanding of the institutional context of its inventory system. The DOT has about 6,400 km of roadway to inventory, with about a 1.17 : 1 urban to rural ratio (a slightly different ratio than shown in Table 31 for the roadway system as a whole). The impetus to a major upgrade in inventory capability was a 1984 bridge collapse, and the major focus areas of the inventory since then have been maintenance and safety. DOT personnel have grown accustomed to and make frequent use of "drivers-view" images provided at 17 workstations scattered throughout the DOT offices. The inventory unit desires flexibility in its systems to be able to provide information to a wider range of "customers" in the future, including some outside the DOT.

Select a Mode of Transport

The van mode has been the predominant choice of the Connecticut DOT. Only van systems provide the range of elements and the library of images the information consumers expect from the inventory unit. Satellite systems soon may be cost-effective for some elements in dense states like Connecticut, but are unlikely any time soon to be able to deliver the maintenance-related and safety-related details the DOT expects.

Select a Georeference Technology

GPS supplemented by DMI and INS seem like the logical georeferencing choices for the Connecticut DOT. Connecticut has enough tree cover, urbanization, and rugged terrain that GPS probably would not be sufficient alone, and a DMI is an inexpensive and sufficient supplement when GPS receivers are blocked. The decision on INS should reduce to the level of detail the DOT and other information "customers" need on horizontal and vertical alignment. To this point, the DOT has not strongly demanded those alignment details, and the georeferencing precision offered by GPS has been sufficient. However, some of the new "customers" of inventory information may desire the detailed alignment information that an INS can provide.

Select Descriptive Data Collection Technologies

The expectation within the Connecticut DOT that the inventory unit will deliver "driver-eye" images leads to the choice of digital images as the primary data collection technology. As the experiment results showed, the current Connecticut DOT procedure for recording measurements from the images is limited in the number of measurements and in the accuracy of measurements. Thus, the inventory unit should investigate (and is investigating) more robust and sophisticated photogrammetric software digital measurement systems. The inventory unit should have its technicians in the vans record data manually as much as possible and should experiment with voice recognition to improve the efficiency of the technician in the van recording data manually.

Next, the data presentation technology selection process (Figure 41) is examined in terms of the Connecticut DOT.

Computerized Database?

The Connecticut DOT has moved strongly away from a paper database handled by manual techniques, and there is no reason to reverse that trend. The DOT has been willing to invest in computer technology and has seen many benefits from that choice through the years.

Mainframe or PC?

This next decision point in the selection of a presentation system is a huge one largely made by players outside the inventory unit. The Connecticut DOT, like most DOTs, historically has relied on a mainframe for the bulk of its computing, including inventory functions. However, the increasing power, expanding communications capabilities, and decreasing costs of networked PCs and the expanding range of available software have led to a trend in that direction, even in the state DOTs. For these reasons, plus the demands of "customers" outside the DOT with no access to the DOT mainframe, the Connecticut DOT inventory systems should migrate (and are migrating) toward networked PCs as well.

Import Data to GIS?

GISs provide many functions that may be useful to the "customers" of inventory data, including visualization, querying, data layering, and various built-in spatial analysis tools. Already collecting high-quality, georeferenced images and inventory data, it is highly likely that the Connecticut DOT can gain much efficiency in these functions with relatively little extra cost by using a GIS.

Information Shared On Line or Off Line?

The inventory unit already provides data on line to its current DOT customers through its 17 workstations. Evolution into a PC network will allow easier on-line connections to a wider range of users.

Centralized Database or Distributed Databases?

The institutional context in the Connecticut DOT seems to point to a centralized database. If other units of the Connecticut DOT collect "inventory" data besides the inventory unit, the inventory unit should act as a centralized conduit or "market" between point of collection and the "customer" for those other data.

Centralized or Distributed GIS Software?

The tradition of sharing information on line throughout the Connecticut DOT seems to indicate that many of the users and potential users of inventory data are computer literate and trainable. Also, supportive as they have been of the needs of the inventory unit, the Connecticut DOT management may not be able to provide the inventory unit with more staff to fulfill many requests for GIS analyses. Thus, the likelihood is that distributed GIS software would be the best choice. This answer feeds directly into the choice of a GIS package, of course, and means that user-friendliness would be a high priority.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

The research on existing and emerging data collection and data presentation technologies and the validation and demonstration of the most promising technologies described in the previous chapters led to the key findings and ideas for future research presented below. The findings will help state DOTs to better plan their roadway inventory systems, maximizing productivity while minimizing cost. The ideas for future research will help state DOTs to foresee directions that they should consider in roadway inventory systems. The research team's findings on data collection technologies include the following:

- The institutional barriers to efficient data collection and presentation are often more imposing than the technical barriers. To overcome the institutional barriers, inventory units should concentrate on answering specific questions and should develop information systems plans.
- Although a wide array of roadway inventory data collection technologies is available to state DOTs, the emergence of new, non-traditional inventory data collection technologies such as high-resolution satellite imagery will significantly benefit roadway inventory practice.
- No single existing or emerging data collection technology can collect all desired roadway inventory data efficiently. Therefore, as part of planning roadway inventory systems, state DOTs must carefully analyze and evaluate different inventory data collection technologies to determine the most suitable one for their inventory practices.
- Regardless of the modes of transport and descriptive technologies that state DOTs will decide to use, determination of the precise location of roadway data elements must be based on one or more georeferencing technologies. The GPS is becoming the dominant georeferencing technology, which can be used for all modes of transport and integrated with other sensors such as DMI and INS to improve the reliability and accuracy of the outcome.
- Collecting roadway inventory data using van systems is popular. Although vans equipped with the required set of data collection technologies can be purchased or leased, state DOTs may consider developing their own data collection vans. By outfitting their own data collection vans with a custom set of georeferencing and descriptive technologies, state DOTs can probably save on the initial cost of the van system (compared with purchasing a similar system from vendors). However, this option will work only if the state DOT has available the skilled personnel (such as technicians and programmers) and sufficient fabrication facilities.
- High-resolution satellite digital imagery will play a role in roadway inventory data collection in the future. However, collection of roadway inventory data from high-resolution satellite imagery is possible currently for only a limited number of roadway data elements.
- Collection of many descriptive elements is possible using digital image measurement systems. Currently, these systems are about as accurate and consume as much labor as manual observations. Many agencies will find it best to collect descriptive data with both digital images and manual observations.

The research team recommends the following areas for future research related to roadway inventory data collection:

- Periodic identification and evaluation of emerging roadway and non-roadway data collection methods. This is inevitable given that new data collection technologies potentially applicable to roadway inventory practice are continually emerging.
- Development of techniques to automatically extract roadway features from digital imagery collected by van systems. These automated techniques will require less input from the operator, will improve the performance of the data collection process, and may lower the overall data collection cost.
- Development of automated techniques to extract roadway features from high-resolution satellite imagery. It is anticipated that in the near future there will be many high-resolution satellites available for any given coverage area, that the number of vendors who will provide a range of satellite imaging products will increase, and that the cost of acquiring and processing satellite imaging will decrease. Despite the fact that through satellite imagery it is possible only to extract a limited number of roadway features, the automated techniques will make the collection of roadway features a simple and inexpensive task.

- Evaluation of new advances in voice recognition technology for data collection. The profession needs a rigorous, scientific test of the technology to convince potential users of its accuracy and user-friendliness.

The research team's findings on roadway data presentation technologies include the following:

- For roadway data presentation, several technologies are possible, including DBMSs, SLD technologies, GISs, image processing software, and the Internet and within-agency intranets. Presentation using AVL systems or virtual reality will also be possible.
- GISs are becoming the dominant tool for organizing, storing, analyzing, and presenting roadway inventory data. GISs are advantageous for presenting roadway data because they provide several desired components in a single package and provide easy-to-use overlay display capabilities, complex query capabilities, and network analysis capabilities. The research team anticipates that because GISs support standard DBMSs, where roadway inventory data can be stored and retrieved, and because there is a trend toward integrating SLDs and GISs, the demand for their use in roadway inventory practice will rapidly increase.
- The research team envisions that roadway inventory data presentation will benefit significantly from the Internet or intranets. Use of the Internet is becoming commonplace in many transportation activities. It has already been used by GIS vendors to develop the next generation of GISs (i.e., Internet GIS solutions). The use of the Internet in state DOTs will allow the distribution of roadway inventory data over several sites. Through this distribution, a division can maintain its own database and can share the other division's databases using the Internet.

The research team recommends the following research related to roadway data presentation:

- Investigation into AVL systems for real-time collection and presentation of roadway data. Although AVL technologies have made strides in navigation, dispatching, and other applications, their applicability to roadway inventory data collection and presentation has not been explored. The research team envisions that a custom AVL system will provide a new approach in automating the tasks of collecting and presenting roadway inventory data. In particular, there is the possibility of increased automation in collecting and presenting roadway inventory data in real time through AVL systems and technologies.
- Development of optimal strategies for using Internet GIS solutions for roadway data presentation. Because the Internet is continuing to become the backbone of information infrastructures in many organizations, its use in many transportation activities, including roadway inventory, is inevitable. Furthermore, the growing trend by GIS vendors to develop Internet GIS solutions will make SLD production simple, fast, and inexpensive.

The research team also urges further study of the institutional barriers to acquiring and using efficient information systems in state DOTs. Great strides in the efficient delivery of accurate information to decisionmakers are possible. The research team recommends that future research related to institutional barriers be based on answering the question "what data do we need?" rather than the question "what data can we collect?"

REFERENCES

Baumgartner, A., C. Steger, C. Wiedemann, H. Mayer, W. Eckstein, and H. Ebner. Update of Roads in GIS from Aerial Imagery: Verification and Multi-Resolution Extraction (1997).

Bonsall, P., F. Ghahri-Saremi, M. Tight, and N. Murler. "The Performance of Handheld Data-Capture Devices in Traffic and Transport Surveys." *Traffic Engineering and Control*, Vol. 29, No.1 (January 1988).

Bourguignon, J., P. Daly, G. Frazer, W. Nelson, and C. Clift. "National Rural Electric Cooperative Association Map Display in Utility Vehicles Project at Cobb Electric Membership Cooperative." AM/FM International Conference Proceedings, Aurora, CO (1994).

Burrus, D., and R. Gittines, *Technotrends: How to Use Technology to Go Beyond Your Competition*. Harper Business (1993).

Chang, Y.L., and X. Li. "Adaptive Image Region-Growing." *IEEE Trans Image Process,* Vol. 3 (1994) pp. 868–872.

Clark County Mapping Project, Project Report, Center for Mapping, Ohio State University (1994).

Coetsee, J., A. Brown, and J. Bossler. "GIS Data Collection Using GPS Van Supported by a GPS/Inertial Mapping System." Proceedings of ION GPS-94, Utah (1994).

Dai, X., and S. Khorram. "Development of a Feature-Based Approach to Automated Image Registration." Proceedings of the IEEE International Geoscience and Remote Sensing Symposiums (IGARSS'97), Singapore (August 1997) pp. 243–245.

Datta, T., and L. Herf. "Cost-Effectiveness Analysis for Various Inventory Procedures." *ITE Journal* (September 1986).

DeFrain, L., R. Miller, and J. Darlington. "Development of an Instrumented Vehicle to Measure Roadway Curve and Grade." *Research Project 92 G-280*. Materials and Technology Division, Michigan Department of Transportation (1993).

Devore, J. *Probability and Statistics for Engineering and Science, Third Edition*. Brooks/Cole Publishing Company (1991).

Drakopoulos, A., and E. Ornek. Using Photolog Data Processing to Evaluate Existing Horizontal Roadway Geometry Characteristics. Paper presented at the 78th Annual Meeting of the Transportation Research Board, Washington, DC (January 1999).

El-Sheimy, N. "A Mobile Multi-Sensor System for GIS Application in Urban Centers." ISPRS Conference Proceedings, Vienna, Austria (July 1996)

Erdas Field Guide, Atlanta, Georgia (1991).

Everest, G. C. *Database Management: Objectives, System Functions, and Administration*. McGraw-Hill, New York (1986).

Firestone, L., S. Rupert, J. Olson, and W. Mueller. "Automated Feature Extraction: The Key to Future Productivity." *Photogrammetric Engineering and Remote Sensing* (October 1996).

Fischler, M. et al. "Detection of Roads and Linear Structures in Low-Resolution Aerial Imagery Using a Multisource Knowledge Integration Technique." *Computer Graphics and Image Processing*. Vol. 15 (1981).

Fletcher, R. Dynamic Electric Utility GIS Database. ESRI User Conference (1996).

Forlani, G., E. Malinverni, and C. Nardinocchi. "Using Perceptual Grouping for Road Recognition." International Archives of Photogrammetry and Remote Sensing, *ISPRS,* Vol. 31, Part B4, Austria (1996).

Geman, D., and B. Jedynak. "An Active Testing Model for Tracking Roads in Satellite Images." *IEEE Transactions on Pattern Analysis and Machine Intelligence*. Vol. 18, No. 1 (1996).

GeoDynSeg User's Manual, Bentley Systems, Inc. (1998).

Gruen, A., and H. Li. "Semi-automatic Linear Feature Extraction by Dynamic Programming and LSB-Snakes." *Photogrammetric Engineering and Remote Sensing*. Vol. 63, No. 8 (1997).

Harkey, D. "ARAN Curve and Grade Study." Highway Safety Research Center, The University of North Carolina at Chapel Hill (1997).

Hoffmann-Wellenhof, B., H. Lichtenegger, and J. Collins. *GPS: Theory and Practice*. Springe-Verlag, New York (1992).

Hudson, J. "Current Developments in Roadway Image Acquisition Systems." Paper Presented at the 76th Annual Meeting of the Transportation Research Board, Washington DC (1997).

Hughes, J. "Technology Trends Mark Multimedia Advancements." *GIS World*, Vol. 9, No. 11 (November 1996).

Hutchinson, S., and L. Daniel. *Inside ArcView*, World Press (1995).

ITE Manual of Transportation Engineering Studies, Institute of Transportation Engineers, Prentice Hall (1994).

Karimi, H. A. "A Flexible Computing Environment for Solving Spatial Problems." *URISA Journal*, Vol. 8, No. 20 (1996).

Karimi, H. A., and J. E. Hummer. "Collection and Presentation of Roadway Inventory Data." Interim Report to National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC (1997).

Karimi, H. A., X. Dai, A. J. Khattak, and J. E. Hummer. "Roadway Feature Extraction and Delineation from High-Resolution Satellite Imagery." Paper submitted to EOM for publication review (1998).

Karimi, H., and J. Blais. "Current and Future Directions in GISs." *Computers, Environment, and Urban Systems*, Vol. 20, No. 2 (1996).

Karimi, H., and E. Krakiwsky. "Design Concepts for Knowledge-Based Route Guidance Systems." IEEE Position Location and Navigation Symposium (PLANS '88) Florida (1988).

Lambda Technologies International. The GPSVision Field Data Collection System (1998).

Landphair, H., and T. Larsen. "Applications of 3-D and 4-D Visualization Technology in Transportation." *NCHRP Synthesis of Highway Practice 229,* Transportation Research Board, National Research Council, Washington, DC (1996).

Lawless, D., and S. Bourgeois. City of Aurora Automatic Location Tracking System (ALTS) Pilot Project Report (1995).

Lee, H., M. A. Weissman, and J. P. Powell. "Measuring Highway Inventory Features Using Stereoscopic Imaging System." Applications of Advance Technologies in Transportation Engineering, Proceedings of the 2nd ASCE International Conference, Minneapolis, MN (August 18–21, 1991).

LRS Technical Manual, 1995 Edition. Commonwealth of Pennsylvania, Department of Transportation, Bureau of Maintenance and Operations Roadways Management Division (1995).

Lucius, A. "Mobile Mapping System Provides Exact Positioning, Prevents Lawsuits." *Civil Engineering News* (1997).

Mandli Communications. RoadView IV™ User's Manual and Software Documentation (1997).

Mastandrea, A., B. Swindall, and G. Klassen. "Development and Implementation of an Automated Facility Inventory System." *Transportation Research Record 1500,* Transportation Research Board, Washington, DC (1995).

Measurement Science Inc. The VISAT Mobile Mapping System: The Inverness Park Pilot Project (November 1997).

Meehan, W. J. AM/FM/GIS—Enabling Redesign of Electric Utility Operations. In *Automated Mapping and Facilities Management Conference Proceedings,* Aurora, CO (1994).

Miller, R. "An Instrumented Vehicle to Measure Roadway Curve and Grade and Application to GIS." Proceedings of the AASHTO GIS for Transportation Conference (1993).

Moyer, D., and D. Pierzinski. Summary Report: 1997 Geographic Information Systems for Transportation (GIS-T) Symposium. North Carolina (March 1997).

Neter, J., W. Wasserman, and M. Kutner. *Applied Linear Statistical Models, Third Edition.* IRWIN (1990).

Novak, K., and J. Nimz. Transportation Infrastructure Management: Seneca County Creates a Complete Inventory of its Transportation Infrastructure. GIS for Transportation Symposium, Greensboro, NC (March 1997).

Pavlidis, T., and Y. T. Liow. "Integrating Region Growing and Edge Detection." *IEEE Trans Pattern and Machine Intelligence*, Vol. 12 (1990) pp. 225–233.

Pawlovich, M., E. Jaselskis, and R. Souleyrette. "Emerging Concepts in Innovative Sign Management Programs." *Transportation Research Record 1553*, Transportation Research Board, National Research Council, Washington DC (1996) pp. 12–17.

Roadware Corporation. Data Collection Technologies, undated.

Roadware Corporation. Georgia Department of Transportation Test Results (January 1995).

Roadware Corporation. Kansas Department of Transportation Test Results (1996).

Roadware Corporation. North Carolina Test Results. Sponsored by the FHWA (1994).

Schwarz, K., and N. El-Sheimy. "Kinematic Multi-Sensor Systems for Close Range Digital Imaging." Proceedings of ISPRS Commission V, Working Group III (1997).

Shaw, L. E., and M. F. Guthrie. Eaton County—Michigan Global Positioning Systems Pilot Study. Geographic Information Systems for Transportation Symposium, North Carolina (1997).

Smailus, T., D. Bullock, and D. Besly. "Implementation of a Multimedia Highway Sign Database." *ITE Journal* (September 1996).

Vaidya, A., D. Baraniak, and K. Novak. CONRAIL's GIS Incorporates Kinematic GPS and Stereo Digital Imaging. AM/FM International Conference Proceedings, Aurora, CO (1994).

Vonderohe, A., et al., "Adaptation of Geographic Information Systems for Transportation," *NCHRP Report 359*. Transportation Research Board, National Research Council, Washington, DC (1993).

Whited, J., and S. Kadolph. "Automated Collection of Sign Inventory Information by Integrating Global Positioning System (GPS) with Videologging Data Collection Activities." Office of Planning Services, Iowa Department of Transportation (1995).

Zaho, Y. *Vehicle Location and Navigation Systems*. Artech House, Inc., MA (1997).

APPENDIXES A THROUGH D

UNPUBLISHED MATERIAL

Appendixes A through D contained in the research agency's final report are not published herein. For a limited time, these appendixes will be available on a loan basis or for purchase ($5.00) on request to NCHRP, Transportation Research Board, Box 289, Washington, D.C., 20055.

Appendix A: State DOT Telephone Survey Questionaire
Appendix B: State Telephone Survey Response Summary
Appendix C: Summary of the Site Visits
Appendix D: Research Methodology for Evaluation of Descriptive Accuracy

APPENDIX E

TEST PROTOCOL FOR EVALUATION OF NEW DESCRIPTIVE DATA COLLECTION METHODS

INTRODUCTION

Roadway agencies and vendors occasionally need to evaluate improvements in data collection systems due to the evolution of data collection technologies. This appendix presents the recommendations of the research team for a standardized test protocol for such evaluations. Use of the protocol should ensure that fair and consistent tests on accuracy of data collection are given to improved systems, regardless of who conducts the test or where the test is conducted.

In general, the protocol consists of in-office preparation, collection of inventory data in the field, and in-office data processing and evaluation. Thus, the test protocol activity timing is divided into three time periods: pre-trip (in-office), during the trip or in the field, and post-trip (in-office). Figure E-1 presents a blueprint of the test protocol.

The pre-trip activities involve defining data collection methods, data collection environments, inventory elements, controls during the experiment, any auxiliary measures that may help with the final decision, and the measure of effectiveness (MOE); considering sample sizes; and determining field staffing during data collection. The field activities involve data collection setup, inventory data collection, and collection of ground truth data. The last part of the protocol involves in-office data processing, extraction of inventory data, accuracy assessment, auxiliary factor analysis, and a decision on performance acceptability. A description of each activity follows.

PRE-TRIP ACTIVITIES

Define Data Collection Methods

This activity consists of defining the data collection methods. A definition of the data collection method includes specification of different technologies for mode of transport, georeference, and descriptive data collection. Different technologies are available for selection. Table E-1 aids the evaluator with selection of various technologies used in inventory data collection. Some examples of data collection methods include data collection by using a specific van system, manual observations recorded by paper and pencil, and manual observation recorded by voice recognition.

Define Data Collection Environment

Research conducted under NCHRP 15-15 showed that the descriptive accuracy of different collection technologies varies with the roadway environment. Therefore, the evaluator must specify the type of roadway environment that will be encountered during data collection. Roadway environments include interstate, two-lane rural, and urban streets. These three environments make up the bulk of roadways that an agency maintains. However, other roadway environments that fall somewhere between these are possible. The interstate provides the most consistent environment from state to state.

Define Inventory Data Elements

Research during NCHRP 15-15 indicated that descriptive accuracy is element-specific. Therefore, the evaluator must specify the inventory elements to be collected during field data collection. Table D-3 (Appendix D) provides a list of inventory elements that were found important during NCHRP 15-15 research. The table also gives information on elements that are represented by the important inventory elements. Evaluators may include inventory elements besides the ones mentioned in Table D-3. Considerations for inclusion of inventory elements should be based on coverage of the x, y, and z coordinates, elements located close and far away from the roadway edge, and short and long measurements.

Define Controls

Controls include phenomena that may affect the accuracy of descriptive inventory data but which the evaluator should not allow to vary to get a consistent evaluation of the technologies. Recommended controls include temperature, daylight conditions, and weather and calibration of equipment. Most van systems for data collection use temperature-sensitive technologies (e.g., cameras). Evaluators must make sure that the temperature during data collection is controlled. This is usually accomplished by housing the technology in a temperature-controlled environment. Similarly, data should be collected under similar daylight and weather conditions. Calibration of equipment is an important factor that must be controlled during an evaluation. Data collection under clear weather and bright, sunny conditions are recommended.

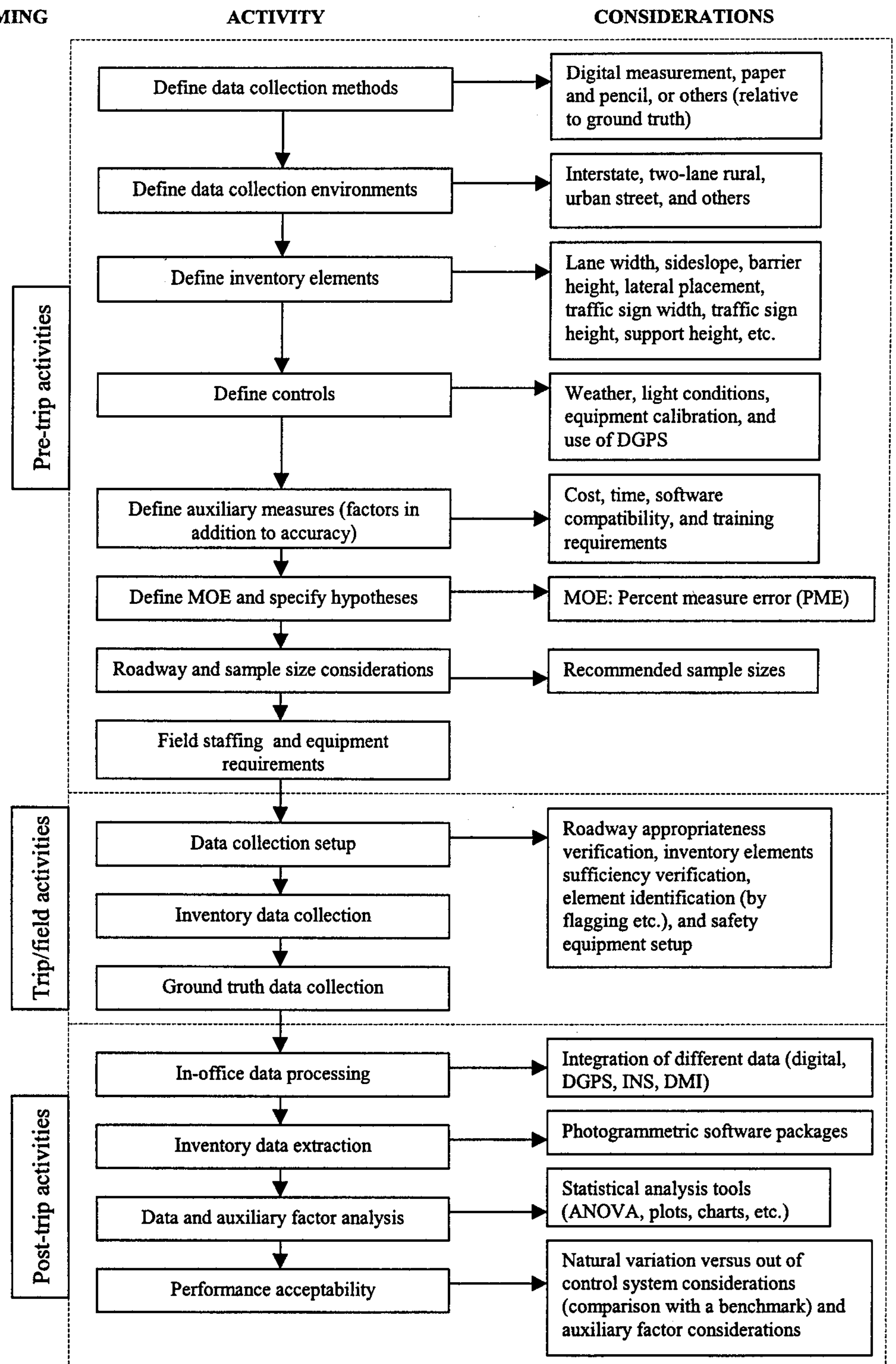


Figure E-1. Test protocol blue print.

Define Auxiliary Factors

This activity consists of defining additional factors that the evaluator may wish to consider regarding a particular data collection method. The options include cost, time, software compatibility issues, and training requirements.

Define MOE and Specify Hypotheses

During this activity, the evaluator must specify the MOE for the evaluation and the hypotheses under investigation. The recommended MOE for descriptive data accuracy is the percent measurement error (PME). It is defined as follows:

TABLE E-1 Technologies employed during inventory data collection

Technology Category	Technologies
Transport	Motorized vehicle Non-motorized vehicle Walk
Georeference data collection	Visual estimate Tape measure DMI (measuring wheel, vehicle odometer, or other specialized distance measuring instrument) GPS/DGPS INS Image registration technology
Descriptive data collection	Visual estimate Plain paper and pencil Printed form and pencil Electronic writing pad Computer with keyboard Rangefinder Audio tape/voice recognition Touch-sensitive screen Film camera Video camera Digital camera Laser Ground-penetrating radar High-resolution image capture Specialized inventory software Photogrammetric software Custom software

$$\text{PME} = [(\text{observation with specific technology} - \text{ground truth})/\text{ground truth}] * 100$$

where observation with specific technology refers to a descriptive observation made on an inventory element and ground truth refers to a more exact description of the inventory element (usually obtained with a more precise measuring instrument such as a tape measure for short distances).

The use of PME as the measure of effectiveness for descriptive accuracy of inventory data has several useful properties. Its sign allows the user to determine if a particular method of data collection is overestimating or underestimating the true dimension of the inventory element. That is, a positive PME sign indicates that the particular method is overestimating true measurement, while a negative PME sign indicates underestimation. The use of field measurement in the denominator of the above equation normalizes for the size of the inventory element. Thus, errors in inventory elements of different sizes are comparable. The use of PME is simple and straightforward.

Roadway and Sample Size Considerations

The proper choice of sample roadways for evaluation of the collection technologies is important because roadway characteristics affect the quality of data as well as the safety of the data collection crew. Roadways should be chosen such that they are representative of highways on which the technologies would generally be used.

The sample size in any experiment depends upon the variability in the population. For a known population variability and assumed permitted error, it is possible to estimate an adequate sample size. The research team did not find any scientific information on sample sizes for inventory data collection in the literature and, therefore, collected as much data as possible within the budget and time constraints of NCHRP 15-15 in its tests. Tables E-2 through E-5 present summaries of the collected data at the four locations in those tests. Based on the variability in the collected data, Table E-6 presents recommended sample sizes for different inventory elements under the three roadway environments. Sample sizes for various inventory elements in the urban environment are significantly larger than their counterparts in the other two environments due to the larger variability of inventory elements encountered on urban roadways. The recommended sample sizes provide guidance on the number of observations to be made on the different inventory elements in the field. Agencies may collect larger samples than Table E-6 to improve the power of the findings.

Field Staffing and Equipment Estimates

Before proceeding to the field, adequate resources must be allotted for field activities. Allocation of resources will depend on equipment required during data collection, sample sizes, location of data collection, traffic on the roadway being inventoried, productivity of the particular collection technologies, and weather.

The research team recommends the use of at least a two-person crew during field activities. Safety equipment such as traffic cones, flags, flashing lights on top of vehicles, safety vests, and hard hats must be provided for field use. Sometimes ground truthing may require specialized equipment. For example, the research team devised a "slope meter" to accurately measure road sideslopes during NCHRP 15-15 data collection.

Post-trip resources for data processing such as computers and personnel must also be taken into account at this stage of the evaluation. Table E-7 provides a list of items to consider during an evaluation.

TABLE E-2 Sample characteristics for data collected in Milwaukee, WI

	Two-lane Environment		Interstate Environment		Urban Environment	
Method / Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width (m)	3.35 0.00 17	3.65 0.41 17	3.70 0.05 35	3.58 0.06 35	5.06 1.72 18	6.42 6.67 18
Roadside Slope (degrees)	9.25 4.70 16	10.83 266.34 16	8.48 9.94 27	7.70 17.30 27	-	-
Barrier Height (m)	0.76 0.01 6	0.73 0.05 6	0.84 0.08 15	0.82 0.0.05 15	-	-
Driveway Width (m)	22.69 450.28 9	22.69 450.28 9	-	-	9.47 16.49 14	8.54 18.40 14
Street Light Spacing (m)	-	-	-	-	39.39 142.46 13	28.38 73.77 13
Sign Width (m)	0.49 0.01 6	0.67 0.15 6	2.07 0.82 10	2.89 2.13 10	0.58 0.03 6	0.65 0.03 6
Sign Height (m)	1.01 0.02 6	0.90 0.01 6	1.39 0.02 7	1.40 0.03 7	0.99 0.01 6	1.05 0.03 6
Sign Support Height (m)	1.94 0.09 16	1.62 0.06 16	2.24 0.32 31	2.42 3.01 31	2.00 0.05 20	2.11 0.10 20
Sign Lateral Offset (m)	4.41 0.67 17	3.90 0.75 17	5.37 1.12 31	6.60 6.70 31	0.60 0.11 17	0.96 0.13 17

Note:
All linear measurements originally recorded in feet
Cell values represent:

Mean Variance No. of Observations

ACTIVITIES DURING THE TRIP

Data Collection Setup

Data collection setup consists of verification of the appropriateness of the chosen roadways, identification of sufficient inventory elements, and taking safety precautions. The data collection crew should drive the candidate roadways to assess suitability for data collection. This first pass also allows crew members to identify sufficient numbers of inventory elements for the evaluation purpose. In case imagery is involved, data collectors can put 2-in.-by-2-in. orange flags beside inventory elements of interest to facilitate location of the elements in the images. Safety equipment such as traffic cones can be set up during this stage of the evaluation.

Inventory Data Collection

The inventory data collection consists of using the selected collection technologies to collect sample data. Information on data collection time should also be recorded.

Ground Truth Data Collection

Collection of ground truth data involves making accurate observations on inventory elements. The ground truth data serve as a benchmark for accuracy evaluation of the sample data collected with the technologies under investigation. Ground truth data should be collected last to avoid biasing the sample data. Typical means for collection of ground truth descriptive data include a tape measure and measuring wheels. Specialized equipment may sometimes be needed for measurement of some inventory elements.

POST-TRIP ACTIVITIES

In-Office Data Processing

In-office data processing consists of integrating different data collected in the field. The processing depends on the technologies used for collection of data. Significant integration may be involved if a van system with a host of collection technologies are used. The processing should result in a usable data set from which inventory elements may be extracted.

TABLE E-3 Sample characteristics for data collected in Denver, CO

	Two-lane Environment		Interstate Environment		Urban Environment	
Method / Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width (m)	3.47 0.02 13	3.54 0.10 13	3.66 0.00047 16	3.60 0.14 16	4.67 2.59 12	4.80 3.12 12
Roadside Slope (degrees)	6.00 2.00 7	7.83 26.88 7	11.66 1.33 12	7.81 15.60 12	-	-
Barrier Height (m)	0.71 0.01 6	0.73 0.12 6	0.68 0.00 9	0.70 0.01 9	-	-
Driveway Width (m)	11.43 53.30 10	16.51 55.35 10	-	-	13.71 19.91 15	11.09 6.83 15
Street Light Spacing (m)	-	-	-	-	63.74 270.39 11	60.12 366.92 11
Sign Width (m)	1.52 0.93 7	1.47 0.49 7	2.30 1.60 11	2.34 1.51 11	1.17 0.22 7	0.93 0.12 8
Sign Height (m)	1.05 0.22 7	1.02 0.09 7	2.31 2.12 11	2.23 1.41 11	1.17 0.22 7	1.33 0.21 7
Sign Support Height (m)	2.24 0.03 13	2.05 0.15 13	2.04 0.22 18	2.12 0.34 18	2.10 0.003 14	2.46 0.12 14
Sign Lateral Offset (m)	6.12 3.61 10	6.41 2.77 10	7.36 3.34 18	7.87 7.37 18	1.54 0.70 12	1.77 1.06 12

Note:
All linear measurements originally recorded in feet
Cell values represent:

Mean Variance No. of Observations

Inventory Data Extraction

Extraction of inventory data usually includes an observer looking at the collected data and extracting pertinent information on relevant inventory elements. The particular technology for extraction of inventory elements depends on the data collection technologies used. For example, observers could extract information by looking at a video log of the roadway and then keying in data, or they could use photogrammetric software packages to extract inventory elements from digital images collected by a van system. An account of the time spent in data extraction must also be kept.

Data and Auxiliary Factor Analysis

This stage of the evaluation consists of statistical analyses of the collected data for descriptive accuracy. The PME provides information on descriptive accuracy of an inventory element. The evaluator can conduct analysis of variance (Neter et al., 1990; Devore, 1991) on the data to obtain information on the factors that affect accuracy of the descriptive data. Plots, charts, and diagrams indicating the effects of the factors indicated to be important are useful for presentation of the results.

Auxiliary factors such as cost and time involved in data collection, processing, and feature extraction must also be taken into account at this stage of the evaluation.

Performance Acceptability

Performance acceptability criteria include descriptive accuracy, cost, time, training requirements, and software compatibility issues. Tables E-8 through E-11 summarize descriptive accuracies of the different data collection technologies evaluated in NCHRP 15-15. Based on this information, Table E-12 recommends levels of accuracy for the manual and digital methods of data collection. The values in Table E-12 represent a benchmark against which agencies can compare their evaluation results.

TABLE E-4 Sample characteristics for data collected in Madison, WI

	Two-lane Environment		Interstate Environment		Urban Environment	
Method / Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width (m)	3.37 0.007 13	3.45 0.27 13	3.65 0.00 16	3.67 0.003 16	4.05 0.99 13	5.03 1.68 13
Sign Width (m)	0.99 0.59 4	1.02 0.69 4	2.57 1.62 9	2.62 1.48 9	0.59 0.01 4	0.57 0.004 4
Sign Height (m)	1.21 0.12 4	1.14 0.33 4	1.35 0.75 9	1.31 0.66 9	0.80 0.005 4	0.67 0.03 4
Sign Support Height (m)	1.95 0.008 13	1.72 0.01 13	2.05 0.23 16	2.11 0.44 16	2.08 0.008 13	2.09 0.04 13
Sign Lateral Offset (m)	4.33 0.25 13	3.88 0.58 13	5.71 1.20 16	5.64 2.16 16	0.72 0.02 13	0.81 0.06 13

Note:
All linear measurements originally recorded in feet
Cell values represent:

Mean Variance No. of Observations

TABLE E-5 Sample characteristics for data collected in Rocky Hill, CT

	Two-lane Environment		Interstate Environment		Urban Environment	
Method / Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width (m)	3.35 0.00 23	3.51 0.04 23	3.67 0.17 25	3.65 0.22 25	3.35 0 19	3.49 0.05 19
Driveway Width (m)	9.34 16.96 23	11.09 33.90 23	-	-	12.47 15.02 27	14.95 21.87 27
Street Light Spacing (m)	-	-	-	-	20.83 10.84 6	26.25 56.67 6
Sign Lateral Offset (m)	2.03 0.12 22	2.90 0.97 22	6.05 2.09 20	4.97 0.49 20	1.71 0.15 21	2.80 0.79 21

Note
All linear measurements originally recorded in feet
Cell values represent:

Mean Variance No. of Observations

TABLE E-6 Recommended sample sizes

Inventory Element	No. of Observations
Lane Width	10
Roadside Slope	30
Barrier Height	15
Driveway Width	10
Street Light Spacing	10
Sign Width	10
Sign Height	15
Sign Support Height	10
Sign Lateral Offset	20

Sample Size = (std dev. * $t_{0.95}$ / permitted error)^2
Assumed permitted error = 5%, $t_{0.95}$ = 1.96
Sample sizes less than ten are reported as ten observations

TABLE E-7 Staffing and equipment items

Category	Detail
Personnel	Number of persons required during data collection using the experimental system Number of persons required during ground truthing Number of persons required for data post processing
Equipment	Mode of transport Selected technologies under evaluation Ground truthing equipment Safety equipment including: Safety truck Safety vests and hard hats Vehicle-mounted flashing lights Flags and traffic cones

TABLE E-8 PME characteristics for data collected in Milwaukee, WI

	Two-lane Environment		Interstate Environment		Urban Environment	
Method Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width	-5.71 133.66 6.63	0.74 40.62 4.86	2.98 33.87 4.32	-0.30 44.09 4.26	-18.92 101.14 18.92	-1.32 51.67 5.35
Roadside Slope	-15.23 1036.46 29.27	-13.83 12969.37 67.12	-6.89 1256.0 26.59	-19.9 806.07 27.92	-	-
Barrier Height	18.96 2720.59 24.10	5.02 469.65 16.50	-2.66 75.47 5.33	-1.17 547.13 14.78	-	-
Driveway Width	15.48 663.48 23.21	-10.41 244.22 16.65	-	-	16.80 1012.59 29.65	-2.40 111.97 6.99
Street Light Spacing	-	-	-	-	36.22 99.77 36.22	-0.47 171.84 10.44
Sign Width	12.50 187.50 12.50	38.58 1674.84 38.58	-22.33 185.30 23.66	8.49 175.62 10.23	4.16 104.16 4.16	16.87 168.61 17.54
Sign Height	12.99 763.35 18.11	-1.51 18.84 2.95	-5.71 136.39 8.88	-4.95 117.73 8.47	-1.71 266.87 13.14	2.43 38.45 4.96
Sign Support Height	17.36 165.62 18.37	-1.95 61.41 6.35	5.61 263.66 12.16	8.85 2912.34 20.58	-5.28 372.64 14.68	-2.17 43.28 4.93
Sign Lateral Offset	38.85 9033.43 40.92	10.35 196.90 12.86	-5.56 685.88 22.04	6.97 77.71 8.28	-15.84 1732.09 36.82	38.18 5594.75 51.43

Note: Cell values represent:

PME Mean PME Variance PME Absolute value

TABLE E-9 PME characteristics for data collected in Denver, CO

	Two-lane Environment		Interstate Environment		Urban Environment	
Method Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width	-3.53 55.16 7.49	-1.82 60.82 4.67	-0.68 32.84 2.84	-2.76 23.37 4.16	-2.03 73.78 6.89	0.09 148.17 9.71
Roadside Slope	-30.94 572.10 35.01	-16.53 1792.96 38.15	30.40 826.95 32.78	-10.26 3321.95 44.20	-	-
Barrier Height	8.74 22.19 8.74	12.54 3213.28 30.16	0.46 1.93 0.46	3.79 278.96 12.56	-	-
Driveway Width	-32.10 285.84 32.10	-0.73 38.38 4.78	-	-	17.03 1261.21 26.20	3.97 72.06 4.88
Street Light Spacing	-	-	-	-	14.24 981.49 26.33	-6.95 219.15 13.05
Sign Width	-4.13 226.63 12.06	0.61 286.38 12.30	1.20 185.05 9.02	3.51 48.86 5.37	-2.94 155.99 8.98	10.49 470.41 16.76
Sign Height	12.85 1008.61 27.13	13.11 808.47 23.46	1.95 128.08 7.60	3.59 95.46 8.69	-0.84 138.28 6.55	15.94 728.83 18.87
Sign Support Height	10.90 153.66 11.96	1.80 515.61 14.89	0.52 92.11 6.97	4.53 378.60 13.34	-13.36 77.26 13.36	0.07 37.97 4.29
Sign Lateral Offset	9.51 528.42 18.93	15.41 768.91 16.59	5.10 268.90 14.84	8.40 158.22 11.58	4.48 211.02 10.76	18.04 725.23 23.90

Note: Cell values represent:

PME Mean PME Variance PME Absolute value

TABLE E-10 PME characteristics for data collected in Madison, WI

	Two-lane Environment		Interstate Environment		Urban Environment	
Method Element	Manual	Digital	Manual	Digital	Manual	Digital
Lane Width	-1.73 86.73 4.53	-0.78 5.92 2.07	-1.48 2.12 1.74	-1.17 3.36 1.81	-19.81 13.74 19.81	-0.67 17.41 3.26
Sign Width	-7.29 73.78 7.29	-8.15 374.29 17.87	-7.21 799.10 20.81	-0.45 2953.71 32.39	3.125 247.39 9.37	1.73 100.79 7.98
Sign Height	-2.82 489.59 15.31	-12.44 984.85 23.55	-7.67 1115.78 26.08	-9.67 598.89 17.26	6.41 474.19 18.59	-11.35 383.65 14.13
Sign Support Height	-0.67 39.02 5.18	-12.43 28.91 12.43	-10.14 41.43 10.14	-8.85 124.86 12.01	7.34 1129.65 13.81	6.56 810.72 13.67
Sign Lateral Offset	16.66 383.34 21.34	3.68 417.65 15.86	2.15 494.93 18.64	-1.33 245.90 12.43	3.36 1227.38 22.57	10.45 784.86 19.95

Note: Cell values represent:

PME Mean PME Variance PME Absolute value

TABLE E-11 PME characteristics for data collected in Rocky Hill, CT

Method / Element	Two-lane Environment Manual	Two-lane Environment Digital	Interstate Environment Manual	Interstate Environment Digital	Urban Environment Manual	Urban Environment Digital
Lane Width	-4.83 24.10 4.83	-0.32 54.68 4.60	-14.41 63.13 14.41	-14.81 75.50 14.81	-4.32 55.72 7.33	-0.78 15.25 2.49
Driveway Width	-1.71 2579.47 31.18	18.77 5919.71 39.11	-	-	-14.38 456.51 21.30	-0.06 278.91 11.61
Street Light Spacing	-	-	-	-	-18.22 351.81 23.10	3.14 1017.59 21.19
Sign Lateral Offset	-5.12 473.22 19.78	30.05 899.40 33.08	6.67 3324.33 21.21	-12.44 1177.05 24.46	-10.66 228.13 15.10	42.33 454.40 42.35

Note: Cell values represent:

PME Mean PME Variance PME Absolute value

TABLE E-12 Recommended accuracy performance benchmark

Inventory element	Two-lane rural	Rural interstate	Urban
Lane Width	-4	-4	-3
Roadside Slope	-10	10	-
Barrier Height	5	10	-
Driveway Width	5	-	3
Streetlight Spacing	-	-	10
Sign Width	5	5	3
Sign Height	5	5	5
Sign Support Height	5	5	5
Sign Lateral Placement	10	10	5

Note: Values in table represent mean PME

Table 25 (main text) presents average time and cost information from this project for the different methods of data collection. Collection time in the field was somewhat less with the use of a van system. However, in-office processing and feature extraction can take more time when compared with the manual method of data collection. This must be weighed against other benefits that may accrue from use of van systems (e.g., permanent digital imagery of the roadway and reduced exposure of the data collection crew). The cost of the two data collection methods depends on the technologies used during data collection. Additional costs may be incurred during training of agency personnel and maintenance of equipment. The final decision on the acceptability of a data collection method will depend on a trade-off between costs and benefits.

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The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

THE NATIONAL ACADEMIES

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