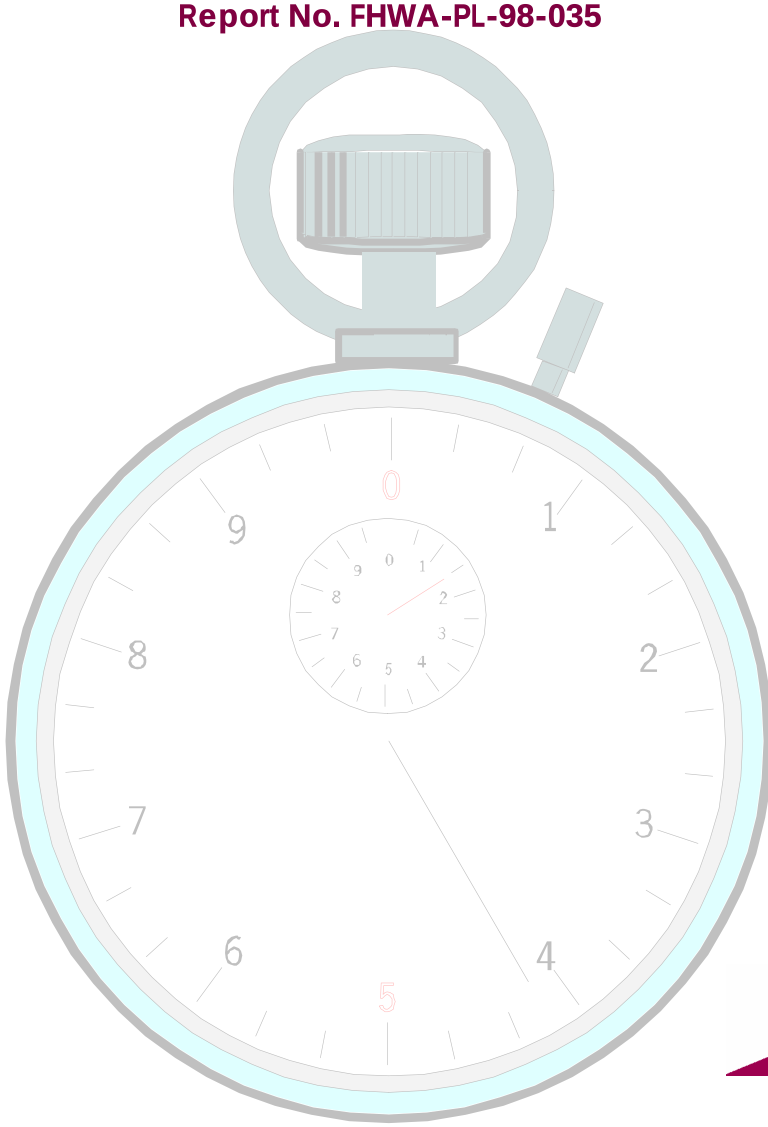
TRAVEL TIME
DATA COLLECTION HANDBOOK

Report No. FHWA-PL-98-035



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March 1998

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Travel Time Data Collection Handbook!

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16. Abstract

This Travel Time Data Collection Handbook provides guidance to transportation professionals and practitioners for the collection, reduction, and presentation of travel time data. The handbook should be a useful reference for designing travel time data collection efforts and systems, performing travel time studies, and reducing and presenting travel time data. Agencies new to travel time data collection may wish to adopt sections of the handbook as standard procedures, whereas agencies with data collection experience may wish to incorporate specific details or criteria.

Initial chapters of the handbook describe how to design data collection activities, including the determination of parameters such as study size and scope, data collection technique, and other critical study elements. Chapters 3 through 6 include a description of each data collection technique, major advantages and disadvantages, cost and equipment requirements, and step-by-step instructions. Related experience with the data collection techniques is included for examples of applications. Chapter 7 provides guidance for reducing travel time data and preparing tabular and graphical presentations.

The chapters of the handbook are as follows: Chapter 1, Introduction; Chapter 2, Developing and Implementing a Data Collection Plan; Chapter 3, Test Vehicle Techniques; Chapter 4, License Plate Matching Techniques; Chapter 5, ITS Probe Vehicle Techniques; Chapter 6, Emerging and Non-Traditional Techniques; and Chapter 7, Data Reduction, Summary, and Presentation.

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METRICATION

An attempt was made by the authors to provide all applicable quantities in metric units in adherence with state and federal reporting guidelines. Some complex figures and/or tables adapted from other sources are provided in the original English units because of the difficulty in creating an electronic version.

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LIST OF ACRONYMS

AAA	American Automobile Association
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway Transportation Officials
ADEPT	Automatic Debiting Electronic Payment in Transport
ADVANCE	Advanced Driver and Vehicle Advisory Navigation Concept
APTS	Advanced Public Transportation System
ARTS	Advanced Rural Transportation System
ATMS	Advanced Traffic Management Center
ATR	Automatic Traffic Recorder
AVCS	Advanced Vehicle Control System
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
BTD	Brazos Transit District
BYU	Brigham Young University
Caltrans	California Department of Transportation
CAPITAL	Cellular Applied to ITS Tracking and Location
CASI	Computer-Assisted Self-Interviewing
CATS	Chicago Area Transportation Study
or	Computer Aided Transportation Software
CBD	Central Business District
CMS	Congestion Management System
CTPS	Central Transportation Planning Staff
CUTR	Center for Urban Transportation Research
CV	Coefficient of Variation
CVO	Commercial Vehicle Operations
DART	Dallas Area Rapid Transit
DGPS	Differential Global Positioning System
DMI	Distance Measuring Instrument
DMV	Department of Motor Vehicles
DOD	Department of Defense
DOT	Department of Transportation
ETC	Electronic Toll Collection
ETTM	Electronic Toll and Traffic Management
FCC	Federal Communications Commission
FCI	Freeway Congestion Index
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
HCM	Highway Capacity Manual
HICOMP	Highway Congestion Monitoring Program

LIST OF ACRONYMS (Continued)

HOV	High-Occupancy Vehicle
HPMS	Highway Performance Monitoring System
IDOT	Illinois Department of Transportation
ISTEA	Intermodal Surface Transportation Efficiency Act
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
LOS	Level of Service
LPR	License Plate Recognition
LSU	Louisiana State University
LTB	London Transport Bus
MDI	Model Deployment Initiative
MOE	Measure of Effectiveness
MPO	Metropolitan Planning Organization
MTPS	Mobile Telephone Positioning Systems
MVRAP	Moving Vehicle Run Analysis Package
NCHRP	National Cooperative Highway Research Program
NMEA	National Marine Electronics Association
NPRA	Norway Public Roads Administration
NTCIP	National Transportation Communications for ITS Protocol
PATH	Program for Advanced Transit and Highway
PDA	Personal Digital Assistant
PSAP	Public Safety Answering Point
RCE	Research Center of Excellence
RF	Radio Frequency
SA	Selective Availability
SIP	Standards Implementation Plan
SRD	Standards Requirement Document
TDMA	Time Division Multiple Access
TIC	Transportation Information Center
TMC	Transportation Management Center
TRAC	Washington State Transportation Center
TRANSCOM	Transportation Operations Coordinating Committee
TRANSMIT	TRANSCOM System for Managing Incidents and Traffic
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
VMT	Vehicle Miles Traveled
WIM	Weigh-in-Motion
WSDOT	Washington State Department of Transportation

1 INTRODUCTION

Travel time, or the time required to traverse a route between any two points of interest, is a fundamental measure in transportation. Travel time is a simple concept understood and communicated by a wide variety of audiences, including transportation engineers and planners, business persons, commuters, media representatives, administrators, and consumers. Engineers and planners have used travel time and delay studies since the late 1920s to evaluate transportation facilities and plan improvements. Commuters use a “travel time budget,” theorized to be between 20 and 30 minutes per one-way commute, to locate their housing relative to work locations. The media report travel times and delays on urban freeways and streets with language like “. . . an accident on the northbound lanes of the Beltway has traffic delayed 10 to 15 minutes . . .”

A renewed interest in travel time studies in the 1990s may be attributed to several factors:

- **Congestion management systems**, mandated by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, commonly use travel time-based performance measures to evaluate and monitor traffic congestion.

- **A changing analytical and funding environment** requires that certain transportation analyses (e.g., major investment studies) compare different transportation modes for a common funding source. Travel time is a common element among all transportation modes.

- **Increasing involvement in transportation decisions** by non-technical persons (e.g., politicians, advocacy groups, and the general public) requires analytical techniques and measures that are simple and easy to understand, yet rigorous enough for technical analyses. Travel time-based measures and analyses meet both of these needs.

1.1 Objective of the Handbook

The primary objective of this handbook is to provide guidance to transportation professionals and practitioners in the collection, reduction, and reporting of travel time data. The handbook should be a useful reference for designing travel time data collection efforts and systems, performing travel time studies, and summarizing travel time data. The handbook does not constitute a standard, specification, or regulation, but instead serves as a compilation of experience and information. Agencies new to travel time data collection may wish to adopt sections of the handbook as standard procedures, whereas other agencies with time-tested procedures and experience may wish to incorporate specific details or criteria.

This handbook also introduces the wide variety of uses for travel time data, but does not contain specific guidance or instructions on data analyses. A companion "Travel Time Applications" handbook also developed at the Texas Transportation Institute (TTI) focuses on travel time data applications and provides more comprehensive discussions with specific examples.

IMPORTANT ☞	The primary objective of this handbook is to provide guidance in the collection, reduction, and reporting of travel time data. A companion handbook focuses on travel time data applications.

1.2 Handbook Organization

The handbook is organized into the following seven chapters:

- **Chapter 1, Introduction** - contains an overview of the handbook and an introduction to the basic concepts and techniques used to collect travel times.

- **Chapter 2, Developing and Implementing a Data Collection Plan** - provides general guidance in creating and using a travel time data collection plan. Answers are provided to common questions like: "What data collection technique should I use?", "On what days and at what time should I collect data?", and "How do I sample travel times over time and space?"

- **Chapter 3, Test Vehicle Techniques** - provides instructions for collecting travel time data using active test vehicles in combination with varying levels of instrumentation: manual (clipboard and stopwatch), an electronic distance-measuring instrument (DMI), or a global positioning system (GPS) receiver.

- **Chapter 4, License Plate Matching Techniques** - provides instructions for collecting travel times by matching vehicle license plates between consecutive checkpoints with varying levels of instrumentation: tape recorders, video cameras, portable computers, or automatic license plate character recognition.

- **Chapter 5, ITS Probe Vehicle Techniques** - provides guidance on obtaining travel times using intelligent transportation system (ITS) components and passive probe vehicles in the traffic stream equipped with signpost-based transponders, automatic vehicle identification (AVI) transponders, ground-based radio navigation, cellular phones, or GPS receivers.

- **Chapter 6, Emerging and Non-Traditional Techniques** - includes information about several techniques that are currently being researched or tested. Emerging techniques include the use of inductance loop detectors, weigh-in-motion stations, and video cameras for collecting or estimating travel times.

- **Chapter 7, Data Reduction, Summary, and Presentation** - contains information about the reduction, summarization, and presentation of travel time data and provides many examples of tabular and graphical summaries.

1.3 Existing Guidelines

Several existing guidelines for travel time studies have been incorporated into this handbook. Guidelines produced by Berry and Green (1), Berry (2), and the National Committee on Urban Transportation (3) in the 1950s provided the foundation for travel time studies. The Institute of Transportation Engineers' (ITE) *Manual of Transportation Engineering Studies* (4) serves as a standard reference on travel time studies for many transportation engineers. The *1994 Highway Capacity Manual* (5) contains guidance for conducting travel time studies to evaluate quality of traffic flow for arterial streets. Volume II of NCHRP Report 398, *Quantifying Congestion: User's Guide* (6) provides guidance related to selecting and applying travel time-based measures for quantifying congestion and describes the steps and procedures for collecting travel time data.

Many of these guidelines, however, focus on the test vehicle technique and provide little information about newer data collection techniques or sampling procedures. This handbook is intended to be comprehensive and fill the gaps in existing travel time data collection guidelines. The handbook also contains information about emerging techniques that may substantially reduce the costs of collecting travel time data. The next section contains an overview of the data collection techniques that are addressed in this handbook.

1.4 Overview of Techniques

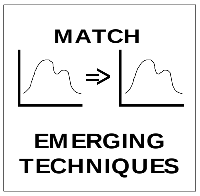
Several data collection techniques can be used to measure or collect travel times. These techniques are designed to collect travel times and average speeds on designated roadway segments or links. Because these techniques differ from point-based speed measurement, the resulting travel time and speed data are much different than spot speeds. A general overview of the various techniques is provided in the following paragraphs.

IMPORTANT ☞ The handbook contains four categories of travel time data collection techniques: test vehicle (Chapter 3), license plate matching (Chapter 4), ITS probe vehicle (Chapter 5), and emerging and non-traditional techniques (Chapter 6).

Test vehicle techniques (often referred to as "floating car") are the most common travel time collection methods and consist of a vehicle(s) that is specifically dispatched to drive with the traffic stream for the express purpose of data collection. Data collection personnel within the test vehicle control the speed of the vehicle according to set driving guidelines ("average car", "floating car", or "maximum car": see Chapter 3 for more details). A passenger in the test vehicle can manually record travel times at designated checkpoints using a clipboard and stopwatch, or computer instrumentation may be used to record vehicle speed, travel times or distances at preset checkpoints or intervals. An electronic DMI attached to the vehicle's transmission can be coupled with a portable computer to record speeds and distances traveled up to every half-second or less. A GPS receiver coupled with a portable computer can be used to record the test vehicle's position and speed at time intervals as frequent as every second.

License plate matching techniques consist of collecting vehicle license plate characters and arrival times at various checkpoints, matching the license plates between consecutive checkpoints, and computing travel times from the difference between arrival times. License plate matching for travel times can be performed in a number of different ways. The manual method involves recording license plate characters using voice tape recorders, then later transcribing the license plates into a computer for subsequent matching. A portable computer-based method relies on human observers to transcribe the license plate numbers into the computer in the field, then match the license plates by computer at a later time. Video cameras or camcorders can be used to collect license plates with manual transcription into a computer being performed by humans at a later date. A video and character recognition-based method collects license plate images using video, and relies on character recognition software to recognize and automatically transcribe the license plate number for subsequent computer matching.

ITS probe vehicle techniques utilize passive instrumented vehicles in the traffic stream and remote sensing devices to collect travel times. The ITS probe vehicles can be personal, public transit, or commercial vehicles and often are not driving for the express purpose of collecting travel times. ITS probe vehicles also typically report travel time data to a transportation management center (TMC) in real-time. Probe vehicles may be equipped with several different types of electronic transponders or receivers. A signpost-based system, typically used by transit agencies for tracking bus locations, relies on transponders attached to roadside signposts. AVI transponders are located inside a vehicle and are used in electronic toll collection applications. Ground-based radio navigation systems use triangulation techniques to locate radio transponders on vehicles, and are used in route guidance and personal communication systems. The monitoring of cellular telephone activity is also being tested for potential travel time collection applications. GPS receivers use a network of 24 satellites to determine vehicle position and are becoming common for route guidance and "mayday" security applications.



Emerging and non-traditional techniques are currently being researched or developed, or may be considered non-traditional when compared to existing methods. These techniques use a variety of methods, such as inductance loops, weigh-in-motion stations, or aerial video to estimate or calculate travel times. Most of the emerging techniques are currently in developmental or testing stages and have not been extensively field-tested or applied. The experience with these emerging techniques is provided for the reader's information. Future editions of this handbook may include more detailed information on these emerging techniques as they develop and mature.

1.5 Travel Time and Speed Definitions

Travel time is broadly defined as "the time necessary to traverse a route between any two points of interest." Travel time can be directly measured by traversing the route(s) that connects any two or more points of interest. Travel time is composed of *running time*, or time in which the mode of transport is in motion, and *stopped delay time*, or time in which the mode of transport is stopped (or moving sufficiently slow as to be stopped, i.e., typically less than 8 kph, or 5 mph). Figure 1-1 illustrates the concepts of running time and stopped delay time.

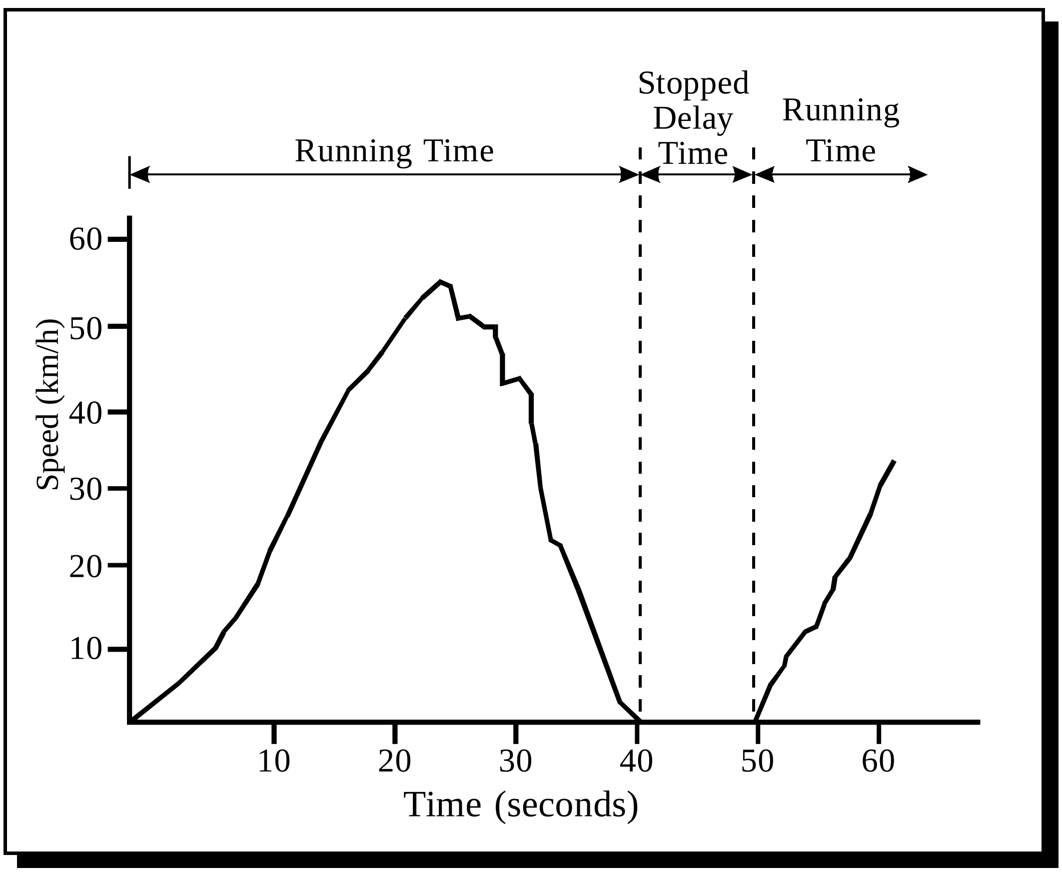


Figure 1-1. Illustration of Running Time and Stopped Delay Time

Travel time can also be estimated in certain cases by assuming the average speed at a particular point (spot speed) is constant for a relatively short distance (typically less than 0.8 kilometer, or 0.5 mile). The assumption of consistent speeds over a short roadway segment is most applicable to uninterrupted flow facilities (e.g., freeways or expressways) with stable traffic flow patterns. The estimated travel time can be computed using the average spot speed, or time-mean speed, and the roadway segment length (Equation 1-1).

Average or mean travel times are computed from individual travel times by using standard statistical formulas or computer software. The reader is reminded that the computed average travel time is only an estimate for the entire population of vehicles or persons that traveled the designated roadway during the time period of interest.

Speed values can be calculated using travel times, but there are several types of speeds that should be distinguished (7). The **time-mean speed** is the arithmetic average speed of all vehicles for a specified period of time (Equation 1-2). For example, dual inductance loop detectors in traffic management systems are typically configured to report a time-mean speed at 20-second intervals.

The **space-mean speed** is the average speed of vehicles traveling a given segment of roadway during a specified period of time and is calculated using the average travel time and length for the roadway segment (Equation 1-3). For example, transponder-based probe vehicle systems collect travel times between instrumented locations and an average travel time is computed from individual probe vehicle travel times. The space-mean speed is then calculated by dividing the distance between instrumented locations by the average travel time. The time-mean speed is associated with a point over time, whereas the space-mean speed is associated with a section of roadway. In nearly all cases involving the calculation of average speeds from individual travel times, the space-mean speed should be used. Time-mean speeds are most commonly used in reference to a single point along a roadway and averaged over a time period (e.g., loop detectors and other point detection devices). Equation 1-5 shows the relationship between time-mean speeds and space-mean speeds.

CAUTION !! Time-mean speed is associated with a single point along a roadway over time, whereas the space-mean speed is associated with a specified length of roadway. Use space-mean speeds when reducing and analyzing travel time data.

Average running speeds can be calculated by using the average running time, which does not include any stopped delay time (Equation 1-4). If there is no stopped delay, the average running speed is equal to the space-mean speed. Running speeds may be appropriate if one does not want to include any stopped delay along a route, such as stopped delay due to traffic signals on an arterial street. Table 1-1 contains an example of the calculation of these different speed parameters using travel times as input. The table illustrates the calculation of space-mean and time-mean speeds and shows the difference between the two speed values to be approximated by Equation 1-5.

$$\begin{matrix} \textit{Estimated Travel Time} \\ \textit{(seconds)} \end{matrix} = \frac{\textit{Segment Length (km)}}{\textit{Time-Mean Speed (km/h)}} \times \textit{(3,600 sec/hour)} \tag{1-1}$$

$$\textit{Time-Mean Speed, } \bar{v}_{TMS} = \textit{avg. speed} = \frac{\sum v_i}{n} = \frac{\sum \frac{d}{t_i}}{n} \tag{1-2}$$

$$\textit{Space-Mean Speed, } \bar{v}_{SMS} = \frac{\textit{distance traveled}}{\textit{avg. travel time}} = \frac{d}{\frac{\sum t_i}{n}} = \frac{n \times d}{\sum t_i} \tag{1-3}$$

$$\textit{Average Running Speed, } \bar{v}_r = \frac{\textit{distance traveled}}{\textit{avg. running time}} = \frac{d}{\sum \frac{t_{ri}}{n}} = \frac{n \times d}{\sum t_{ri}} \tag{1-4}$$

where: d = distance traveled or length of roadway segment;
n = number of observations;
v_i = speed of the *i*th vehicle;
t_i = travel time of the *i*th vehicle; and
t_{ri} = running time of the *i*th vehicle.

$$\bar{v}_{TMS} \approx \bar{v}_{SMS} + \frac{S^2{}_{SMS}}{\bar{v}_{SMS}} \tag{1-5}$$

where: $\bar{v}_{TMS}$ = sample time-mean speed;
$\bar{v}_{SMS}$ = sample space-mean speed; and
S^2_{SMS} = sample variance of the space mean speed.

Table 1-1. Comparison of Time-Mean and Space-Mean Speeds

Data Items	Run 1	Run 2	Run 3	Run 4	Run 5	Sum	Average	Variance
Travel Time (sec)	153	103	166	137	127	686	137.2	
Running Time (sec)	142	103	141	137	127	650	130.0	
Stopped Delay Time (sec)	11	0	25	0	0	36	7.2	
Average Travel Speed (km/h)	44.7	66.4	41.2	49.9	53.9	256	51.2	95
Average Running Speed (km/h)	48.1	66.4	48.4	49.9	53.9	n.a.	52.6	

Section Length = 1.9 km

Difference between Time-Mean Speed and Space-Mean Speed
Time-Mean Speed = ∑(speeds) / no. of runs = 256 / 5 = 51.2 km/h
Space-Mean Speed = no. of runs × distance / ∑ (travel times) = 5 x 1.9 / 686 = 49.8 km/h
Therefore, difference = 1.4 km/h

Check Equation 1-5: Time-Mean Speed ≈ 49.8 + 95 / 49.8 ≈ 51.7 km/h ≈ 51.2 km/h

In simple terms, the space-mean speed is the distance traveled divided by an average travel time, whereas the time-mean speed is an average of individual vehicle speeds. Space-mean speeds weight slower vehicles' speeds more heavily, as the slower vehicles are within the segment of interest for a longer period of time.

In mathematical terms, the space-mean speed is also known as a harmonic mean speed. Wardrop (8) developed a relationship between time-mean speed and space-mean speed, which is shown as Equation 1-5 (9). The equation indicates that time-mean speed is only equal to the space-mean speed when the space-mean speed variance is equal to zero (i.e., all vehicles in the traffic stream travel at the same speed). For all other cases when the space-mean speed is greater than zero, the time-mean speed will always be greater than the space-mean speed. The space-mean speed is statistically more stable than the time-mean speed, particularly for short roadway segments or small travel times. Typically, the differences between time-mean speed and space-mean speed are about 1 to 5 percent, or about 1.6 km/h (1 mph) over a range of speeds (10). Numerical simulation shows that the difference between these two speed values become less discernable as speeds increase.

1.6 Direct Measurement Versus Estimation

Transportation analyses use data from two fundamental sources:

- Data that is **directly collected or measured** in actual traffic conditions; and
- Data that is **estimated** through the use of computer simulation models or surrogate estimation techniques.

Figure 1-2 illustrates the relationship between these sources of data in transportation analyses. As indicated in the figure, one may use any combination of direct measurement and estimation (as indicated by the solid diagonal line in the figure). Analyses relying solely on data collection would fall at the top right of the square, whereas analyses relying entirely on estimation are located at the bottom left of the square. The unique combination of data collection and estimation used for an analysis depends upon the needs and constraints of the analysis, analysis budget, available personnel and tools, and other constraints.

The information in this handbook concentrates on the collection or direct measurement of travel times (Chapter 6 contains several travel time estimation methods). Transportation analysts should be careful to recognize and treat accordingly the source of the data in the analysis and decision-making process.

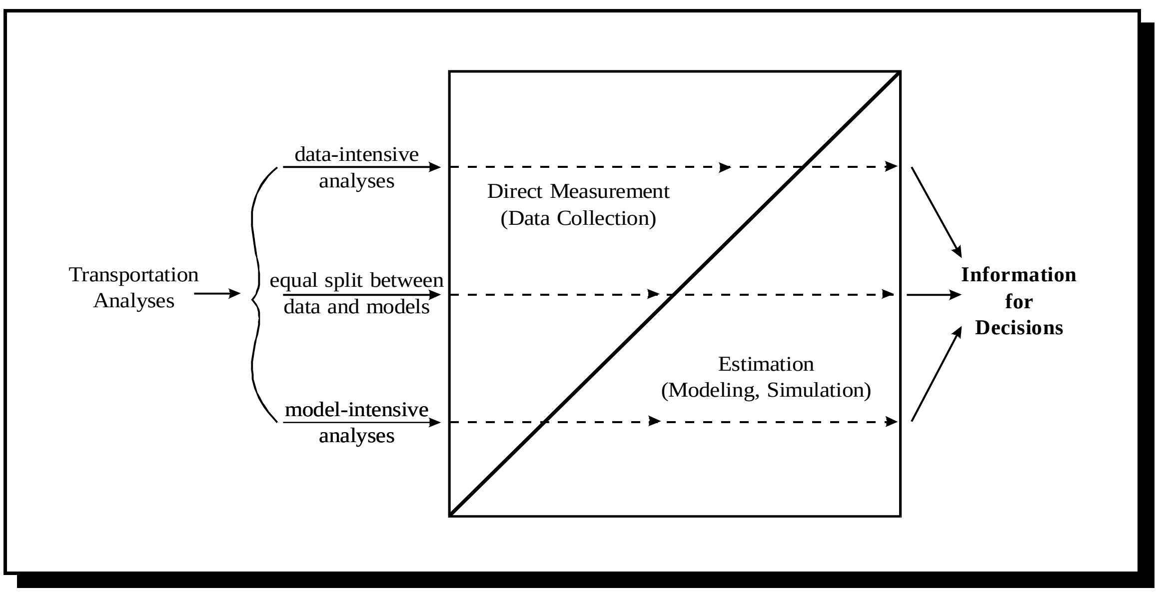


Figure 1-2. Relationship Between Direct Measurement and Estimation Techniques in Transportation Analyses

1.7 References for Chapter 1

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2 DEVELOPING AND IMPLEMENTING A DATA COLLECTION PLAN

This chapter contains information and guidance on developing and implementing a data collection plan for travel time studies. Adequate planning, training, and preparation are vital to successful data collection activities. Figure 2-1 illustrates a generic travel time data collection process that can be used to plan and execute a travel time study.

The first several sections of this chapter describe the process of establishing study objectives and understanding the uses and users of the data being collected. Guidance is provided on setting the study scope, in terms of the geographic scale and inclusion of different time periods and facility types. The travel time data collection techniques are summarized and compared to assist in selecting the collection technique that is most appropriate. Data collection scheduling and data sampling are also discussed. The use of training and pilot studies are introduced as ways to improve the effectiveness and accuracy of data collection. The chapter concludes with general information about progress tracking, data reduction, and quality control.

2.1 Establish Study Purpose and Objectives

The study purpose and objectives establish the need for data and information in a transportation analysis and should be defined as the first step in any data collection activity. Once established, the study's purpose and objectives will help to guide the data collection to successful completion. Not only will the study's purpose and objectives be used to develop a data collection plan, they may also be used throughout the study process for clarification of tasks or resolution of ambiguous issues.

It is not uncommon for travel time data to be collected for several purposes with the main objective to establish a database of current roadway operating conditions. Similar steps should be taken to identify all required uses and ensure that the travel time data meet the minimum requirements (i.e., "smallest common denominator") for all applications. If the different studies or uses have competing needs, agency personnel may simply have to prioritize their data needs.

Examples of travel time study purpose or objective statements include the following:

> "The purpose of this study is to determine travel time information on major (Kansas City Metropolitan Region) streets and highways . . . The study will be used to . . . identify the extent and location of traffic congestion and specific problem areas . . ., serve as a data base to check speeds in the current computer networks. . ., allow comparisons with the 1987 and 1977 Travel Time and Delay studies. . ., and provide information . . . to determine areas where future studies are warranted. . ." (1);

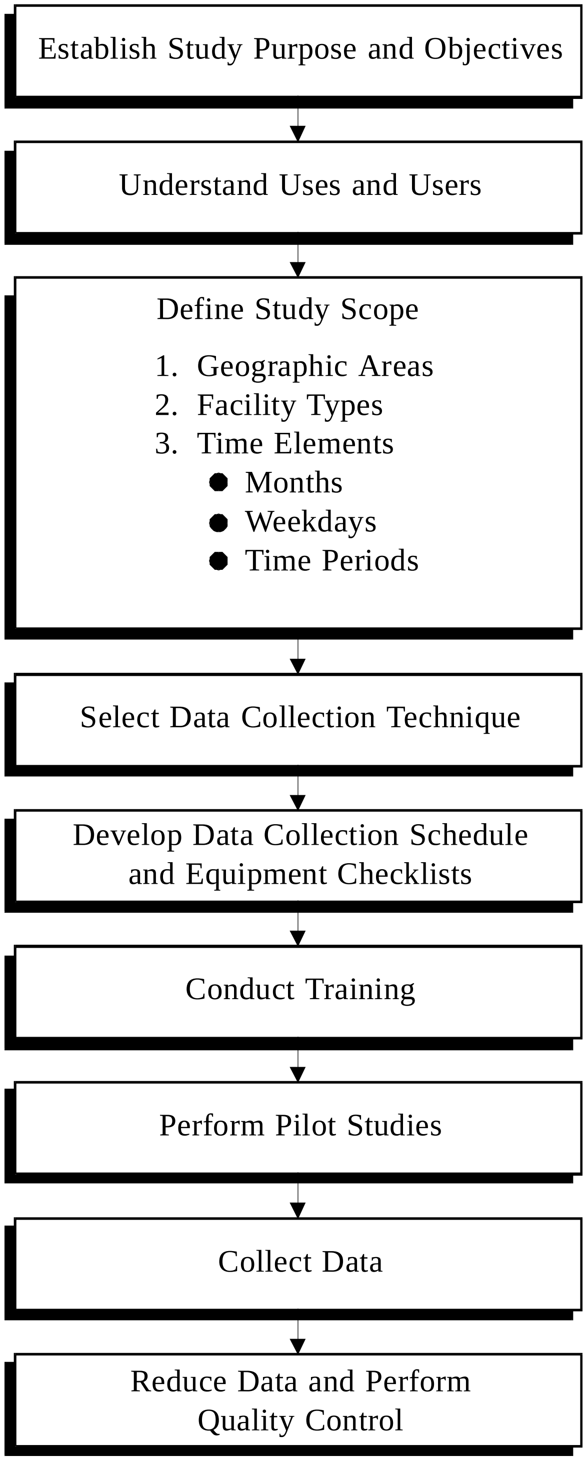


Figure 2-1. Travel Time Data Collection Process

> "The purpose of this study was to obtain effective travel times for representative links in the road network. These are used in computer models. . . In conjunction with the travel time runs, a vehicle delay study was also conducted to identify specific congested locations and also to determine the types and causes of delay . . ." (2)

2.2 Understand Uses and Users

The uses and users of the travel time data to be collected are as important as the study purpose and objectives. In many cases, the uses of the data are the motivation behind the study and should have been considered in establishing the study objectives. The users of the travel time data are an important consideration, as they affect several variables in the collection and presentation of data. Table 2-1 provides a perspective on the uses and users of travel time data. The table matrix illustrates the wide number of uses, and also the different uses for technical and non-technical audiences.

Travel time data often are collected for several purposes or potential uses. For example, travel time data might be collected for the congestion management process and also be used to calibrate travel demand forecasting models or as input to mobile source emissions models. For situations in which the travel time data must be used for several purposes, the data should be collected for the use that requires the finest level of detail. The travel time data can then be aggregated or analyzed to meet other study needs. In the earlier example, the mobile source emissions model may require second-by-second speeds to capture the acceleration and deceleration patterns in congestion. Once the second-by-second speed data has been collected, it can be aggregated for less data-intensive uses such as calibrating a travel demand forecasting model or monitoring area-wide congestion trends.

The emerging practice of using data collected by intelligent transportation system (ITS) applications for planning and evaluation purposes illustrates an important point about understanding uses and users of data. Until recently, ITS components were seen as providing valuable data only for operating transportation facilities. Several transportation agencies have recognized the many uses of ITS data for planning and evaluation applications and are beginning to share data resources where ITS applications have been deployed.

IMPORTANT ☞ Clear identification of study objectives, uses and users, and audience are a critical, yet often overlooked, step in the study design process.

Table 2-1. Uses and Users of Travel Time Data

Uses of Travel Time Data	Primary Users	
	Technical	Non-Technical
Planning and Design		
Develop transportation policies and programs		✔
Perform needs studies/assessments	✔	✔
Rank and prioritize transportation improvement projects for funding	✔	✔
Evaluate project-specific transportation improvement strategies	✔	
Input/calibration for air quality/mobile source emission models	✔	
Input/calibration for travel demand forecasting models	✔	
Calculate road user costs for economic analyses	✔	
Operations		
Develop historical travel time data base	✔	
Input/calibration for traffic models (traffic, emissions, fuel consumption)	✔	
Real-time freeway and arterial street traffic control	✔	
Route guidance and navigation	✔	✔
Traveler information		✔
Incident detection	✔	
Evaluation		
Congestion management system/performance measurement	✔	
Establish/monitor congestion trends (extent, intensity, duration, reliability)	✔	
Identify congested locations and bottlenecks	✔	✔
Measure effectiveness and benefits of improvements	✔	✔
Communicate information about transportation problems and solutions		✔
Research and development	✔	

2.3 Define Study Scope

A well-defined study scope that is clearly linked to the study objectives ensures that the travel time study will produce the necessary data. The study scope should answer three important questions:

1. Where do we collect travel time data? (Geographic Areas)
2. On what facilities do we collect travel time data? (Facility Types)
3. When do we collect travel time data? (Time Elements)

The study scope not only defines the ranges of effort during the travel time study, but also delineates the applicability of the results from data collection and analysis. Although this may appear to be a foregone conclusion, inadequate samples of data are often extended or extrapolated to make inaccurate conclusions about an entire population. Sampling procedures, however, can be used in travel time studies to collect statistically significant samples of data. Sampling procedures over both time and space are discussed later in this chapter and in subsequent chapters (for each technique).

2.3.1 Geographic Areas

The geographic scope defines the boundaries of the study. Examples of geographic scope include:

- A short section of roadway in the vicinity of a planned or implemented transportation improvement (e.g., before-and-after study);

- A transportation corridor between defined points, perhaps including a freeway, frontage roads, and parallel arterial street(s) (e.g., major investment study);

- Several transportation corridors that service a central business district or an activity center; and

- All major transportation corridors within a defined zone, sub-area, or region (e.g., congestion management system).

If a study's geographic scope only includes a selected number of corridors or roadways, travel time data would most likely be collected on each facility (i.e., no sampling). However, if the geographic scope encompasses an entire urban area or region, sampling procedures may be applied to achieve cost-effective data collection. Sampling procedures consist of collecting data for a statistically significant percentage of the entire roadway system being considered, then drawing conclusions about the entire roadway system from the sampled percentage. Sampling is most applicable for planning applications in which the required accuracy is typically less than that required for design or operational analyses.

2.3.2 Facility Types

The next step in defining the study scope is specifying the transportation facility types or functional classes of roadways. Like the geographic scope, the facility types considered in a travel time study should be based upon the study objectives. Facility types or classifications can be based upon different schemes, like those used in travel demand forecasting models, traffic operations models, or roadway inventory data bases. Table 2-2 contains examples of common roadway classifications from a variety of different sources. Collector and local streets are typically not considered in travel time studies because of their decreased functional role in providing mobility or throughput (3).

Table 2-2. Urban Roadway Functional Classification Categories

Travel Demand Forecasting Model (varies)	Highway Performance Monitoring System (HPMS), Urban (4)	AASHTO 1994 "Green Book," Urban (3)	1994 Highway Capacity Manual (HCM), Urban and Suburban (5)
Radial freeways	Interstate highways	Interstate highway	Freeways
Circumferential freeways	Other freeways and expressways	Other freeways	Multilane suburban highways
Principal arterials (divided/undivided)	Other principal arterials	Other principal arterials	Class I Arterial
Minor arterials (divided/undivided)	Minor arterials	Minor arterials	Class II Arterial
			Class III Arterial

The primary or ultimate use(s) of the travel time data will dictate the specific functional classification scheme to be used. For example, travel time data primarily collected for validating planning models will likely use classification categories corresponding to the specific travel demand forecasting model (i.e., similar to first column of Table 2-2). If the data will be used for other purposes, such as congestion management, it can be reclassified into categories that may be more appropriate for operational purposes, such as the HPMS or HCM classifications. Classification schemes used by other state, regional, or local agencies may also influence the choice of classification categories. In addition, the Federal Highway Administration (FHWA) has published additional guidance on highway functional classification (6).

The functional classification scheme should group roadways so that all roadways within a given group have similar traffic and operating characteristics. Grouping roadways with similar operating characteristics into a single classification strata or group permits the use of stratified sampling (if so desired). With stratified sampling, the number of roadway samples collected within the classification groups can be varied based upon the variability of data for roadways within a particular group.

A stratified facility sampling plan (i.e., 100 percent sampling of all facilities versus statistical sampling from each functional class) may also be considered in this step. Sampling of travel times on a regional network of freeways and arterial streets may be desirable where funds are not available for the desired data collection frequency or where you wish to concentrate data collection resources on the most critical routes of the network. The use of a sampling plan may also depend upon the application(s) of the travel time data. For example, regional system performance monitoring efforts may only require travel time data on a sample of freeways and arterial streets in the region. A corridor or before-and-after study, however, may require more detailed travel time data and necessitate data collection on all facilities under study (100 percent sample).

CAUTION
!!

Stratified sampling of data is typically considered when the desired precision can be achieved through sampling or when funds are not available for the complete roadway network. Proceed with caution and the assistance of a statistician.

The steps for establishing a stratified sampling plan are as follows:

1. **Establish the functional classification groups** to be used in the travel time study (Table 2-2). This step was discussed on the previous page.

2. **Designate the routes** that are located within the geographic scope and a functional classification group. This step consists simply of designating corridors that are within the study boundaries.

3. **Sub-divide routes into "segments,"** which are shorter sections of roadway (lengths vary by functional classification) with similar operating characteristics and geometric cross sections. The segment lengths may vary depending upon the data collection technique, but should be no longer than the following general ranges:

Freeways/Expressways:	1.6 to 4.8 km (1 to 3 mi)
Principal Arterials:	0.6 to 3.2 km (1 to 2 mi)
Minor Arterials:	0.8 to 3.2 km (½ to 2 mi)

Shorter segment lengths than these maximum lengths can be used for specific operational analyses with the caveat that segments lengths less than 0.4 to 0.8 km (¼ to ½-mile) may produce travel times with greater variability. Segment breakpoints, or route checkpoints, may be located at major interchanges, major signalized intersections, jurisdictional boundaries, and transition points between different roadway cross sections or land uses. For freeways and expressways, on-ramp merge points and lane drop locations are the best breakpoints for matching the cause of the traffic speed to the effects. For arterial streets, segment breakpoints are best located at major intersections or where changes in roadside activity occur. Professional judgment and local knowledge of traffic conditions should be used in defining segments. Site surveys or corridor reconnaissance during peak periods can also help in defining segment termini.

4. **Use sample size and finite population correction equations** (Table 2-3) to determine the number of roadway segments to sample within each functional classification group. The sample size calculations rely on three variables:

   - **Coefficient of variation (c.v.)** - a relative measure of variability, defined as the standard deviation divided by the mean. The c.v. can be estimated from existing data or the default values in Table 2-3 can be used for estimates of c.v. (7).

   - **Z-statistic** (or t-statistic for samples less than 30) - a function of the desired confidence level (e.g., 95 percent confidence level) for the sample mean (Table 2-3). The most commonly used confidence levels for stratified segment sampling are typically in the 80 to 95 percent range, but may also depend upon budget constraints.

   - **Relative permitted error** - expressed as a percentage, which is one-half of the desired confidence interval for the sample mean (e.g., ± 5 percent). The most commonly used error levels are between 5 and 10 percent, but vary depending upon the use of the travel time data (Table 2-3).

5. **Select the roadway segments to sample** within each functional classification (stratification) group. Theoretically, stratified random sampling techniques are used to randomly select the necessary sample size of roadway segments. The random selection of roadway segments scatters data collection sites around the geographic area, significantly increasing the costs of data collection for methods such as test vehicle. An alternative to random sampling is presented in the following paragraphs.

   Prioritized sampling, in which 10 to 20 percent of the critical or most congested segments are fully sampled, while the remaining 80 to 90 percent of the roadway segments are randomly sampled from different routes. Although prioritized sampling may not conform to the thorough statistical methods that exist for stratified random sampling, it concentrates data collection efforts on the most critical or congested locations. One or more of the following factors can be used for prioritizing data collection:

- perceived bottlenecks or congested locations;
- percent change in congestion level (if available);
- average daily traffic volume per lane; or
- average daily traffic volume.

These factors should rank the roadway segments with the highest congestion or the fastest growing congestion as "high priority." Depending upon the number of roadway segments, the top 10 to 20 percent of segments could be designated as "high priority," thereby collecting data on these segments on an annual or frequent basis.

Once the top 10 to 20 percent of roadway segments have been designated as "high priority" for data collection, the remaining roadway segments should be randomly chosen from the routes to accomplish the sample sizes for each strata group as outlined earlier. With this technique, data will be collected on the "high priority" segments and some randomly selected segments on a frequent basis (e.g., annual).

The prioritized sampling technique ensures that reliable, timely data exists for severely congested segments, and that the remaining, less critical segments are sampled on a less frequent basis. It will ensure that travel times at major bottlenecks such as lane drops, bridge/tunnel approaches, and freeway entrance locations are measured.

Table 2-3. Sample Size Estimation Equations

Coefficient of Variation, c.v.

$$c.v. = \frac{\sigma}{\mu} \approx \frac{s}{\bar{x}} \qquad (2\text{-}1)$$

where: σ = population standard deviation
μ = population mean
s = sample standard deviation
$\bar{x}$ = sample mean

Uncorrected Sample Size, n′

$$n' = \frac{c.v.^2 \times z^2}{e^2} \qquad (2\text{-}2)$$

where: z = z-statistic based on confidence level
e = relative permitted error level (%)

Sample Size, n (corrected for finite population):

$$n = \frac{n'}{1 + \frac{n'}{N}} \qquad (2\text{-}3)$$

where: n' = uncorrected sample size
N = population size

Coefficient of Variation can be estimated from existing data or the following default values can be used for estimates of c.v. (7):

Freeways/Expressways: c.v.'s range from 15 to 25 percent (depending upon traffic volume)

Principal/Minor Arterials: c.v.'s range from 20 to 25 percent (depending upon traffic volume)

The **Z-statistic** is based on the desired confidence level. Z-statistics are provided below for commonly used confidence levels (8):

Desired Confidence Level	Z-statistic
99 percent	2.575
95 percent	1.960
90 percent	1.845
85 percent	1.440
80 percent	1.282

The **relative permitted error, e,** is expressed as a percentage of the sample mean, and is typically based upon the use of the data. Commonly used error levels are (7):

- ± 5 percent for design and operational analyses; and
- ± 10 percent for planning and programming studies.

2.3.3 Time Elements

There are several time elements that must be considered in establishing the scope for travel time data collection activities:

- months of the year;
- days of the week; and
- time periods, or time of day.

These three time elements are discussed in the following sections.

Months of the Year

Travel time data are commonly used to represent "typical" or "average" annual conditions, and should be collected during months that have typical or average traffic volume patterns. As with defining other time elements in the scope, traffic volume patterns from automatic traffic recorder (ATR) stations can be used to determine typical or average months for data collection. Table 2-4 contains data from an ATR station in Houston, Texas, and illustrates how this data can be used to define typical or average months. Those months with traffic volumes within approximately 2 percent of the annual average daily traffic (AADT) volumes are candidate months for data collection. As a general rule of thumb, the spring (i.e., March, April and May) and fall months (i.e., September, October, and November) are commonly considered average conditions if no ATR traffic volume data is available for specific areas or corridors.

For special studies that seek to examine congestion associated with non-work trips, one may wish to look at specific times of the year in which traffic patterns differ from typical or average months. Examples include (but are not limited to): summer or winter months near high use recreational areas; the holiday shopping season (late November and December) near large retail shopping centers; months when large universities or schools are not in session; or months coinciding with regional festivals or special events. However, if travel time data are desired for typical daily traffic conditions, these times of the year should be avoided.

Table 2-4. Using ATR Station Traffic Volume Data to Select Typical Months

ATR Station S-139, US 59, Houston, Texas				
Month and Season	**Average Day**		**Average Weekday (Mon - Fri)**	
	Volume	**Percent AADT**	**Volume**	**Percent AADT**
January	173,684	93.4	194,036	104.3
February	188,691	101.4	208,530	112.1
March	187,877	101.0	205,970	110.7
April	189,651	102.0	209,040	112.4
May	183,365	98.6	201,914	108.6
June	185,515	99.7	204,611	110.0
July	180,276	96.9	198,917	106.9
August	189,668	102.0	209,063	112.4
September	183,898	98.9	205,073	110.2
October	196,253	105.5	216,036	116.1
November	188,704	101.4	207,470	111.5
December	184,524	99.2	202,960	109.1
Annual Average	**186,009**	**100.0**	**205,302**	**110.4**

Source: adapted from reference (9).

Note: Shaded months ± 2 percent of annual average (e.g., candidates for data collection).

Days of the Week

Traditionally, data collection efforts for many transportation agencies have been focused on the middle weekdays (i.e., Tuesday, Wednesday, and Thursday). Monday and Friday are typically excluded from data collection because a small number of weekdays are sampled (typically less than 20 for most study budgets), and these days' high variation from conditions during the middle of the week would necessitate a much larger sample of weekdays.

ATR station data or other 24-hour traffic volume counts can also help to establish the day-to-day variation between weekdays. As a general rule, if study budgets only permit data collection to occur on a given facility less than five separate weekdays, then sampling should be concentrated between Tuesday and Thursday. If budgets permit sampling of five or more weekdays for a given facility, then data collection should be evenly distributed over all five weekdays (e.g., Monday through Friday). Weekend days (e.g., Saturday or Sunday) should be sampled if the study focus relates to recreational or weekend-based trips.

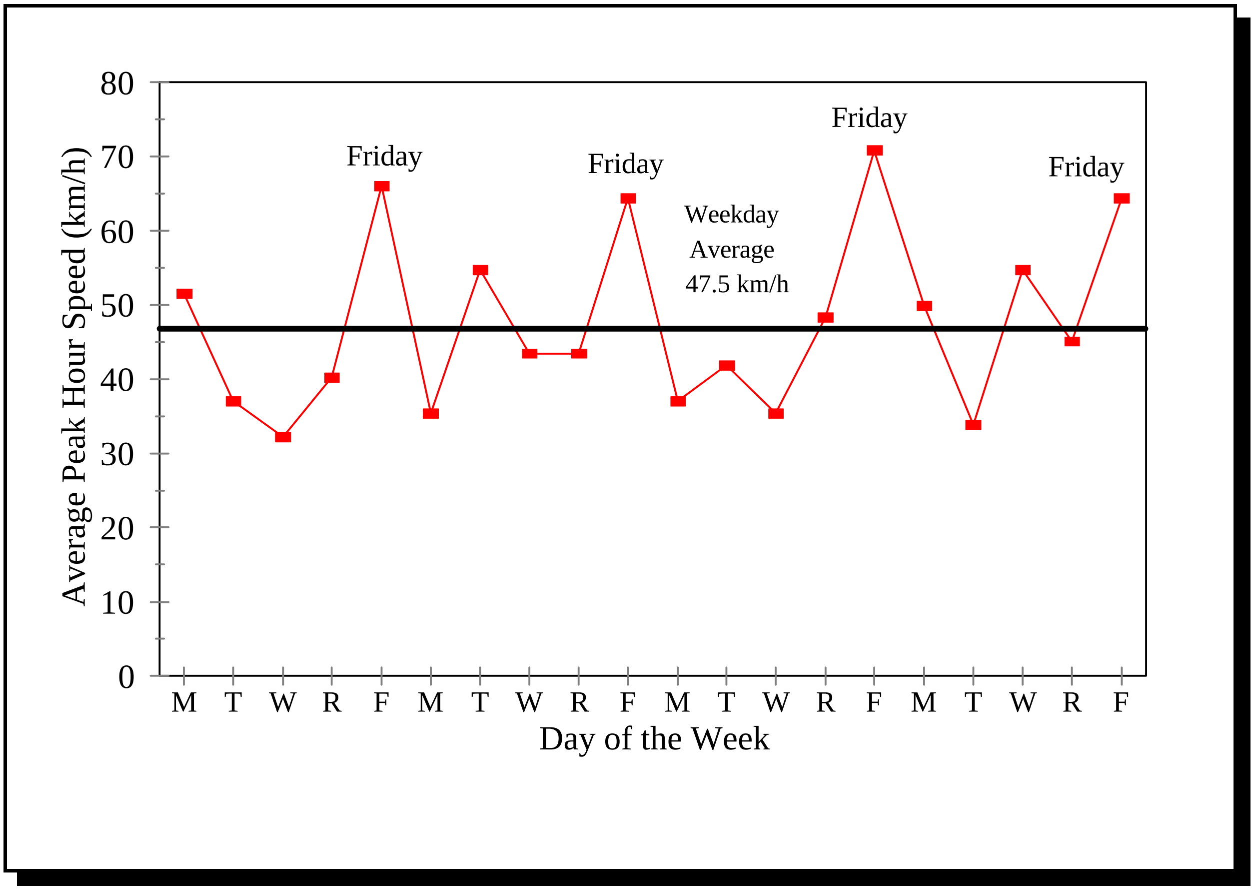
For example, Figure 2-2 shows morning peak hour data from a Houston freeway (I-10, Katy Freeway). The average speeds were collected throughout the peak hour by about 20 passive probe vehicles equipped with AVI transponders. The figure illustrates that Friday speeds are consistently higher than other weekdays and the average weekday speed. If a study budget only permitted the sampling of speed data from, say two to three weekdays per facility, then those weekdays that exhibit conditions closest to average "typical" conditions would be chosen. For this example, the study should sample weekdays between Monday and Thursday. If, however, the study budget permitted the sampling of speed data from five or more weekdays, the data collection should be distributed over all weekdays.

EXPERT TIP ☺ When budgets only permit data collection on less than five weekdays, concentrate on Tuesday through Thursday. If data can be collected for five or more weekdays, use all five weekdays to obtain average travel times.

Recurring holidays or events should be considered when scheduling the specific days for data collection. These days are avoided when sampling a small number of weekdays because of their variance from "typical" day-to-day operating conditions. Unless data is desired specifically for these events, the following times should be avoided when sampling weekdays :

- established holidays (e.g., Memorial Day, Independence Day, Veteran's Day);
- other celebrated days (e.g., St. Patrick's Day, Valentine's Day);
- changes in local school schedules (e.g., spring break, summer recess);
- day after time changes (e.g., Daylight Savings, Standard Time changes); and
- special events (e.g., professional sports games, regional festivals).

If large samples of weekdays (i.e., 75 to 100 percent of all possible days) are available, as is the case with some ITS data collection technologies, data from all days should be included to provide a truly representative value for the "average" weekday.



Source: data from reference (10), Appendix B

Figure 2-2. Illustration of Weekday Speed Variation (Morning Peak Hour Speeds, I-10 Freeway in Houston, Texas)

Time Periods

The time periods define the ranges in the time of day that travel time data will be collected. Like other elements of the study scope, the time periods will likely be determined by the study objectives. For travel time studies that are focused on identifying congestion trends and problems, three time periods are commonly considered:

1. **Morning Peak Period** - encompasses all congestion during the peak morning commute, typically sometime between the hours of 6 a.m. and 9 a.m.;

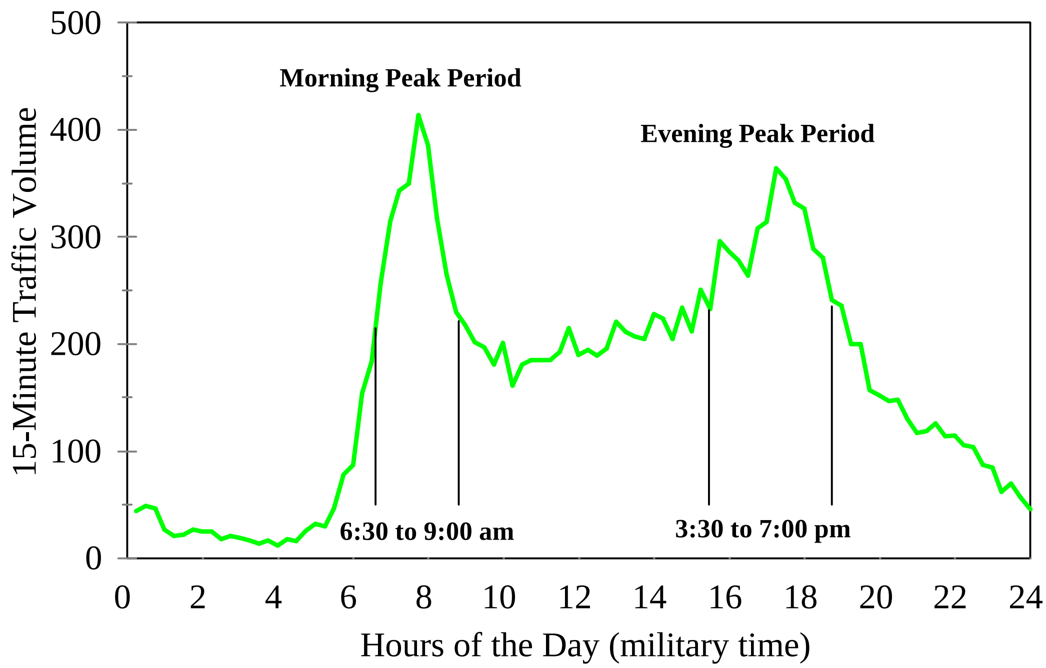
2. **Off-Peak Period** - includes periods of free-flow traffic during the middle of the day or late in the evening, typically between 10 a.m. and 11 a.m., 1 p.m. to 3 p.m., or after 7 p.m. The hours before and after 12 noon (11 a.m. to 1 p.m.) should be avoided if the "lunch hour" traffic is significant. Off-peak travel times are used to establish free-flow conditions for calculating congestion measures; and

3. **Evening Peak Period** - encompasses all congestion during the peak evening commute, typically some time interval between the hours of 4 p.m. and 7 p.m.

For studies relating to weekend or recreational travel, these typical "commuter" time periods should be adjusted to coincide with the times of congestion or peak traffic conditions.

The time periods for data collection should be matched to local traffic conditions and congestion patterns for the geographic area under consideration. The time periods can be defined by examining travel time data from previous studies or traffic volumes from inductance loop detectors, ATR stations, or 24-hour counts. The traffic volumes should come from a representative sample of facilities on which data is to be collected. On single corridors, traffic volumes taken at both end points and the middle of the corridor can better establish predominant congestion and traffic patterns throughout the corridor.

Figure 2-3 contains an illustration of defining time periods based upon traffic volume data. Note in the figure that the peak period includes both the build-up and dissipation of congestion, as evidenced by the peak volumes. The duration of the time period(s) depends upon the duration of congestion, which commonly varies by the population size of communities. In large metropolitan areas like Los Angeles, Houston, or New York, the peak periods may last two to three hours or more. In smaller towns and cities, congestion and the resultant peak period may last less than a single hour. The minimum duration of time for a peak period definition should be one hour (peak or "rush" hour).



Source: 15-minute loop detector data from TransGuide (San Antonio) web site "http://www.transguide.dot.state.tx.us/statistics.html"

Figure 2-3. Defining Peak and Off-Peak Time Periods Using Traffic Volumes

2.4 Select Data Collection Technique

Several data collection techniques are available to measure travel times. A specific technique, or combination of techniques, should only be selected after considering the study and data needs and the advantages and disadvantages of each technique. The travel time data collection techniques in this handbook are grouped into four general categories:

- "active" test vehicle techniques;
- license plate matching techniques;
- "passive" ITS probe vehicle techniques; and
- emerging and non-traditional techniques.

The first step in selecting a data collection technique should be to **investigate any existing sources of travel time or speed data**. For example, travel time or speed data may be available from other agencies or through transportation management centers. The deployment of ITS in major urban areas is a potentially rich source of travel time and speed data for a number of operational and planning studies. Because data from ITS components may only be available for a limited geographic area or corridor, additional data collection may be necessary to supplement existing data for area-wide or regional studies.

Once all existing sources of data have been identified, the second step is to **consider all needs and potential uses** for the travel time data. Some studies or analyses may require detailed travel time and delay information for specific corridors. Test vehicle techniques are most appropriate when analyses require detailed data about intermediate travel times and delay. In these cases, detailed information can be obtained by active test vehicles that traverse the routes or corridors of interest. License plate matching techniques are not well-suited for gathering intermediate travel time and delay, but do gather large sample sizes and provide more insight into travel time variability among drivers and throughout the time period. For example, license plate matching techniques have been used in several instances to compare the travel time reliability of general-purpose freeway lanes and high-occupancy vehicle (HOV) lanes.

The final consideration is the **budget and equipment resources allocated to data collection or available to the agency**. Available equipment (e.g., portable computers, video cameras) or study budgets may limit the data collection to one of several techniques. Some agencies may have analysis tools that are capable of exploiting certain data collection techniques. For example, agencies with geographic information systems (GIS) capabilities should consider the many advantages of GPS data collection. The chosen data collection technique should also match personnel capabilities and experience. Some test vehicle and license plate matching techniques are technology-intensive and require adaptable, experienced personnel that have available time and/or resources.

Table 2-5 contains a qualitative comparison of the travel time data collection techniques (Liu provides a complementary comparison in 11), and Table 2-6 summarizes the major advantages and disadvantages of each technique. These tables can be used to determine which technique best fits your data needs.

EXPERT TIP ☺	Steps in selecting a data collection technique: investigate existing potential data sources, assess potential applications and data needs, and determine budget and equipment allocation. Then refer to Tables 2-5 and 2-6.

Survey or interview methods are also used to obtain estimates of travel times for various purposes, including development and calibration of planning models. Most travel survey methods require drivers to record or recall travel times for trips during a given time period. This handbook does not include descriptions for survey recall methods, as the accuracy level is not consistent with other techniques in this handbook (12). However, useful travel time data may be extracted if travel survey methods use vehicles instrumented with GPS devices or similar instrumentation. In these cases, the appropriate sections in this handbook may be used based upon the vehicle instrumentation. Readers should refer to FHWA's *Travel Survey Manual* for detailed documentation of survey methods (13).

The following criteria are used in Table 2-5 to compare travel time data collection techniques:

- **Initial or capital costs** - typical costs of equipment necessary to perform data collection. For all ITS probe vehicle techniques except GPS, it is assumed that the vehicle-to-roadside communication infrastructure does not exist;

- **Operating efficiency** - relative costs of data collection per unit of data;

- **Required skill or knowledge level** - typical skill or knowledge level required for data collection personnel;

- **Data reduction and/or processing** - typical time and cost associated with reducing and/or processing field data;

- **Route flexibility** - transportability of data collection equipment to different routes in short periods of time;

- **Accuracy** - typical accuracy of the technique relative to the true average travel time (assumes adequate quality control procedures);

- **Sampling rate over time** - ability to collect travel time data at frequent time intervals (for a given facility) without excessive equipment;

- **Sampling rate over space** - ability to collect travel time data at closely-spaced distance intervals (for a given facility) without excessive equipment; and

- **Sampling rate of vehicles** - ability to collect travel time data that is representative of the numerous vehicle types and driving behaviors in the traffic stream.

Table 2-5. Qualitative Comparison of Travel Time Data Collection Techniques

Technique	Initial or Capital Costs	Operating Costs (per unit of data collected)	Required Skill or Knowledge Level	Data Reduction and/or Processing	Route Flexibility	Accuracy and Representa-tiveness[a]	Sampling Rate		
							Time	Space	Vehicles
Test Vehicle									
Manual	low	high	low	poor	excellent	fair	low	moderate	low
DMI	moderate	moderate	moderate	good	excellent	good	low	high	low
GPS	moderate	moderate	moderate	good	excellent	good	low	high	low
License Plate Matching									
Manual	low	high	low	poor	good	fair	low	low	moderate
Portable Computer	moderate	moderate	moderate	good	good	good	moderate	low	high
Video with Manual Transcription	low	moderate	moderate	fair	fair	excellent	high	low	high
Video with Character Recognition[b]	high	low	high	good	fair	excellent	high	low	high
ITS Probe Vehicle[c]									
Signpost-Based	high	moderate	high	good	poor	good	moderate	low	low
AVI	high	low	high	good	poor	excellent	high	low	moderate
Ground-based Radio Navigation	high	low	high	fair	good	good	moderate	moderate	moderate
GPS	moderate	low	high	fair	good	good	moderate	high	moderate
Cellular Phone Tracking	high	low	high	fair	good	good	high	moderate	moderate

Rating scales are relative among the techniques: [high, moderate, low] or [excellent, good, fair, poor].

Notes: [a] Assumes that adequate quality control procedures are used.
[b] Assumes that necessary equipment is purchased (as opposed to contracting data collection services).
[c] Assumes that vehicle-to-roadside communication infrastructure does not exist.

Table 2-6. Advantages and Disadvantages of Travel Time Data Collection Techniques

Data Collection Technique	Advantages	Disadvantages
Test Vehicle		
Manual	• low initial cost • low required skill level	• high operating cost per unit of data • limited travel time/delay information available • limited sample of motorists
Electronic DMI	• moderate initial cost • very detailed speed/delay data available	• lacks geographical referencing (e.g., GIS) • limited sample of motorists
GPS	• moderate initial cost • data easily integrated into GIS • detailed speed/delay data available • can provide useful data for travel surveys	• reception problems in urban “canyons”, trees • limited sample of motorists
License Plate Matching		
Manual	• low initial cost	• high operating cost per unit of data • accuracy may be questionable • data reduction time-consuming
Portable Computer	• low operating cost per unit of data • travel times from large sample of motorists • continuum of travel times during data collection	• accuracy problems with data collection, spurious matches • limited geographic coverage on single day
Video with Manual Transcription	• travel times from large sample of motorists • continuum of travel times during data collection	• data reduction time-consuming • limited geographic coverage on single day
Video with Character Recognition	• low operating cost per unit of data • travel times from large sample of motorists • continuum of travel times during data collection	• high initial costs (if equipment purchased) • limited geographic coverage on single day
ITS Probe Vehicle		
Signpost-based Transponders	• low operating cost per unit of data	• typically used for transit vehicles (includes loading/unloading times) • sample dependent on equipped vehicles
AVI Transponders	• low operating cost per unit of data • very accurate	• very high initial cost for AVI infrastructure • limited to instrumented locations • sample dependent on equipped vehicles
Ground-based Radio Navigation	• available consumer product	• typically used for transit vehicles • sample dependent on equipped vehicles
GPS	• increasingly available consumer product • low operating cost per unit of data	• sample dependent on equipped vehicles • privacy issues
Cellular Phone Tracking	• widely available consumer product	• accuracy questionable for detailed applications • privacy issues

The comparability of average travel times from different data collection techniques may be of concern if agencies compare data from several different sources. Little research has been performed to quantitatively compare average travel time samples using different techniques to the true average travel time. To some degree, each technique may yield slightly different values for the same conditions. Steps should be taken to avoid biases that affect the representativeness of travel time data from certain techniques. Analysts should also recognize and understand the source of potential biases in the data they are using, especially in cases where biases may be suspected. For example, test vehicle techniques may yield data with less variability than license plate matching data (because the test vehicle driver purposefully minimizing variability by "floating" with traffic). Or, probe vehicle data may be biased toward higher speeds because of the driving characteristics of select groups of motorists.

UNKNOWN ??	Travel times collected using different data collection techniques may yield slightly different results. Data managers and users should recognize the potential biases inherent in the technique(s) they are using.

2.5 Develop Data Collection Schedule and Equipment Checklists

A schedule of data collection activities should be developed once the study scope, data collection technique, and other major parameters have been determined. An example of a data collection schedule for test vehicle runs is shown in Table 2-7. Similar tables showing date, time, and facilities being surveyed can be developed for other travel time collection techniques. A schedule is particularly helpful with implementing the data collection effort and in informing data collection personnel of their specific responsibilities. The content of the schedule includes the specific days and time of day that data is to be collected. If possible, the schedule should also contain the names of persons assigned to specific duties or stations for each day of data collection.

Equipment checklists should be used to ensure the proper assignment and continued operation of data collection equipment. These checklists are especially important for equipment-intensive travel time collection methods, such as computerized methods of test vehicle or license plate matching. A sample equipment checklist for video license plate matching is shown in Table 2-8. Checklists typically have columns to record the following information:

- time, date, and location of use;
- make, model, or serial identification number;
- names or initials of person(s) using equipment (check-in and check-out); and
- instructions for any necessary field calibration.

Table 2-7. Example of Data Collection Schedule for Test Vehicle Runs

Travel Time Runs--Week 1 (May 26, 1997)				
Day & Date	Time Period	Freeway Facility	VAN 3582 **HALF HR** Start by 3:30 pm Last run by 6:00 am	VAN 3583 **EVEN HR** Start by 4:00 pm Last run by 6:30 am
Monday, 5/27/97	PM	I-45	Bill S.	Jim R.
Tuesday, 5/28/97	AM	I-10	Dale T.	Sam P.
	PM	I-10	Bill S.	Jim R.
Wed., 5/29/97	AM	I-45	Dale T.	Sam P.
	PM	I-45	Bill S.	Jim R.
Thursday, 5/29/97	AM	US 59	Dale T.	Sam P.
	PM	US 59	Bill S.	Jim R.
Friday, 5/30/97	AM	I-45	Bill S.	Jim R.

Table 2-8. Example of Equipment Checklist

Equipment Checklist and Sign-Out

Route Number: Equipment Set Number:
Segment: Survey Team Number:
Location Description: Date: Time Period:

Equipment	**Person**	**Make**	**Model**	**ID/Serial #**
Hi-8 mm camcorder				
camera remote				
camera case				
CL-2x extender				
camera batteries				
camera remote batteries				
video leads (red and black)				
S-video cable				
linear polarizing filters				
UV lens filter				
DC-10 DC adaptor				
marine battery				
5" color monitor				
monitor cable				
monitor case				
Hi-8 mm video tapes				
tape labels				

Other Incidental Supplies:

☐ Watch ☐ Pen/Paper ☐ Safety Cones ☐ Cellular Phone ☐ Chains/Locks
☐ Phone Numbers ☐ Safety Vest ☐ Rain Gear ☐ Clipboard

Source: adapted from reference (14).

2.6 Conduct Training

The attitude and knowledge of data collection personnel play a major role in the quality of collected data. All data collection personnel should be adequately trained on the travel time data collection technique to ensure a consistent level of knowledge. The training or briefing may be best accomplished in small groups in which each person has the ability to ask questions and practice using the data collection equipment. A training session should include the following key points:

- purpose(s) of the data collection, including sponsorship, analysis goals, and end uses of the data;
- step-by-step details of the data collection technique and equipment operation;
- troubleshooting techniques to fix equipment problems in the field; and
- specific procedures or requirements for canceling data collection because of weather, traffic incidents, or equipment problems.

IMPORTANT ☞ Adequate training is necessary for a consistent level of quality data. Ensure that your data collection effort has training built into the budget.

Training sessions should also impart the following attitudes to data collection personnel (13):

- *This job is important* - stress the importance of the study, how it is to be used in solving problems and meeting project needs;
- *I must follow instructions* - teach the importance of following instructions, the necessity of proper field procedures, and the importance of accuracy and consistency;
- *I am a professional* - each person collecting data should believe: "I have a job to do; I am a professional being paid for services rendered";
- *Research is important* - communicate the value of research, how research information improves our ability to make decisions, solve problems, and save money and resources; and
- *The accuracy and reliability of data is my responsibility* - stress that each person is responsible for collecting data that is accurate, reliable, and has been collected according to instructions provided.

2.7 Perform Pilot Studies or Trial Runs

Pilot travel time studies or trial runs should be conducted before the actual data collection begins. If the data collection personnel are experienced, pilot studies may be considered optional. Pilot studies can be performed over several days on a sample (approximately five to ten percent) of the facilities that will be included in the data collection effort. The purpose of pilot studies or trial runs are the following:

- become intimately familiar with the data collection equipment and process;
- become familiar with data collection corridors and cross streets;
- perform corridor or site surveys and measure exact distances; and
- identify problems or necessary resources as early as possible.

Also, travel time variability data obtained during pilot studies can potentially be used to check and/or adjust previously calculated sample sizes. After the pilot studies have been completed, all data collection personnel should provide feedback about the ease and utility of the data collection process. The feedback can then be used to modify the data collection procedures to ensure quality data.

2.8 Collect Data

Depending upon the scope of the study, data collection may extend through several months or even throughout the entire year. A manager of data collection activities should be assigned to track the progress of data collection, troubleshoot equipment and personnel problems, and supervise the data reduction and quality control measures.

The data collection supervisor should establish clear policies and procedures for canceling data collection in the field because of extreme or unusual conditions. Such extreme or unusual conditions that could merit field cancellation of data collection include:

- severe weather (e.g., heavy rain, tornados, ice);
- unusual traffic conditions (e.g., severe accidents, police chases); and
- equipment malfunction (e.g., dead batteries, broken video camera lens).

EXPERT TIP ☺

Define clear protocol for unusual circumstances prior to data collection. The use of cellular phones by data collection personnel in the field can save time and money.

Several other types of qualitative information should be gathered during data collection that could prove useful in the data reduction and analysis stages. Useful qualitative information includes:

- weather conditions (e.g., sunny, rain, foggy);
- pavement conditions (e.g., dry, wet, icy);
- observations about unique traffic conditions or incidents; and
- media reports about construction closures, incidents, or other special events that may affect traffic conditions.

Information that may be roadway or site-specific, such as weather or pavement conditions, should be recorded on data collection sheets or summaries. General area or regional information, such as special events, should be recorded in a common file location.

2.9 Reduce Data and Perform Quality Control

The first several days of travel time data should be reduced and analyzed soon after it has been collected to ensure that field personnel are collecting quality data. This early data reduction and quality control can potentially identify equipment problems or data discrepancies that are not obvious, particularly in electronic data collection systems. Data reduction or quality control records, such as those shown in Table 2-9, can also help to track progress.

Table 2-9. Example of Quality Control and Progress Tracking Forms

Morning Peak Period Travel Time Runs (7 to 9 a.m.)										
Freeway	Run 1		Run 2		Run 3		Run 4		Run 5	
	Driver	Q.C.	Driver	Q.C.	Driver	Q.C.	Driver	Q.C.	Driver	Q.C.
I-10 (Katy)	S.T.	R.B.	S.T.	R.B.	S.T.	R.B.				
I-45N (North)	B.E.	R.B.	B.E.	R.B.						
I-45S (Gulf)										
US 59N (Eastex)										
US 59S (Southwest)				Note: Responsible personnel can either initial or place an "X" in each cell once the run/QC has been completed.						
US 290 (Northwest)										

2.10 References for Chapter 2

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2.11 Additional Resources for Data Collection Planning

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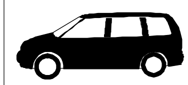
3 TEST VEHICLE TECHNIQUES



"ACTIVE"
TEST VEHICLE

The test vehicle technique has been used for travel time data collection since the late 1920s. Traditionally, this technique has involved the use of a data collection vehicle within which an observer records cumulative travel time at predefined checkpoints along a travel route. This information is then converted to travel time, speed, and delay for each segment along the survey route. There are several different methods for performing this type of data collection, depending upon the instrumentation used in the vehicle and the driving instructions given to the driver. Since these vehicles are instrumented and then sent into the field for travel time data collection, they are sometimes referred to as "active" test vehicles. Conversely, "passive" ITS probe vehicles are vehicles that are already in the traffic stream for purposes other than data collection. ITS probe vehicle techniques are discussed in Chapter 5.

This chapter describes three levels of instrumentation used to measure travel time with a test vehicle:

- **Manual** - manually recording elapsed time at predefined checkpoints using a passenger in the test vehicle;

- **Distance Measuring Instrument (DMI)** - determining travel time along a corridor based upon speed and distance information provided by an electronic DMI connected to the transmission of the test vehicle; and

- **Global Positioning System (GPS)** - determines test vehicle position and speed by using signals from the Department of Defense (DOD) system of earth-orbiting satellites.

Historically, the manual method has been the most commonly used travel time data collection technique. This method requires a driver and a passenger to be in the test vehicle. The driver operates the test vehicle while the passenger records time information at predefined checkpoints. Technology has automated the manual method with the use of an electronic DMI. The DMI is connected to a portable computer in the test vehicle and receives pulses at given intervals from the transmission of the vehicle. Distance and speed information are then determined from these pulses.

GPS has become the most recent technology to be used for travel time data collection. A GPS receiver is connected to a portable computer and collects the latitude and longitude information that enables tracking of the test vehicle. Each of these test vehicle techniques is described in detail in the following sections of this chapter. The following elements are included for each technique: overview, advantages and disadvantages, cost and equipment requirements, data collection instructions, data reduction and quality control, and previous experiences.

Since the driver of the test vehicle is a member of the data collection team, driving styles and behavior can be controlled to match desired driving behavior. The following are three common test vehicle driving styles (1):

- *Average car* - test vehicle travels according to the driver's judgement of the average speed of the traffic stream;

- *Floating car* - driver "floats" with the traffic by attempting to safely pass as many vehicles as pass the test vehicle; and

- *Maximum car* - test vehicle is driven at the posted speed limit unless impeded by actual traffic conditions or safety considerations.

The floating car driving style is the most commonly referenced. In practice, however, drivers will likely adopt a hybrid of the floating car and average car because of the inherent difficulties of keeping track of passed and passing vehicles in high traffic volume conditions

IMPORTANT ☞ Most travel time studies incorporate a hybrid of the floating car and average car driving styles. Differences between individual test drivers will probably account for more variation than exist between these two driving styles.

3.0.1 General Advantages and Disadvantages

Test vehicle techniques have the following **advantages:**

- Provides for the determination of driving styles (e.g., "floating car"), which provides consistent data collection;

- Advanced test vehicle techniques (e.g., DMI or GPS use) result in detailed data that cover the entire study corridor; and

- Relatively low initial cost.

Test vehicle techniques have the following **disadvantages:**

- Sources of possible error from either human or electric sources that require adequate quality control;

- Advanced and detailed data collection techniques (e.g., every second) can provide data storage difficulties; and

- The travel time estimates for the corridor are based on only one vehicle that is in the traffic stream.

Detailed advantages and disadvantages of the three instrumentation levels for the test vehicle technique are described in subsequent sections of this chapter. Table 3-1 provides a relative comparison of the three different instrumentation levels.

Table 3-1. Comparison of Test Vehicle Travel Time Data Collection Techniques

Instrumentation Level	Costs			Skill Level		Level of Data Detail	Data Accuracy	Automation Potential
	Capital	Data Collection	Data Reduction	Data Collection	Data Reduction			
Manual-Pen and Paper	Low	Moderate	High	Low	Moderate	Low	Low	Low
Tape Recorder	Low	Low	High	Low	Moderate	Low	Low	Low
Portable Computer	Moderate	Low	Moderate	Moderate	Moderate	Low	Moderate	Moderate
Distance Measuring Instrument (DMI)	High	Low	Low	Moderate	Low	High	Moderate	High
Global Positioning System (GPS)	High	Low	Moderate	Moderate	High	High	High	High

Note: Rating scale is relative among the instrumentation levels shown: [high, moderate, low].

3.0.2 Sample Sizes

Sample size requirements for the test vehicle technique dictate the number of “runs” that must be performed for a given roadway during the time period(s) of interest. The use of minimum samples sizes, or a minimum number of travel time runs, ensures that the average travel time obtained from the test vehicle is within a specified error range of the true average travel time for the entire vehicle population. The standard sample size equation is shown as Equation 3-1 (2). Using the relationships in Equations 3-2 and 3-3, Equation 3-4 is derived for use by practitioners in computing sample sizes for test vehicle travel time runs.

$$Sample\ Size,\ n = \left(\frac{t \times s}{\varepsilon}\right)^2 \tag{3-1}$$

where: t = t-statistic from Student's t distribution for specified confidence level;
s = standard deviation of travel time; and
ε = maximum specified allowable error.

$$Coefficient\ of\ Variation,\ c.v. = \frac{s}{\bar{x}} \tag{3-2}$$

$$Relative\ Error,\ e = \frac{\varepsilon}{\bar{x}} \tag{3-3}$$

where: $\bar{x}$ = mean travel time

$$Sample\ Size,\ n = \left(\frac{t \times s}{\varepsilon}\right)^2 = \left(\frac{t \times (c.v. \times \bar{x})}{(e \times \bar{x})}\right)^2 = \left(\frac{t \times c.v.}{e}\right)^2 \tag{3-4}$$

If sample sizes approach 30 or more (uncommon for test vehicle runs), the normal distribution can be used in place of the Student's t distribution and Equation 3-5 is applicable.

$$Sample\ Size,\ n = \left(\frac{z \times c.v.}{e}\right)^2 \quad \begin{array}{c} if\ estimated\ sample\ size \\ is\ greater\ than\ 30 \end{array} \tag{3-5}$$

As shown in Equations 3-4 and 3-5, minimum sample sizes are based upon three parameters:

- **T-statistic, t -** value from the Student's t distribution for (n-1) degrees of freedom. The t-statistic is based upon the specified confidence level (two-tailed test) in the travel time estimate. Because the degrees of freedom for the t-statistic rely on a sample size, n, an initial sample size estimate must be assumed. Iterative calculations should be used to provide better estimates for the degrees of freedom. If sample sizes approach 30 or more, a z-statistic from the normal distribution may be substituted for the t-statistic.

- **Coefficient of variation, c.v. -** the relative variability in the travel times, expressed as a percentage (%). The c.v. values can be calculated from empirical data using

Equation 3-2, or approximate values of 9 to 17 percent can be used from other studies (Table 3-2) (2,3,4).

- **Relative allowable error, e** - the relative permissible error in the travel time estimate, expressed as a percentage (%). The relative error is specified by the study designer and will depend upon the uses of the travel time data. Commonly specified relative errors are ± 5 percent for operations and evaluation studies and ± 10 percent for planning and policy-level studies (3).

Table 3-2. Coefficients of Variation for the Test Vehicle Technique on Freeways and Arterial Streets

Freeways		Arterial Streets	
Average Daily Traffic (ADT) Volume per lane	Average Coefficient of Variation (%)	Traffic Signal Density (signals per database)	Average Coefficient of Variation (%)
Less than 15,000	9	Less than 3	9
15,000 to 20,000	11	3 to 6	12
Greater than 20,000	17	Greater than 6	15

Source: adapted from reference (3).

Coefficients of variation for travel times will range depending upon the physical and traffic control characteristics of the roadway (e.g., number of signals, signal progression, ramp access spacing) and the traffic conditions (e.g., free-flow versus stop-and-go congestion). Research of the test vehicle method in 1949 by Berry and Green produced coefficients of variation for urban streets ranging from 9 to 16 percent (5). Subsequent studies found coefficients of variation ranging from 5 to 17 percent (6). Several other empirical study results have indicated that coefficients of variation are on the order of 8 to 17 percent (2). A recent National Cooperative Highway Research Program (NCHRP) study confirmed these estimates of variation for varying conditions on freeways and arterial streets, as shown in Table 3-2 (3). These coefficient of variation estimates should be checked against data that is collected to ensure the validity of estimated sample sizes.

Therefore, minimum sample sizes or number of travel time runs can be calculated using Equation 3-4 and Table 3-2. The t-statistic (or z-statistic for samples greater than 30) can be obtained from most basic statistics texts. The permitted relative error should be based upon the intended uses of the travel time data. Tables 3-3 and 3-4 show minimum sample sizes for various combinations of confidence level and permitted relative error.

Table 3-3. Illustrative Test Vehicle Sample Sizes on Freeways

Average Daily Traffic (ADT) Volume per lane	Average Coefficient of Variation, (%) Table 3-2	Sample Sizes (iterative calculations using Equation 3-4)		
		90% Confidence, ± 10 % Error	95% Confidence, ± 10 % Error	95% Confidence, ± 5 % Error
Less than 15,000	9	5	6	15
15,000 to 20,000	11	6	8	21
Greater than 20,000	17	10	14	47

Source: adapted from reference (3).

Table 3-4. Illustrative Test Vehicle Sample Sizes on Arterial Streets

Traffic Signal Density (signals per mile)	Average Coefficient of Variation, (%) Table 3-2	Sample Sizes (iterative calculations using Equation 3-4)		
		90% Confidence, ± 10 % Error	95% Confidence, ± 10 % Error	95% Confidence, ± 5 % Error
Less than 3	9	5	6	15
3 to 6	12	6	8	25
Greater than 6	15	9	12	37

Source: adapted from reference (3).

Many agencies perform the maximum number of test vehicle runs that is practical given available data collection budgets (typically 3 to 6 runs per route). While this is a common practice, it should be recognized that the potential accuracy of the data falls at or below the lowest accuracy range shown in Tables 3-3 and 3-4 (90 percent confidence level, ±10 percent error).

IMPORTANT ☞ After the minimum number of travel time runs is determined, these runs should be evenly distributed throughout the data collection time period and over several different weekdays.

To evenly distribute the travel time runs, some agencies use approximate headways between test vehicles (e.g., 30-minute headways) as a way to distribute runs evenly throughout a time period. The length of the travel time run and the number of test vehicles will influence the minimum headways that can be achieved for any particular day.

The Institute of Transportation Engineers' (ITE) *Manual of Transportation Engineering Studies* (1) contains travel time data collection guidelines, and suggests the calculation of sample sizes based upon the average range in running speed (as opposed to the standard deviation or coefficient of variation). The average range is supposedly used in sample size calculations to determine, in the field, whether additional runs were necessary beyond a minimum that has already been collected.

Subsequent research by Strickland (7) and Quiroga and Bullock (8) questioned the validity of ITE's sample size guidelines, suggesting that actual sample sizes using average ranges should be much higher. Both research efforts use the average range as an estimator for the standard deviation in the sample size equation. The authors assert that the range is a simpler, more intuitive statistical measure. The ITE guidelines and this recent research suggest conducting several travel time runs, then computing range values and corresponding travel times. There are several problems with this suggested approach of using ranges to compute sample sizes:

- One cannot accurately budget or plan travel time data collection because the necessary sample sizes (calculated using range) are not known until data collection has already begun;

- Standard deviation is considered a more statistically robust measure of variability, which is the factor that directly controls minimum sample sizes;

- Sample size calculations using standard deviation are just as easy using range, and can easily be automated using computer spreadsheet or database programs; and

- Sample sizes should be designed and monitored by a study manager, not data collection personnel in the field, given each person's typical experience.

3.0.3 Data Collection Considerations

This section describes data collection, reduction, and quality control considerations for the test vehicle technique. Consideration of these elements will aid in a successful data collection effort.

General Considerations

- **Data collection forms** - Many travel time data collection forms are available and the form used should fit the needs of the study. Examples of these forms are shown later in Section 3.1.4 of this chapter. Not only does the form provide a medium for recording data, it serves as a guide for the test vehicle driver to follow. Common landmarks are often provided on the data collection forms. These landmarks provide the driver with a highly visible reference for a checkpoint (e.g., overpasses, businesses). Landmarks are especially helpful for large travel time studies in which drivers may not be familiar with each route or for freeway facilities where high speeds and inadequately marked cross streets cause difficulty in determining the proper checkpoint.

- **Extra supplies** - Ensure that additional supplies are available to alleviate the need to reschedule data collection activities. Inexpensive items such as extra pens or pencils, data collection forms, extra stopwatches or batteries are all relatively inexpensive when compared to having to reschedule and recollect the data for a study.

- **Fuel vehicles** - Most data collection is conducted during the morning and evening peak periods. This typically requires some staff to work extensive hours (i.e., start work early or stay late). Drivers should fill the vehicles with fuel at the end of the data collection period. Missed runs or late starts can be avoided and the potential for makeup runs are reduced.

- **Field communication** - Inevitably, there are always questions about the data collection technique, incidents, and technical or mechanical problems. Most of these questions could be immediately answered by the data collection supervisor. The use of cellular phones or pay phones can provide valuable guidance to field personnel. Drivers and observers should be provided with the supervisor's phone number(s) and encouraged to call if they have questions. A couple minutes of the supervisor's time can avoid the cost and time of rescheduling data collection.

- **Report problems** - With any data collection effort, problems may occur. Major accidents and anomalies (e.g., trains, signal malfunction, flooding) will have a great effect on travel time and should be reported directly to the supervisor. Equipment or mechanical problems are also extremely important. In addition, broken or faulty equipment can result in inaccurate data or safety problems and should be corrected as soon as possible. For these reasons, it is important that the data collection personnel realize the need to report problems.

- **Synchronize clocks** - All the stopwatches, computers, and vehicle clocks should be synchronized to within several seconds of one another for consistent times. Variations in start times can cause overlap or nonuniform coverage of the desired time periods. This is especially important when multiple test vehicles are collecting data on one study route to ensure the desired headway between vehicles is provided. It is important to note that computer clocks usually require a military format or an "a.m." or "p.m." designation. If no designation is provided, the default is "a.m." This can lead to the recorded times being 12 hours off, which may affect the recorded date as well.

- **Fleet vehicles -** The test vehicle technique may require the use of a special data collection vehicle instrumented with DMI or GPS equipment. It is generally advisable that fleet vehicles be used for these purposes. If personal vehicles are used, vehicle insurance should be evaluated to ensure that it includes liability requirements. Personal vehicle use may cause some problems with mileage reimbursement. Proper logging of mileage and some quality control or auditing process is required to prevent inaccurate or abuse of mileage charges. The problem of personal vehicle reliability can also be a problem (i.e., staff inability to conduct runs because their car would not start or mechanical breakdown during the run).

- **Periodic review of driving styles** - A review of test vehicle drivers' driving style is suggested before the beginning of each new study. There is a potential for wide variability among different persons' driving styles. Reviewing techniques will result in more consistent and accurate data collection results.

- **Quality control of data entry** - Most procedures require adequate quality control. The data entry from pen and paper or audio tape to electronic format requires staff to enter information into an ASCII text, spreadsheet, or database file. A supervisor should check the field sheets or audio compared to the electronic format on a sampling basis. The supervisor may review either a few entries per page or an entire page on a random basis. If problems arise, further checks are warranted and should be pursued.

- **Consistent electronic file naming** - Most data collection efforts will result in many electronic computer files. Naming of electronic files for different studies over several years becomes problematic without a consistent file naming scheme. Route names, direction, time, and date are some variables that can be used to create a file name. It may be useful to have drivers keep a log book of the travel time run including file name, start time, and any other relevant notes for the run. This may aid in sorting out and managing the raw data files.

- **Automation and quality control** - Automation of reduction and analysis procedures for individual travel time runs can reduce review time and potentially improve data quality. Spreadsheet and database programs can be used to provide average speeds for links and speed profiles. The speed profile for each travel time run should be reviewed before any aggregation of travel time runs is performed since this aggregation will mask errors. These errors (e.g., incorrect speeds along the corridor) may be discovered by reviewing the speed profiles. Quality control with regard to the formulas entered into the spreadsheet or database should also be performed. If automation is utilized, errors in spreadsheet or database calculations only need to be checked once. If automation is not used, the analysis formulas should also be sampled and checked with manual calculations.

- **Backup data** - The loss of computer data is always a concern. The study team should be prepared for lightning, computer viruses, equipment malfunction, or power surges. Saving all field data collection sheets as well as making printouts or backups of all electronic files will reduce the risk of losing the travel time data that has been collected.

Considerations Prior to Data Collection

Many planning elements should be considered prior to the data collection effort. These include the following:

- Preparation of a preliminary work schedule considering holidays, vacations, and other significant dates;

- Determination of the number of student, technician, and professional personnel that will be required to conduct the study;

- Scheduling and completing any service that will be required on the vehicles prior to the data collection effort (e.g., oil changes); and

- Training of drivers in driving styles and data collection methods. This includes an explanation of the appropriate driving style, special instructions for equipment operation, and explanation of relevant data collection forms.

Weekly Considerations

The following elements should be addressed on a weekly basis during the data collection effort:

- Cleaning the exterior and interior of vehicles;

- Checking vehicle tires including tread, sidewalls, and air pressure; and

.

- Updating a data collection progress report (see Table 2-8). A weekly progress report aids in ensuring that the data collection effort remains on schedule. If some travel time runs must be rescheduled due to an incident or suspect data, the weekly progress report helps in rescheduling these travel time runs. A progress report is especially valuable for large data collection efforts.

Daily Considerations

The following elements should be addressed on a daily basis during the data collection effort:

- Check the computer hard drive(s) for adequate data storage space;

- Check the battery life of the computer power source. If a power converter or cigarette lighter is being used from the vehicle, the connections should be investigated to ensure they are secure to avoid a power loss;

- Download data to the desktop storage computer for GPS and DMI test vehicle methods. For manual methods, the data may be reduced at a later date;

- Document any relevant information of importance about a particular travel time run. Depending upon the study design, this may include elements such as incidents, construction, and weather conditions;

- Fill the vehicle with gasoline if the tank has less fuel than required for a full data collection period after the daily data collection activities are completed;

- Fully document any problems with the data collection (e.g., incidents, accidents, vehicle difficulty, running late) for future reference; and

- Determine and address any problems that may have resulted during previous data collection efforts. Identify how to correct and prevent the problem in the future.

3.1 Manual Method

With the manual method, a trained driver uses one of the driving styles described at the beginning of this chapter while a passenger uses pen and paper, an audio tape recorder, a portable computer to record cumulative travel times along the study route. The test vehicle runs may be performed at prescribed start times or test vehicle headways. The focus of this section will be on collecting travel time data using pen and paper, including discussing equipment and personnel requirements, necessary procedures, and associated costs. Audio tape recorders and portable computers have been introduced to improve the quality and efficiency of the pen and paper technique. Although the discussion throughout this section will be based using pen and paper, these semi-automated improvements will also be discussed.

Travel time data are generally collected at checkpoints with 0.4 to 0.8 km (0.25 to 0.5 mi) spacing, depending upon the type of facility and the amount of additional data collected (e.g., queues, stops, construction, incidents). Driving in congested conditions increases the driver's workload, thus reducing the amount and/or frequency of data collection observations or checkpoints. A driver and observer collection team can be used to safely record all the required study information.

IMPORTANT ☞ Travel time data are generally collected at checkpoints with 0.4 to 0.8 km (0.25 to 0.5 mi) spacing, depending upon the type of facility and the amount of additional data collected (e.g., queues, stops, construction, incidents).

Pen and Paper Technique

The pen and paper technique requires a driver and a recorder, one or two stopwatches, data collection forms, and a test vehicle. The test vehicle is driven along the study route throughout the time period of interest, using set headways (typically 30 minutes) if desired. The recorder starts the first stopwatch as the driver passes the first checkpoint, recording the cumulative elapsed time at subsequent checkpoints on the field sheet. A second stopwatch may be used to record the amount of delay time incurred by the test vehicle when slowed or stopped (0 to 8 km/h, or 0 to 5 mph), also noting the cause of the delay. This procedure is followed through the entire course until the time at the final checkpoint is recorded. Several runs are usually made on the same route, requiring the test vehicle to return to the starting point. Data is typically collected on the study route in the reverse direction with little or no additional cost. The stop watches are reset, a new field data collection sheet is prepared, and the above procedure is repeated until the end of the study time period.

Audio Tape Recorder Variation

The audio tape recorder variation follows the same procedure outlined above for the pen and paper technique. However, a voice-activated tape recorder can be utilized to record the times instead of writing the times on paper. This method reduces or eliminates recording errors associated with the pen and paper technique. Transcription errors from documenting time intervals in the field are eliminated, but errors due to transcribing the audio tapes are possible. Speaking clearly into the tape recorder and having the individual who made the tape in the field transcribe the data aids in reducing transcription error with the audio tape variation.

Portable Computer Variation

A portable computer variation of the manual method has also been adopted to reduce errors and staff requirements. The portable computer variation utilizes the internal clock on the computer combined with some specialized software to record the travel times. There are no distance collection capabilities. Available or easily developed software can record the portable computer's clock time. The same pen and paper procedure is utilized, but the stopwatches and pen and paper are replaced by the portable computer's internal clock and computer files. This results in a reduction in staff requirements for field data collection and data entry. Computer keys are used to record predetermined checkpoints as well as other incidents and accidents. A time stamp as well as a description is written to the computer file.

Once the field travel time information is collected, reduction of the computer time stamps is required. Most data reduction and analyses are conducted using computer spreadsheets or databases. Pen and paper and audio tape methods require staff to transcribe the written or recorded times to electronic format. The pen and paper method requires two employees to collect the field information and someone to enter the information into electronic format. Incrementally, it is likely that tape recorders can aid the travel time data collection effort for a minimal additional equipment cost while reducing staff requirements. Transcription of audio tapes is still required and some degree of potential transcription errors still exist. In addition, there is the incremental cost effectiveness of using a portable computer over both the pen and paper and audio tape recorder methods due to the reduction of errors in collection and summarization of the travel time information. Using the portable computer accurately records the time to a data file, which eliminates any transposition and transcription errors and provides a consistent electronic file format that can aid in automation.

Having pointed out the advantages and disadvantages of the audio tape and portable computer variation, the discussion below will be based on the traditional pen and paper method. Equipment and staff requirements and associated costs will be based on this pen and paper technique. With all the manual methods, an element of human error exists in that the observer could inaccurately mark the predetermined checkpoints. Driver knowledge of each checkpoint location is essential. If the observer records the time at an improper location, either before or after the correct checkpoint, a faster or slower calculated speed will result. It is difficult, if not impossible, to correct for this type of human error with the manual method. DMI or GPS instrumentation can correct or eliminate this type of human error. Although these techniques solve some of the problems of the manual method, there are other considerations that the practitioner should realize. These are described in Sections 3.2 and 3.3 of this chapter.

3.1.1 Advantages and Disadvantages

The manual method (pen and paper) has the following **advantages**:

- No special equipment needs;
- Low skill level (no special hardware training); and
- Minimal equipment costs.

The manual method (pen and paper) has the following **disadvantages**:

- High labor requirements (driver and observer);

- Low level of detail (average speeds for 0.4 to 0.8 km, or 0.25 to 0.5 mi). Average speed and delay are reasonable while queue length and speed profiles are difficult;

- Greater potential for human error (potential for marking wrong checkpoints or inaccurate times);

- Potential data entry errors (e.g., recording travel time errors in the field and transcription errors from field sheet to electronic format);

- Cost and time constraints prohibit large sample sizes; and

- Little automation potential and only estimates of emission, fuel consumption, and other performance measure limitations due to the averaged speeds over 0.4 to 0.8 km (0.25 to 0.5 mi).

3.1.2 Cost and Equipment Requirements

This section will detail hardware, software, and personnel needs that are necessary when considering the implementation of any of the manual methods for travel time data collection. The cost and equipment requirements for the manual test vehicle technique are minimal. However, the cost of data collection can vary largely depending upon the skill level of the data collection personnel.

A detailed description of the procedure is explained in Section 3.1.3. The equipment for the different manual test vehicle techniques vary. The typical equipment and personnel requirements for the manual method are as follows.

- **Clipboards and stopwatches** - Hard writing surfaces are helpful for observers to record information on the field data collection sheets. Stopwatches provide the second increment of time which are useful for travel time data collection. Stopwatches that have large numbers are also helpful.

- **Portable audio recorders** - A voice activation feature starts the audio tape recorder from a pause mode, reducing the amount of tape and time recorded as well as the time required to transcribe the recording.

- **Portable computer** - Necessary for recording computer time stamps for the portable computer variation.

- **Power supply** - External power required by the portable computer supplied through the cigarette lighter. Batteries can be used but can prove to be unreliable.

- **Data storage computer** - Generally located back at the office, this desktop computer is used to store and process the field travel time data.

- **Test vehicle** - Vehicle used by the driver and/or recorder to travel the predetermined route. No special equipment is required for the manual method. A fleet or personal vehicle can be utilized with the proper insurance and mileage reimbursement.

- **Collection software** - In addition to a portable computer, the portable computer variation requires specialized software, either commercially available or developed, that utilizes the internal computer clock to record a time stamp.

- **Test vehicle driver** - Personnel are required to drive a test vehicle on the study route and perform the required tasks associated with travel time data collection.

- **Observer/Recorder** - Depending on the selected test vehicle method and the desired data collection, the observer records the elapsed time at the beginning checkpoint and all subsequent checkpoints as well as delay and queue information.

- **Data entry/reduction personnel** - Staff required to transcribe the travel time and distances to link speeds and perform any other required analysis. Computer programs, macros, and automation can reduce or eliminate this step of the process.

- **Supervision and management** - This includes a data collection manager who monitors the overall data collection, reduction, and analysis. This cost varies depending on the size and scope of the project, automation of data collection, reduction and analysis needs, as well as other study needs.

Table 3-5 provides cost information for the manual test vehicle technique. It should be noted that a good deal of quality control is required to ensure that all runs have been completed and that errors in recording, transcribing, or reducing the data are detected and corrected. In many cases, this may require runs to be recollected. Untrained and inexperienced data collection personnel can dramatically increase the cost of travel time data collection.

Table 3-5. Estimated Costs for the Manual Test Vehicle Technique

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
Clipboards, Stop Watches	$20 to $50 per test vehicle
Optional: Portable tape recorders (voice activated)	$30 to $100 each
Optional: Portable Computer (Laptop/Palmtop)	$1,500 to $3,000/$500 to $700
Vehicle Operating Cost	$0.28 to $0.32 per mile
Software	
Optional: Collection Software (Commercial or Developed)	Varies
Personnel	
Test Vehicle Driver	$6 to $10 per hour
Observer/Recorder	$6 to $10 per hour
Data Entry/Reduction Personnel	$6 to $10 per hour
Supervision and Management	Varies

Consider the following cost estimates that present the expected differences in person-hours and capital costs for the various manual method variations. Assume that one would like to perform data collection during a peak period of 4 hours using the manual method. Assuming that one owns a data storage computer and the necessary spreadsheet software for analysis, the pen and paper manual technique costs are as follows (note that this results in 9 person-hours per 4 hours of data collection, plus vehicle operating expenses that will vary):

- 1 stop watch, clip board, data sheets, and pens/pencils ($25 total);

- 1 driver for 4 hours at 10 dollars per hour ($40 total);
- 1 observer for 4 hours at 10 dollars per hour ($40 total); and
- 1 hour of data reduction at 10 dollars per hour ($10 total).

With the same assumptions as above, the optional audio tape recorder variation costs are as follows (note that this results in 6 person-hours per 4 hours of data collection plus vehicle operating expenses):

- 1 stop watch, clip board, data sheets, and pens/pencils ($25 total);
- 1 voice activated portable tape computer ($100);
- 1 driver for 4 hours at 10 dollars per hour ($40 total); and
- 2 hours of data reduction at 10 dollars per hour ($20 total).

Finally, with the same assumptions as above, the portable computer variation costs are listed below (note that this results in 5 person-hours per 4 hours of data collection plus vehicle operating expenses).

- 1 laptop computer ($2,000);
- Software for data collection ($150);
- 1 driver for 4 hours at 10 dollars per hour ($40 total); and
- 1 hour of data reduction at 10 dollars per hour ($10 total).

3.1.3 Data Collection Instructions

The data collection instructions for using the manual test vehicle technique are explained in this section. The following steps should be performed before data collection is started (see Chapter 2 and earlier sections of this chapter):

1. Define the routes to be studied;
2. Designate the checkpoints and locations where link times and speeds are desired;
3. Define the time period during which data will be collected;
4. Determine the number of travel time runs that are necessary;
5. Develop a travel time data collection schedule; and
6. Training of test vehicle drivers along with one to two hours performing sample runs.

Training should include three aspects: 1) how to drive in the traffic stream (i.e., driving style); 2) how to fill in the data collection forms for the travel time run; and 3) how to check the equipment prior to the travel time run to ensure that it is ready for operation.

Once the necessary planning and preparation have been completed, the following steps should be performed to collect the data:

1. **Assemble equipment**. The following checklist can help ensure that all the necessary equipment is available and functioning properly:

   - test vehicle;
   - data collection forms;
   - map of the study route;
   - procedures on when to abort runs;
   - pens, pencils, and clipboard; and
   - stopwatches.

2. **Fill out field data collection form.** The recorder must fill out the run information pertaining to route, direction, date, scheduled start time, actual start time, weather, lightning, and pavement conditions. The driver should look over the checkpoints to become familiar with the name and order of the checkpoints.

3. **Begin to drive the travel time route**. The driver can then begin to drive the travel time route using the prescribed driving style.

4. **Mark beginning point of travel time run.** The driver will need to start the run at a consistent location while the recorder starts the stopwatch and marks the beginning of the travel time run.

5. **Mark all checkpoints or links and incidents.** The recorder should record the cumulative elapsed time at all predefined checkpoints. Incidents or queuing information should also be recorded by starting the second stopwatch. Reasons for the delay should also be recorded (e.g., queuing due to construction).

6. **Stop, record time, and reset stopwatches at the end of the run.** At the last checkpoint or ending point, the stopwatch should be stopped, the elapsed time recorded, and any notes about the run recorded before resetting the stopwatch to prepare for another run.

7. **Perform all subsequent travel time runs.** Typically, multiple travel time runs are conducted. It is advisable to collect data in both directions. Non-peak direction information can provide information about off-peak travel at little or no additional cost.

After personnel are properly trained and the drivers are proficient in preparing equipment for data collection, the actual data collection effort is quite simple. Upon completion of the travel time run, the data must be reduced to a common format for analysis. This can include transcribing times from field sheets or audio tape. If portable computers are being used, the data need to be downloaded to a desktop storage computer. Data management and storage are critical. Consistent file naming aids with associating a data file with its respective facility and run. Data management is essential to ensure that once data are collected the files are not overwritten as new data files are added. This is especially true for large data collection efforts. Care must be taken to ensure the data are collected, stored, and managed carefully to optimize data storage and reduce accuracy errors. All field data sheets should be kept even after the data has been entered into electronic format. Original sheets can be used for quality control and provide insight or reasons for unexpected travel times or conditions.

Examples of data collection forms are shown in Figures 3-1, 3-2, and 3-3. Figure 3-1 shows "short-hand" techniques that can be used to mark queues and incidents. Figure 3-2 shows an example data collection form for the average vehicle method from ITE's *Manual of Transportation Engineering Studies*. Figure 3-3 illustrates a sample data collection form from Chapter 11 of TRB's *1994 Highway Capacity Manual*.

Additional Data Collection Considerations

Past experience with the manual test vehicle technique has resulted in a wealth of knowledge. The following lists were developed based upon the past experience of others. Section 3.0.3 provides a list of general considerations for all test vehicle techniques. The following sections describe helpful tips for the manual (pen and paper) method and variations of the method (i.e., audio tape recorder, portable computer).

Pen and Paper

> **Large Display on Stopwatches** - A large stopwatch display will reduce the errors in reading the stopwatch (e.g., "8"s being confused with a "3" or "5"). These errors are nearly impossible to find unless the errors are very drastic (i.e., negative speeds result when an "8" is written as a "3").

Audio Tape Recorder

> **Voice-activated audio tape recorders** - A valuable feature on some audio tape recorders is voice activation. This feature starts the recording when sound is detected. Voice activation will reduce the tape and battery use during the travel run. It will also reduce the time required to reduce the travel time data since only a small portion of the tape has recorded data. Without this feature, data reduction personnel are required to listen to the entire tape and they must attempt to fast forward and stop where checkpoints

IH 10 KATY FREEWAY - MAINLANES - WB | DATE: 5/28/96

SECTION LIMITS LANDMARK	CUM. MILE	INT MILE	CUM. TIME	ADVERSE CONDITIONS WEATHER, LIGHT, PAVEMENT, INCIDENT, CONSTRUCTION
Hogan Street Overpass Overpass past SPRR Overpass	---	---	---	
Taylor Overpass	1.00	1.00	2:24	Queue Starts
Shepherd Overpass, Texaco on right	2.70	1.70	7:30	
SPRR Stair-stepped overpass	3.60	0.90	10:12	
Washington Overpass, Dennys on right	3.90	0.30	10:55	Construction Starts
East Terminus At structure	4.82	0.92	13:41	
West Loop (610) Overpass	5.40	0.58	15:25	
AVL Flyover At structural beam	5.85	0.45	16:46	
Silber Shell on left	6.35	0.50	17:58	Construction Ends - Queue Ends
Antoine Underpass	6.80	0.45	18:45	
Wirt Exxon on left	7.37	0.57	19:32	
Bingle Underpass	8.19	0.82	20:26	
Blalock Fiesta on right	9.55	1.36	22:03	Stall Right Shoulder-Queue Starts
Bunker Hill Texaco on left	10.18	0.63	22:50	
Gessner AVL Exit At structure	10.63	0.45	23:26	Light Rain
Gessner Memorial City Mall on left	10.93	0.30	23:50	
West Belt (Beltway 8) Overpass	12.08	1.15	25:06	
Wilcrest Underpass	12.83	0.75	25:56	

ADVERSE CONDITIONS

WEATHER	LIGHT	PAVEMENT	CONSTRUCTION	INCIDENTS
Overcast	Dark or Twilight	Wet	Minor (off shoulder)	Minor (off road)
Light Rain or Drizzle	Sun Glare	Ice or Snow	Major (lane blockage)	Major (lane blockage)
Heavy Rain	Fog			

DIRECTIONS

AT END OF WB RUN	AT END OF EB RUN
• Exit at Fry Road • Take overpass to make U turn • Stop and enter data at shell gas station • Turn onto frontage road and take ramp to IH 10 EB	• Exit IH 10 at Smith Street • Turn left into Bank 1 drive through teller area • Enter data • Turn left onto Louisiana and take ramp to IH 10 W

Figure 3-1. Example 1 of Manual Test Vehicle Data Collection Form

TRAVEL-TIME AND DELAY STUDY
AVERAGE VEHICLE METHOD
FIELD SHEET

DATE __________ WEATHER ________________ TRIP NO. _________________

ROUTE ________________ DIRECTION ___________________________________

TRIP STARTED AT _____________ AT ____________________________________
(LOCATION) (MILEAGE)

TRIP ENDED AT ______________ AT _____________________________________
(LOCATION) (MILEAGE)

CONTROL POINTS			STOPS OR SLOWS		
LOCATION	TIME		LOCATION	Delay (seconds)	

TRIP LENGTH TRIP TIME TRAVEL SPEED

RUNNING TIME STOPPED TIME RUNNING SPEED

SYMBOLS OF DELAY CAUSE: S-TRAFFIC SIGNALS SS-STOP SIGN LT-LEFT TURNS

PK-PARKED CARS DP-DOUBLE PARKING T-GENERAL

PED-PEDESTRIANS BP-BUS PASSENGERS LOADING OR UNLOADING

COMMENTS ____ RECORDER ___________________

Source: adapted from reference (1).

Figure 3-2. Example 2 of Manual Test Vehicle Data Collection Form

TRAVEL TIME FIELD WORKSHEET

Arterial________________________________ Date________________

Driver____________________ Recorder________________ Direction________________

SIGNAL LOCATION	DISTANCE (MI)	Run No. Time CUMULATIVE TT (SEC)		STOP TIME (SEC)	Run No. Time CUMULATIVE TT (SEC)		STOP TIME (SEC)	Run No. Time CUMULATIVE TT (SEC)		STOP TIME (SEC)

S – Signal (lower box)
LT – Left Turn (upper box)
P – Pedestrian (upper box)
PK – Parking (upper box)
4W – 4-Way Stop (upper box)

Source: *1994 Highway Capacity Manual*, Chapter 11.

Figure 3-3. Example 3 of Manual Test Vehicle Data Collection Form

- **Data transcription** - Recorders should transcribe the runs that they performed. Differences in annunciation and dialects can cause errors. In addition, observer's notes may be helpful for determining any anomalies in the travel time run. Audio tapes can be reused after sufficient quality control is conducted.

- **Safety** - A driver and a recorder should be used to collect travel time data using the manual test vehicle technique. Occasionally, drivers are required to wait for a headway start time or must enter data. The location of this stopping point should be in a highly visible and populated area. In urban areas, an undesirable or dangerous area may cause a threat to data collection personnel. Drivers should always keep vehicle doors locked in such situations.

Portable Computer

- **General considerations** - As technology increases, there are greater chances of technical problems. There are some problems that can occur using the portable computer variation, but the benefits of requiring only one driver (as opposed to a driver and a recorder) is cost-effective. The fact that data are in electronic format also makes the portable computer version cost-effective. Portable computers are fairly common and the low cost of software and shareware make this method the most desirable manual method. In addition, portable computers do not require additional hardware that must be attached to fleet or personal vehicles.

- **Power Supply** - Portable computers require a generous amount of power. Energy consumption varies with processing and accessing the hard disk. A cigarette adaptor or power inverter solves problems with batteries running out during a travel time run.

- **Screen Savers** - Some computers have a sleep mode and/or screen savers. These programs are designed to reduce power consumption or save the integrity of the screen. However, these programs can interfere with the travel time software operation causing the program to lock, crash, or provide inaccurate results. These features should be disabled for field data collection.

- **Remove Equipment** - Portable computers and other expensive equipment should never be left in a vehicle. Thieves may break into the vehicle, steal the equipment, and damage the vehicle.

3.1.4 Data Reduction and Quality Control

Several steps are necessary in data reduction for the manual test vehicle technique:

1. **Review field data sheets and/or computer files.** Incidents, accidents, and anomalies should be recorded. These comments can provide valuable insight to field conditions at the time of the travel run.

2. **Transcribe travel time from field sheets or audio tape.** Travel times and delay information should be transcribed to a consistent electronic format. A systematic review of entered data will provide a quality control check as well. Spot checking one entry per travel time run is one method of checking the consistency from field sheet to electronic format.

3. **Calculate and plot link speeds.** Perform relative calculations of speed, percent time, and other desired MOEs. The data can then be plotted for easy visual comparison.

4. **Review tabulated results and speed profile for each run for reasonableness.** Tabulated results and speed profiles provide a valuable tool for the supervisor to review each run. Questions such as the following can be quickly assessed: Do the average speeds reflect the expected or historical trends? Are bottlenecks reflected on the speed profile?

Analysis for all variations of the manual test vehicle techniques listed above are similar. Since the travel times are recorded at predetermined checkpoints, known distances can be obtained from field measurements or scaled from maps. By knowing the distance and travel time(s) between each checkpoint, a space-mean speed can be calculated. The limited amount of data from checkpoints, typically spaced at 0.4 to 0.8 km (0.25 to 0.5 mi), can be analyzed manually with a spreadsheet, database, or statistical analysis package with relative ease. The size (i.e., number of corridors and number of runs) and frequency (i.e., number of times a year and number of years) of the study may determine the desired level of automation.

EXPERT TIP ☺

The level of automation for data reduction should be determined by the size and frequency of travel time studies. Automation can initially be time-consuming but it often pays off over several years.

Desired analyses can be performed after the data reduction procedure has been completed. Aggregation of travel time runs should only be performed after each individual run is scrutinized for accuracy. Aggregation masks errors and can skew results. This makes it extremely difficult to determine where the error occurred. Therefore, quality control is essential. Further analyses and/or aggregation for different time periods, functional classes, and/or area types can also be conducted.

CAUTION !! Data quality control is very important at all stages of collection, reduction, and analysis to ensure that the data and analysis results are accurate and reliable.

Quality control checks should be in place to ensure that the quality and quantity of data is being reported as accurately as possible. Field data collection sheets should be reviewed for completeness. The route information in the header and the time information should be logical to ensure field recording errors are not continued further into the process. Logical checks include: time is increasing, transposition errors, and comparison against other runs or historical data. The data entry is another source of error with interpretation, transposition, or simple typing errors. These can be checked by comparing a sampling of the entered data to the raw data. At any point, if errors are detected, a more careful screening of the data may be required. If automation is employed, errors in spreadsheet or database calculations only need to be checked once. If automation is not employed, the analysis formulas should also be sampled and checked with manual calculations.

Amount and Type of Data

The amount of data collected from the test vehicle technique varies. Only a limited number of control checkpoints can be safely, accurately, and effectively gathered. As previously mentioned, control checkpoints spaced approximately 0.4 to 0.8 km (0.25 to 0.5 mi) are typical for this technique. Congestion cause and effect data, as well as delay data, can usually be collected with moderate results. Observers can usually record the cause of delay such as incidents, accidents, or stalls. Delay information is obtained by recording the time from the stop watch and the odometer reading from the vehicle. The delay information is somewhat difficult to collect because of the "stop-and-go" nature of congested traffic conditions. It is sometimes difficult to define the start and end of a rolling queue. Experience, some predefined condition such as below a specified speed, being stopped at a traffic signal, or other criteria will aid field personnel in consistently collecting the required data.

3.1.5 Previous Experience

Nearly all agencies that have conducted travel time studies in the past 20 years have used the manual test vehicle technique. This section describes specific experience gained by the Texas Transportation Institute from extensive travel time studies over the past 10 to 15 years in Houston, Texas.

Texas Transportation Institute, Houston, Texas

The Texas Transportation Institute (TTI) has been extensively involved in the collection of travel times for a host of ongoing studies. One study is *An Evaluation of High-Occupancy Vehicle Lanes in Texas* (9). The data collection, reduction, and analysis of travel times for this ongoing study have covered most of the methods reported in this chapter. The pen and paper method was originally used due to its simplicity and flexibility. Travel times were collected in the field by using a stopwatch and pen and paper to record the travel times. Once the data was collected, the data was entered into a spreadsheet and the average speeds were calculated. Moderate checks for data entry were conducted to ensure that transposition errors were caught. Further processing of the data was conducted using a software package for statistical analysis. Comparisons of the data were made from other quarters and other years.

Five years ago, several methods of travel time data collection were tested. The audio recorder method provided a reduction in staff required to collect the travel time data. The travel time information and procedures were the same except for the method of recording the clock times. As with all methods there were many lessons learned.

- **The person who records the travel time should enter the information into electronic format.** On several occasions the dialects and annunciations caused errors for data entry.

- **Voice-activated tape recorders work best.** Standard tape recorders provided a lot of tape to fast forward through. Further, many checkpoints were missed because the pause button was not turned off or tape was not rolling when the times were recorded to the audio tape.

- **Observers should announce the checkpoint and the time.** Failure to do so results in guess work and interpretation of what checkpoint was being recorded and sometimes the delay information was interpreted as checkpoint times.

- **Prompt reduction and analysis of data provided the best results.** Supervisors could question drivers on travel conditions if unexpected results were encountered.

- **Extra batteries and tapes should be provided.** Battery life is unpredictable and for a small cost the rescheduling of data collection is prevented. On most audio tape recorders there are two tape speeds. If the faster tape speed is selected, the recorder could run out of tape before all the runs are completed. Once the data from one data collection effort has been entered, the tapes can be used again.

3.2 Distance Measuring Instrument

The electronic distance measuring instrument (DMI) is used for a variety of applications, such as route numbering, emergency 911 addressing, acreage and volume calculations, as well as general linear distance measuring for pavement markings. These instruments are very accurate once calibrated (plus or minus one foot per mile, or 0.19 meter per kilometer).

Travel time data collection with manual DMIs was conducted in the early 1970s. Original DMI units used an adding machine tape or printer to record the distance and speed from the unit. A circular graph known as a tachograph was used to continually record distance and speed. These manual DMI units used a magnetic wheel sensor to measure revolutions. Calibration was provided by knowing the number of revolutions over a fixed distance. When properly calibrated, these devices provided accurate results. However, there were some problems with this technology. Wheel sensors would fall off or not read properly and sometimes unbalance the wheel. Data media was paper format, either circular graphs or adding machine tape, which were difficult to read and required large amounts of data entry. The advent of the electronic DMI solved these problems.

Figure 3-4 illustrates the equipment typically used in electronic DMI data collection. The electronic DMI calculates distance and speed using pulses from a sensor attached to the vehicle’s transmission. These pulses are sent from the transmission to the sensor based on the vehicle’s speed. The DMI converts the pulses to units of measure and calculates a speed from an internal clock. The DMI unit is able to send the data to a portable computer for storage. Specialized software can be used to record the electronic information, eliminating the data entry and errors associated with the older models. Notes can also be added to the end of the file to describe incidents or other relevant information about the travel time run. A consistent data format allows for automation of reduction and analysis of travel time information.

Commercial and proprietary software can be used to interact with the DMI or read the pulses directly from the transmission sensor. The DMI is essentially a specialized piece of hardware/software that interprets the pulses from the transmission sensor and converts them into a distance. Most software packages provide a data collection module (field data collection) as well as reduction/analysis software. These software packages allow collection for multiple runs and data reduction including tabular summaries and speed profiles. Some DMI manufacturers have proprietary collection and analysis software, while others provide example computer code to read the data from the DMI. This allows users to develop and customize the data collection and analysis software. File format, sample rate, and report format are among the most relevant issues for researchers and practitioners to customize in the data collection and analysis software. Appendix A contains additional information about computer software available for test vehicle techniques.

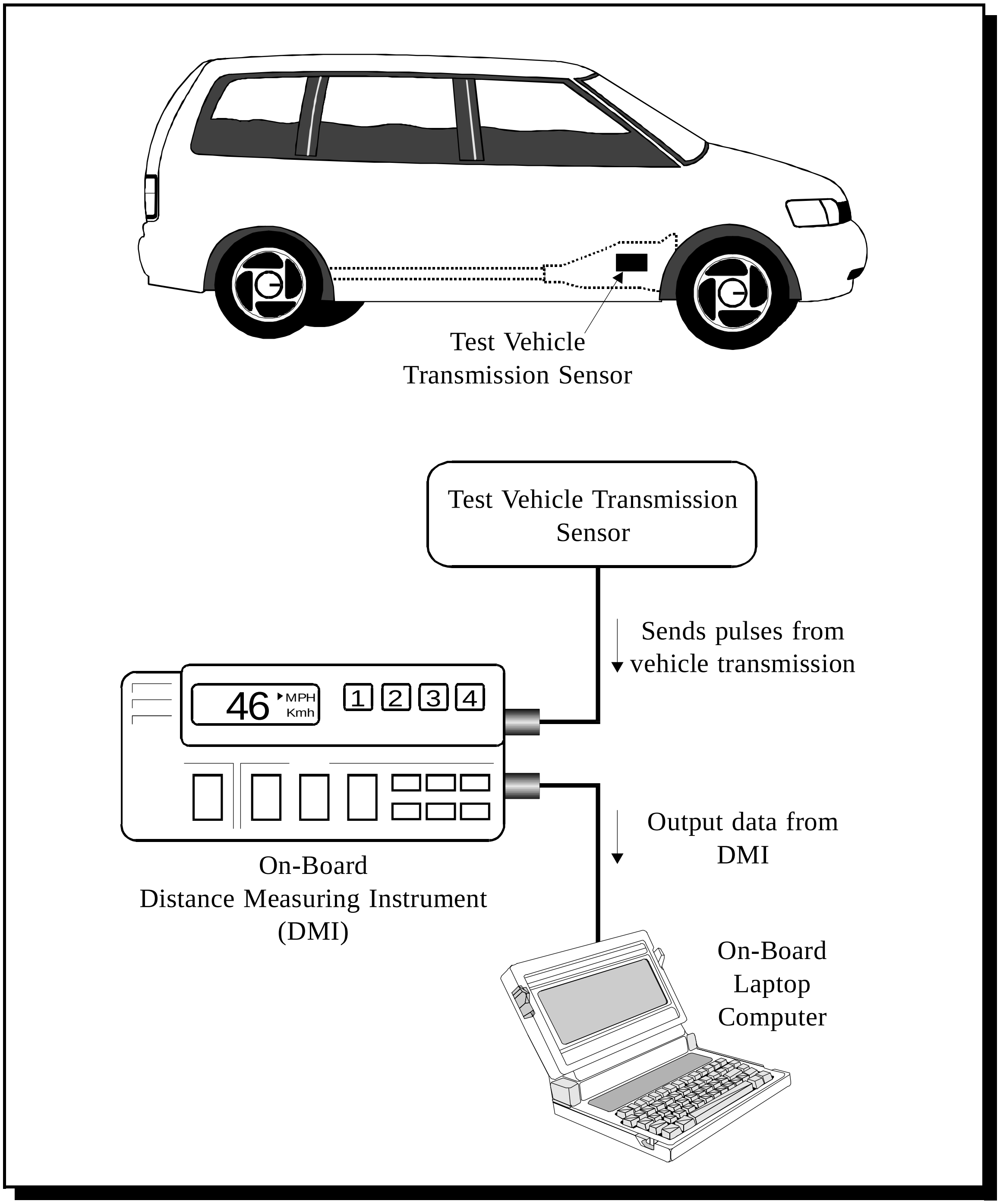


Figure 3-4. Typical Equipment Setup for DMI Test Vehicle Data Collection

3.2.1 Advantages and Disadvantages

Test vehicle data collection with an electronic DMI has the following **advantages** (as compared to the other test vehicle methods):

- Reduction in staff requirements compared to the manual method. There is no passenger recording information. No data to enter or errors associated with data entry (e.g., transposition, format);

- Reduction in human error including missed checkpoints or incorrectly recording information. However, the starting point or first checkpoint must be accurately marked;

- Offers some redundancy of checkpoint locations as long as the first checkpoint is marked properly;

- Commercially available software provides a variety of collection and analysis features;

- Field notes, incidents, and anomalies electronically recordable at the location the incident occurred available in most software packages;

- Increased amount and variety of data available for applications including determining queue lengths, stopped delay, average speed, link speeds, detailed speed profiles, input to models for planning, emissions, or fuel consumption, and performance evaluation computation;

- Relatively cost-effective and accurate;

- Provides data in a consistent format to aid in the automation of data reduction and analysis automation; and

- Proven technology.

Test vehicle data collection with an electronic DMI has the following **disadvantages**:

- Storage requirements for the vast amount of data collected;

- Must be calibrated to obtain accurate results;

- Requires accurate marking of first checkpoint;

- Not readily adaptable to a geographic information system (GIS) (raw data are not geocoded); and

- Some assembly is required, including the sensor wiring. It cannot be moved from one vehicle to another.

3.2.2 Cost and Equipment Requirements

This section details the hardware, software, and personnel needs for travel time data collection with an electronic DMI:

- **Test vehicle driver** - Personnel are required to drive a test vehicle on the study route and perform the minimal required tasks associated with travel time collection.

- **Data reduction personnel** - Staff required to transform the travel time and distances to link speeds and perform any other analyses required. Computer programs, macros, and automation can reduce or eliminate this step of the process.

- **Supervision and management -** This includes management personnel who monitor the overall data collection, data reduction, and analysis of the system operation. This cost varies depending on the size and scope of the project, automation of data collection, reduction and analysis needs, as well as other study needs.

- **Transmission sensor** - Reads pulses from the test vehicle transmission.

- **Distance measuring instrument (DMI)** - Hardware unit that interprets the information from the transmission sensor and converts it to a distance and speed.

- **Portable computer** - Necessary for recording travel time data in the test vehicle.

- **Power supply** - External power required by the portable computer supplied through the cigarette lighter. Batteries can be used but usually prove to be unreliable.

- **Data storage computer** - Generally located back at the office, this computer is used to store and process the field travel time data.

- **Test vehicle** - Fleet or agency vehicle used by the driver to travel the survey route. A transmission sensor must be attached to the vehicle for the DMI method.

- **Collection/Reduction/Analysis software** - Software that is purchased or developed that either reads the information from the transmission sensor or DMI unit with the ability to generate useful statistics and speed profiles. Appendix A provides more detail on system requirements and vendor contact information for this software.

Figure 3-4 illustrates the equipment requirements and setup. The DMI is connected to the transmission sensor via a modular phone-type connector. The DMI data is output to the on-board portable computer. The portable computer stores the data at given time intervals as the vehicle travels the roadway. When the travel time run is completed, the portable computer information is downloaded to a data storage computer.

Table 3-6 displays estimated costs for software, hardware, and personnel requirements. Moderately skilled personnel are required for electronic DMI data collection. A general knowledge of computer and software operation is necessary. Generally, this can be provided with a half-day of training. Data reduction personnel skill level depends on the complications that may occur. Most analysis software requires clean raw data with no field errors (e.g., incorrectly marked start point, incorrect units, incorrect calibration number). Most software has limited tolerance for such mistakes. Some errors can be corrected if caught early and the proper data is retrieved from the DMI unit. All DMI data collection requires a transmission sensor. Some software packages interface directly with the transmission sensor, while others require hardware (e.g., DMI or electronic count board) to interface with the transmission sensor. Analysis software is usually bundled with the collection software. Varying degrees of further analysis can be performed with any proprietary spreadsheet or database software depending on the level the collection/analysis software developer provides.

The data storage computer is also shown in Table 3-6 for completeness. However, this is generally not an added cost because an existing computer can be used for the data storage, provided there is ample space on the hard drive. In addition, it is likely that the portable computer may already be owned. Therefore, it would not incur a cost. Generally, the cigarette lighter on the vehicle or a battery pack is used as a power source.

Table 3-6. Estimated Costs for the Electronic DMI Test Vehicle Technique

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
Transmission Sensor	$75 to $150
Electronic DMI Unit with RS-232 Connection	$450 to $650
Portable Computer	$1,500 to $3,000
Vehicle Operating Cost	$0.28 to $0.32 per mile
Software	
DMI Collection/Reduction/Analysis Software	$150 to $1,000
Proprietary Analysis Software (Spreadsheets, Database, GIS)	$200 to $3,000
Personnel	
Test Vehicle Driver	$6 to $10 per hour
Data Reduction Personnel	$6 to $10 per hour
Supervision and Management	Varies

A variety of hardware and software configurations are available. This will result in different costs and capabilities. For example, a transmission sensor, DMI unit, cable, and collection,/reduction software that requires a proprietary spreadsheet may cost about $1,170. The system chosen should be based on the current and potential need for the data and what each hardware and software system will provide. Other considerations include ease of use for collection and analysis and the types of analysis and level of detail that raw data can be provided.

3.2.3 Data Collection Instructions

The following steps should be performed before data collection starts (see Chapter 2):

1. Define routes to be studied;
2. Designate checkpoints or desired time/distance collection interval;
3. Define the time period during which data will be collected;
4. Determine the number of travel time runs that are necessary; and
5. Train test vehicle drivers with one to two hours of practice runs.

Training should include three aspects: 1) how to drive in the traffic stream (i.e., driving style); 2) how to operate the electronic DMI unit; and 3) how to check the equipment prior to the travel time run to ensure that it is ready for operation.

Once the necessary planning and preparation have been performed, the following steps should be performed to collect the data with an electronic DMI:

1. **Inspect equipment.** Ensure that all equipment is operating correctly:

   - All connections between the DMI, transmission sensor, portable computer, and power supply should be checked to ensure they have not become unattached.

   - Check DMI for proper calibration number and distance and speed data collection units (miles, mph or km, km/h). Different analysis software may require different units for reduction.

2. **Turn on equipment**. The operator then turns on the portable computer and the DMI unit. Depending upon the software being utilized, the operator will be prompted for necessary identifying information about the travel time run. After completion of these data inputs, the portable computer should begin to display information as the data are collected. The operator should ensure that the data appear to be collecting in the appropriate manner and line-by-line data are scrolling up the screen.

3. **Begin to drive the study route**. The driver can then begin to drive the study route and the DMI unit will collect the distance and speed of the test vehicle and send the information to the portable computer.

4. **Mark beginning point of travel time run.** The driver will need to start the run at a consistent location and mark (with a pre-determined keystroke) the beginning of the travel time run.

5. **Mark all checkpoints or links and incidents.** If the starting point is known, all subsequent checkpoints can be derived. It is advisable to mark all checkpoints (with a predetermined keystroke) in accordance with the software manufacturer's instructions to provide redundancy. Incidents or queuing should also be noted by the observer to provide annotation of events that may alter traffic operations.

6. **Perform all subsequent travel time runs.** Typically, multiple travel time runs are conducted in both directions to provide an average travel time based on an adequate sample size.

Upon completion of the travel time runs, the portable computer can be taken to the office to download the information onto a desktop computer for permanent storage.

Once personnel are trained and drivers are proficient in preparing the equipment, the actual data collection effort is quite simple. Data management and storage are critical. Consistent file naming aids in associating a data file with its respective facility, direction, time, and date. These data management considerations are especially true for large data collection efforts, and care must be taken to ensure the data are collected, stored, and managed carefully to optimize data storage and reduce errors.

CAUTION !!	Adequate data management and consistent file-naming schemes are essential to ensure that once data is collected, the files are not overwritten as new data files are added.

Additional Data Collection Considerations

- **Calibration** - Calibration is very important in collecting accurate distance information with an electronic DMI. The calibration is vehicle dependent and varies by tire size, wear, and pressure. Not only is tire maintenance necessary for accurate DMI data collection, it is a safety and cost issue. Properly maintained tires last longer and are more fuel efficient. The calibration log sheet shown in Table 3-7 provides documentation of fluctuations in calibration and tire pressure.

IMPORTANT ☞	Vehicle and electronic DMI calibration should be conducted before every large data collection effort and periodically throughout data collection.

The calibration procedure involves putting the unit in calibration mode and driving a 305-m (1,000 ft) course. Calibration numbers can easily be changed, but if there are an equal number of DMI units and test vehicles, a helpful solution is to assign each vehicle a DMI unit. The tire pressure and calibration will still need to be checked periodically, but this will reduce changing and the potential errors of having the incorrect calibration number. The reader is encouraged to review Section 3.0.3 for additional data collection considerations for the test vehicle technique.

Table 3-7. Example of Weekly DMI Calibration Log

DMI Unit	Vehicle #	DMI Unit CAR #	Tire Pressure FL/FR/RL/RR	Calibration #	Driver's Name	Calibration Date
before#2	3582	2	30 / 31 / 33 / 29	819	Benz	5/15/95
correct#2	3582	2	31 / 33 / 33 / 32	822	Benz	5/15/95
			/ / /			
			/ / /			
			/ / /			
			/ / /			
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			/ / /			
			/ / /			

3.2.4 Data Reduction and Quality Control

Several steps are necessary in the reduction of DMI travel time data:

1. **Review field data sheets and computer files.** Observers should record incidents, accidents, and anomalies. These comments can provide valuable insight into field conditions at the time of the travel time run.

2. **Check data file length and units**. Most analysis software requires the field output file to be in consistent units, typically distance is in feet or miles and speed is in mph. A quick and easy check is to ensure that the travel time run distance recorded is at least as long as the predefined route. Data files that are too long or too short typically mean the driver deviated from the prescribed route or an improper calibration number was used. Another consideration is that the file may have been misnamed.

3. **Run analysis software.** Most analysis software packages provide both a tabular format and a speed profile.

4. **Review tabulated results and speed profile for each run for reasonableness.** Both forms provide a valuable tool for the supervisor to review each run. Questions such as the following can be quickly assessed: Do the average speeds reflect the expected or historical values? Are bottlenecks reflected on the speed profile?

Desired analyses can be performed after the data reduction procedure has been completed. Aggregation of travel time runs should only be done after each individual run is scrutinized for accuracy. Aggregation masks errors and can skew results. This makes it extremely difficult to determine where the errors may have occurred. Therefore, quality control is essential. Analysis can be aggregated and averaged for different time periods, functional classes, and/or area types.

3.2.5 Previous Experience

California Department of Transportation

The California Department of Transportation (Caltrans) uses DMI software they developed to collect travel time information for congestion management and delay analysis purposes (10). The "tach run" methodology utilizes information collected by varying numbers of test vehicles traveling in the traffic stream to estimate recurring congestion delay. It should be noted that a tach run is simply the nomenclature used at Caltrans for a travel time run, and they are the same. With the exception of District 07, all of the urban Caltrans districts currently use this method to produce recurring congestion delay estimates. As this handbook went to press, Caltrans was considering the termination of this program.

Currently, test vehicles traverse the congested segments of freeway [i.e., areas where speeds less than 56 km/h (35 mph) are experienced for at least 15 minutes] during typical weekday peak periods, 6:00 to 9:00 a.m. and 3:00 to 6:00 p.m., Tuesdays through Thursdays. Several vehicles negotiate the segments at 15- to 20- minute headways. A minimum of four satisfactory observations are collected each year, one during the morning and afternoon peak periods for the spring and fall seasons. A satisfactory set of observations is defined as a complete run conducted under representative recurring congestion conditions. Therefore, if an accident is observed during the tach run, or the equipment malfunctions, the run is aborted.

As peak periods lengthen, however, it becomes increasingly likely that runs will have to be extended to fully capture recurring congestion delay on the California highway system. In addition, some concern has been expressed regarding recurring recreational congestion. For example, vehicles on Interstate 80 and Highway 50 in District 03 encounter increased delays on Friday and Sunday nights during the ski season.

After a successful tach run, the raw data is downloaded and input into a Caltrans computer program that computes speed, travel time, and delay. The delay is calculated as the difference between the time required to travel the specified distance at 56 km/h (35 mph) and the actual travel time (when speeds are less than 56 km/h (35 mph) for at least 15 minutes). The program automatically generates speed profiles and delay tables, from which congestion maps are produced.

Although the procedures for analyzing data and generating output are relatively simple for this methodology, the data collection process is extremely time consuming. It is estimated that over 100 hours are required per set of observations. A set of observations represents a tach run on a section about 8 to 16 center-line km (5 to 10 center-line miles) in length. Incidents and equipment failures often result in aborted runs. Data can be adjusted, however, for missing pulses. Due to the labor-intensive nature of the tach run methodology, the operating costs incurred are somewhat higher than those for other field study techniques. Additional costs include the purchase and maintenance of both the test vehicles and the on-board equipment. However, these are small compared to the costs involved in annual operations. Table 3-8 shows the expenditures in person-years for 1992-93 and the funds allocated for 1993-94 for the Highway Congestion Monitoring Program (HICOMP). The funds for each district represent the amount used/allocated for implementation of the tach run methodology, with the exception of District 07, which uses detectors.

Table 3-8. HICOMP Expenditures (Person-Years)

	Total Person-Years (1992-93)	Allocated Person-Years (1993-94)	Congested Directional Miles (1992)	Person-Years per Mile (1992)
District 01				
District 02				
District 03	0.8	0.68	41	0.0195
District 04	5.07	4.44	240	0.0211
District 05	0.29	0.12		
District 06	0.34	0.44	13	0.0262
District 07	2.27	2.50	521	0.0044
District 08	2.27	1.20	117	0.0194
District 09				
District 10		0.12		
District 11	0.83	1.10	104	0.0080
District 12	1.77	1.29	189	0.0094
Headquarters	0.87	2.45		
Other	0.28			
Total	**14.79**	**14.34**	**1225**	

Source: adapted from reference (10).

In 1992-93, the urban districts utilizing the tach run method accounted for 77 percent of the funds allocated by Caltrans for congestion monitoring. Only 57 percent of statewide recurring congestion delay was located in these districts. If and when peak periods are lengthened and/or extended to weekends, the proportion of funds spent by districts using tach runs to monitor congestion delay will likely increase. It is also interesting to note the range in expenditures per mile for these districts, from 0.0080 person-year/mile (0.0050 person-year/km) (District 11) to 0.0262 person-year/mile (0.1628 person-year/km) (District 06).

Although individual tach runs provide fairly accurate speed information, the accuracy of the methodology as a whole is somewhat uncertain. Not only must the tach vehicles be properly calibrated (known distance equals distance derived from tachometer data) at the beginning of each season, but additional calibrations may become necessary if vehicle tires are either rotated or replaced before the end of the season. As with any field study methodology, the number of observations included in the sample affects the reliability of the results (e.g., average speed and travel time).

Variability between districts and vehicle operators represents another factor to consider when evaluating the accuracy of this method. Additional observations and shorter headways are desirable for statistical purposes, but they are impractical due to the prohibitive costs of additional tach runs. Further study of the accuracy of the current methodology is recommended.

Unlike surrogate or traffic models, the tach run methodology does not produce output beyond what is required for estimating delay. It does, however, provide accurate spot speeds, space-hour statistics (e.g., mile-hours of congestion), and the opportunity to observe freeway sections under peak period conditions. The latter assists Caltrans in recognizing operational problems. The speed plots produced can also help to pinpoint bottleneck locations. If runs including observation of incidents are completed, travel time data could also be used for some non-recurring congestion applications.

The tach run methodology is not the most comprehensive field study technique. However, unlike the detector methodology, the initial start-up costs are minimal as only a few vehicles, tachometers, and portable computers are required. It is also extremely simple to implement and maintain. Unfortunately operating costs are high and the accuracy of the methodology is questionable. In particular, there is a lack of uniformity between vehicle operators and districts with regards to the following: when to abort a run, vehicle headways, the period of time to be studied, and the method of calculating delay. For more accurate delay estimates, a more complete picture is desirable (e.g., freeway conditions between tach vehicles) and different methods should be considered. Extending the peak periods and performing tach runs on weekends, although costly, would improve the current methodology.

Brigham Young University (BYU)

Thurgood developed a speed-based Freeway Congestion Index (FCI) to measure recurring congestion on freeways (11). A 9.7 km (6 mi) segment of I-15 in Salt Lake City was used to test the viability of the FCI. The FCI reflects both the extent (length) and duration of congestion on a given freeway segment, and can be used to compare different freeway segments of differing sizes or changes in congestion over time. The FCI is based on the distance that travel speed falls below 64 km/h (40 mph). This was based on the HCM LOS E/F (e.g., forced flow conditions).

A series of travel time runs were conducted using the Moving Vehicle Run Analysis Package (MVRAP) software (see Appendix A for more details) to collect detailed travel time and speed data. The instrumentation of the vehicle included the use of a DMI, an on-board computer, and the MVRAP software. The MVRAP software collected speed information from the DMI on a distance basis every 60 meters (200 feet). The "average car" travel time data collection method was employed. Test vehicles collected data along the test routes at 20- to 30-minute headways.

Speed profiles were printed and a horizontal line at 64 km/h (40 mph) was drawn and the distance below the threshold speed was measured. It was noted that the MVRAP software could not be modified to yield a distance traveled below any selected speed and thus required the manual calculation. The information is collected by the program and software modification calculates the FCI.

The study also found the speed or travel time runs taken from a single lane can be used accurately to represent the other lanes on the freeway facility. Although the level of congestion generally decreases somewhat going from the outside lane to the inside lane, regression equations have been developed that accurately provide an FCI for all lanes based on measurement of congestion in only one lane.

General Experiences

Several studies have been performed that summarize the experiences from many state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) in utilizing DMIs for travel time data collection. Studies range from before-and-after analyses to overall congestion management. Although many different measures of effectiveness (MOEs) are often employed in these studies, travel time and speed are a fundamental aspect of the data collection. Isochronal (time contour maps), delay estimates, and average speed comparisons with the posted speed limit and using the HCM LOS values are among the most popular. Other studies have developed more unique MOEs such as a ratio comparing average peak speed to uncongested (free-flow) conditions. In addition, Appendix A contains valuable information about some of the data collection and data reduction software packages that were used in select studies. The reader is encouraged to review these sections for additional information.

3.3 Global Positioning System

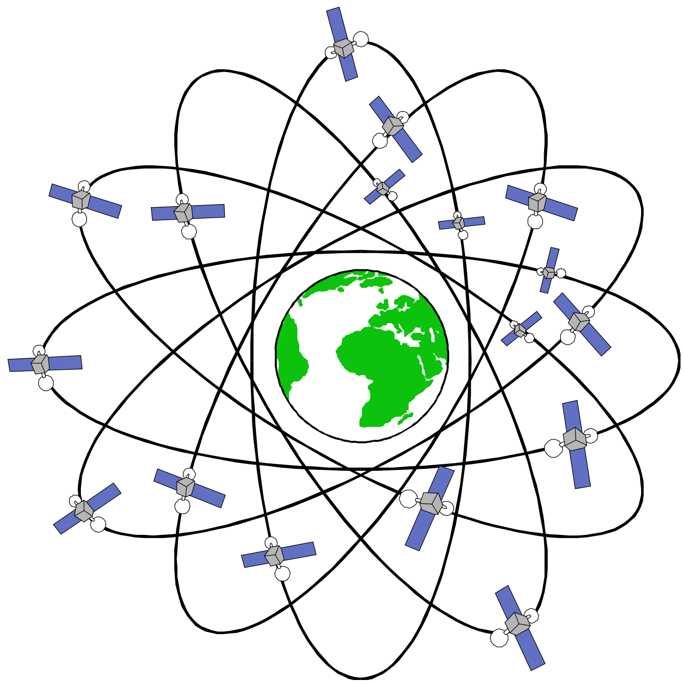
The global positioning system (GPS) was originally developed by the Department of Defense (DOD) for the tracking of military ships, aircraft, and ground vehicles. Signals are sent from the 24 satellites orbiting the earth at 20,120 km (12,500 mi) (see Figure 3-5). These signals can be utilized to monitor location, direction, and speed anywhere in the world. A consumer market has quickly developed for many civil, commercial, and research applications of GPS technology including recreational (e.g., backpacking, boating), maritime shipping, international air traffic management, and vehicle navigation. The vehicle location and navigation advantages of GPS have found many uses in the transportation profession (12).

Due to the level of accuracy that GPS technology provides, the DOD has altered the accuracy of the signal for civilian use. This is called selective availability (SA), and when it is activated precision can be degraded to about 91 meters (300 feet). In the absence of selective availability activation, accuracy can be within 18 meters (60 feet) (13). However, with the use of the differential global positioning system (DGPS), accuracy can be improved. DGPS utilizes a receiver placed at a known location to determine and correct the signal that is being provided when SA is activated. A commercial market has developed to provide differential correction hardware as well.

Many recent developments will affect the future use of GPS in civil applications. Currently, the U.S. Department of Transportation is considering the expansion of the Coast Guard marine DGPS beacon system. This includes the existing beacons utilized for DGPS along coastal areas and in the major inland waterways. However, such an expansion would provide a much broader system that would include interior areas throughout the nation (14). In addition, the Clinton administration has approved the release of the SA restrictions within the next ten years. This will provide much more accurate information for civil and commercial use (12,14).

There is also a significant market increase for in-vehicle GPS units. Japan currently holds the largest market for in-vehicle navigation systems. In 1995, the country had 60 million vehicles and there were 500,000 in-vehicle systems sold. This was up 150,000 from the previous year. In the U.S., one study showed that one-half of U.S. consumers are familiar with in-vehicle navigation systems while almost one-fifth expressed an interest in owning such a system for their vehicle (13). It is estimated that GPS in-vehicle navigation systems will not be viewed as a luxury item in the next five years (15). Current efforts to provide a world standard for in-vehicle navigation mapping will also provide compatibility between the many manufacturers in the market (16).

This section of the handbook will aid the practitioner in the use of GPS for travel time data collection. The previous experiences are included at the end of this section to provide insight into practical matters that arise when collecting data using the GPS technique. The final previous experience is in Lexington, Kentucky, and it describes the use of GPS receivers for collecting personal travel survey data. This use differs from the typical GPS test vehicle travel time data collection technique described throughout this chapter since the motorists are not trained and do not drive on specified corridors. However, there are many similarities in equipment use and data collection and analyses that are valuable to travel time data collection so it is included in this section.



Source: adapted from reference (12).

Figure 3-5. The GPS Satellite Constellation

3.3.1 Advantages and Disadvantages

Test vehicle data collection with a GPS unit has the following **advantages** (as compared to other test vehicle methods):

- Reduction in staff requirements compared to the manual method. No passenger is needed for writing (recording) information;
- Reduction in human error, including missed checkpoints or incorrectly recording information;

- GPS provides the locations. There are no checkpoints to be concerned with and there is no "starting point" problem as with the DMI method;

- No vehicle calibration is necessary as with the DMI method;

- Increased amount and variety of data available for applications including determining queue lengths, stopped delay, average speed, link speeds, detailed speed profiles, input to models for planning, emissions, or fuel consumption, and performance measure evaluation computation;

- Relatively portable and accurate;

- Provides automatic geo-coding of detailed speed data; and

- Dependent on another "proven" system. Since GPS is operated by the DOD for defense purposes, the system is monitored and maintained closely.

Test vehicle data collection with a GPS unit has the following **disadvantages**:

- Vast amount of data collected and storage requirements;

- Losing signals from the satellites due to "urban canyons" (i.e., traveling on streets adjacent to tall buildings), tunnels, trees, and power lines;

- Building or retrieving the base map;

- Equipment is generally not user-friendly as delivered. Wiring of equipment and some assembly is usually required;

- Difficult to stay updated on what equipment to purchase and what is necessary. It is a rapidly changing area;

- Requires time to learn how to set up the geographic information system (GIS) to use the incoming data. GIS software is an integral part of using the GPS system for travel time data collection efforts. GIS software is often used to display the GPS positional data on a roadway network. In addition, GIS software packages are a valuable tool for the calculation of desired measures (e.g., travel time, average speed); and

- The DOD can always disable the global positioning system when it desires.

3.3.2 Cost and Equipment Requirements

The following hardware, software, and personnel requirements are necessary for utilizing GPS for travel time data collection.

- **GPS receiver** - Required to process GPS signal information from the earth-orbiting satellites.
- **GPS antenna** - Required to receive GPS signals from the earth-orbiting satellites.
- **Differential correction receiver (if desired)** - Receives signals from land-based stations to determine corrected positional information. This information may be transmitted from a U.S. Coast Guard beacon or a private service (see differential signal service fee).
- **DGPS antenna (if desired)** - Receives signals from the land-based differential correction station.
- **Differential signal service fee** - Fee charged for the use of the FM signal or other frequency band for obtaining differential correction information. Fees vary based upon the desired positional accuracy.
- **Portable computer** - Necessary for positional data collection in the field.
- **Power supply** - Necessary for both the GPS receiver and the portable computer. Generally supplied through the cigarette lighter or a battery pack.
- **Data storage computer** - Generally located back at the office. This computer is used to store the positional data obtained in the field.
- **GPS software** - Allows for the logging of GPS information that is received from the GPS receiver.
- **GIS and compatible analyses software** - GIS software allows the positional data to be viewed on a roadway network. Compatible analysis software, generally on a GIS platform, allow for the calculation of desired speed and delay measures.
- **Test vehicle drivers** - Individuals who drive the GPS instrumented vehicles to collect travel time data.
- **Data reduction personnel** - Individuals who reduce the travel time data to prepare it for analyses.

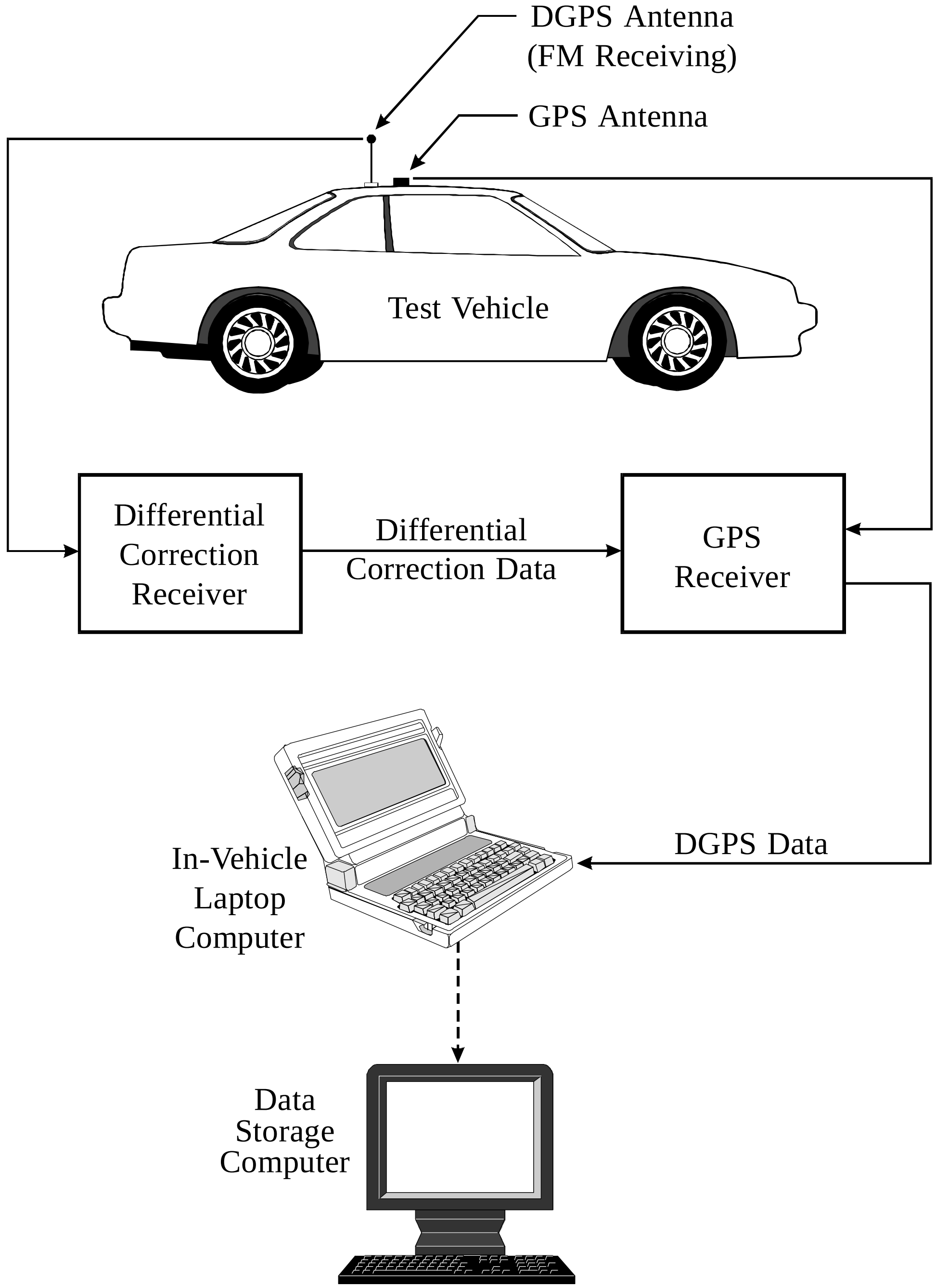
- **Supervision and management** - This includes management personnel who monitor the overall data collection, data reduction, and analysis of the data collection effort. This cost varies depending upon the scope and size of the data collection effort.

Figure 3-6 illustrates the equipment needs for GPS travel time data collection. The test vehicle is shown at the top of the page with the GPS and DGPS antennas resting on the roof of the vehicle. The DGPS antenna is connected to the differential correction receiver, and the GPS antenna is connected to the GPS receiver. The differential correction data is then transferred to the GPS receiver. The GPS receiver uses the differential correction data to correct incoming signals, and then the corrected information is output to the in-vehicle portable computer. The portable computer stores the data at user-defined time intervals as the vehicle travels down the roadway. When the travel time run is completed, the portable computer information is downloaded to a data storage computer.

Table 3-9 displays estimated costs for hardware, software, and personnel for the GPS test vehicle technique. As the technology for GPS receivers and equipment has advanced, costs have continued to decrease. In addition, with increasing accuracy, the units become more costly. The differential correction receiver also has two costs associated with it. The first cost is for the unit itself, and the second cost is for "renting" the FM signal or other frequency band from the service provider. The data storage computer is also shown in the table for completeness. However, this is generally not an added cost because an existing computer can be used for the data storage provided there is ample space on the hard drive. Since it is likely that the palmtop or portable computer may already be owned, it would not incur a cost. Generally, the cigarette lighter on the vehicle or a battery pack is used as a power source.

The GPS logging software that is listed in the table is used to record the data in an ASCII text format as it is sent from the GPS receiver. Some vendors provide proprietary software that serves this purpose. The GIS software cost estimate includes the cost of the general mapping software and a typical analysis package.

Consider the following cost estimate: Assume one would like two- to five-m (7 to 16 ft) accuracy with the use of DGPS, must purchase a palmtop computer, and already owns a computer for data storage and the necessary GIS software. The initial capital costs of the instrumentation of the vehicle is under $1,700. Vehicles can generally be appropriately instrumented for under $2,000 with this technology.



Source: adapted from reference (17).

Figure 3-6. Typical Equipment Setup for GPS Test Vehicle Technique

Table 3-9. Estimated Costs for the GPS Test Vehicle Technique

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
GPS Receiver	$300 to $500
GPS Antenna	$100 to $150
Differential Correction Receiver (Hardware) FM Signal Service Fee: Sub-meter accuracy 2-5 meter accuracy 10-meter accuracy	$350 to $500 $700 to $800 per year per unit $200 to $300 per year per unit $70 to $100 per year per unit
DGPS Antenna	$30 to $70
Data Storage Computer	$2,000 to $3,000
Software	
GPS Logging Software	$25 to $50
GIS Software	$2,000 to $3,000
Personnel	
Test Vehicle Driver	$6 to $10 per hour
Data Reduction Personnel	$6 to $10 per hour
Supervision and Management	Varies

Considerations When Selecting Hardware and Software

This section presents issues that one may want to consider when selecting a GPS receiver and/or other elements of hardware and software for GPS travel time data collection purposes. The reader is encouraged to review Appendix A for further discussion of software for GPS travel time data collection.

- **The number of channels that the GPS unit is capable of tracking** - It has been suggested that receivers capable of tracking five or more satellites simultaneously should be considered since they provide more accuracy (18). Although only three satellites are required for two-dimensional positioning (i.e., latitude and longitude), if a satellite signal becomes obstructed it is helpful to have additional satellites being tracked (19).

- **The types and quality of the speed algorithm used within the GPS unit** - There are two methods that can be used by the GPS receiver to calculate velocity. One method is to utilize a speed averaging algorithm where changes in position and time are utilized to determine velocity. Another method calculates the velocity vectors by determining the doppler effects of the satellite signals. Since the velocity is being used to calculate distance and position information, speed data that is based upon previous points (i.e., a speed averaging algorithm) is not appropriate. A doppler-based velocity algorithm provides more accurate information (19).

- **The interface protocol between the receiver and mapping software** - The major manufacturers of GPS receivers provide a proprietary protocol for logging GPS data to the data processing software. Generally, the National Marine Electronics Association Standard 183 (NMEA 183) protocol is also included, which is based on marine navigation. This format contains many of the features applicable for travel time data collection applications along roadway segments. The software logging the GPS information must support the protocol utilized by the receiver (19).

- **The availability and quality of the base map to ensure accuracy** - The accuracy of the base map may be an important consideration depending upon the application of the data. Differential correction can be used to provide more accuracy for the travel time data. Due to the limited accuracy of some base maps that are available, the corrected GPS data may be more accurate. Travel time runs may be performed with the corrected GPS data to create the base map or a more accurate base map may be obtained. This depends on the accuracy desired and the accuracy of the GPS equipment being used. The previous experiences described in Section 3.3.5 explain different methods of establishing and using the base map.

- **User-friendly and understandable data logging software** - The logging software that is being used to record the GPS positional data is a critical element in the data collection effort. Generally, logging software is proprietary to the GPS receiver vendor or created by the user. To aid in selecting or developing data logging software, the following items are suggested:

    - *Consistent file names* - File naming should be a logical name and/or menu driven. This ensures that the files are appropriately named to include the time, date, route, direction, and facility type. This consistency allows for the automation of file naming and prevents the over-writing of data files.

- *Consider the file format that will be needed for analysis* - It is possible that a proprietary logging software will produce a file that is not in the appropriate form for necessary analysis. Without an acceptable format that can be analyzed, file conversion may be necessary. Data files should be tested to ensure that the format is compatible with analysis software to ensure that fields are not truncated and the level of accuracy is maintained.

- *Ensure a standard time is recorded on the data* - If the logging software uses Greenwich Mean Time, a configuration file that allows the user to change the time to a standard time that is easily understood may be desired. Such a configuration should be flexible enough to consider daylight savings time. Converting to a standard time is even more necessary if the data are post-processed to ensure that there is not confusion after the data are collected.

- *User-defined flags should be flexible* - There will inevitably be situations that require documentation while performing the travel time run. These include stalled cars, accidents, or rainy weather. Specific keys on the laptop keyboard should be defined that can be pressed while performing the travel time run to "flag" these situations. Ideally, the users meaning of the flag should be printed in the data file. Allowing the keys to be changeable provides flexibility depending upon what is desired to be documented in the travel time run. Further, if the messages are printed out there is not confusion when they may be changed. See page A-29 in Appendix A for an example of a flag that indicates a "Stall on Right Shoulder" in a DMI data file.

- *User-changeable questions at the end of the travel time run* - Similar to the flags described above, questions at the end of the travel time run are useful in assessing any additional incidents and/or comments that the driver may desire to document. Allowing these questions to be changeable also allows for flexibility depending upon the study scope and objectives.

3.3.3 Data Collection Instructions

The following steps should be performed before data collection starts (see Chapter 2).

1. Define the routes to be studied;
2. Define the time period during which data will be collected;
3. Determine the time interval at which GPS position data will be saved;
4. Determine the number of travel time runs that are necessary; and
5. Train test vehicle drivers with one to two of practice runs.

Training should include three aspects: 1) how to drive in the traffic stream (i.e., driving style); 2) how to operate the GPS equipment and logging software; and 3) how to ensure the equipment is ready for operation.

Once the necessary planning and preparation has been performed, the following steps should be performed in collecting the data with the GPS equipment.

1. **Install and inspect equipment**. Check the following:

   - The antennae for the GPS receiver and DGPS receiver (if applicable) should be checked that they are securely fastened to the roof of the vehicle.

   - All connections between the GPS and DGPS receivers and antennas, power supply, and portable computer should be checked to ensure they have not become unattached.

   - The communication settings (e.g., baud rates, comms port connections) for both the GPS and DGPS receivers should be checked to see that they are set correctly. This can generally be performed with the proprietary software that is supplied.

2. **Turn on equipment**. The operator then turns on the portable computer and the GPS receiver. Depending upon the software being utilized, the operator will be prompted for necessary identifying information about the travel time run. After completion of these data inputs, the portable computer should begin to display information as the data are collected. The operator should ensure that the data appear to be collecting in the appropriate manner and line-by-line data are scrolling up the screen.

3. **Prepare log sheets**. Fill out the log sheet describing the travel time including the driver's name, date, time, and other relevant information.

4. **Begin to drive the travel time route**. The driver can then begin to drive the travel time route and the GPS unit will collect the time and position information.

5. **Complete log sheet**. After the travel time run, complete the log sheet with further relevant information describing the travel time run (e.g., weather changes, incidents).

6. **Put data collection equipment away**. After shutting down the computer, place cables, antenna, and other equipment into proper storage for the next travel time run.

Upon completion of the travel time run, the portable computer can then be taken to the office for downloading the information onto a desktop computer for permanent storage. At the end of the travel time run, a log sheet may also be completed to include any details about the travel time run.

After training of personnel has been performed and the drivers are proficient in checking that the equipment is ready for data collection, the actual data collection effort is quite simple. As with the DMI method described above, the data management and storage becomes critical. This is especially true for large data collection efforts, and care must be taken to ensure the data are collected, stored, and managed carefully to optimize data storage and reduce accuracy errors.

3.3.4 Data Reduction and Quality Control

Several steps are necessary in the data reduction of GPS travel time information.

1. **Insert necessary information into the base map**. There are several input requirements to the base map that are necessary to perform reduction of the data. These inputs include street names, cross-street information, and reference (checkpoint) locations for travel time segment definition. Setting up the base map with these inputs prior to further data reduction only needs to be performed once.

2. **Convert raw log file to GIS import format**. The file that is collected from the GPS receiver and saved to the portable computer must be converted to a format that GIS can import. Files need to be converted to the format appropriate for the GIS software being used for analysis purposes.

3. **Adjust collected data to match base map (if desired)**. Apply "map matching" or appropriate software algorithms that "snap" the collected data to the base map information. It may be desired to snap all data points to the existing map to provide a common reference system for aggregation of data along the predetermined links. Some agencies then aggregate the GPS travel time data into predefined segments for further analysis. This technique reduces data storage requirements but may limit future analysis capability. Others have suggested that all GPS data points be retained to permit "dynamic segmentation" for future analyses.

UNKNOWN
??

There are differing opinions about whether to aggregate GPS data into predefined roadway segments. If data storage is available, all GPS data points should be stored to permit "dynamic segmentation."

Quality Control Considerations

Several checks can be made on the data to ensure that adequate results are being achieved. The following quality control considerations can be applied in the data reduction stages.

- **Evaluating the number of data points** - After the travel time data are brought into the GIS mapping software, the number of points provided by the GPS receiver can be checked to ensure that there are enough points covering the network. Gaps in the data indicate locations where obstructions may occur (e.g., trees, tunnels) or where the GPS receiver may be malfunctioning. This simple visual inspection can be very useful in realizing obvious errors.

  Software packages (proprietary or otherwise) generally provide a method to annotate data files for rain, construction, or other factors that may affect the travel time or accuracy of the GPS data along the corridor. These comments should be reviewed to determine possible causes of inaccurate data.

- **User-developed software techniques** - In a recent study, researchers developed a method to read the GPS receiver information into a spreadsheet to check the distances of the traveled routes to ensure they were complete (20).

- **Post-processing differential correction** - GPS data may be corrected with a post-processing method rather than utilizing DGPS in the field. Post-processing involves obtaining differential correction information after the travel time run has been performed for the time in which it was performed. Post-processing may be required for some data points even though differential correction has been applied int he field. This situation may occur if there are interruptions in the differential correction signal during data collection. The differential correction information is then applied to the collected data for correction. As the post-processing is performed, reasonableness checks can be performed to evaluate the data.

- **Perform a pilot study** - It is very important to perform a pilot study of the data collection effort. This is true for any of the test vehicle techniques. The pilot study should include every step of the data collection, reduction, and analysis process. This will ensure that the entire process can be evaluated and valuable lessons can be learned. The pilot study can provide insight into whether more or different data should be collected, the process can be automated and to what extent, and other ways that the process may be made more efficient.

3.3.5 Previous Experience

Louisiana State University

Research performed at the Remote Sensing and Image Processing Laboratory at Louisiana State University (LSU) developed a methodology to use GPS in collecting, reducing, and reporting travel time data for congestion management systems (17,21).

The data collection methodology began with the development of a base map at the interchange of I-10 and I-12 that was being studied. Since adequate base maps of the site did not exist, the base map was developed in the GIS software with the use of the data collected from the GPS units themselves. The study routes in this corridor were driven in both directions with the use of GPS to collect data every second. All entrance and exit ramps at the interchange were also driven to ensure all portions of the interchange were included. In addition, ramps, lane drops, and signalized intersections were included (21).

The next step in the methodology was the determination of checkpoints along the route since travel time and average speed studies generally average these measures over a specific link length. Two rules were used in the establishment of the checkpoint locations. The first was to establish a checkpoint at all physical discontinuities (e.g., signalized intersections, significant unsignalized intersections, lane drops, exit ramps, entrance ramps, other geometric discontinuities). The second guideline used in the determination of checkpoints was a nominal spacing of five checkpoints every mile. This resulted in 2,397 segments with an average segment length of 0.21 km (0.13 mi) (17,21).

After the determination of the checkpoint locations, it was important to link each of the segments to a relational database. The use of a unique identifier for each segment allowed for associating the number of lanes and posted speed limit to each section. In addition, analyses performed over different dates and times could be associated with specific segments (21).

Travel time data were collected in the morning and afternoon peak hours as well as during off-peak periods. To aid in the data reduction effort, a data reduction software macro was developed. The macro aids in transforming the GPS point-by-point data into travel times and average speeds over the segment. When the user clicks on a specific segment along the corridor, the data reduction application recognizes the segment and determines entrance and exit times and updates the user interface (21).

This methodology was used to collect travel time on 531 km (330 mi) of urban highways in three metropolitan areas in Louisiana: Baton Rouge, Shreveport, and New Orleans. The travel time data included 183,000 segment travel time and speed records derived from approximately 2.9 million GPS points collected on 48,279 km (30,000 mi) of travel time runs. The study found that undergraduate students could be trained to perform the data reduction in one to two hours and were proficient with the process within ten hours. As a general rule, they found that data could be reduced about eight times faster than it was collected (i.e., a two hour data collection run would take 15 minutes to reduce to segment identifiers, route travel time, and average speed) (21).

The LSU researchers concluded that using GPS technology was efficient and cost-effective in measuring travel time and average speed along the corridor. The GPS technology was found to provide an accurate depiction of the test vehicle's location and speed (17,21). An additional benefit of the LSU research was the graphical output and presentation methods with the data. These methods are further discussed in Chapter 7, which describes different data summary and presentation techniques.

Central Transportation Planning Staff (CTPS), Boston, Massachusetts

Travel time was identified as a performance measure for the Boston area's congestion management system (CMS). Several data collection techniques for travel time data were considered, but GPS was selected for use. GPS was the selected method since it provided the high potential for more accurate data at a reduced cost. Further, the Central Transportation Planning Staff in Boston selected the GPS technology since it allows for the collection of an increased amount of data (i.e., collected every second) that may be utilized for analyses of queue lengths, stopped delay, and speed profiles for the CMS (20).

Several months went into the development of an interface in the GIS software to allow for standardizing the editing process of the data collected with the GPS receivers. The menu within the GIS software allows for the calculation of key performance measures such as travel time and average speed along predetermined segments. A file is then produced that contains characteristics of the segment including the route, date, segment name, segment start and end times, segment length, and average speed for every segment in which GPS data were collected (20).

The study also compared data collection utilizing the manual method with the GPS method. These techniques were compared on one segment. The traditional manual method that was used employed a passenger in the test vehicle who wrote down the time as they reached predetermined checkpoints. The information was then entered into a spreadsheet to calculate travel times and speeds.

Data was collected with GPS units in one-second increments and included longitude, latitude, time, altitude, and other information. A passenger/recorder was not necessary when collecting data in this manner. The study found that there was general agreement between the traditional manual method and the GPS technology. The differences in distance between segments was less than 0.16 km (0.1 mi) and all the speeds were within 8 km/h (5 mph) (20).

It is interesting to note that differential correction was not used for the GPS travel time data collection in this study. Since the study was only interested in determining average speeds along the corridor, those performing the study were not concerned that the points match exactly to the base map. Therefore, differential correction was not used in the study. Quality control checks such as viewing each data collection run in the GIS map environment, and viewing the data in spreadsheet form allowed the research team to realize if the data were suspect. The CTPS staff in Boston have been very pleased with the use of the GPS technology for travel time data collection.

Texas Transportation Institute (TTI), San Antonio, Texas

The Texas Department of Transportation (TxDOT) is sponsoring the Texas Transportation Institute (TTI) in using GPS technology for travel time data collection in San Antonio. The study will use GPS data collection to provide an historical database of travel time information for approximately 241 centerline km (150 centerline mi) of freeway and arterial roadways in San Antonio. The data will be used for the Model Deployment Initiative (MDI) that is underway in San Antonio.

Palmtop computers are being used in the study to collect the GPS travel time data. Differential correction is also being used to add accuracy to the data collection effort. Figure 3-7 contains a diagram of the equipment used in the study. The GPS data logging software developed by TransCore is also being used. Figure 3-8 shows a sample of the data being collected and recorded at one-second intervals along the travel time routes. The logging software records the latitude, longitude, day, time, speed, direction, GPS rating, and user flags. The direction is measured in degrees from true North increasing eastwardly. The GPS rating represents whether the data is new (equal to one) or old. Generally the output data are new except when the machine is warming up and when there are interruptions in the data stream. When the machine is first warming up and not moving, old data are used to determine location information.

The final column for user flags represents user-specified flags that have been predefined. For example, the "s" in Figure 3-8 represents signals along the arterial route. The data logging allows for defining different keys to represent different environmental or traffic situations or for marking the endpoints of the travel time run (e.g., s = signals, c = construction, r = rain, e = end of run, b = beginning of run). The driver of the test vehicle can simply press the predetermined key on the keyboard of the portable computer to mark the location in the travel time run to annotate the data.

Figure 3-9 shows a sample of a field data collection form that is being used in the study to record start times, file names, incidents, and environmental conditions during the travel time run. This form provides a location for recording up to six travel time runs for a given direction in the peak period. The study is expected to perform at least five travel time runs in each peak period. Note that the form also contains a shaded region at the bottom that confirms when the file has been downloaded to the data storage computer.

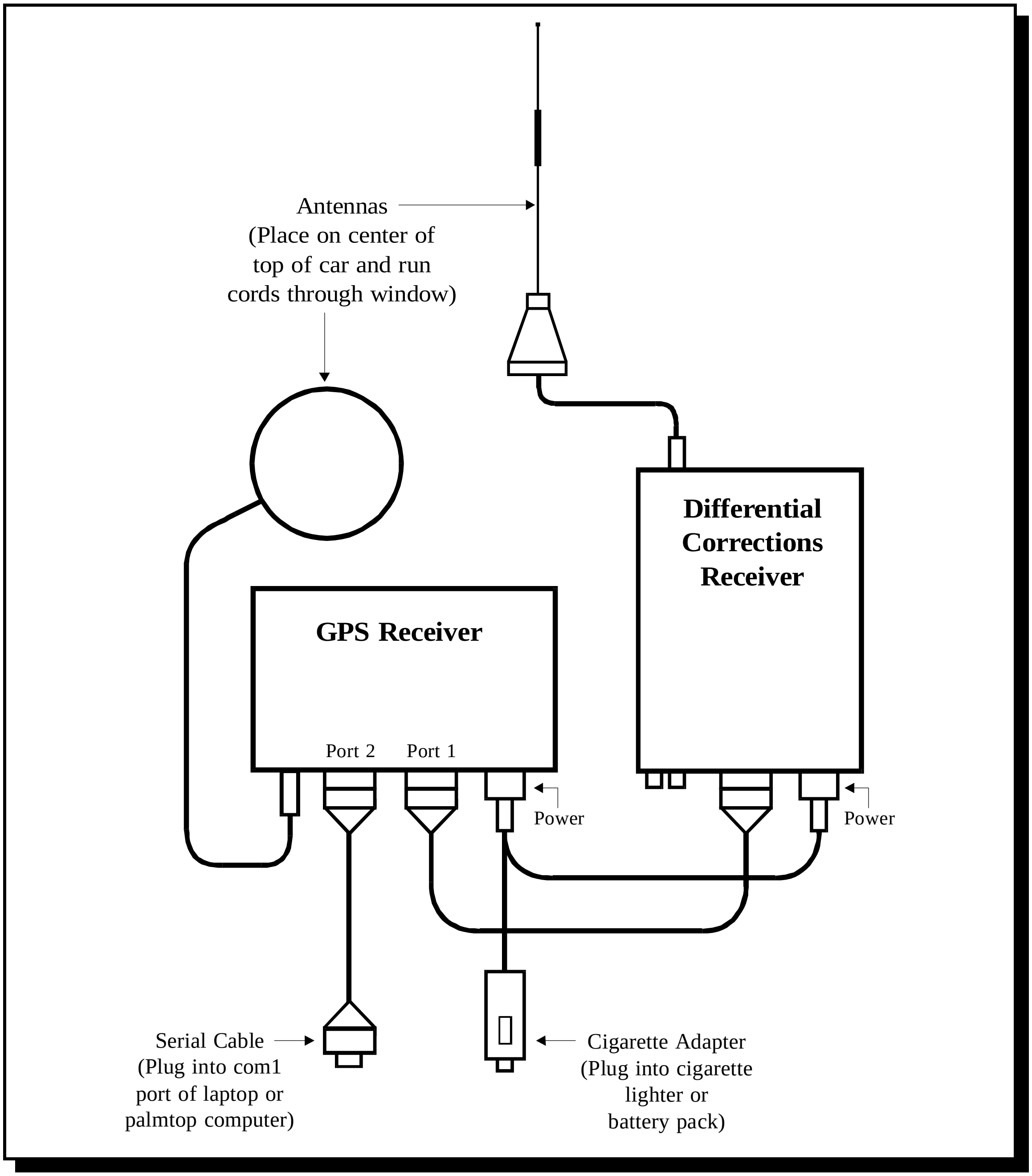


Figure 3-7. Equipment Used for GPS Data Collection in San Antonio, Texas

Latitude	Longitude	Day	Time	Speed	Direction	GPS Rating	User Flag
29.52574	-98.538	Thu	19:38:08.0	11	-132	1	
29.52571	-98.538	Thu	19:38:09.0	13	-133	1	
29.52567	-98.5381	Thu	19:38:10.0	15	-136	1	
29.52562	-98.5381	Thu	19:38:11.0	16	139	1	S
29.52557	-98.5352	Thu	19:38:12.0	17	-139	1	
29.52551	-98.5382	Thu	19:38:13.0	19	-139	1	
29.52544	-98.5383	Thu	19:38:14.0	21	-140	1	
29.52537	-98.5384	Thu	19:38:15.0	23	-140	1	
29.52534	-98.5384	Thu	19:38:16.0	24	-140	1	
29.52522	-98.5385	Thu	19:38:17.0	26	-141	1	
29.52514	-98.5386	Thu	19:38:18.0	26	-141	1	
29.52509	-98.5386	Thu	19:36:19.0	26	-140	1	S
29.52497	-98.5387	Thu	19:38:20.0	27	-140	1	
29.52493	-98.5388	Thu	19:38:21.0	26	-140	1	
29.52476	-98.5389	Thu	19:38:23.0	27	-135	1	
29.52472	-98.539	Thu	19:38:23.0	27	-138	1	
29.52463	-98.5391	Thu	19:38:24.0	25	-138	1	
29.52454	-98.5392	Thu	19:38:25.0	28	-135	1	
29.52444	-98.5393	Thu	19:38:26.0	29	-140	1	
29.52436	-98.5393	Thu	19:35:27.0	30	-135	1	
29.52425	-98.5394	Thu	19:38:28.0	30	-139	1	
29.52417	-98.5395	Thu	19:35:29.0	31	-135	1	
29.52403	-98.5397	Thu	19:38:31.0	30	-140	1	
29.52397	-98.5397	Thu	19:38:31.0	30	-137	1	
29.52389	-98.5398	Thu	19:38:32.0	31	-138	1	
29.52378	-98.5399	Thu	19:38:33.0	32	-136	1	
29.5237	-98.540	Thu	19:38:34.0	32	-139	1	
29.52355	-98.5401	Thu	19:38:36.0	33	-140	1	
29.52348	-98.5402	Thu	19:38:36.0	34	-138	1	

Figure 3-8. Sample Data from Data Logging Software

Driver: ____

Date: ____

AM

Route: BANDERA / CULEBRA

Direction: SE (IH-410 to IH-10)

	Start Time:	**Start Time**:	**Start Time**:	**Start Time**:	**Start Time**:	**Start Time**:
	File: Trip ___.gps	**File**: Trip___.gps	**File**: Trip___.gps	**File**: Trip ___.gps	**File**: Trip___.gps	**File**: Trip___.gps
Route Section Limits	**Incident Type (if any)**					
IH 410 to Callaghan						
Callaghan to Skyview						
Skyview to Hillcrest						
Hillcrest to Ligustrum						
Ligustrum to Cheryl						
Cheryl to Gen. McMullen						
Gen. McMullen to 24th						
24th to 19th						
19th to Zarzamora						
Zarzamora to IH 10						

Incident Types

1 - Accident Lane 1 (inside lane)
2 - Accident Lane 2 (middle lane)
3 - Accident Lane 3 (outside lane)
O - Accident in Opposite Direction
L - Stall on Left Shoulder
R - Stall on Right Shoulder
M - Multiple Lanes Blocked
CS - Construction Start
CE - Construction End
D - Debris in Road
Q - Queue
SQ - Signal Queue

Weather	**Weather**	**Weather**	**Weather**	**Weather**	**Weather**
☐ Clear	☐ Clear	☐ Clear	☐ Clear	☐ Clear	☐ Clear
☐ Overcast	☐ Overcast	☐ Overcast	☐ Overcast	☐ Overcast	☐ Overcast
☐ Lt. Rain/Drizzle	☐ Lt. Rain/Drizzle	☐ Lt. Rain/Drizzle	☐ Lt. Rain/Drizzle	☐ Lt. Rain/Drizzle	☐ Lt. Rain/Drizzle
☐ Heavy Rain	☐ Heavy Rain	☐ Heavy Rain	☐ Heavy Rain	☐ Heavy Rain	☐ Heavy Rain
Light	**Light**	**Light**	**Light**	**Light**	**Light**
☐ Normal Daylight	☐ Normal Daylight	☐ Normal Daylight	☐ Normal Daylight	☐ Normal Daylight	☐ Normal Daylight
☐ Dark or Twilight	☐ Dark or Twilight	☐ Dark or Twilight	☐ Dark or Twilight	☐ Dark or Twilight	☐ Dark or Twilight
☐ Sun Glare	☐ Sun Glare	☐ Sun Glare	☐ Sun Glare	☐ Sun Glare	☐ Sun Glare
☐ Fog	☐ Fog	☐ Fog	☐ Fog	☐ Fog	☐ Fog
Pavement	**Pavement**	**Pavement**	**Pavement**	**Pavement**	**Pavement**
☐ Dry	☐ Dry	☐ Dry	☐ Dry	☐ Dry	☐ Dry
☐ Wet	☐ Wet	☐ Wet	☐ Wet	☐ Wet	☐ Wet
☐ Ice/Slickness	☐ Ice/Slickness	☐ Ice/Slickness	☐ Ice/Slickness	☐ Ice/Slickness	☐ Ice/Slickness
Any Incidents?	**Any Incidents?**	**Any Incidents?**	**Any Incidents?**	**Any Incidents?**	**Any Incidents?**
☐ Yes	☐ Yes	☐ Yes	☐ Yes	☐ Yes	☐ Yes
☐ No	☐ No	☐ No	☐ No	☐ No	☐ No

OFFICE USE ONLY

File Downloaded?	**File Downloaded?**	**File Downloaded?**	**File Downloaded?**	**File Downloaded?**	**File Downloaded?**
☐ Yes, Init.______	☐ Yes, Init.______	☐ Yes, Init.______	☐ Yes, Init.______	☐ Yes, Init.______	☐ Yes, Init.______
☐ No	☐ No	☐ No	☐ No	☐ No	☐ No
File Name:	**File Name:**	**File Name:**	**File Name:**	**File Name:**	**File Name:**

Figure 3-9. Field Data Log Form Used for GPS Data Collection in San Antonio, Texas

TransCore

TransCore (formerly known as JHK & Associates) has been extensively involved in the use of GPS technologies for transportation applications through research sponsored by the Federal Highway Administration (FHWA). A recent study in Northern Virginia investigated all aspects of the GPS travel time data collection effort including data processing and analysis. The study incorporated the use of data smoothing, map matching, path building, and data assimilation techniques to determine the travel time information along several routes. TransCore performed an alternatives analysis along a 64 km (40 mi) section of Route 1 between Prince William County and the Capital Beltway (I-95). Several parallel arterial and freeway segments were included. Data were collected with approximately 190 GPS travel time runs with two GPS units for a two week period during the morning and evening peak periods in both directions. The following objectives were established for the data collection technique to be used (19,22):

- Quantify roadway performance in ways the general public can understand;
- Quantify traffic flow characteristics for problem location and model calibration; and
- Determine the dynamics and precise location of traffic congestion.

The GPS technology was selected for the travel time data collection for the following reasons (19).

- **Less labor intensive than other methods** - This enabled the study budget to accommodate better coverage (both in time-of-day and facilities) and increase the number of observations per roadway.

- **Equipment was simple to use and portable** - This made it possible to involve a larger number of staff members, which, in turn, provided the vehicle and driver the flexibility needed to schedule early morning and late evening data collection runs.

- **Provided automatic geo-coding of detailed speed information** - This made it possible to analyze detailed traffic flow characteristics without significant investment in staff time and resources that would be required to apply traffic simulation tools.

- **Relatively inexpensive** - Savings were realized at a number of points in the analysis process. Data collection is the most obvious, but savings were also recognized in map production, graphics presentation, data analysis, data summary, problem identification, and level of service analysis.

Network map matching was an important aspect of this study. Since differential correction was not used and travel time information for each link was desired, algorithms were developed that would shift the points to the network map. Census TIGER files were used in concert with the GPS Data Logging Software developed by TransCore. The study concluded that map matching, which includes data smoothing and shape matching algorithms, is a useful tool when it is desired to match the GPS data to the network map.

Map matching algorithms cannot simply assign data collected with GPS receivers to the nearest roadway link. This causes the points to "jump" from the roadway to the cross street and back to the roadway as the collected points pass through an intersection. Including the direction of travel into the algorithm may reduce the likeliness of this problem. In order to eliminate the problem, the map matching algorithm must match a group of points to the base map, not individual data points (19).

The use of data smoothing and shape matching algorithms is also important. The smoothing algorithm compares the individual data points to groups of points to ensure they are aligned correctly. For example, if a group of data points have an eastbound orientation and one individual point is oriented north, the algorithm will orientate the northbound point to match the group with the eastbound orientation (19). The shape matching algorithm is used to fit GPS data to corners and curves on the roadway network. After a corner or curve is identified, the algorithm fits the set of GPS data to the network coordinates. The TIGER files represent roadways connected at sharp angles, while the GPS data is collected as a smooth series of points. The data smoothing and shape matching algorithms must recognize the smooth curve in the GPS data as a turn and convert it into a sharp-angled turn for matching to the map network (19).

A path-tracing algorithm was also a valuable component for network matching. If the network is not accurate, the GPS data does not include right-angle turns, or the grid is too dense and contains a large number of similar shapes, additional problems with map matching can occur. The path-tracing algorithm identifies the most likely location for GPS data when a particular movement as shown in an individual GPS data point cannot be made. The points prior to this individual point are reassigned to a new path until a common match is found between the network and the GPS data. In addition, the path-tracing algorithm considers traffic prohibitions (e.g., one-way streets, freeways, and intersections with turn restrictions) (19).

Finally, TransCore's experience indicated that it is sometimes necessary to break up the collected GPS data into different paths. This may be necessary due to an incomplete network or the possibility that the GPS data collection vehicle left the travel run corridor by going into a driveway or parking lot. In these cases the map matching could be terminated until the vehicle re-enters the corridor in which data are being collected. Although this feature is quite useful, TransCore points out that this adds significantly to the complexity of the algorithm (19).

The TransCore experience demonstrates the capability of map matching algorithms. Although it is generally not necessary to snap every data point to the existing network map, this does provide a network referencing system for additional applications. It may be desirable to snap all data points to the existing map to provide a common reference system for aggregation of data along the predetermined links. An automated procedure that performs map matching as described above is useful for these applications (e.g., performance measure calculation).

Lexington, Kentucky (GPS for Personal Travel Surveys)

The experience explained here was primarily for the collection of personal travel survey data using GPS, but travel time data were collected as well. Travel times of interest in most personal travel surveys are typically at a trip level (i.e., from trip origin to destination). It differs from the typical GPS test vehicle applications described throughout this chapter because the drivers are not trained and they are not restricted to drive on specified corridors. However, the discussion is appropriate in this section because practitioners can gain valuable insight from the conclusions and experience of this research effort since the vehicles are instrumented in a manner similar to traditional test vehicle techniques. Further, data reduction and analysis are performed similarly through the use of a GIS platform.

Transportation planners and policy-makers are often concerned about personal travel and changes in personal travel. A recent study has been performed to utilize the benefits of GPS technology in the collection of personal travel surveys (20). The personal travel surveys included the collection of data relating to trip purpose and frequency, as well as overall trip times. The Federal Highway Administration sponsored the study with the cooperation of the Lexington Area Metropolitan Planning Organization (MPO). The three primary objectives of the study are as follows:

1. Develop a method and hardware to integrate GPS technology with self-reported travel behavior to improve travel behavior data.

2. Document the differences between self-reported travel and GPS recorded travel and document the pros and cons of each method.

3. Determine the potential for using GPS technology with regional and national travel behavior surveys, with particular regard to subjective responses to privacy.

To meet these objectives, sampling of listed telephone numbers was performed and 100 households were selected for the study. The Lexington Area (MPO) covers the counties of Fayette and Jessmine over approximately 1195 sq. km. (461 sq. mi.) and a population near 350,000 persons. An automatic data collection process was utilized to collect data in this study area by using a GPS receiver, personal travel survey software that allows the recording of important travel characteristics (e.g., identifying driver or passengers), palm-top computer, memory card, and connecting cables. Differential correction of the GPS data was not performed. At the trip start, the motorists recorded travel information including identifying the driver and passenger(s) and their trip purpose(s). A GIS platform was used to analyze and investigate the results of the travel patterns.

Overall, the project was rather successful in achieving the objectives described above. The first objective above is based on technology aspects of the hardware and software. The study found that the relatively low-cost and portable GPS equipment was responsive to the technology and it could be shipped to users for self-installation and operation. The touch-screen interface was used and was also received well, even with the older population. Map-matching techniques were also successfully used to match the GPS data points to the GIS map.

The second objective stated above is based upon the advantages and disadvantages between self-reported travel and the data reported from the GPS units. Traditionally, personal travel surveys are performed with telephone or mail-back surveys, but the technology described here allows the motorist to record trip information in the vehicle through the touch-screen interface. This computer-assisted self-interviewing (CASI) technique routinely collects data (e.g., trip start and end times, trip distances, route choice, origin/destination, travel speed, and functional class) with more accuracy. Much of this information can be easily viewed and determined with the aid of the GIS platform. Recall interviews were performed inquiring about previous personal trip information, and it was found that 61.4 percent of the recall trips were matched to the GPS information collected. “Matching” entailed comparisons between recall trip start times and durations compared to the personal digital assistant (PDA) within an established range and professional judgement about trip characteristics being matched.

The final objective addresses the future potential of the technology for studies of this sort. The study found that the GPS technology is quite successful and that motorists are accepting of the technology. The research team expresses the advantages of travel data collection with the aid of GPS receivers and technology. The need for future standardization of hand-held computer operating systems and GPS PCMCIA cards is mentioned. It is further noted that GPS use in transportation is a relatively new area and that more work is needed in identifying transportation needs and data users for integration into GIS and GPS hardware and software. This would aid the test vehicle application discussed in this chapter and in section 5.5. Additionally, it is noted that although the use of a PDA in conjunction with the GPS receiver may be desirable in some cases, written trip diaries can still be used if budgets do not permit the acquisition of PDA units.

The research team also notes that the visibility and contrast of the computer touch-screen should be a key consideration. The contrast of the screen did cause difficulty for some respondents. The questions themselves that are prompted on the computer must be very understandable, along with a user-friendly system, to ensure that the data are reliable. Finally, some complaints were received about the large amount of sometimes cumbersome cabling. This could be greatly reduced if the GPS antenna can be placed inside of the vehicle. Further, for a large-scale deployment, the research team suggests sturdier and harder equipment.

3.4 References for Chapter 3

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Global Positioning System (GPS)

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See Chapter 5 for further GPS references that relate to ITS probe vehicle techniques.

4 LICENSE PLATE MATCHING TECHNIQUES

This chapter contains information on travel time collection using license plate matching techniques. In general, license plate matching techniques consist of collecting vehicle license plate numbers and arrival times at various checkpoints, matching the license plates between consecutive checkpoints, and computing travel times from the difference in arrival times (Figure 4-1). Four basic methods of collecting and processing license plates are considered in this chapter:

- **Manual:** collecting license plates via pen and paper or audio tape recorders and manually entering license plates and arrival times into a computer;

- **Portable Computer:** collecting license plates in the field using portable computers that automatically provide an arrival time stamp;

- **Video with Manual Transcription:** collecting license plates in the field using video cameras or camcorders and manually transcribing license plates using human observers; and

- **Video with Character Recognition:** collecting license plates in the field using video, then automatically transcribing license plates and arrival times into a computer using computerized license plate character recognition.

Each section of this chapter contains the following information for these four methods of license plate matching: overview, cost and equipment requirements, data collection and reduction instructions, and previous experiences and applications.

4.0.1 General Advantages and Disadvantages

License plate matching for travel time collection has the following **advantages**:

- Able to obtain travel times from a large sample of motorists, which is useful in understanding variability of travel times among vehicles within the traffic stream;

- Provides a continuum of travel times during the data collection period and ability to analyze short time periods (e.g., 15-minute averages for continuous data); and

- Data collection equipment relatively portable between observation sites.

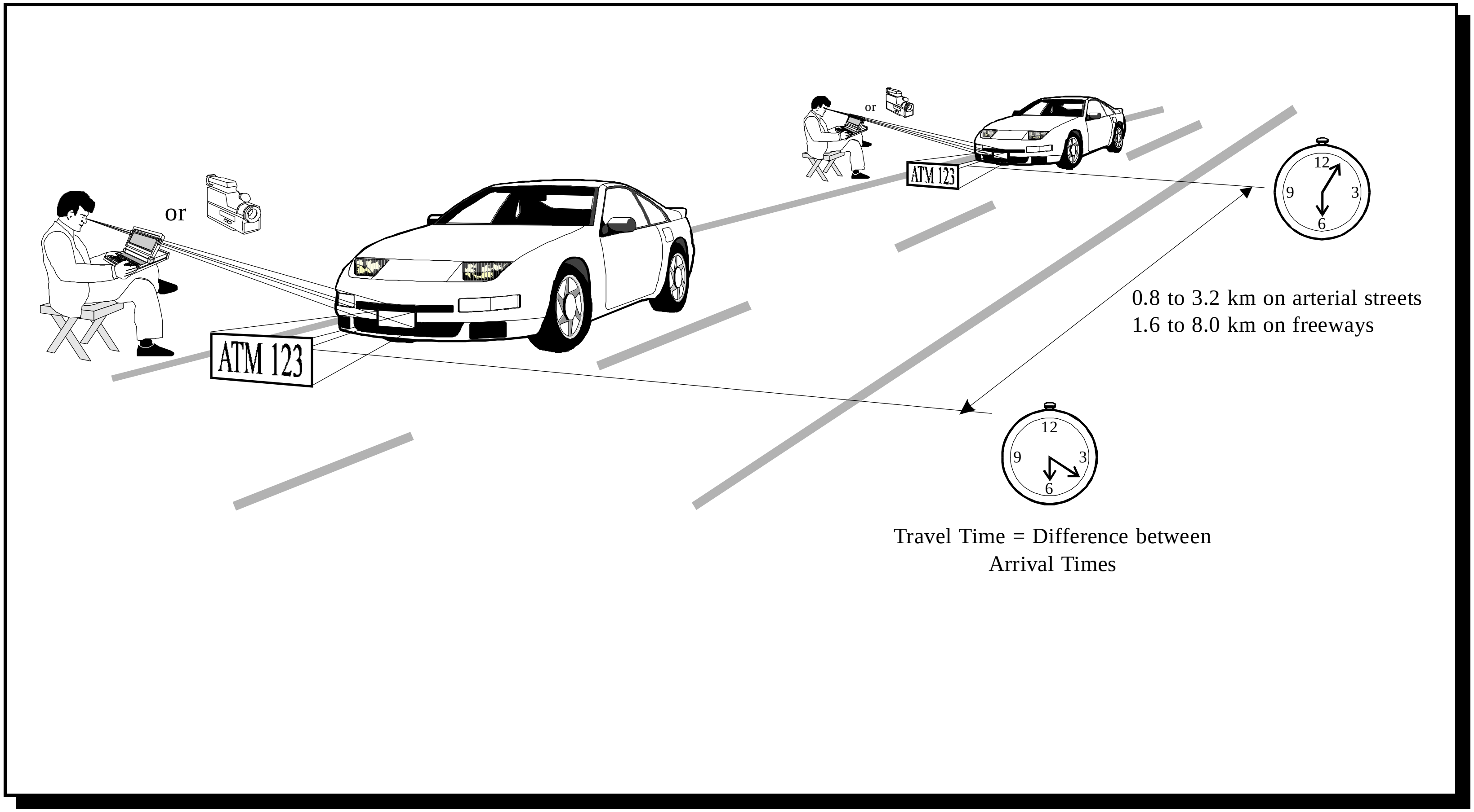


Figure 4-1. Illustration of License Plate Matching Techniques

License plate matching has the following **disadvantages**:

- Travel time data limited to locations where observers or video cameras can be positioned;
- Limited geographic coverage on a single day;
- Manual and portable computer-based methods are less practical for high-speed freeways or long sections of roadway with a low percentage of through-traffic;
- Accuracy of license plate reading is an issue for manual and portable computer-based methods; and
- Skilled data collection personnel required for collecting license plates and/or operating electronic equipment.

Each method of license plate matching also has relative advantages and disadvantages (Table 4-1). This table can be used to select the instrumentation level that best fits the study need and data collection budget.

4.0.2 Designation of Mid-Route Checkpoints

Checkpoints are designated locations along a route where license plate characters and arrival times are noted. The number of checkpoints along a route will vary according to the character of the roadway and the street network configuration. Along roadways with a relatively high level of access, checkpoints should be spaced closer than roadways with lower levels of access. Vehicle trip patterns also affect the designation of mid-route checkpoints, with long-distance trips being more amenable to widely spaced checkpoints. Checkpoints should also be located at major interchanges, intersections, jurisdictional boundaries, and transition points between different roadway cross-sections or land uses.

The following are suggested guidelines for spacing checkpoints for license plate matching (1):

- **Freeways/Expressways** - high access frequency - 1.6 to 4.8 km (1 to 3 mi)
- **Freeways/Expressways** - low access frequency - 4.8 to 8.0 km (3 to 5 mi)
- **Arterial Streets** - high cross street/driveway frequency - 0.8 to 1.6 km (½ to 1 mi)
- **Arterial Streets -** low cross street/driveway frequency - 1.6 to 3.2 km (1 to 2 mi)

These ranges are approximate, and actual segment lengths may vary according to the roadway network and desired detail of study. Corridor and site surveys should be used in selecting the most desirable checkpoints and their spacing. An attempt should be made to select checkpoints that are consistent with current roadway inventory or other databases.

Table 4-1. Comparison of Instrumentation Levels for the License Plate Matching Technique

Instrumentation Level	Costs			Skill Level		Typical Sample Sizes	Level of Data Detail [1]	Accuracy	Automation Potential
	Capital	Data Collection	Data Reduction	Data Collection	Data Reduction				
Manual	Very Low	Moderate	High	Low	Low	Low	Moderate	Low	Low
Portable Computer	Moderate	Low to Moderate	Low	Low	Moderate	Moderate	Moderate	Moderate	High
Video with Manual Transcription	Low	Moderate	High	Moderate	Low	High	High	Moderate to High	Moderate
Video with Character Recognition [2]	High	Moderate	Low	Moderate to High	Moderate to High	High	High	Moderate to High	High

Notes: [1] Refers to the level of data detail throughout the data collection time period.
[2] Assumes that equipment is purchased (versus contracting services).

4.0.3 Observer or Video Recorder Positioning

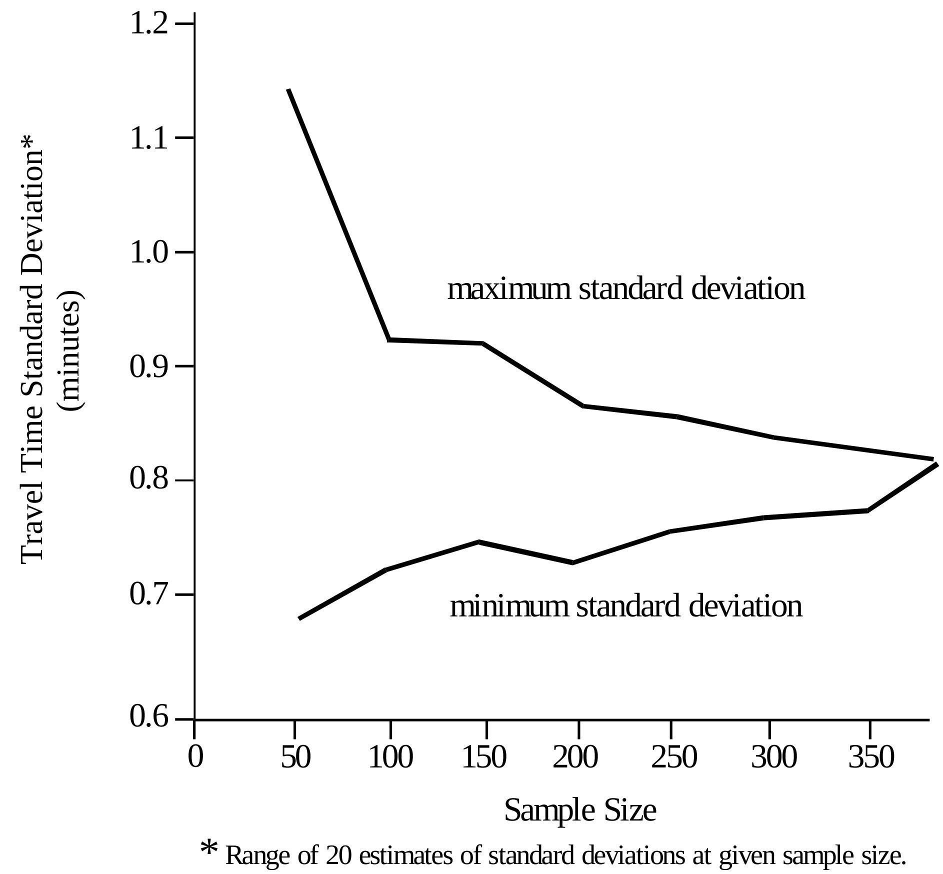
The positioning of observers or video recorders is paramount to the safe and effective collection of vehicle license plate characters. In general, license plate characters are easiest to read when viewed from as small a horizontal angle as possible (i.e., close to "head-on"). The ideal position in most cases is immediately adjacent to the right shoulder or curb, or possibly in the median of divided facilities. Overpasses can provide a safe vantage point for observing plate characters. Safe vantage points can also be found behind some type of barrier, guardrail, bridge column, etc., particularly along high-speed facilities. For video methods, a telephoto lens increases the number of good vantage points from which to record license plates. Observers should be positioned in inconspicuous locations so that the flow of traffic is not disrupted by curious motorists. In states where front license plates are required, views of oncoming vehicles (recording front license plates) provide the best opportunity to accurately read license plate characters. For observers, an oncoming and departing view of vehicles could provide a second chance to read a rear license plate if the front license plate is missed.

The positioning of observers on the near or far side of an intersection depends upon whether one wishes to include delay from the intersection in the preceding or following segment travel time. Positioning on the far side has been the generally accepted location for most travel time studies. For freeways, entrance and exit ramp connections to the mainlanes are the best checkpoints when attempting to match the cause of congestion with its effects.

4.0.4 Sample Sizes

Vehicle sample sizes typically are not a large concern for license plate matching (as compared to the test vehicle technique) because data collection includes a large number of vehicles. However, the average sample sizes for license plate matching are greater than test vehicle sample sizes because of a difference in the sampled travel time variability for these two techniques. The variability of license plate matching travel time samples generally are higher than test vehicle travel time samples because license plate matching captures a wide range of driving patterns and vehicle types. The test vehicle technique uses a limited number of drivers (data collection personnel) that reduce travel time variability by "floating" with traffic.

Early research in 1952 by Berry (2) found that sample sizes ranging from 25 to 102 license matches were necessary for a given roadway segment and time period. Many subsequent guidelines in the literature report a minimum sample size of 50, including ITE's *Manual of Transportation Engineering Studies* (3). Recent research using video and character recognition confirmed that minimum sample sizes of 50 license matches were adequate for a wide range of travel time variability (Figure 4-2) (4). For planning purposes, 50 license matches can be used as the target sample size. Once travel time data has been collected, procedures in the next several paragraphs can be used to determine whether the actual number of license matches meets the statistically required sample sizes for a given confidence and error level.



Source: adapted from reference (4)

Figure 4-2. Standard Deviation as a Function of Sample Size

The required minimum sample sizes for license plate matching are calculated using Equation 4-1. (More discussion on this and other sample size equations can be found in Section 3.0.2.) This equation is most useful in ensuring that collected data meets minimum statistical sample sizes. This equation was used in combination with travel time variability estimates (Table 4-2) to produce illustrative license matching sample sizes, shown in Table 4-3. Because license plate matching encompasses a large number of motorists with different driving patterns, the travel time variability, and hence the sample sizes, will be larger than those associated with the test vehicle technique.

$$\textit{Sample Size, } n = \left(\frac{t \times c.v.}{e}\right)^2 \approx \left(\frac{z \times c.v.}{e}\right)^2 \quad \textit{if estimated sample size is greater than } 30 \qquad (4\text{-}1)$$

Table 4-2. Approximate Coefficients of Variation for License Plate Matching

Source (Reference Number)	Reported Coefficients of Variation	Traffic and Roadway Conditions
Berry and Green, 1949 (5)	0.15 to 0.31	free-flow and congested and arterial streets, 1- to 2-hour time periods
Berry, 1952 (2)	0.12 to 0.25	rural highways and congested arterial streets, 1- to 2-hour time periods
Dandy and McBean (6)	0.05 to 0.33	highways and arterial streets
Shuldiner, D'Agostino and Woodson (4)	0.05 to 0.15	freeway and arterial streets, 15- to 30-minute time periods
Suggested Coefficients (15- to 30-minute time period)	0.10 0.20	freeways and arterials, low to moderate traffic freeways and arterials, congested traffic
Suggested Coefficients (1- to 2-hour time period)	0.25 0.35	freeways and arterials, low to moderate traffic freeways and arterials, congested traffic

Table 4-3. Illustrative License Plate Matching Sample Sizes

Traffic Signal Density (signals per mile)	Average Coefficient of Variation, (%) Table 4-2	Sample Sizes (iterative calculations using Equation 3-4)		
		90% Confidence, ± 10% Error	95% Confidence, ± 10% Error	95% Confidence, ± 5% Error
Low to moderate traffic, 15- to 30-minute period	10	4	5	18
Low to moderate traffic, 1- to 2-hour time period	20	12	18	62
Congested traffic, 15- to 30-minute time period	25	18	27	96
Congested traffic, 1- to 2-hour time period	35	34	48	189

Matching percentages, or the number of matched license plates divided by the number of collected license plates, can be applied to the license match sample sizes in Table 4-3 to obtain planning estimates of required vehicle plates to collect. Matching percentages can range from about **5 to 20 percent** (4,7,8) and depend upon several factors:

- distance between observation sites;
- number of intersecting streets/interchanges;
- percent of through traffic and typical trip length; and
- matching and screening algorithms.

For example, assume that a sample size of 62 vehicles (95 percent confidence level and 5 percent relative error, Table 4-3) is necessary for accurate travel times along a particular section of an arterial street. For arterial streets, the matching percentage is approximately 10 percent. The number of license plates that **should be collected at both observations sites** along this arterial street is approximately [62/0.10], or **620 license plates**. A stationary observer with a portable computer can collect between 400 and 700 plates per hour (assuming sufficient volume), whereas a video camera is capable of collecting between 80 to 95 percent of the total traffic volume (4,8).

EXPERT TIP ☺	Sample sizes are typically not a large concern with the video or portable computer-based license matching techniques. However, minimum sample sizes should be verified with variability values from field data.

4.0.5 License Plate Syntax

Each state in the U.S. has established rules and guidelines for license plate fonts and syntax. For example, one state may distribute license plates with the following syntax: "ATM123", where the first three characters are letters and the last three characters are numbers. Very few states issue plates with more than seven characters (this may help to identify the origin state of the plate). Also, some states do not use numbers or characters that look similar. For example, many states do not use the letters "O" or "Q" because of the similarities to the number "0". Also, some states have different syntaxes for different types of vehicles (e.g., commercial vs. trucks vs. passenger cars). If desired, this syntax can be used to eliminate commercial vehicles or tractor-trailer combinations that typically do not travel at speeds characteristic of the traffic flow. Before collecting license plate data, one should check with the state's department of motor vehicles (DMV) to identify particular license plate syntax rules. The syntax of license plates can help in decreasing the occurrence of misread or mismatched license plates.

4.1 Manual Methods of License Plate Matching

For the purposes of this handbook, manual methods of license plate matching are those that require the field personnel to read license plates in the field and transcribe the plates into a computer in the office after the actual time of data collection. License plates can be collected in the field using simple pen and paper or an audio tape recorder.

4.1.1 Advantages and Disadvantages

Manual license plate matching has the following **advantage** (as compared to other methods of license plate matching):

- Minimum amount of simple field equipment required.

Manual license plate matching has the following **disadvantages**:

- Collection of large samples of license plates in the field is difficult; and
- Transcription of license plates is very labor-intensive (typically 10 hours per hour of data collection).

4.1.2 Cost and Equipment Requirements

The cost and equipment requirements for the manual license plate matching technique are minimal. The cost of license plate transcription and matching may vary depending upon the skill level of personnel used to perform this task. Table 4-4 contains information about hardware, software, and personnel requirements and approximate costs.

Table 4-4. Estimated Costs for the Manual License Plate Matching Technique

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
Portable tape recorder, non voice-activated (one per checkpoint)	\$30 to \$60
Miscellaneous field supplies and equipment (stools or chairs, audio tapes, batteries, fuel for transportation, etc.)	\$250
Personnel	
Observer/recorder (minimum of one per checkpoint)	\$6 to \$10 per hour
License plate transcription and matching (approx. 10 hours per hour of data collection)	\$6 to \$10 per hour
Study supervision and management	Varies

4.1.3 Data Collection Instructions

The following steps should be performed before license plate collection begins (see Chapter 2 and Sections 4.0.2 through 4.0.5 in this chapter):

1. Define the routes to be studied;
2. Designate the checkpoints and specific locations where observers will be positioned;
3. Define the time period during which data will be collected;
4. Compute number of license plates needed for minimum sample sizes; and
5. Train personnel and practice reading one to two hours of license plates in actual roadside conditions.

Once the necessary planning and preparation have been performed, the following steps should be performed in collecting and matching license plates.

1. **Inventory and check equipment.** All equipment should be inventoried and checked before proceeding to the data collection sites. **Watches and clocks should be synchronized at this time**. Ensure that each observer has a backup power supply (extra batteries).

2. **Arrive at site early.** Observers should arrive at the data collection site 20 to 30 minutes in advance of when they are scheduled to begin data collection. This ensures that observers can find the most suitable and comfortable location, and prepare the equipment. This time can also be used to ensure that **audio tapes are labeled** with the time, date, and specific location of the data collection.

3. **Begin data collection at scheduled times.** Observers should speak clearly into the tape recorder when vehicles pass the checkpoint. Unless several observers are at a single site, vehicle license plates should be sampled from all lanes. At slow vehicle speeds, the full license plate (typically six characters) should be recorded. At higher speeds (greater than 80 km/h or 50 mph), observers may only be able to collect four characters of the license plate. Observers should call out the time approximately every 15 minutes for quality control purposes. These time checks can be used as an additional time check in transcribing the tapes at a later date.

   Several general techniques have been used to make license plate collection using tape recorders easier and more effective. These techniques are summarized as follows:

   - *Reading the first four characters on the plate* - The collection of four characters has been used by most agencies, and experience has indicated that the first four are easier to read than the last four. The collection of all six characters, where practical on lower speed arterial streets, can decrease the occurrence of spurious license matches.

   - *Collection of the plate number while the vehicle is approaching* - This technique allows the observer to record the plate number at the instant the vehicle crosses the designated checkpoint. Headlight glare during low-light periods may require collecting plate numbers while the vehicle is going away.

   - *Collection of as many plates as possible* - The probability of matching plate numbers increases for each additional plate entered; observers should be encouraged to accurately record as many as possible.

   - *Representative sampling of through-lanes* - Studies have shown that speeds vary across lanes, so sampling of all through-lanes is necessary to collect representative speed samples. For high-volume roadways, however, sampling from all through lanes will produce a low percentage of matches. In this case, observers should concentrate on a lane that has a speed representative of the average traffic flow, but also collect a few speed samples from all through lanes. Auxiliary and turning lanes should be avoided because of the low number of matches for the high percentages of turning traffic.

- *Collection during daylight hours* - Although collection during night-time hours is possible, it complicates plate-reading and often creates safety problems.

4. **Take short breaks or use extra personnel.** For tape recording, observers' eyes may become fatigued after one hour of data collection. If the data collection is to last several hours, provisions should be made for short (five-minute) breaks or for extra personnel to relieve the original observers.

5. **Ensure that tapes are labeled correctly.** Once the license plate collection has been completed, ensure that the audio tapes are labeled correctly with the time, date, and specific location of the data collection.

6. **Transcribe the license plates into a computer.** Transcription of the license plates from the audio tapes into a computer is performed in the office. For audio tapes, transcribers should play the tape back at regular speed. A computer program should be used to attach a time stamp to each plate once it has been entered. There are several license plate collection programs that can be used either in the field or office to time stamp license plate entries. Also, some spreadsheets or text editors provide a time stamp feature, as do several basic computer programming languages. License plate transcription from audio tapes takes approximately two to three hours per hour of tape.

7. **Match the license plates.** License plates can be matched using special license matching software, database or statistical analysis software, or spreadsheet functions. The license plate matching should incorporate an algorithm to remove spurious matches, which occur if plate characters are incorrectly read or only four characters are recorded. For example, if only the first four characters are collected, "ATM123" could be matched with "ATM189". Several types of screening algorithms can be used to reduce spurious matches:

   - *Use of "speed limits"* - automatically delete any match that falls outside of preset speeds, typically less than 5 km/h or greater than 125 km/h.

   - *Use of standard deviations* - automatically delete any match that falls outside of three or four standard deviations for the time period.

   - *Visual inspection of travel time/speed profile* - graphs of travel time/speed can be used to visually identify and remove outlying data points.

   The results of the license matching process will be individual vehicle speeds at different times throughout the data collection time period. These speeds can be averaged for the entire time period (i.e., peak hour or peak period), or for smaller intervals of the entire time period (e.g., 15- or 30-minute summaries). Chapter 7 contains more information on reducing and summarizing data.

8. **Consider destroying all license plate records because of privacy issues.** After license plates have been matched and travel times computed, one may want to consider destroying or deleting all license plate records. This can eliminate potential problems with privacy issues or objections to the permanent storage of license plate records by public agencies.

4.1.4 Previous Experience

Many transportation agencies may have experience with manually collecting license plates for origin-destination or travel time studies. The added requirement of recording the arrival time of each license plate, however, makes the license plate travel time study more complex than an origin-destination study. Because of these complexities and its low-technology nature, the literature contains little information about manual methods of license plate matching.

Schaefer provides guidelines for license plate matching surveys that are applicable for manual methods (9). Schaefer's guidelines address the following practical issues and statistical considerations related to license plate matching surveys:

- performing site visits and developing a survey plan;
- addressing issues related to temporary employees for conducting surveys;
- preparing equipment and training considerations;
- designing license plate surveys (e.g., number of plate characters, sample sizes); and
- considering data analysis techniques and error correction.

Many of Schaefer's guidelines have been addressed in this chapter of the handbook; however, the reader is encouraged to refer to these guidelines for more details on the above considerations.

4.2 Portable Computer-Based License Plate Matching

Portable computer-based methods of license plate matching consist of entering license plates into portable (laptop or palmtop) computers in the field. Full or partial license plates may be entered into the computer depending on typical vehicle speeds, and a computer program provides the time stamp automatically. This method does not require the transcription of license plates or time stamps in the office; only the license matching is performed in the office. A new variation of this portable computer-based method uses voice recognition for license plate entry, as opposed to observers manually entering license plates (more information on this variation is contained in Section 4.2.4, Previous Experiences).

4.2.1 Advantages and Disadvantages

Portable computer-based license plate matching has the following **advantages** (as compared to other methods of license plate matching):

- field computer entry of license plates dramatically decreases reduction time; and
- data collection and reduction can be automated with computer programs.

Portable computer-based license plate matching has the following **disadvantages**:

- accuracy of license plate observations can be problematic;
- low sampling of vehicles in traffic stream due to computer entry limitations;
- moderately high equipment costs for large-scale studies; and
- requires highly motivated and moderately skilled observers because of fatigue.

4.2.2 Cost and Equipment Requirements

The cost and equipment requirements for portable computer-based license plate collection are slightly more than those for manual methods of license plate collection. A large cost savings can be realized because no manual license plate transcription is required in the office; computer programs can be used to match the license plates and time stamps already in a computerized format. Table 4-5 contains information about software, hardware, and personnel requirements and approximate costs.

Table 4-5. Estimated Costs for the Portable Computer-Based License Plate Matching Technique

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
Laptop computer and accessories (power supply or additional batteries, carrying case) (one per checkpoint) **or** Palmtop computer and accessories (power supply, additional batteries, carrying case)	$2,500 **or** $750
Miscellaneous field supplies and equipment (stools or chairs, computer diskettes, batteries, fuel for transportation, etc.)	$250
Software	
License plate collection and matching software (see Appendix B for software)	$0 to $100 per computer
Personnel	
Observer (minimum of one per checkpoint)	$10 to $15 per hour
Study supervision and management	Varies

4.2.3 Data Collection Instructions

The following steps should be performed before license plate collection begins (see Chapter 2 and Sections 4.0.2 through 4.0.5 in this chapter):

1. Define the routes to be studied;
2. Designate the checkpoints and locations where observers will be positioned;
3. Define the time period during which data will be collected;
4. Compute approximate number of license plates needed for minimum sample sizes;
5. Obtain or develop license plate collection and matching software (see Appendix B for software);

6. Training and two to three hours of practice reading and entering license plates in actual roadside conditions; and
7. Develop a data management and file naming convention that reduces errors and eases data reduction.

Once the necessary planning and preparation have been performed, the following steps should be performed in collecting and matching license plates.

1. **Inventory and check equipment.** All equipment should be inventoried and checked before proceeding to the data collection sites. **Computer clocks and wrist watches should be synchronized at this time**. Ensure that each observer has a backup power supply (extra batteries).

2. **Arrive at site early.** Observers should arrive at the data collection site 20 to 30 minutes in advance of when they are scheduled to begin data collection. This ensures that observers can find the most suitable and comfortable location and prepare the computer for license plate entry. Observers should use the predefined computer file-naming convention for the license plate entry, or should fill in the site information in the computer program. Typical data items to be collected for each site include:

    - Computer filename that contains license plates;
    - Study route and direction;
    - Time and date of data collection;
    - Location of observer;
    - Roadway cross section characteristics;
    - Weather conditions; and
    - Other comments.

    This information can be stored in the header or first line of the license plate computer file. An example of a data entry screen for this information is provided in Figure 4-3.

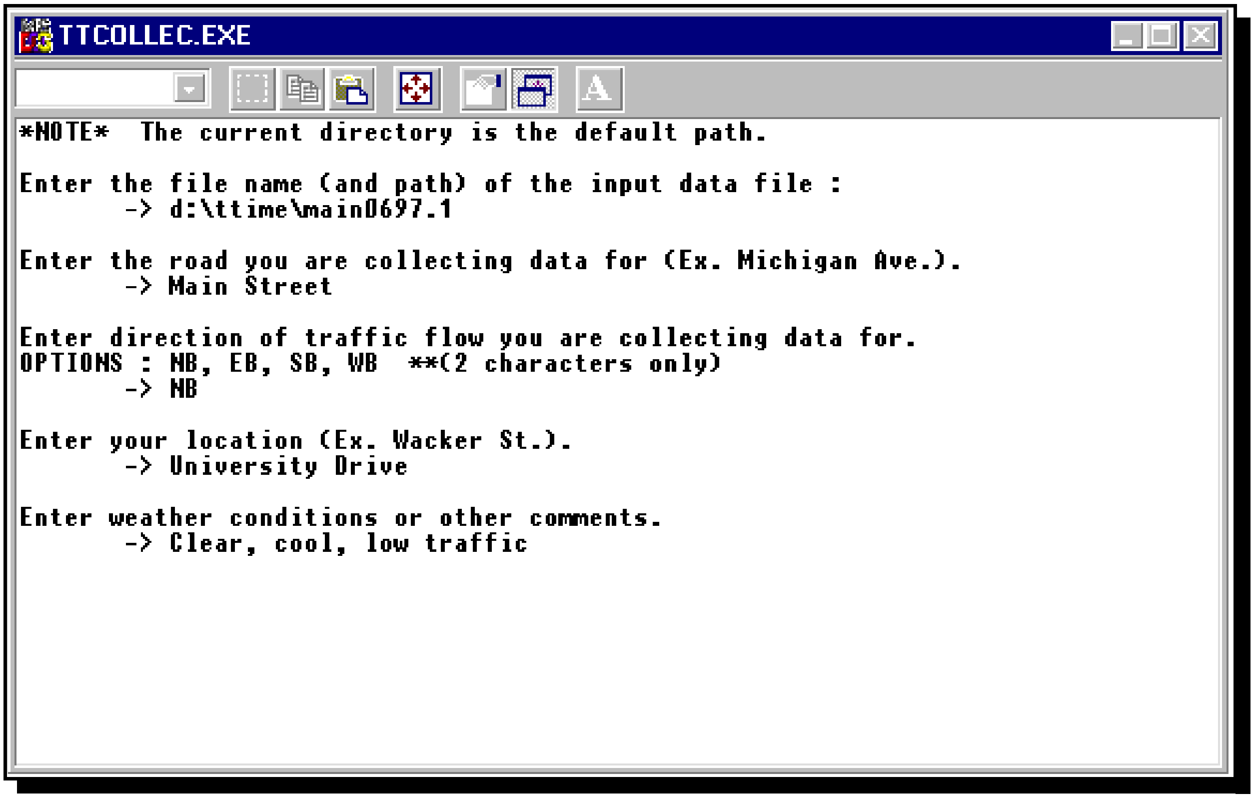


Figure 4-3. Example of Data Entry Screen for Site Information

3. **Begin data collection at scheduled times.** Observers should enter the license plates as soon as the vehicle crosses the designated checkpoint. Unless several observers are at a single site, vehicle license plates should be sampled from all lanes. At slow vehicle speeds, the full license plate (typically six characters) can be recorded. At higher speeds (greater than 80 km/h or 50 mph), observers may only be able to collect four characters of the license plate. If data collection lasts longer than the portable computer battery life, arrangements should be made for a continuous power source or a means to switch spare computer batteries.

   Several general techniques have been used to make license plate collection easier and more effective. These techniques were summarized on pages 4-11 and 4-12.

   - Reading the first four characters on the plate;
   - Collection of the plate number while the vehicle is approaching;
   - Collection of as many plates as possible;
   - Representative sampling of through-lanes; and
   - Collection during daylight hours.

CAUTION !! Vehicle speeds and travel times may vary significantly by lane. If a representative sample of license plates can not be collected from all through lanes, concentrate on the one or two lanes most representative of the traffic stream.

4. **Take short breaks or use extra personnel.** Observers' eyes may become fatigued after as little as one hour of data collection. If the data collection is to last several hours, provisions should be made for short (five-minute) breaks or for extra personnel to relieve the original observers.

5. **Ensure the format and content of license plate files.** Before leaving the site, observers should exit the license plate collection program and ensure that the license plate files are labeled and formatted correctly.

6. **Match the license plates.** License plates can be matched using special license matching software, database or statistical analysis software, or spreadsheet functions. The license plate matching should incorporate an algorithm to remove spurious matches, which occur if plate characters are incorrectly read or only four characters are recorded. For example, if only the first four characters are collected, "ABC123" could be matched with "ABC189". Several types of screening algorithms can be used to reduce spurious matches (see page 4-12):

   - Use of "speed limits";
   - Use of standard deviations; and
   - Visual inspection of travel time/speed profile.

   The results of the license matching process will be individual vehicle speeds at different times throughout the data collection time period. These speeds can be averaged for the entire time period (i.e., peak hour or peak period), or for smaller intervals of the entire time period (15- or 30-minute summaries). Chapter 7 contains more information on reducing and summarizing data.

7. **Consider destroying all license plate records because of privacy issues.** After license plates have been matched and travel times computed, you may want to consider destroying or deleting all license plate records. This can eliminate potential problems with privacy issues or objections to the permanent storage of license plate records by public agencies.

4.2.4 Previous Experience

Several agencies have experience with conducting portable computer-based travel time studies. This method has been used for several applications in the Seattle area. The Chicago Area Transportation Study (CATS) used computerized license plate matching for area-wide travel time studies. The Volpe Center coordinated extensive testing of portable computer-based license plate matching in Boston, Massachusetts; Seattle, Washington; and Lexington, Kentucky. The Texas Transportation Institute (TTI) developed license plate collection and matching software, and also tested portable computer-based license plate matching for evaluating the travel time savings and reliability of HOV lanes in Houston and Dallas. Information about these experiences are contained in the following sections.

Seattle--Comparison of Floating Car and License Matching

Rickman et al. (10) compared portable computer-based license plate matching to the floating car method and examined several issues related to license plate matching. The study conducted by Rickman et al. compared the average travel times from license plate matching results to those obtained from floating car runs (Table 4-6). The conclusions of the comparison found no statistically significant difference in average travel times between average travel times obtained by license plate matching or floating car runs. However, the license plate matching sample sizes for similar time periods were 2 to 15 times greater than floating car sample sizes.

Table 4-6. Comparison of Floating Car and Computerized License Plate Travel Time Methods

Route, Direction and Time Period	Mean Travel Times		Sample Size		t-statistic[a]
	Floating Car	License Plate	Floating Car	License Plate	
Bel-Red Road Eastbound PM	590	590	5	27	0
148th Avenue Southbound PM	453	487	3	45	-0.44
NE Eighth Eastbound PM	242	264	6	11	-0.40
148th Avenue Southbound AM	247	257	5	38	-0.27

Source: adapted from reference (10).
Not [a] The Student's t-statistic is used here to compare the mean travel times of two travel time distributions. All t-values are within the critical t-value at the level of alpha=0.005, and the associated degrees of freedom for each test. This indicates that there is no statistical difference between the two travel time methodologies.

Rickman et al. also experimented with ways to reduce spurious or incorrect matches. Several of the techniques that were recommended include:

- establishing a minimum and maximum travel time expected during the study and eliminating matches outside these limits;
- using graphs to recognize unrealistic outliers;
- using smaller time intervals for license plate matching (e.g., 15 minutes vs. one hour); and
- recording more digits of the license plate.

Other important information gathered from Rickman et al.'s study includes:

- A good typist can collect about 900 four-character license plates per hour (provided adequate volume), with as many as 100 matches for a freeway section with one to two exits;
- Even with complex networks, between 11 and 40 valid travel times per hour were obtained using license plate matching; and
- Collecting four characters from the license plates provides the best combination of ease of data entry and a low level of spurious matches.

Seattle--Use of Voice Recognition on Portable Computers

Washburn and Nihan (11) have experimented with using voice recognition on portable computers as a means to input license plates. The tests indicated that entry accuracy rates as high as 95 percent can be obtained with voice recognition. In their tests, Washburn and Nihan used commercially-available IBM voice recognition engines and two different portable computers, representing a lower and upper-end processing speed:

- Low-speed processor: 80486 processor at 50 MHZ, 8 MB of RAM; and
- High-speed processor: Pentium processor at 120 MHZ, 32 MB of RAM.

High-quality microphones and sound card/speaker systems were added to the portable computers, which were then tested at an arterial street and freeway site. The results of the tests at the arterial street site are shown in Table 4-7. The authors arrived at the following conclusions from the study:

- Voice recognition can provide entry accuracy rates in excess of 95 percent;

- Use of the military alphabet (e.g., A=alpha, B=bravo, etc.) in enunciating license plate characters provides a higher rate of recognition, as does the use of a high-quality microphone; and

- Voice recognition enables a single observer at some sites that may have required two observers (e.g., where one must use binoculars, other enters license plates).

Table 4-7. Summary of Voice Recognition Performance on Arterial Streets

Arterial Test	Time Period (minutes)	Flow Rate (vphpl)	Voice Recognition		Keyboard Entry	
			Sample Rate	Accuracy Rate	Sample Rate	Accuracy Rate
Test 1	27	618	56.8%	90.8%	n/a	n/a
Test 2	26	771	60.1%	96.3%	55.6%	94.0%
Test 3	12	720	73.0%	97.0%	73.0%	89.8%

Source: adapted from reference (11).
Note: Test 1 used the lower quality microphone and the slower processing speed computer. Tests 2 and 3 used the higher quality microphone and the faster processing speed computer.

Chicago Area Transportation Study (CATS)

The Chicago Area Transportation Study (CATS) used portable computer-based license plate matching for travel time data collection on Chicago area arterial streets (12,13). The study included 394 km (245 miles) of the strategic regional arterial system, which was divided into 68 individual roadway segments. The estimated cost of the study was $75,000, amounting to approximately $305 per mile of roadway. Travel time data were collected for three time intervals:

- morning peak (6:30 to 8:30 a.m.);
- mid-day (11:30 a.m. to 1:30 p.m.); and
- evening peak (3:30 to 6:30 p.m.).

Other relevant information about CAT's experience with license plate matching include:

- Computer programs, "SPEEDRUN" and "MATCH", were developed in the BASIC programming language to collect and match the license plates;

- Field observers collected the last four characters of the license plate;

- It was theorized that field observers were able to collect license plates from about 50 to 65 percent of the vehicles that passed on the arterial street;

- Field observers sampled as many plates as possible from all lanes;

- The target sample size for number of matches was 26. Actual number of matches obtained in the field ranged from 5 to 143 for a 20-minute interval; and

- Spurious matches were reduced by 1) eliminating matches with speeds less than 8 km/h (5 mph) and greater than 160 km/h (100 mph), 2) eliminating matches with speeds more than two standard deviations from the mean, and 3) using graphs to visually identify outliers.

CATS has since abandoned all efforts of computerized license plate matching for travel time data collection, instead using the manual test vehicle technique. They have also been considering the use of GPS equipment.

Volpe Center Field Tests

Liu and Haines (14), of the Volpe Center, conducted field tests of several travel time data collection techniques in 1993. The techniques tested in this study included:

- license plate matching using portable computers;
- license plate matching using video cameras and character recognition;
- floating car (test vehicle);
- probe vehicle;
- automatic vehicle identification; and
- loop detectors.

The portable computer-based license matching was tested in Seattle, Washington and Lexington, Kentucky. “Palmtop” computers were used in Seattle and larger “laptop” computers were used in Lexington. Typically two field observers were used at each checkpoint, with each person reading license plates from one specific lane. The observers only collected four of the six characters from the license plate. Major findings from these field tests were:

- Selection of travel time collection methodology depends upon data needs (as they relate to sample size and sample efficiency);

- Portable computer-based method is easy to perform, very portable, requires minimal training, and is particularly well-suited for arterial street use;

- Its limitations are the degradation of observer performance over time, ineffectiveness for high speed locations, the possibility of spurious matches with partial plate (four-character) collection (which points to the need for a screening/quality control process), and the inability to collect intermediate delay data;

- Observers could collect license plates from about 60 percent of the passing vehicles, resulting in approximately 100 to 200 matches per segment per hour; and

- Equipment costs were approximately $1,800 per checkpoint and personnel costs were between $650 and $775 per route per day.

Texas Transportation Institute (TTI)

The Texas Transportation Institute (TTI) developed license plate collection and matching software as part of the National Cooperative Highway Research Program (NCHRP) Project 7-13, "Quantifying Congestion" (1). Also, Turner et al. (7) used the license plate collection and matching software to evaluate the travel time savings and reliability of HOV lanes in Houston and Dallas, Texas. Documentation of the license plate collection and matching software, "TTCOLLEC" and "TTMATCH", is contained in Appendix B.

Turner et al. (7) quantified the travel time savings and reliability of HOV lanes for two freeway corridors in Houston and Dallas, Texas using portable computer-based license plate matching. License plates were collected concurrently from vehicles in the freeway general purpose lanes and the HOV lanes during morning and evening peak periods. Observation points were separated by significant distances, ranging from 5.3 to 11.1 km (3.3 to 6.9 mi). Table 4-8 shows the results of the license plate collection and matching.

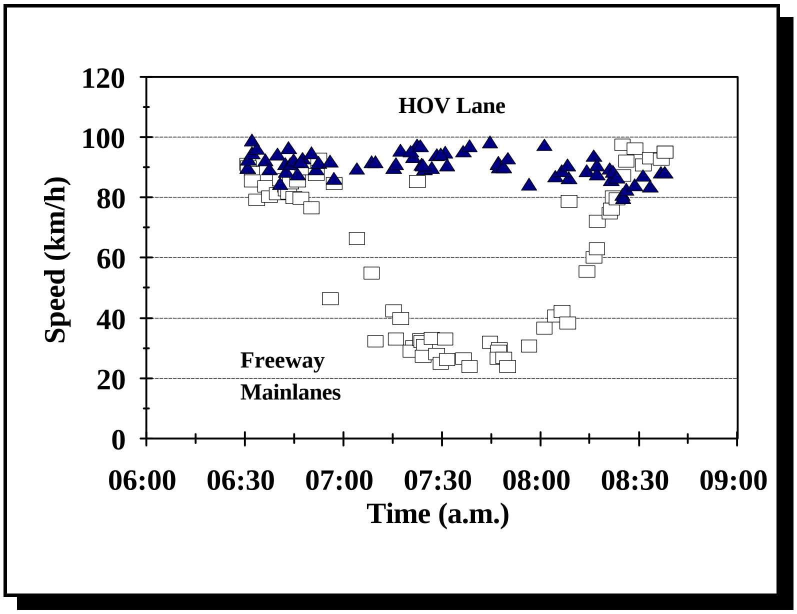
License plate observers collected only the first four characters of the plate, and were able to collect between 300 and 500 license plates per hour. Observers for the freeway lanes (three lanes total per direction) estimated that they were able to collect about 10 to 20 percent of the total number of vehicles. Observers for the HOV lane (one lane total) estimated that they were collecting about 50 percent of the total number of vehicles. Plate matching percentages on the freeway general purpose lanes ranged from 3 to 13 percent. These matching percentages were low because of the long segment lengths and high number of freeway entrance and exit ramps. Matching percentages for the HOV lanes ranged from 32 to 54 percent, and were high because of the limited number of access points to the HOV lanes.

Figures 4-4 and 4-5 show two illustrations that are easily constructed using the large sample sizes available with the license plate matching method. Figure 4-4 contains the continuum of freeway and HOV lane speeds throughout the peak period, and illustrates a significant speed reduction due to congestion. Figure 4-5 shows a speed distribution for a particular roadway segment. The speed or travel time distributions can be examined for normality by conducting statistical tests.

Table 4-8. License Plate Collection and Matching Statistics from Houston and Dallas, Texas

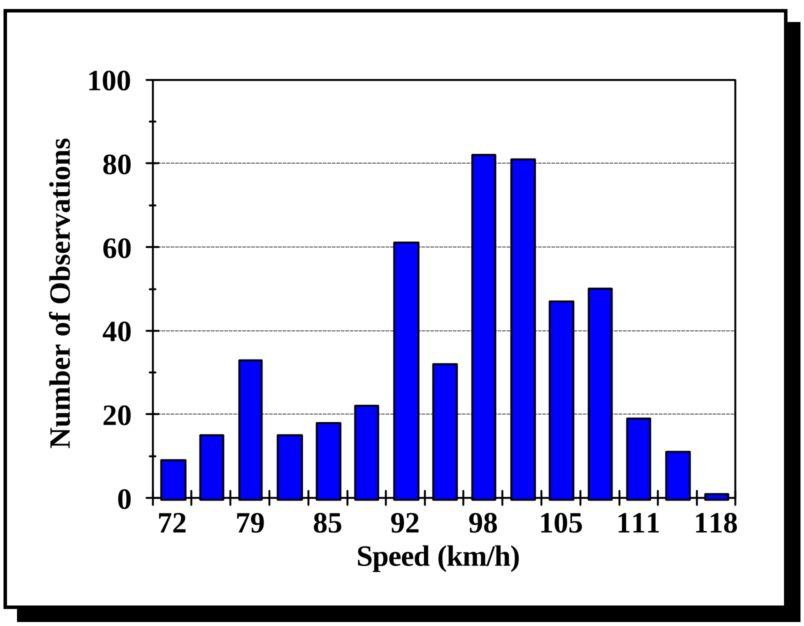
Time Period and Date	Roadway Segment	Segment Length	General Purpose Lanes		HOV Lane	
			Collected Plates	Audited Matches [a]	Collected Plates	Audited Matches [a]
6 to 9 am, July 7	IH-10 EB, SH 6 to Gessner	11.1 km (6.9 mi)	1,144 903	48 (5%)	433 590	197 (45%)
3:30 to 6:30 pm, July 7	IH-10 WB, Gessner to SH 6	11.1 km (6.9 mi)	1,018 1,167	33 (3%)	867 417	198 (47%)
6 to 9 am, July 8	IH-10 EB, Gessner to Washington	9.3 km (5.8 mi)	904 1,064	46 (5%)	543 596	175 (32%)
3:30 to 6:30 pm, July 8	IH-10 WB, Washington to Gessner	9.3 km (5.8 mi)	1,184 1,237	60 (5%)	926 1,017	436 (47%)
6 to 9 am, July 13	IH-30 WB, Jim Miller to CBD Ramp	8.4 km (5.2 mi)	1,000 875	70 (8%)	774 999	283 (37%)
4 to 7 pm, July 13	IH-30 EB, CBD Ramp to Dolphin	5.3 km (3.3 mi)	1,095 1,524	144 (13%)	857 909	4 (1%)[b]
6 to 9 am, July 13	IH-30 WB, Jim Miller to CBD Ramp	8.4 km (5.2 mi)	1,124 844	70 (8%)	806 1,066	317 (39%)
4 to 7 pm, July 13	IH-30 EB, CBD Ramp to Dolphin	5.3 km (3.3 mi)	1,422 1,292	154 (12%)	999 920	486 (53%)

Notes: [a] Number of matches after use of “speed limits” and visual inspection of data.
[b] Obvious error in recording correct plate characters.



Source: adapted from reference (7).

Figure 4-4. Peak Period Speed Profile for IH-30 Freeway and HOV Lane: Dallas, Texas



Source: adapted from reference (7).

Figure 4-5. Speed Frequency Distribution for IH-30 HOV Lane: Dallas, Texas

4.3 Video with Manual Transcription

This method of license plate matching relies on video cameras or camcorders to collect license plates in the field and human personnel to transcribe the license plates into a computer in the office after the actual time of data collection. Video collection of license plates is preferred over the manual collection (pen and paper, tape recorder) of license plates because:

- video provides a permanent record of license plates and traffic conditions;

- video permits the reading of license plates in a controlled environment in which plate characters can be closely examined;

- video provides information about traffic flow characteristics such as traffic volume and vehicle headway; and

- video can provide a time stamp for accurate determination of arrival times.

4.3.1 Advantages and Disadvantages

License plate matching using video with manual transcription has the following **advantages** (as compared to other methods of license plate matching):

- video provides a permanent, easily-review record of traffic conditions;
- accuracy may be better than manual methods; and
- able to capture a larger sample of the total number of vehicles.

Manual license plate matching has the following **disadvantage**:

- transcription of license plates is labor-intensive (typically 10 hours per hour of data collection).

4.3.2 Cost and Equipment Requirements

The cost and equipment requirements for video-based method of license plate collection are minimal. The cost of license plate transcription and matching may vary depending upon the skill level of personnel used to perform this task. Table 4-9 contains information about hardware, software, and personnel requirements and approximate costs.

Table 4-9. Estimated Costs for Video with Manual Transcription

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
Video recorder and accessories (tripod, power supply, additional lens, carrying case) Video playback system (4-head VCR) and monitor	$1,000 to $2,500 (depends upon quality of camcorder) $750 to $1,500
Miscellaneous field supplies and equipment (stools or chairs, video or audio tapes, batteries, fuel for transportation, etc.)	$250
Personnel	
Observer/video taper (minimum of one per checkpoint)	$15 to $20 per hour
Study supervision and management	Varies
License plate transcription and matching (approx. 10 hours per hour of video tape)	$6 to $10 per hour

4.3.3 Data Collection Instructions

The following steps should be performed before license plate collection begins (see Chapter 2 and Sections 4.0.2 through 4.0.5 in this chapter):

1. Define the routes to be studied;

2. Designate the checkpoints and specific locations where observers or video recorders will be positioned;

3. Perform site reconnaissance and find best camera positions (e.g., clear away wire mesh fences if necessary and permitted);

4. Define the time period during which data will be collected;

5. Train personnel with use of cameras and practice recording two to three hours of license plates in actual roadside conditions.

Once the necessary planning and preparation have been performed, the following steps should be performed in collecting and matching license plates.

1. **Inventory and check equipment.** All equipment should be inventoried and checked before proceeding to the data collection sites. **Watches and video camera clocks should be synchronized at this time**. Ensure that each observer has a backup power supply (extra batteries).

2. **Arrive at site early.** Observers should arrive at the data collection site 20 to 30 minutes in advance of when they are scheduled to begin data collection. This ensures that observers can find the most suitable and comfortable location, and prepare the equipment. For video taping, observers may want to tape one to two minutes of video for instant playback to ensure that the camera is positioned and operating correctly. Monitors should be used to check the quality of video before starting data collection. This time can also be used to ensure that **video tapes are labeled** with the time, date, and specific location of the data collection.

3. **Begin data collection at scheduled times.** For video recording, it is possible to capture one to two lanes of traffic per camera before the license plate characters become illegible. A fast shutter speed of at least 1/1000 second or faster should be used to provide stop motion and clear, frame-by-frame resolution of license plate characters. A time stamp that includes seconds or frames should be displayed on the video to create a permanent time record. Once video taping begins, the observer(s) only need to occasionally check the camera to ensure that camera settings are still adequate and that the camera is recording to tape. If data collection lasts longer than two hours, arrangements should be made for switching video tapes. A 12-volt marine battery should be used to provide enough power for prolonged periods of data collection.

4. **Check quality of video on frequent basis.** Field personnel should check the quality of video throughout the data collection period to adjust for changing light conditions and to ensure that the proper view is still being recorded.

5. **Ensure that tapes are labeled correctly.** Once the license plate collection has been completed, ensure that the video tapes are labeled correctly with the time, date, and specific location of the data collection.

6. **Transcribe the license plates into a computer.** Transcription of the license plates from the video tapes into a computer is performed in the office. A four-head VCR provides the best results in freezing video frames for reading license plates. Some VCRs also provide advanced editing features that allow frame-by-frame advance and

review. A screen line should be chosen on the video that is nearest to the designated checkpoint, and thin dark-colored tape can be used to mark this screen line on the video monitor. When a vehicle passes this screen line on the monitor, the license plate characters and video time stamp are entered into a spreadsheet or database.

7. **Match the license plates.** License plates can be matched using special license matching software, database or statistical analysis software, or spreadsheet functions. The license plate matching should incorporate an algorithm to remove spurious matches, which occur if plate characters are incorrectly read or only four characters are recorded. For example, if only the first four characters are collected, "ATM123" could be matched with "ATM189". Several types of screening algorithms can be used to reduce spurious matches:

   - *Use of "speed limits"* - automatically delete any match that falls outside of preset speeds, typically less than 5 km/h or greater than 125 km/h.

   - *Use of standard deviations* - automatically delete any match that falls outside of three or four standard deviations for the time period.

   - *Visual inspection of travel time/speed profile* - graphs of travel time/speed can be used to visually identify and remove outlying data points.

   The results of the license matching process will be individual vehicle speeds at different times throughout the data collection time period. These speeds can be averaged for the entire time period (i.e., peak hour or peak period), or for smaller intervals of the entire time period (e.g., 15- or 30-minute summaries). Chapter 7 contains more information on reducing and summarizing data.

8. **Consider destroying all license plate records because of privacy issues.** After license plates have been matched and travel times computed, one may want to consider destroying or deleting all license plate records. This can eliminate potential problems with privacy issues or objections to the permanent storage of license plate records by public agencies.

4.4 Video with Character Recognition

The most automated form of license plate matching is accomplished using video and computerized optical character recognition. With this method, license plates are collected using high quality video (typically Super VHS or Hi-8 mm, although Hi-8 mm is preferred because of smaller tape sizes). The license plates are read and matched by a computer using hardware/software that performs optical character recognition. Several license plate recognition (LPR) systems permit manual review of "unreadable" license plates, or those plates that the computer is unable to recognize. The manual review process can be used to improve the reading rate in cases where license plates are damaged or partially illegible.

Because of their relatively high costs, automated LPR systems have primarily been used at critical automated enforcement installations, such as electronic toll plazas, weigh-in-motion stations, or remote sensing of mobile source emissions. A few consultants also use LPR systems to perform large-scale origin-destination and travel time studies.

The collection and matching of license plates using automated LPR systems in real-time has been implemented in the United Kingdom and is currently being tested by the Minnesota and Washington DOTs. In fact, the United Kingdom has planned to install nearly 3,000 video cameras over 10,000 km (6,000 mi) of British highway to provide real-time traffic information (travel times via LPR systems) (15,16,17). These real-time license plate reading and matching techniques are being utilized to provide traveler information (typically travel times) as part of ITS strategies. No recommendations or guidelines are provided in the handbook for these real-time license matching methods. However, agencies should recognize the potential opportunities that these systems offer when implemented as part of an ITS infrastructure.

4.4.1 Advantages and Disadvantages

Video with character recognition has the following **advantages** (as compared to other methods of license plate matching):

- automated license plate recognition dramatically decreases data reduction time;
- video provides a permanent record (if saved) that can be reviewed at any time; and
- video captures a large sample of the total vehicle traffic.

Video with character recognition has the following **disadvantages**:

- accuracy of license plate recognition is sensitive to ambient conditions;
- equipment is costly for small studies;
- method is technologically intensive and typically requires outsourcing; and
- LPR technology is not mature for some vendors and not standardized among vendors.

4.4.2 Cost and Equipment Requirements

Because of the high equipment costs for automated LPR systems, several options are presented here for the video with character recognition method of license plate matching:

Option 1. Outsourcing or contracting the entire data collection process, including video collection, license plate recognition and matching, and data reduction. This technique has been used by several agencies throughout the United States.

Option 2. Outsourcing or contracting **only the license plate recognition**, with video collection and data reduction performed internal to your agency. This approach may be considered if you have high quality video resources available and if a vendor/consultant is willing to provide only the license plate recognition.

Option 3. Purchasing video cameras and LPR system for extensive agency use. This approach should be considered if your agency has a considerable, ongoing need for license plate collection (e.g., automated enforcement, origin-destination, or travel time studies).

Because automated LPR systems require high quality video with specific lighting and plate size specifications, most vendors or consultants prefer to perform the video collection to ensure high plate reading rates (Option 1 above). LPR systems do require extensive training and technical knowledge, making Options 2 and 3 appear less desirable for most transportation agencies.

Table 4-10 contains approximate cost and equipment requirements for Option 1 (contract all data collection) and Option 3 (purchase equipment and perform data collection internally). Cost and equipment requirements for Option 2 can be derived from this information or directly from a consultant willing to perform the license plate matching.

CAUTION !!

Significant experience is needed in collecting video and matching license plates using an automated LPR system. Approach vendor's claims with caution and ask for their previous experience in license plate matching studies.

Table 4-10. Estimated Costs for Video with Character Recognition

Equipment/Personnel	Unit Cost (1998 dollars)
Option 1--Contracting Entire Data Collection	
Video collection, license plate recognition and matching, and data reduction	$300 to $400 per lane-hour
Option 3--Purchase All Equipment and Perform Internally	
Video specialists (min. of one per checkpoint)	$15 to $25 per hour
Video camera and accessories (tripod, power supply, lenses, carrying case)	$4,000 to $6,000 per camera
Monitor for portable camcorder	$1,500 per camera
LPR hardware and software	$30,000 to $50,000 per unit
Miscellaneous field supplies and equipment (stools or chairs, video tapes, batteries, fuel for transportation, etc.)	$1,000
Training	$5,000
Study supervision and management	Varies

4.4.3 Considerations for Automated License Plate Recognition Systems

This section contains background information on automated license plate recognition (LPR) systems. This information is provided as background for study planning and discussions with LPR vendors or suppliers. A complete discussion of optical character recognition is beyond the scope of this handbook.

At least 15 vendors claim they currently offer LPR systems (4 of them are U.S.-based) (18); however, the capabilities of each system may vary. There are no industry standards at this time for performance of LPR systems, although individual vendors may have performance specifications. A typical LPR system consists of the following components (18):

- **Video-image acquisition unit** - uses video camera and external (e.g., inductance loop or laser beam) or internal (software or processor-based recognition of plate) trigger to capture images of the vehicle license plate;

- **Central processing unit** - processing part of workstation that handles image manipulation and control;

- **Character recognition engine** - hardware or software-based engine that uses neural networks and/or character templates to perform character recognition; and

- **Storage or transmission subsystem** - part of workstation that stores or transfers image records and machine-read results (text license plate, read date, and time).

The license plate character font and syntax is useful in training automated LPR systems and improving the license plate reading rate. The font refers to the particular style of lettering, whereas the syntax refers to the number and placement of characters on the plate and their sequence.

Each state in the U.S. has established rules and guidelines for license plate fonts and syntax. Most LPR systems typically use a limited number of font templates that would recognize a majority of the possible fonts encountered. The automated processing of license plates can be somewhat slower when several font templates are used, but this is only an issue when plate reading and matching is performed in real-time. For several travel time studies, analysts have chosen to disregard any out-of-state license plates, thus eliminating problems of numerous font templates. Some LPR systems can be trained (through neural networks) to recognize certain problematic characters or font styles.

The syntax of license plates also can help in increasing the accuracy and reading rate of automated LPR systems. For example, one state may distribute license plates with the following syntax: “ATM123”, where the first three characters are letters, and the last three characters are numbers. Very few states issue plates with more than seven characters (this may help to identify the origin state of the plate). Also, some states do not use numbers or characters that look similar. For example, many states do not use the letters “O” or “Q” because of the similarities to the number “0”. Also, some states have different syntaxes for different types of vehicles (e.g., commercial vs. trucks vs. passenger cars). If desired, this syntax can be used to eliminate commercial vehicles or tractor-trailer combinations that typically do not travel at speeds characteristic of the traffic flow.

The accuracy of automated LPR systems is another consideration in their use for travel time measurement. To date, no standardized tests have been performed to compare the accuracy of these systems under various conditions. A number of factors can affect an automated LPR system's ability to correctly identify license plate characters (18):

- vehicle speed;
- volume of vehicle flow;
- ambient illumination (day, night, sun, or shadow);
- spacing between vehicles (headway) because of occlusion;
- weather (rain, snow, fog);
- vehicle type (passenger car, truck, tractor-trailer, etc.);
- plate mounting (rear only or front and rear);
- plate variety and jurisdiction;
- camera-to-plate distance;
- plate tilt, rotation, and skew;
- presence of a trailer hitch; and
- communications pathway.

When discussing performance and accuracy specifications with LPR system vendors, it is important to specify the conditions under which the accuracy is to be achieved. The license plate capture and reading rate may vary from as low as 15 to 20 percent for poor visibility or weather conditions, to as high as 85 to 90 percent for ideal conditions. The accuracy of the system also depends upon two critical functions:

- **Capturing the entire license plate within the image field-of-view** - the accuracy of this step can be affected by the external or internal trigger mechanism, but also is affected by camera field-of-view and vehicle position within or between lanes; and

- **Correctly recognizing the characters of the license plate** - this step's accuracy is based upon the character recognition engine, which is typically proprietary for each vendor.

The accuracy of automated LPR systems can be evaluated in two ways:

$$LPR\ System\ Accuracy\ (\%) = \frac{N_{LPR}}{N_{Manual}} \tag{4-2}$$

where: N_{LPR} = number of plates correctly interpreted by LPR system
N_{Manual} = number of plates able to be read by a person using raw video signals on a monitor

or:

$$LPR\ System\ Accuracy\ (\%) = (Rate_{recognition} \times Rate_{interpretation}) \times 100 \qquad (4\text{-}3)$$

where: $Rate_{recognition}$ = rate of successful plate recognition in field of view (expressed as a decimal)

$Rate_{interpretation}$ = rate of successful interpretation of entire plate content (expressed as a decimal)

If automated LPR systems are not used for measuring travel times in real-time, there are opportunities to improve the accuracy. One technique involves training the LPR system to recognize certain difficult-to-read characters. Another technique consists of a person reviewing those plates that the LPR system could not read, then simply manually entering those license plates that can be recognized by the human eye. The latter technique has been used extensively by one vendor in several fields tests in the U.S., which are discussed further in Section 4.3.5, *Previous Experiences*. There will be a small percentage of license plates (typically five to ten percent) that may not be readable, either because of mud, damaged or worn plates, or visual obstructions such as tow hitches.

4.4.4 Data Collection Instructions

Data collection instructions are provided here for collecting clear, usable video of vehicle license plates for automated LPR systems. If you will be using a vendor or consultant to perform the license plate reading only, you should contact the vendors/consultants as soon as possible to determine their video requirements and specifications for accurate character recognition.

The following steps should be performed before license plate collection begins (see Chapter 2 and Sections 4.0.2 through 4.0.5 in this chapter):

1. Define the routes to be studied;
2. Designate the checkpoints and locations where observers will be positioned;
3. Perform site survey to identify vantage points and camera positioning;
4. Define the time period during which data will be collected; and
5. Train with video camera equipment.

Once the necessary planning and preparation has been performed, the following steps should be performed in collecting license plates using video:

1. **Inventory and check equipment.** All equipment should be inventoried and checked before proceeding to the data collection sites. **Video camera clocks and wrist watches should be synchronized at this time**. Ensure that each observer has a backup power supply (12-volt marine battery).

2. **Arrive at site early.** Observers should arrive at the data collection site 60 minutes in advance of when they are scheduled to begin data collection. This ensures that observers can find the most suitable and comfortable location, and prepare the video camera for license plate collection. Video tapes labels should include:

    - study route and direction;
    - location of observer;
    - date and time (start and end time); and
    - camera identification number.

3. **Begin data collection at scheduled times.** Several general techniques have been used to make license plate collection easier and more effective. These techniques are summarized as follows:

    Straight-on, elevated camera positioning - The best position for the camera is a straight-on, elevated shot, with as little horizontal angle as possible. This prevents the excessive lateral movement of the license plate between video frames, and makes the plate image easier to automatically acquire. Typically the only place to get straight-on video is from an overpass structure, in which a zoom lens will likely be necessary for making plates legible.

    Collection of the rear license plate - Because front plates are not required by all states in the U.S., the rear license plate is commonly captured for LPR systems.

    Representative sampling of through-lanes - Studies have shown that speeds vary across lanes, so sampling of all through-lanes is necessary to collect representative speed samples. For high-volume roadways, however, sampling from all through lanes will produce a low percentage of matches. In this case, observers should concentrate on a lane that has a speed representative of the average traffic flow, but also collect a few speed samples from all through lanes. Auxiliary and turning lanes should be avoided because of the low number of matches for high percentage of turning traffic.

    Collection during clear, daylight hours - Although collection during night-time hours is possible, it complicates plate-reading and often creates safety problems.

4. **Consider destroying all license plate records because of privacy issues.** After license plates have been matched and travel times computed, you may want to consider destroying or deleting all license plate records. This can eliminate potential problems with privacy issues or objections to the permanent storage of license plate records by public agencies.

4.4.5 Previous Experience

There have been several applications of video with character recognition license plate matching in the U.S. These experiences have involved the use of a single vendor's automated LPR system for various travel time, origin-destination, and vehicle occupancy studies. This video camera and LPR system has been used in several field applications, examples of which will be summarized in this section:

- series of field trial tests for travel time collection by the Volpe Center in 1993;
- collection of traffic performance data for Hillsborough County, Florida's congestion management system; and
- collection of travel time savings and reliability data for HOV lanes in Seattle, Washington.

Other experience with automated LPR systems in the United States and Europe, in particular, have focused on enforcing electronic toll collection systems.

Volpe Center Field Tests

Liu and Haines (14), of the Volpe Center, conducted field tests of several travel time data collection techniques in 1993. The techniques tested in this study included:

- license plate matching using portable computers;
- license plate matching using video cameras and character recognition;
- floating car (test vehicle);
- probe vehicle;
- automatic vehicle identification; and
- loop detectors.

The video and character recognition-based license matching was tested in Boston, Massachusetts; Seattle, Washington; and Lexington, Kentucky. High-quality video cameras (Hi-8 mm) were used to collect video in the field, with each camera focused on a single lane. All six characters of the license plates were read automatically using a vendor's automatic license plate reading (LPR) system. The vendor's LPR system also enabled license plate characters to be extracted manually if the machine vision component was unable to automatically read the license plate characters.

Major findings from these field tests were:

- Primary advantages of automated license plate reading include the use of all license plate characters in matching for increased accuracy, ability to capture large samples of vehicles, and low labor intensity compared to other license matching techniques;

- Major limitations of automated license plate reading include constraints on camera location and positioning, limited success in less-than-ideal conditions, and the evolving machine vision technology;

- The video camera and LPR system were capable of capturing and identifying about 50 percent of the vehicle license plates in the traffic stream (manual reduction of video has been estimated to capture about 90 percent);

- The automatic LPR system was capable of processing at least 1,800 plates per hour, or about one plate per second (manual reduction has been estimated to require 10 hours for each hour of video tape); and

- Approximately 40 to 100 license plate matches were obtained during 15-minute time periods (about 160 to 400 per hour) for varying traffic volume and geometric conditions.

In another paper discussing the results of these field tests, Liu (19) presents several analytical methods that were used to screen or audit the license matches. Liu recommended that 30-minute time periods be used for plate matching and computation of average travel time and speed statistics. This length of time helps to reduce the potential for spurious matches. Initial “speed limits” were set at 24 and 137 km/h (15 and 85 mph); therefore, any plate matches with speeds below 24 km/h (15 mph) or above 137 km/h (85 mph) were removed from the valid data set. For specific locations with recurring congestion, Liu recommends that the lower speed limit of 24 km/h (15 mph) be reduced or dropped entirely. The number of plate matches with travel times outside of two standard deviations also was noted as a means to identify and screen spurious matches.

Hillsborough County, Florida Congestion Management System

The Center for Urban Transportation Research demonstrated video and character recognition-based license plate matching methods for the collection of traffic data for the Hillsborough County Congestion Management System in Florida (20). Researchers obtained travel times, origin-destination information, and average vehicle occupancies from the video that was collected. The study collected two hours of video for three consecutive morning peak periods on several freeway sites in Tampa, Florida (six hours of total tape per site). Traffic volume counts were collected concurrent with the video using pneumatic tubes.

Varying combinations of manual entry and automated license plate reading were used in the demonstration. Manual review and entry were used in cases when license plate characters could not be read accurately by the LPR system. For the three-day test, the plate capture rate (i.e., plates read divided by total license plates) ranged from 63 to 85 percent. Fifteen and thirty-minute analysis periods were used to summarize statistics such as mean travel time, standard deviation, and coefficient of variation. The researchers concluded that the video and character recognition-based method offers substantial time savings as compared to manual observation methods, with slightly higher to comparable costs per survey.

Seattle--HOV Lane Surveys

In 1995, the Washington Department of Transportation (WashDOT) contracted with the same automated LPR vendor to perform surveys of the travel times for two HOV corridors in Seattle (the Volpe field tests were performed in Seattle in 1993) (21). Four weekdays of license plate collection were performed, with each day consisting of a four-hour morning peak period and a four-hour evening peak period. As with other license plate collection efforts, one camera per lane is used to capture license plates of an adequate size for automated processing by the LPR system. The distance between camera observation points was 1.75 km (1.09 mi) and 5.75 km (3.57 mi) on SR 520 and IH-5, respectively.

Over the four-day period, approximately 90,000 license plates were read by the automated LPR system, which was estimated to be about 75 percent of the total traffic volume passing the camera observation points. About five percent of the plates were unreadable because the plates images were in poor focus, too dark or bright, or otherwise ill-suited for automated processing. A combination of automatic processing and manual entry of unreadable plates was used to improve the license plate capture rate. License plate matching results and corresponding travel time statistics were summarized for 15-minute intervals, and illustrated the travel time savings of the HOV lane versus the freeway general purpose lanes.

West Virginia

Researchers with the West Virginia University and the West Virginia DOT have documented specifications for automated LPR systems that are to be used in collecting travel time and origin-destination data (22). Their recommendations focused on transportability and set-up requirements, traffic operations and roadside safety, and the technical attributes of an LPR system (i.e., video source, light source, triggering mechanism, and image processor). Technical specifications were also provided for use by other agencies in contracting or performing work with automated LPR systems.

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5 ITS PROBE VEHICLE TECHNIQUES

The probe vehicle techniques discussed in this section are unique in that they are typically intelligent transportation system (ITS) applications designed primarily for collecting data in real-time. Their primary application is for a specific purpose other than travel time data collection, such as real-time traffic operations monitoring, incident detection, and route guidance applications. However, these systems can be used for the collection of travel time data. Since these probe vehicles are used for travel time data collection but are already in the traffic stream for a different purpose, they are sometimes referred to as "passive" probe vehicles. In contrast, the test vehicle techniques discussed in Chapter 3 are sometimes referred to as "active" test vehicles. Coordination is often necessary between the agency responsible for the system operation and the agency that would like to utilize the system for travel time data collection. This distinction removes these probe vehicle techniques from other techniques, such as tje test vehicle or license plate matching techniques.

This chapter presents guidelines for designing and maintaining ITS probe vehicle data collection systems to cost-effectively collect quality data that may be developed from existing ITS applications.

5.0.1 General Advantages and Disadvantages

ITS probe vehicle systems for travel time data collection have the following **advantages**:

- **Low cost per unit of data** - Once the necessary infrastructure and equipment are in place, data may be collected easily and at low cost. There is no need to routinely set up and disassemble equipment.

- **Continuous data collection** - Travel time data may be collected 24 hours per day with ITS probe vehicle systems. If the infrastructure is permanently installed, data are collected as long as probe vehicles continue to travel through the system. Note that the hours of data collection may depend upon transit schedules for some probe vehicle systems.

- **Automated data collection** - Data can be collected electronically. Probe vehicle systems are electronic, and data are automatically transmitted from the probe vehicle to the ITS control facility.

- **Data are in electronic format** - Once the data have been collected, they are already in an electronic format. This assists in the processing of raw travel time data into a useful format for analysis.

- **No disruption of traffic** - Since data are collected from probes within the traffic stream, the traffic is not influenced by the experimenter. Probe vehicles are often driven by persons not directly involved with the data collection effort, thus data are not biased towards test vehicle driving styles.

ITS probe vehicle systems for travel time data collection have the following **disadvantages**:

- **High implementation cost** - Probe vehicle systems typically have a high initial cost to purchase necessary equipment, install the equipment, and train personnel to operate the system and collect data.

- **Fixed infrastructure constraints** - Once the fixed infrastructure of receiving antennas is implemented, it is generally not financially feasible to make adjustments in the size and orientation of the system coverage area (GPS is the exception). The coverage area of a probe vehicle system, including locations of antenna sites, should be considered before implementation to ensure that data will be collected at strategic locations. Data cannot be collected outside of the coverage area of the probe vehicle system without expensive infrastructure additions.

- **Requires skilled software designers** - The software that performs the data collection tasks are complex programs and are typically designed in-house or by a consultant. The software is typically customized for a particular probe system.

- **Privacy issues** - Probe vehicle techniques involve tracking vehicles as they travel the freeway and arterial street system. This raises concerns that motorists may be more likely to receive traffic citations or have their travel habits monitored.

- **Not recommended for small scale data collection efforts** - Probe vehicle systems generally have large implementation costs, and they are most cost-effective for collecting data within a large study area.

Five types of ITS probe vehicle data collection systems are presented. These systems typically have a high implementation cost and are suited for large-scale data collection efforts. However, they allow for continuous data collection and for minimal human interaction. Table 5-1 provides a comparison of these probe vehicle data collection techniques. The ITS probe vehicle systems described are:

- **Signpost-Based Automatic Vehicle Location (AVL)** - This technique has mostly been used by transit agencies. Probe vehicles communicate with transmitters mounted on existing signpost structures.

Table 5-1. Comparison of ITS Probe Vehicle Systems/Techniques

Technique	Costs				Data Accuracy	Constraints	Driver Recruitment
	Capital	Installation	Data Collection [1]	Data Reduction			
Signpost-Based Automatic Vehicle Location (AVL)	High	High	Low	High	Low [2]	No. of signpost sites, transit routes, and probes	None - uses transit vehicles
Automatic Vehicle Identification (AVI)	High	High	Low	Low	High	No. of antenna sites and tag distribution	Required - but can use toll patrons
Ground-Based Radio Navigation	Low	Low	Low	Low	Moderate	No. of probes and size of service area	Required
Cellular Geolocation	High	High	Low	Moderate	Low	No. of cell users and cell towers	None - uses current cellular users
Global Positioning System (GPS)	Low	Low	Low	Moderate	High [2]	No. of probes	Required - but can also use currently instrumented vehicles

Notes: [1] Assumes that all data collection software development has been completed.
[2] Unless passenger vehicles are included in the study, samples are composed of transit or commercial vehicles.

- **Automatic Vehicle Identification (AVI)** - Probe vehicles are equipped with electronic tags. These tags communicate with roadside transceivers to identify unique vehicles and collect travel times between transceivers.

- **Ground-Based Radio Navigation** - Often used for transit or commercial fleet management, this system is similar to the global positioning system (GPS). Data are collected by communication between probe vehicles and a radio tower infrastructure.

- **Cellular Geo-location** - This experimental technology can collect travel time data by discretely tracking cellular telephone call transmissions.

- **Global Positioning System (GPS)** - Probe vehicles are equipped with GPS receivers and two-way communication to receive signals from earth-orbiting satellites. The positional information determined from the GPS signals is transmitted to a control center to display real-time position of the probe vehicles. Travel time information can be determined from the collected data.

5.0.2 Sample Size Criteria

Sample size requirements associated with probe vehicle applications are inherently different than sample size requirements for test vehicle or license plate matching techniques. In typical travel time studies, the sample sizes are established by the test conductors prior to data collection. Typically, these sample sizes are established based on desired levels of accuracy associated with the purpose of the travel time study and on budgetary constraints. Since probe vehicle systems are designed to collect data for real-time traffic monitoring, fleet monitoring, or electronic toll collection (ETC), the sample sizes are determined by availability of instrumented probe vehicles in the traffic stream. Probe vehicle samples sizes are considered in the following:

- Design of the probe vehicle system (e.g., distribution of AVI tags);
- Evaluation of probe vehicle system; and
- Analysis of data obtained from a probe vehicle system.

For example, a transit agency using signpost-based automatic vehicle location (AVL) will have equipped a certain number of buses with the necessary hardware, a traffic management system may collect data from an existing fleet of probe vehicles, or an ETC system may provide service to some fixed number of toll patrons. Therefore, the study supervisor has little to no control over the probe vehicle sample size if the data are collected from an existing probe vehicle system.

Practitioners using data collected from probe vehicle systems should consider the achievable sample size when designing their study and analyzing the data. While probe vehicle sample sizes may be fixed at a small number, it does not necessarily mean that the data are not useful. For planning studies that do not demand high statistical accuracy, a few probe vehicles per day can provide sufficient data for analysis (or at least as much as comparable test vehicle techniques). Small probe vehicle sample sizes may not provide sufficient representation for analyses that require high levels of accuracy.

Design of a Probe Vehicle System

In the initial stages of developing and implementing probe vehicle systems to collect travel time data for real-time and planning applications, it is necessary to estimate an effective probe vehicle sample size. This process may involve studying the practices of existing probe vehicle systems and comparing characteristics of respective transportation systems.

Probe vehicle systems are designed to generate a certain database on the purpose of their design. For example, signpost-based probe vehicle systems are designed to monitor the status of a transit agency's bus fleet. Thus, the buses function as probe vehicles within the traffic stream. The size of the transit agency's sample is most likely justified by the number of buses within the fleet and the available funding to equip the buses with the necessary tracking equipment.

A representative sample does not necessarily translate to a large sample size. The nature of some studies does not require large sample sizes to yield desirable results. For instance, a study by the Washington State Department of Transportation (WSDOT) suggested that sample sizes as low as 45 AVI-equipped probe vehicles per day, which averaged 30-minute headways, could yield useful data (1). These data were used to determine the occurrence, duration, severity, and frequency of congestion. The study recommended that the sample size was sufficient for facility performance monitoring, air quality planning and monitoring, and before-and-after studies.

A study by Boyce et al. (2) estimated necessary sample sizes for a dynamic route guidance model based on the results of a static, user-optimal route choice traffic assignment analysis. Their results suggested that about 4,000 probe vehicles were required for a 520 sq-km (200 sq-mi) suburban road network.

Srinivasan and Jovanis (3) developed an algorithm to estimate the number of probe vehicles needed to collect real-time travel time data for advanced traffic management and information systems. Their algorithm estimates the number of probe vehicles based on the time period of 5, 10, or 15 minutes, reliability criterion, the proportion of links to be covered, and the duration of the peak period. Their algorithm was tested on a simulation of the Sacramento, California 440 sq-km (170 sq-mi) network during the morning peak period. Results of the study indicated that the number of required probes increased non-linearly as reliability criterion grew more stringent, that more probes were required for shorter time periods, and that the number of required probes increased as the proportion of link coverage increased.

The Model Deployment Initiative (MDI) in San Antonio, Texas, is deploying an AVI probe vehicle system to collect real-time travel times for route guidance and traveler information purposes. The proposal originally called for the distribution of more than 200,000 AVI transponders. However, their tag distribution efforts were scaled back for several reasons, most notably budget shortages and a reluctance to distribute the AVI tags as part of the required vehicle registration stickers. Current plans in San Antonio are to distribute between 50,000 and 70,000 AVI tags to public volunteers and commuters. Another difficulty with tag distribution in San Antonio was the lack of any toll highways, especially any that could support electronic toll collection.

UNKNOWN ??	Probe vehicle sample sizes vary depending upon local road networks, traffic patterns, and many other variables. The limited research does not permit valid conclusions to be drawn for other urban areas without specific study.

An automatic vehicle identification (AVI) probe vehicle system designed as a traffic monitoring system may advertise for volunteers to serve as probe vehicle drivers. Motorists may be targeted by changeable message board advertising on specific roadways or by popular media. Probe vehicle drivers may be recruited by offering incentives, as well. For instance, a department of transportation may offer AVI tags to motorists free of charge. The free tags could then be used for an electronic toll collection service to conveniently pay toll charges while also participating as probe vehicle drivers in the local traffic monitoring system.

Evaluation of a Probe Vehicle System

The effectiveness of a probe vehicle system is dependent upon its purpose and the size of the probe vehicle sample, among other criteria. A probe vehicle sample size may be periodically reviewed to determine the system's ability to yield accurate real-time travel time information. The necessary sample size for providing accurate data depends on the level of accuracy that is established as a system goal. If the current sample size is equal to or greater than the calculated sample size, the results suggest that the system's current status provides adequate data. If the calculated necessary sample size is greater than the current sample size, the results suggest that additional probe vehicles may be needed.

IMPORTANT ☞	It is possible to evaluate the adequacy of a probe vehicle sample size by calculating a target sample size necessary for meeting specified accuracy criteria and comparing this value to the system's current sample size.

A study of AVI probe vehicles in Houston, Texas suggested that an average of two or three probe vehicles every 15 minutes could yield useful mean travel time data (4). The study found that the Houston traffic monitoring system was collecting real-time travel time data from between 1 and 7 probe vehicles every 5 minutes, or between 2 and 20 vehicles every 15 minutes, along instrumented freeway corridors. The highest number of probe vehicles were observed near major activity centers and the tollways. The study calculated required sample sizes through freeway links within 5-minute and 15-minute intervals based on the coefficients of variation from travel time data and suggested confidence and error constraints. A comparison between the actual probe vehicle sample size and the calculated necessary sample size (based on specified confidence and error constraints) suggested whether or not a sufficient number of probe vehicles were collecting data. Results showed that, for a 90 percent confidence level with 10 percent relative error, 2 or 3 probe vehicles every 15 minutes were sufficient to collect useful travel time data.

Sample Composition

An aspect that should be considered when collecting and analyzing probe vehicle data is the driver or vehicle composition of the sample. Composition refers to the type of vehicles or type of drivers that may compose the sample. It is important to understand the type of vehicles and drivers that are operating the probe vehicles. The sample may be biased if the data were collected by transit vehicles. The following traffic composition characteristics should be kept in mind when composing or evaluating probe vehicle samples:

- vehicle type - automobile, truck, transit vehicle, or other;
- driver type - depends on vehicle type; and
- travel lane representation - certain vehicles may primarily use certain travel lanes.

5.0.3 ITS Data Considerations

National ITS Architecture and Data Standards

Widespread implementation of intelligent transportation system (ITS) projects, including probe vehicle data collection systems, has created a pressing demand for standards and protocols to provide interoperability, compatibility, and interchangeability between various technologies. Interoperability can allow probe vehicles to travel throughout the country and still provide effective data collection or receive traveler information. Compatibility can allow different manufacturers' equipment to communicate without interference. Interchangeability allows one manufacturer's device to be replaced with a device from a separate manufacturer.

ITS applications are encapsulated within a compilation of interrelated user services. Standardization can allow the packaging of user services to form advanced traffic management systems (ATMSs), advanced traveler information systems (ATISs), advanced public transportation systems (APTSs), commercial vehicle operation (CVO) systems, advanced rural transportation systems (ARTSs), and advanced vehicle control systems (AVCSs), and ultimately, one unified national transportation system.

IMPORTANT ☞ Practitioners designing or modifying probe vehicle systems should ensure that their local system is compatible with the National ITS Architecture standards.

Their designs and recommendations should reflect the proposed standards which are set forth by the various organizations and committees charged with that task. The framework for developing standards and protocols has been established by the U.S. DOT through the *National ITS Architecture* project. The project has developed a series of white papers that describe the need for standards, standards development process, example requirements, and an Architecture reference model (5). A standards requirement document (SRD) has been developed to provide definitions of interfaces and necessary priorities for standardization within the Architecture reference model. The project is working towards the development of a standards implementation plan (SIP), which will outline standards, time schedules, and critical milestones for the implementation phase.

The National ITS Architecture provides common structure for the design of ITS. The Architecture designs the functions, such as gathering traffic data, that are necessary to perform certain user services and to implement the vehicles and infrastructure of the system, the information flow between system components, and the communication requirements for the information flows (6). The National ITS Architecture defines how large scale ITS components, such as the ATMSs and ATISs, work together. At the ATMS or ATIS level, these systems will control how freeway systems communicate with traffic signal and control systems.

The National Transportation Communications for ITS Protocol (NTCIP) standards were developed for communications between traffic management centers and signal systems; however, the Federal Highway Administration (FHWA) broadened the protocol to include additional technologies. Simply stated, the NTCIP will define how traffic control systems communicate to their sub-components (7). More information on the current and developing NTCIP standards are available at ITS America's web site at "http://www.itsa.org".

Professional societies play a major role in the development of the National ITS Architecture. For example, the Institute of Transportation Engineers (ITE) is playing an active role in setting national standards and guidelines to simplify operations and maintenance of ITS networks, among other roles. The Institute is ensuring that traffic engineers are informed in the development, adoption, and review of ITS standards.

The Intelligent Transportation Society of America (ITS America) has a Standards and Protocols Committee to coordinate development of ITS standards. The Committee and the FHWA have jointly produced a standards and protocol catalog (Publication No: FHWA-JPO-95-005) which describes the current state and future direction of ITS standards development.

Recent discussion about the National ITS Architecture may result in the addition of a user service that relates to the retention or archival of ITS traffic data. This ITS traffic data, as pointed out in this chapter, could be useful for a wide range of planning, operations, and evaluation activities. The proceedings from the "ITS as a Data Resource" workshop held January 1998 in Washington, DC, is available on the web at "http://www.fhwa.dot.gov/ohim/".

5.1 Signpost-Based Automatic Vehicle Location

Transit agencies have utilized automatic vehicle location (AVL) or automatic vehicle monitoring systems to monitor the position and status of transit fleet vehicles. A variety of AVL systems exist based on such technologies as LORAN-C, ground-based radio navigation, and signpost-based technologies. These technologies are being replaced by the global positioning system (GPS), which is discussed later in this chapter. However, some transit agencies continue to use signpost-based systems successfully, whereas other agencies have reported limited success.

Signpost-based AVL systems are still operated, such as with the London Transport Bus (LTB) system, San Antonio VIA transit system, New Jersey Transit system, and the Seattle Metro system (8,9). This type of system is typically used by relatively large transit agencies in metropolitan areas. Only a few rural transit agencies have used this technology since it requires substantial capital investment and staff resources to develop, implement, and operate.

Signpost-based AVL systems are designed to track the location of fleet vehicles along their routes for real-time fleet monitoring, schedule adherence monitoring, computer-aided dispatching, and schedule evaluating. The system consists of seven main components to collect and store travel time data:

1. infrastructure of electronic transmitters;
2. in-vehicle receiver;
3. in-vehicle odometer sensor;
4. in-vehicle locating unit, or data microprocessor;
5. in-vehicle radio transmitter;
6. central control radio receiver; and
7. central control facility.

Figure 5-1 illustrates the communication processes between the electronic transmitter and transit vehicle and between the transit vehicle and the central computer. Electronic signposts emit unique identification codes. These unique codes are received by approaching fleet vehicles. The signpost identification is stored in the vehicle locating unit where it is assigned a time and date stamp, the corresponding differential odometer reading between sequential signposts, and the vehicle's identification. This data bundle is sent to a central control facility at periodic intervals or upon a controller's prompt. The data transmission to the central computer is mutually exclusive from the occurrence of the signpost transmission.

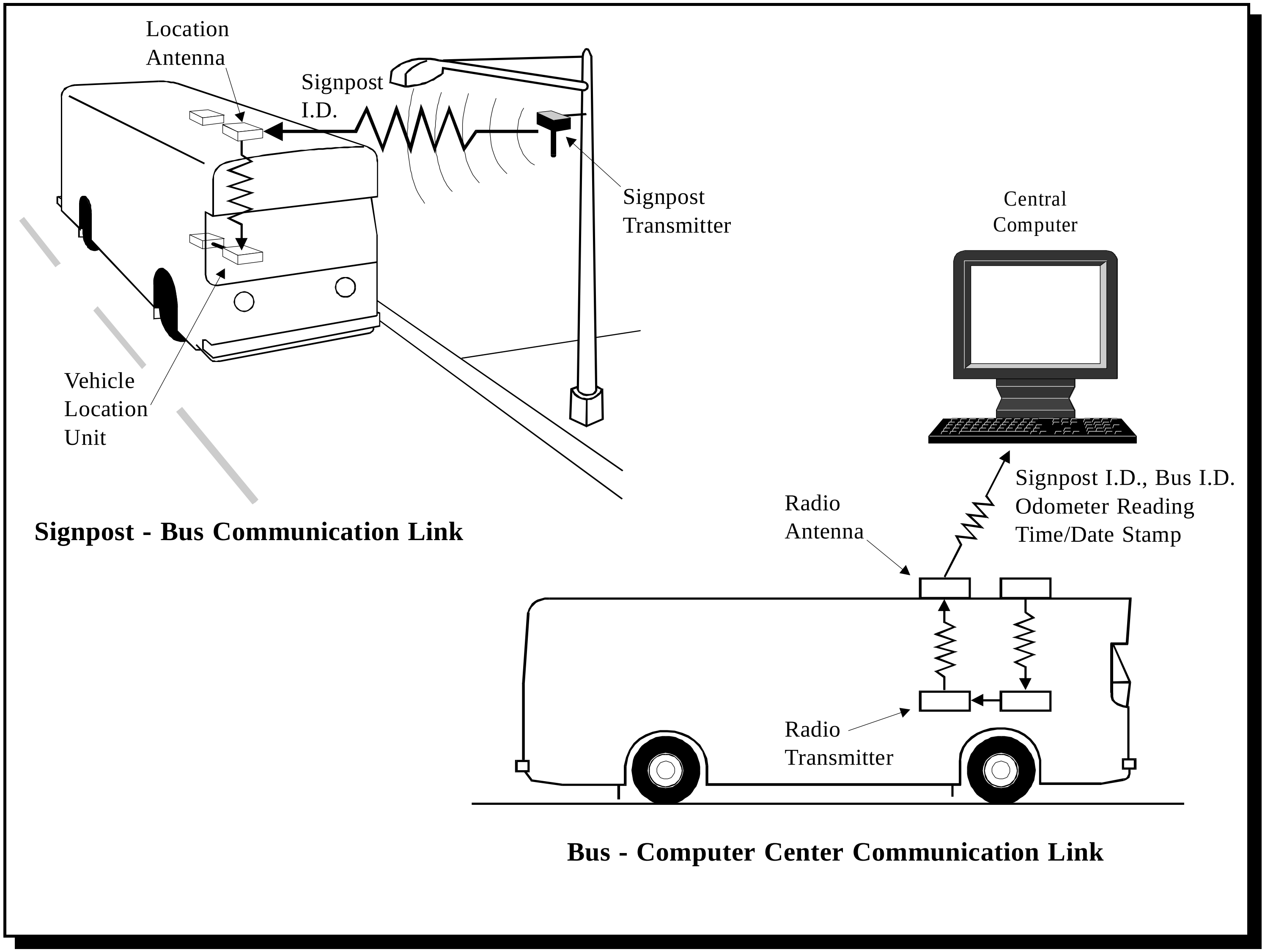


Figure 5-1. Signpost-Based AVL Communication Processes

5.1.1 Advantages and Disadvantages

The **advantages** of signpost-based AVL for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Simple infrastructure** - Signpost-based technology is relatively simple, straightforward and can be implemented quickly (9).

- **Vehicle performance data** - Some signpost-based AVL systems are designed to collect transit vehicle operational performance data, such as fuel consumption, oil pressure, or cooling temperature. These data may be useful for emissions or environmental modeling.

- **Passenger count data** - Some signpost-based AVL systems may be able to collect passenger counts as transit patrons enter and exit the vehicle. These data may be useful for production and attraction counts in trip generation or origin-destination studies.

The **disadvantages** of signpost-based AVL for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Non-representative data** - Since signpost-based AVL systems are typically designed to monitor transit fleet operations, their travel time data reflect the travel habits of transit vehicles and transit drivers. This representation may not be acceptable for travel time studies that wish to target automobile traffic.

- **Limited coverage area** - Since the signpost-based system collects data from transit probe vehicles, the data are limited to roadways that are traveled by transit vehicles.

- **Equipment maintenance** - Transit agencies have reported that odometers and signpost transmitters require routine calibration to prevent erroneous data collection.

- **Outdated technology** - Many transit agencies are upgrading to GPS technology (see Section 5.5). The signpost-based AVL technology has been out-performed by the more accurate and robust global positioning satellites. Signpost-based AVL equipment is also difficult to obtain in the event that equipment needs upgrading or replacement. Vendors of signpost-based equipment are focusing on the more lucrative GPS technology.

- **Complex data reduction** - Although data are in electronic format and can be imported into a spreadsheet or statistical analysis package, the data require extensive editing and quality control. For example, data must be edited to adjust for bus layovers or else link travel times will appear larger than they actually were. Gross data collection errors, from poorly placed or malfunctioning signpost transmitters, will need spot editing.

5.1.2 Costs and Equipment Requirements

A signpost-based AVL system requires an infrastructure of electronic transmitters, several in-vehicle components, and control facility equipment. These components are necessary for data collection tasks. Additional equipment is needed for data reduction after completion of the data collection tasks. This section provides a brief description of both data collection and data reduction equipment. Table 5-2 summarizes the necessary equipment and related costs. Much of the cost information is not available since development of this technology stagnated.

Table 5-2. Estimated Costs for the Signpost-Based AVL Probe Vehicle System

Equipment	Unit Cost (1998 dollars)
Hardware	
Electronic Signpost Transmitters	~ $2,000
In-vehicle Radio Receivers	n.a.
In-vehicle Radio Transmitters	n.a.
In-vehicle Data Processor	n.a.
In-vehicle Odometer Sensor	~ $100
Control Facility Radio Receiver	n.a.
Personal Computer	Varies
Software	
Specialized Software	n.a.
Analysis Software	$150 to $300
Personnel	
Data Reduction Personnel	Varies

Note: n.a. - not available.

Data Collection Requirements

Electronic Transmitters - Electronic transmitters are installed at the side of the roadway. They are typically installed on existing signpost structures. Installation time is typically about two hours.

In-Vehicle Radio Receivers - This device receives the electronic transmitters' signals. It is typically installed on the top or front of the vehicle.

In-Vehicle Data Processor - This collects and stores data (odometer mileage) until the signpost transmission is received and then transmits data to the control facility.

In-Vehicle Odometer Sensor - This device records the distance between signpost transmission receptions. Installation time typically requires about two hours.

Control Facility Radio Receiver - This device receives data transmissions from the probe vehicle fleet.

Personal Computer - Traditionally, agencies have collected and processed data with mainframe computers. Desktop computers can be used to perform the necessary tasks.

Specialized Software - Special software is needed to poll vehicles and collect and process data. Software is typically created in-house or by a consultant. The software also generates reports and data archives which can be analyzed by other software.

Data Reduction Personnel - Individuals who will reduce the data that is being received by the AVL system for use in travel time determination.

Data Reduction Requirements

Personal Computer - Electronic data from the signpost-based system can be analyzed using typical desktop computers. Disk storage requirements depend upon the size of the transit agency's signpost-based AVL system (e.g. link coverage, sample size, number of routes).

Analysis Software - Raw data can be imported into typical spreadsheet or statistical analysis software packages for personal computers. With the necessary understanding of the data to code the software, the data can be analyzed.

5.1.3 System Design Considerations

This section describes several considerations that can facilitate the data collection and reduction process. These recommendations can help ensure that the most useful data are collected to meet the demands of the study.

Select strategic routes - It may not be feasible to include all transit routes in the system coverage area. Selecting strategic links along the transit route to include in the system can ensure that travel time data are collected along critical links (e.g., most congested, greatest demand) in the system.

Identify signpost locations - It is important to consider which locations within the system are the most appropriate for detecting the probe vehicles. This can be done by installing signposts at the beginning, end, and major points throughout the route. Signpost transmitter locations are typically spaced several miles apart.

Obtain signpost use agreement - Once a signpost location has been selected, a post or pole to attach the electronic signpost transmitter must be identified. A pole attachment agreement must be obtained from the owner of the post or pole (e.g., telephone company, electric company, municipality, or private owner).

Attach transmitters to signposts - Transmitter installations on signposts should comply with utilities specifications for attachment method, height, and other criteria. The transmitter power should be appropriately adjusted.

Maintain map-matching database - The map-matching database is necessary to track the probe vehicles throughout the system. Each signpost must have an identification number and its location must be entered into the map-matching database. This database should be continuously updated as changes in the system, such as relocated signposts and route adjustments, are implemented. Verify the mileage of each route by driving it in the field.

Certify working condition of in-vehicle equipment - Odometer sensors should be properly calibrated. All in-vehicle equipment and cables and probe vehicle electrical system should be in proper operating condition.

Provide on-call equipment maintenance staff - On-board equipment and signpost transmitters require constant calibration and routine maintenance. Transit agencies have full-time personnel to maintain the functionality of their equipment.

5.1.4 Data Reduction and Quality Control

Once the raw data have been collected, it is necessary to process the data into a useful format. This section describes several measures that are necessary to develop a useful data set and several measures that assist in performing an efficient analysis.

Data files are typically in an ASCII text format. These data may be imported into a spreadsheet software package or into statistical analysis software for analysis.

IMPORTANT ☞ It is important to consider that the raw data are difficult to interpret without some understanding of the transit agency's bus operations and location of electronic signposts within the roadway network.

This section presents several issues to consider when reducing and inspecting the quality of signpost-based AVL travel time data.

Identify scheduled layover points - The raw data file includes the bus identification number, time that the bus passed an electronic signpost, the location of the signpost, and the physical length of roadway traveled among other data. These data are essential to determine travel times through roadway segments. It is also important to keep in mind that bus schedules include layovers. Layovers detain a bus at a stop along its route. These layover durations should be figured into the travel times by obtaining information on pre-scheduled layovers from the transit agency.

Maintain signpost transmitter locations with map - Additionally, it is necessary to maintain the locations of the electronic signpost transmitters so that a physical roadway reference may be used to interpret the location of time points. Ensure that transmitter locations are updated on the system map when changes are implemented in the field. Signpost transmitters are often relocated in the field, however, the map remains unchanged thereafter.

Interpret physical location of time points - Data are sent from the vehicle to the control center not upon passage of the signpost transmitter, but upon passage of a scheduled point in time (time point). The data describe the distance traveled between sequential time points. Thus, a travel time for a section of roadway is known. However, the physical location of that roadway section can only be inferred. It is possible to approximate the location of a time point since it is known when the vehicle passes a signpost transmitter. The exact location of the transmitter is known, and the location of the vehicle passing within range of the transmitter can be estimated to within about 30 m (100 ft). Based on the difference in time between transmitter passage and time point passage, the approximate roadway location of a time point can be interpreted.

5.1.5 Previous Experiences

Several agencies in the U.S. and Europe have operated signpost-based AVL probe vehicle systems. Their experiences are useful for designing and managing your system. VIA Transit in San Antonio, Texas has operated a signpost-based AVL system to monitor its fleet of buses. The New Jersey Transit agency has used signpost-based AVL technology since 1993 to provide bus operations control centers with accurate real-time information on schedule performance adherence and fleet management. Their system is used to alert and predict service delays. Seattle Metro uses the technology to monitor its bus operations, and data are archived for "next day" access by transit analysts (10). London Transport aims to equip 6,500 vehicles and 700 bus routes with signpost-based AVL technology by the year 2000 (11).

San Antonio VIA Metropolitan Transit

VIA Transit first developed specifications for the signpost-based AVL system in 1983, and this system was developed by the General Railway Signal Communications System. The design of San Antonio's system is similar to that described in the preceding section with only slight modifications. The total system cost of $3.7 million included the development and installation of equipment on 537 buses, all central computer hardware and software, 200 electronic signposts, two un-interruptible power supplies, and all training and documentation (9).

The San Antonio system covers about 3,100 sq-km (1,200 sq-mi). The odometer readings are compared to programmed readings for schedule adherence monitoring. The system can generate a variety of reports, including daily schedule adherence reports by route, time, or location. The schedule adherence reports may illustrate data by route across a range of dates. The software also allows minute-by-minute tracking of individual buses. VIA's experience with the software is that it is a highly specialized code to learn (12).

Data reports can be formatted as text documents. These documents can be imported into a spreadsheet or statistical analysis software package. Figure 5-2 shows a sample of raw data from VIA's signpost-based AVL system. These data correspond to one bus (# 532) traveling along its route.

Several rows of data in Figure 5-2 have missing data. However, beginning in the seventh row of data, bus #532 can be observed traveling along its route. At time point 0005 at 06:11:22, the bus transmits its odometer reading to the control facility. It is determined that it traveled along segment #3686 in a southern direction for a distance of 1.56 km (0.97 mi). On the eighth row of data, bus #532 passes time point 0504 at 06:17:25 after traveling a distance of 3.78 km (2.35 mi). These time points are not synonymous with signpost locations, and there is no way of knowing the precise location of a bus when it reaches a time point. The bus location can only be inferred.

RTE LGRP	BLK	SCHED TIME	LAY OVER	ACTUAL ROUTE RIL	SEG#	TIME PT	TIMEPOINT LOCATION	Dir Cmp	I/O	SEG MILE .01	Bus #	SCHD ADH	TIME OF PASSAGE
034	004	0513	00	034	2856	9999	GARAGE	N	O	0927			
034	004	0538	00	034	2855	1703	NWDR-INGR	S	I	0278	532	033E	05:34:42
034	004	0547	00	034	3189	0808	BDVW-INGR	S	I	0167			
034	004	0553	00	034	3190	0806	WOOD-BAND	S	I	0187			
034	004	0559	00	034	3191	0805	WOOD-ZARZ	S	I	0155			
034	004	0605	00	034	3685	0106	FRED-FLOR	S	I	0128			
034	004	0610	00	034	3686	0005	ST.M-MART	S	O	0097	532	014L	06:11:22
034	004	0617	00	034	3192	0504	ST.M-ALAM	S	O	0235	532	004L	06:17:25
034	004	0624	00	034	3193	0506	ROOS-EADS	S	O	0174	532	017L	06:25:40
034	004	0630	00	034	3194	0418	MCCR-ELES	S	O	0200	532	027L	06:32:43
034	004	0638	00	034	3195	1912	GOLD-VLLY	S	O	0265	532	021L	06:40:04
034	004	0647	10	034	3196	0522	N.BR-HOSP	N	I	0257	532	012L	06:48:14
034	004	0708	00	034	3197	1912	GOLD-VLLY	N	I	0205	532	001L	07:08:04
034	004	0717	00	034	3205	0418	MCCR-ELES	N	I	0174	532	019E	07:15:04
034	004	0727	00	034	3200	0506	ROOS-EADS	N	I	0231	532	001L	07:27:05
034	004	0737	00	034	3183	0504	ST.M-ALAM	N	I	0051	532	006E	07:36:23
034	004	0740	00	034	3184	0013	NAVA-VILL	N	O	0175	532	007E	07:39:16
034	004	0752	00	034	3201	0106	FRED-FLOR	N	O	0157	532	001E	07:51:55
034	004	0800	00	034	3202	0805	WOOD-ZARZ	N	O	0182	532	014E	07:58:36
034	004	0806	00	034	3203	0806	WOOD-BEND	N	O	0171	532	010E	08:05:00
034	004	0813	00	034	2837	0808	BDVW-INGR	N	O	0330	532	017E	08:11:15
034	004	0824	00	034	2855	1703	NWDR-INGR	S	I	0278	532	119L	08:35:56
034	004	0842	00	034	3189	0808	BDVW-INGR	S	I	0167			
034	004	0848	00	034	3190	0806	WOOD-BAND	S	I	0187			
034	004	0855	00	034	3191	0805	WOOD-ZARZ	S	I	0155			
034	004	0902	00	034	3685	0106	FRED-FLOR	S	I	0128			
034	004	0908	00	034	3686	0005	ST.M-MART	S	O	0097			
034	004	0916	00	034	3192	0504	ST.M-ALAM	S	O	0235			
034	004	0925	00	034	3193	0506	ROOS-EADS	S	O	0174	532	016E	09:23:21
034	004	0934	00	034	3194	0418	MCCR-ELES	S	O	0200	532	0353	09:30:31
034	004	0941	00	034	3195	1912	GOLD-VLLY	S	O	0265	532	002L	09:41:15
034	004	0950	04	034	3196	0S22	N.BR-HOSP	N	I	0257	532	019L	09:51:54
034	004	1003	00	034	3197	1912	GOLD-VLLY	N	I	0205	532	017L	10:04:45
034	004	1012	00	034	3205	0418	MCCR-ELES	N	I	0174	532	027L	10:14:43
034	004	1020	00	034	3200	0506	ROOS-EADS	N	I	0231	532	012L	10:21:11

Figure 5-2. Data from San Antonio VIA Transit's Signpost-Based AVL System

VIA's signpost-based AVL system has several important design characteristics and noteworthy operational aspects:

- **Signpost transmitter spacings** are approximately 8 km (5 mi) along the bus routes.
- **Buses polled** every 60 seconds for an odometer reading by the control facility.
- **Difficulty maintaining route/schedule database** since field changes are often implemented to bus routes or schedules. A lag often occurs between the field implementations and the update of the route/schedule database and short-term changes in the bus routes go unnoticed.

- **1 to 2 persons required** to maintain route/schedule database.

- **Aging hardware** and signpost-based technology is difficult to replace.

- **Quality of data** is suspect since data are often erroneous or missing for report generation because vehicles often have malfunctioning equipment, odometers are not calibrated for vehicle's tire size or inflation level, or route/schedule reference database are not updated. Erroneous data are also obtained when a bus passes through a layover point (e.g., transit center or bus stop) since there is no distinction between arrival or departure; however, data between layover points is reliable.

- **Signpost maintenance** requires checking signposts periodically for proper signal transmission. Signpost maintenance is a large expense. Sensitivity of signposts on low-speed facilities should be set at a shorter range than for signposts on freeways. Sensitivity refers to the transmission range of the signpost transmitter.

- **Odometer maintenance** requires odometers that are properly calibrated for each bus.

VIA uses its signpost-based AVL system for real-time location tracking, schedule adherence monitoring, and computer-aided dispatching. They reported that the data have never been requested for use in any other applications other than for their personal fleet management.

New Jersey Transit Agency

The New Jersey Transit agency has used signpost-based AVL technology since 1993 to provide bus operations control centers with accurate real-time information, on schedule performance adherence, and fleet management. Their system is used to alert and predict service delays. Data are also maintained to report on-schedule performance for more effective transit scheduling. An example of raw data from trace files is shown in Figure 5-3. These trace files contain data transaction between the bus radio and control facility. The files are stored at the central control facility.

To the casual observer, the data in Figure 5-3 are difficult to interpret. At 12:54:06.19, vehicle 2675 passes timepoint 1 and transmits its odometer reading to the control facility. The vehicle's last location of 0036 and current location of 0038 are determined by the system. These locations are associated with a link on a map database. Based on the elapsed time to travel between a previous location and the current location, the travel time for a particular link can be estimated.

```
12:31:42.82   LOC_MSG Veh:  2675        Last Loc 005A       Curr Loc 005A       Odm 0     TID 00004813     Trip Id
00002661
12:33:50.98   LOC~MSG Veh:  2675        Last Loc 005A       Curr Loc 0036       Odm 0     TID 00004813     Trip Id
00002661 12:33:51.01   TIMEPT     Veh:  2675      EOT Trip Msg TID 00004813     Trip Id 00002661
12:33:51.01   TIMEPT     Veh:           2675      Timepoint 6 completed by Signpost TID 00004813
12:43:52.06   LOC_MSG Veh:   2675       Last Loc 005A       Curr Loc 0036       Odm 0     TID 00004813     Trip Id
006E117F
12:53:51.91   LOC_MSG Veh:   2675       Last Loc 005A       Curr Loc 005A       Odm 0     TID 00004813     Trip Id
006E117F
12:54:06.17   LOC_MSG Veh:   2675       Last Loc 0036       Curr Loc 0036       Odm 0     TID 00004813     Trip Id
006E117F
12:54:06.19  TIMEPT       Veh:          2675      Immediate Trip Msg TID 00004813         Trip Id 006E117F
12:54:06.19  TIMEPT       Veh:          2675      Timepoint 1 completed by Signpost TID 00004813
12:54:52.25   LOC_MSG  Veh:  2615       SOT Msg TID 00004813 Trip Id 006E117F
12:54:52.29  TIMEPT       Veh:          2675      Immediate Trip Msg TID 00004813         Trip Id 006E117F
13:00:34.06   LOC_MSG  Veh:  2675       Last Loc 0036       Curr Loc 0038       Odm 0     TID 00004813      Trip Id
006E117F 13:00:34.09   TIMEPT      Veh: 2675      Immediate Trip Msg TID 00004813         Trip Id 006E117F
13:00:34.09   TIMEPT      Veh:          2675      Timepoint 2 completed by Signpost TID 00004813
13:02:54.62   SPM$EMPNO_MSG   -   EmpNo    26758 Msg TID 00001134
13:10:34.56   LOC_MSG  Veh:  2675       Last Loc 0038       Curr Loc 0038       Odm 0     TID 00004813     Trip Id
006E117F
13:11:53.29   LOC_MSG  Veh:  2675       Last Loc 0038       Curr Loc 005A       Odm 0     TID 00004813     Trip Id
006E117F
13:11:53.32   TIMEPT       Veh: 2675           Immediate Trip MsgTID 00004813  Trip Id 006E117F
```

Figure 5-3. Data from New Jersey Transit's Signpost-Based AVL System

Seattle Metro Transit System

The Seattle Metro system was designed to provide a method of collecting, storing, and analyzing performance data to improve service analysis and scheduling modifications for its bus fleet (10). Some specific characteristics about Metro's system are:

- **Probe vehicle polling** rate of 30 to 90 seconds;
- **Fast polling rate** of 5 to 15 seconds for individual vehicles;
- **Location accuracy** to within ± 76 m (± 250 ft).

Location accuracy discrepancies were attributed to bus odometer malfunction, in-vehicle receiver failure, in-vehicle processor failure, and the bus being off-route.

London Transport Bus System

The London Transport Bus (LTB) system uses signpost-AVL technology in which in-vehicle transponders communicate with roadside microwave beacons (13). Nine hundred and fifty buses, out of a 6,500 bus fleet, are equipped with AVL tags. The system is used to estimate arrival times for buses and display the information at bus stop variable message signs.

Current operations generate 40 megabytes of data every day. The data are archived for seven days to include the time at which buses pass certain points and the length of time to complete routes. These data can be used to compute journey times. The data set does not include raw location data, thus the layover time at bus stops are included.

5.2 Automatic Vehicle Identification

Automatic vehicle identification (AVI) technologies are in widespread use throughout the United States for a variety of purposes: electronic toll collection (ETC), real-time traffic monitoring, incident management, traveler information, and performance measure data collection. A few large metropolitan areas monitor traffic operations in real-time with AVI technology; however, its primary application is for electronic toll collection. Currently, about 18 U.S. toll collection agencies use AVI to electronically collect tolls (14). An additional 10 toll agencies are planning to use AVI for electronic toll collection by the end of 1998. In Houston, Texas, AVI technology is used for both electronic toll collection and traffic monitoring.

Figure 5-4 illustrates the AVI components and the data collection process. An AVI system collects travel time data by using four primary components:

- ITS probe vehicles equipped with electronic transponders;
- roadside antenna that detects the presence of electronic transponders;
- roadside readers which bundle data; and
- a central computer facility to collect all data.

Tags, also known as transponders, are electronically encoded with unique identification (ID) numbers. Since these tags are often used for electronic toll collection, the tag ID number can be synonymous with the electronic registration number used to determine vehicle ownership in electronic toll collection (15,16). Roadside antennas are located on roadside or overhead structures (e.g., bridge, guide sign), or as a part of an electronic toll collection booth.

The antennas emit radio frequency signals within a capture range across one or more freeway lanes. The radio frequency (RF) capture range may be constantly emitted, or it may be triggered by an upstream loop detector (i.e., as in toll plazas). When the probe vehicle enters the antenna's capture range, the radio signal is reflected off of the electronic transponder. This reflected signal is slightly modified by the tag's unique ID number. The captured ID number is sent to a roadside reader unit via coaxial cable and is assigned a time and date stamp and antenna ID stamp. These bundled data are then transmitted to a central computer facility via telephone line where they are processed and stored. Unique probe vehicle ID numbers are tracked along the freeway system, and the probe vehicles' travel times are calculated as the difference between time stamps at sequential antenna locations.

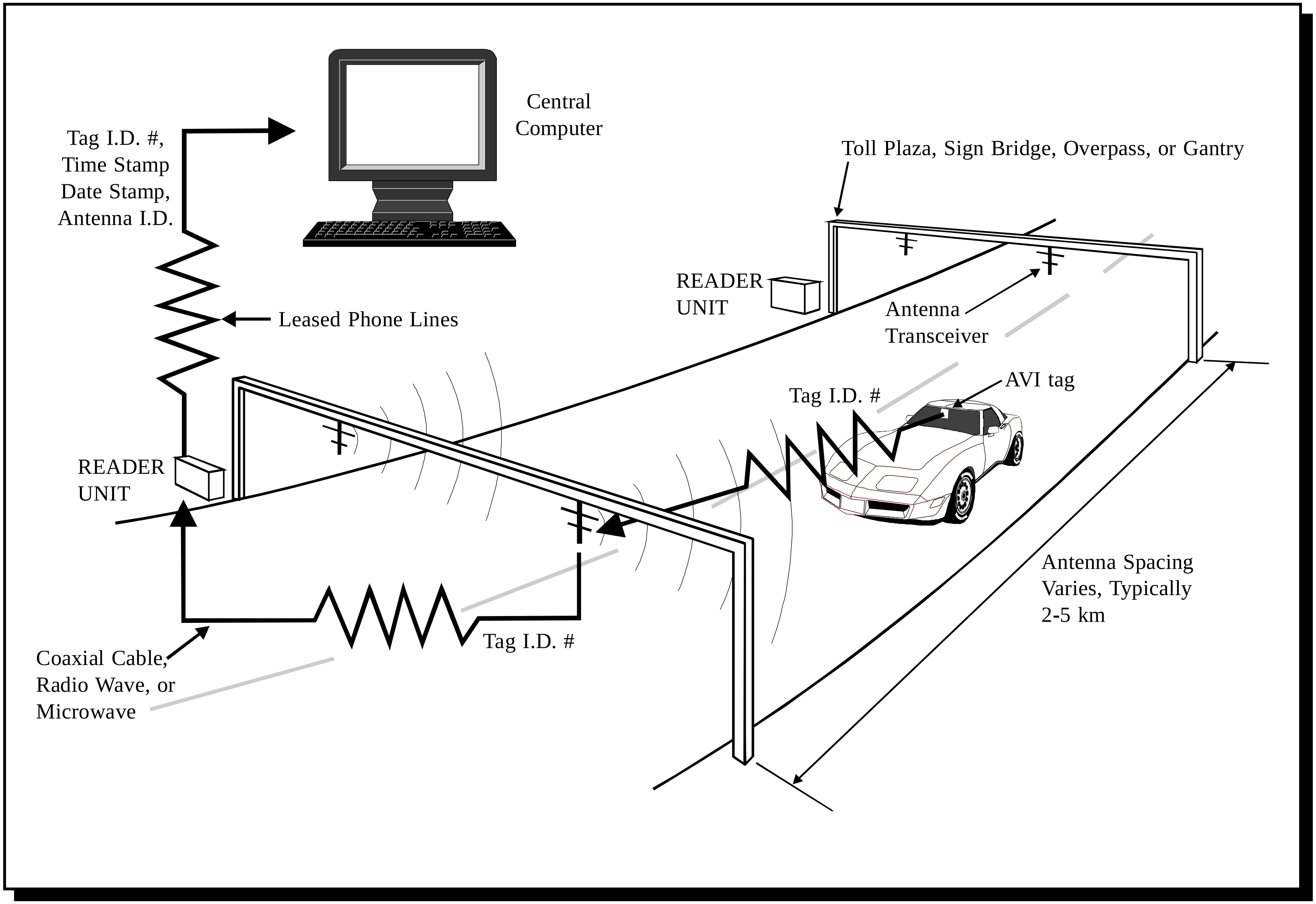


Figure 5-4. AVI Vehicle-to-Roadside Communication Process

The roadside readers have the capability of initiating the dial-up process to the central facility or they may answer dial-in requests for data. The data collection process may slightly differ for some electronic toll collection systems. An ETC plaza may store data for lengthy periods before the data are sent to a central facility.

AVI systems have the ability to continuously collect large amounts of data with minimal human resource requirements. The data collection process is constrained primarily by sample size characteristics and the coverage area of the AVI infrastructure (i.e., antenna readers or ETC booths). AVI technology has demonstrated itself as highly accurate. Since AVI tags are commonly used for toll collection, it is important to have a high detection rate. The Electronic Toll and Traffic Management (ETTM) User Requirements for Future National Interoperability, published by the Standards and Protocols Committee of the Intelligent Transportation Society of America (ITS America), suggests detection rates of greater than 99.5 percent. Agencies using AVI technology have experienced detection rates of between 85 to 99 percent.

Electronic Toll Collection

Many toll agencies in the U.S. are using AVI technology for electronic toll collection. The combination of an electronic toll collection system and a traffic information and management system can be referred to as an electronic toll and traffic management (ETTM) system. This combination offers an expanded utility for vehicles equipped with electronic tags to not only process tolls, but also service ITS applications (17). Electronic toll collection systems can provide useful travel time data, particularly on systems with a large percentage of motorists using ETC. Some system adjustments will most likely be necessary to provide an effective data collection effort. For example, toll plazas are typically spaced further apart than recommended for AVI data collection, and computer systems may not be prepared to archive travel time data.

While most ETC systems are not set up to simultaneously collect and manage travel time data, some existing ETC agencies, such as the Illinois State Toll Highway Authority have begun to utilize AVI technology for travel time data collection in addition to toll processing. Some ETC systems experience between 25 percent to 100 percent of all tollway vehicles having electronic tags. This provides a large sample to collect representative travel time data.

Some modifications may be necessary for ETC systems to collect accurate travel time data. For example, antenna spacings may be too far apart. Also, some ETC systems have open-ended designs in which tolls are transacted at only one antenna per direction. Recall that two sequential antennas are needed to collect travel time data. These and other modifications are feasible, and ETC systems can provide an abundant source of travel time data.

5.2.1 Advantages and Disadvantages

Inherent within the AVI data collection methodology are certain advantages and disadvantages which can affect the quality of travel time data. The AVI technology presents characteristics which can affect the integrity of travel time data. These technological characteristics are presented and briefly discussed in this section.

The **advantages** of AVI probe vehicles for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Continuous data collection** - Travel time data may be collected for entire 24-hour periods for each day of the year since personnel are not required for field data collection. Data may be collected during weekends and holidays, as well. AVI allows data collection during all types of weather and environmental conditions as long as probe vehicles are detected.

- **Minimal personnel requirements** - The AVI data collection process is completely automated. Personnel are not necessary to collect data from the field. Very few personnel are needed to maintain the system and process data (18).

- **Safe data collection** - Since personnel are not required in the field, the risk of injury is eliminated.

- **Minimal human error** - The elimination of manual data collection virtually removes potential of human error from the actual data collection process.

- **Accuracy of data collection** - For small sample sizes, 100 percent of AVI tags can be captured by the antenna (15). The Washington State Transportation Center (TRAC) experienced an 83 percent detection rate. Travel time observations have been validated by simultaneous floating car travel times. AVI tags have been detected at speeds of 180 km/h (110 mph) and when multiple probe vehicles simultaneously pass the same reader site. AVI technology has demonstrated itself as immune from interference from cellular telephones, citizen band radios, and electric generators (1).

- **Lane specific** - Can collect travel time data corresponding to particular lanes.

- **Vast amounts of data** - Since data can be collected continuously and since the system has the potential to collect data from many probe vehicle drivers, the potential exists for vast amounts of travel time data. Data can be collected over an entire year and through all types of environmental conditions.

The **disadvantages** of AVI probe vehicles for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Infrastructure dependent** - The system can collect travel time data only along freeway or arterial street segments that are within the coverage area of AVI infrastructure (i.e., segments equipped with antennas or ETC booths).

- **Electronic tag dependent** - Data collection is limited to the number of tags in use within the study area.

- **Clock drift problems** - Several agencies have reported that maintaining the antennas or ETC booths is expensive and may affect data quality. A common maintenance problem is keeping the clocks, which place the time stamp on each transponder read, in synchronization (1,15).

- **Privacy issues** - The technology requires that unique tag IDs are tracked between sequential antennas to determine travel times. The IDs correspond to individual drivers of probe vehicles, as the drivers are often registered to use an ETC system. The technology may allow individual vehicles to be tracked along the system.

- **Large data storage requirement** - In AVI systems, especially systems with many antenna locations and probe vehicles, a large amount of data storage space is needed.

5.2.2 Costs and Equipment Resources

This section will describe the essential components for collecting travel time data using the AVI probe vehicle technique. The quantity of certain components depends on the application of the technology. Equipment are presented by field hardware requirements and by central facility hardware requirements. Table 5-3 summarizes the needed AVI equipment and costs. As with most probe vehicle systems, they may be installed initially for reasons other than travel time data collection. Therefore, some of the costs presented in Table 5-3 may be subsidized by different agencies benefitting from the system.

Data Collection Requirements

Electronic Tags - These devices are attached to the probe vehicles. They are usually placed on the inside windshield and are about the size of a credit card. Three different tag types (types I, II, and III) are commercially available. The primary difference between transponder types is the ability to write onto the transponder, and these distinctions are relevant primarily for electronic toll collection purposes. Different transponder types allow toll account data to be stored on the transponder instead of in a centralized database. The tag type does not affect the ability to collect travel time data. Individual tag costs have been reported to range from $25 to $100, depending on the quantity of tags purchased (1). If tags are purchased in bulk, a substantial discount is achieved. Tags can be installed easily within five minutes with adhesive tape.

Roadside Antennas - The antennas function as transceivers which receive tag ID numbers and send the tag ID numbers to a roadside reader unit. The antennas are typically mounted over the travel lanes on existing structures. Minimal disruption to traffic is necessary for installation or repair.

Table 5-3. Estimated Costs for AVI Probe Vehicle System

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
Electronic Tags	$20 to $50 each
Roadside Antennas	~ $1,500
Roadside Readers	$10,000 - $30,000
Cable Connections	~ $100/meter
Telephone Connection	$25 to $40
Telephone Communications	Varies
Control Facility Computer	$2,000 - $5,000
Computer Data Storage	$100 - $200/gigabyte
Software	
Specialized Software	Varies
Analysis Software	$150 to $300
Personnel	
Data Reduction Personnel	Varies

Roadside Readers - These units receive the tag ID numbers from antennas and assign the time, date, and antenna location ID stamps. These bundled data are stored and transmitted to a central control facility. The storage durations and update frequencies may be established by the system operators. Readers can cost about $31,000 on average. Readers require frequent maintenance, which has been reported as costly as $256 per lane per site per month.

Cables - Antennas and readers are typically connected by coaxial cables.

Telephone Line - Reader units are often tied into the central computer facility by leased telephone lines. The cost of leasing telephone lines may be a major operational cost. One telephone line is necessary for each reader unit in the field. Fiber optic cable or microwave transmission offers a much quicker by costlier alternative to telephone lines.

Data Management and Reduction Requirements

Specialized Software - Specialized software is required to collect and process incoming tag reads and match them to calculate travel times. Software is often designed in-house, by a consultant, or is a proprietary-based application.

Archive Capacity - Sufficient archival capacity is needed to store historic travel time data. The size of archival depends on the size of the AVI system (i.e., sample size, antennas, tag reads).

Analysis Software - Archived data can typically be analyzed using a common spreadsheet or statistical analysis package.

Data Reduction Personnel - Individuals who will reduce the data that is being received by the AVL system for use in travel time determination.

5.2.3 System Design Considerations

This section will discuss how to design the AVI system to generate data which are most useful for the readers' travel time data needs. Certain hardware configurations, such as antenna spacing, mounting, or capture zone area, may be more appropriate for certain analysis methods or may be more inclusive for a variety of analysis methods. Certain hardware specifications/types may require additional attention than others, and this should be considered.

Electronic Tag Types

Several vendors develop AVI technologies, and a variety of transponders and antennas are commercially available. Currently, three different transponder technologies have been used. These transponder technologies are referred to as types I, II, and III (19). The primary difference between transponder types is the ability to write onto the transponder, and these distinctions are relevant primarily for electronic toll collection purposes. Different transponder types allow toll account data to be stored on the transponder instead of in a centralized database. The technological differences between tag types do not affect their abilities to collect travel time data since the necessary data (i.e., unique ID numbers) are transmitted from the transponders to the roadside units regardless of transponder type.

Maximizing Tag Distribution

It is desirable to distribute as many electronic tags as possible to collect travel time data. A greater number of probe vehicles can provide a more representative sample of the traffic population's travel time characteristics. In order to achieve a desirable level of probe vehicles, it is necessary to attract probe vehicle drivers and distribute the electronic tags. Participation in an AVI system can be achieved by offering probe drivers various incentives. Potential incentives may include the following:

- priority passage through toll facilities;
- priority passage through weigh/inspection stations (for trucks);
- ability to receive in-vehicle travel information;
- free electronic tag;
- voucher for merchandise or fuel;
- registration for roadside maintenance service; or
- some type of payment.

It is also important to ensure participants that their privacy will not be violated. Public concerns have been raised about various privacy issues. A privacy policy should be drafted, perhaps in accordance with the Intelligent Transportation Society of America Privacy Principles, to ensure that individually identifiable data are not improperly managed and personal privacy is not compromised (20). Some common privacy concerns include:

- vehicle/driver tracking;
- automated traffic law enforcement;
- distribution of personal travel history; and
- distribution of personal information.

Vehicle-to-Roadside Communication Media

Other technological differences exist between vehicle-to-roadside communication signals and between roadside antenna types. These differences may affect the accuracy and performance of the AVI system and should be considered when installing or upgrading AVI technologies or when collecting travel time data. The most common vehicle-to-roadside communication signal is radio frequency (RF). However, laser signals have been used. RF signal AVI technologies have been demonstrated to be more reliable than laser technologies, and RF technology is the choice of new ETC systems (21).

Antenna Spacing and Installation Specifications

Antennas are usually mounted on existing overpass or sign structures and antenna spacing often varies as mounting structure spacing varies. More expensive options include constructing a gantry over the roadway for exclusive use of AVI antennas. The level of congestion is often considered in the placement of antennas; antennas are spaced more frequently in areas with greater congestion levels. In addition, antenna spacing is set according to anticipated benefits from incident detection. Incident detection requires more frequent spacings than does simple travel time monitoring. One AVI system designer recommends that antennas are spaced no greater than two minutes apart in sections where speeds are less than 48 km/h (30 mph) during recurring congestion for the purposes of future incident detection (22).

Typical antenna spacings range between about 2 km (1.2 mi) to 5 km (3.1 mi). It is important to consider that adequate antenna spacing varies with variations in mean travel time data. Larger antenna spacings result in decreased sensitivity to variations in mean travel time within the segment. It is important to consider that antennas must be connected to roadside readers. Roadside readers must be connected to the control facility via telephone cable or other transmission medium, and power must be supplied to the readers and antennas. Antenna and reader placement must accommodate these connections.

Roadside Reader Clock Synchronization

AVI roadside reader clocks place a time stamp on the tag read prior to transmitting the data to the control facility. The clocks on readers must be synchronized to ensure that accurate travel times are collected throughout the entire system. It is imperative that sequential reader clocks are synchronized. It is necessary to periodically synchronize clocks. It is also possible to control reader clocks from the control facility by synchronizing all system clocks simultaneously.

Antenna Capture Range Adjustment

Reports suggest that one antenna can cover 18 lanes of traffic; however, practical application limits one antenna to 8 or 9 bi-directional lanes of traffic. Typical installations allow for separate antennas for directional lanes of traffic. The capture range for the RF signal can be adjusted to detect one lane or multiple lanes, thus allowing for detection of specific lanes. Different antenna types allow for different capture range dimensions and are more conducive to monitoring multiple traffic lanes.

Telephone Connection to Reader Units

Analog telephone lines are often used. However, the recurring costs of analog lines presents ISDN lines as an alternative. ISDN lines can be multiplexed into a single channel into the control facility and have smaller long-term costs. However, in the event that power is lost to the ISDN modem, manual re-connection may be required by the telephone company.

5.2.4 Data Reduction and Quality Control

An AVI system requires special software applications to perform the necessary data processing. Software is typically developed by the vendor of AVI equipment, a consultant, or agency operating the AVI system.

Roadside reader units are equipped with computers running software to recognize each tag ID read, bundle the reads with corresponding time and date stamps and antenna ID stamp, and transmit the bundled data to a central computer. The central computer operates software which solicits data from the multiple roadside reader units, typically at some preset time interval.

Once data have been received by the central computer facility, several steps are taken to reduce data into a useful format. This section describes the basic steps in the AVI data reduction process after the data have been transmitted from the field to the central computer.

1. **Store tag read data**. As data enters the central computer, the data must be stored within a local database. For real-time data processing, it is necessary to store data on a shared disk drive to allow for a second computer to compute travel times. The stored data are tag records which are generated each time a probe vehicle passes an antenna. A tag record contains the tag ID, antenna ID, and time and date of tag detection. Figure 5-5 is an example of raw data from the Houston, Texas AVI system tag records. These data entered the computer center from multiple reader units and are in an ASCII text format. This file is accessible through spreadsheet or word processing programs.

2. **Match sequential tag reads**. A software application matches tag records between sequential antennas and then calculates the travel time between the antennas. Travel time is calculated as the difference between two tag record time stamps of the same tag ID.

3. **Filter erroneous data**. The travel time data should be reviewed with a screening algorithm to identify erroneous data. An erroneous data point may result in a tag read from a vehicle which stalled, stopped, or detoured off the route between sequential antennas.

4. **Archive travel time data**. The valid travel time data are then stored within a database management system, such as a relational database. This can be done automatically by system software. Commonly, all travel time data are sent into an archive file which is renamed based on the date. Data can be transferred to an historical database, often consisting of daily binary files containing individual travel time observations on each link within the system. AVI systems have reported daily file sizes of 15 to 20 megabytes for a system collecting 450,000 tag reads, or about 225,000 matched tag reads, per week.

Tag ID	Antenna ID	Checkpt. ID	Read Time	Read Date
123456789	4054	56	0:16:14	3/31/97
234567900	4063	57	0:16:25	3/31/97
345679011	4000	50	0:16:17	3/31/97
456790122	4114	112	0:16:19	3/31/97
567901233	1054	6	0:16:22	3/31/97
679012344	4096	107	0:16:30	3/31/97
790123455	5107	159	0:16:31	3/31/97
901234566	5000	72	0:16:32	3/31/97
1012345677	5155	162	0:15:41	3/31/97
1123456788	5000	72	0:16:34	3/31/97
1234567899	5155	162	0:16:00	3/31/97
1345679010	5138	161	0:16:35	3/31/97
1456790121	4029	54	0:16:34	3/31/97
1567901232	7011	101	0:16:40	3/31/97
1679012343	5070	157	0:16:47	3/31/97
1790123454	5078	173	0:16:52	3/31/97
1901234565	6043	131	0:16:56	3/31/97
2012345676	4042	55	0:16:55	3/31/97
2123456787	4048	58	0:17:06	3/31/97

Figure 5-5. Typical AVI Tag Reads in ASCII Text File

5. **Access archived travel time data**. Travel time data files can be accessed from the archives for specific days. Files may be archived in a binary format. If you are using a spreadsheet package or statistical analysis software, it may be necessary to run a conversion process on the files to transform them into a text format or accessible format.

6. **Consider creating anonymous data file**. The tag read matching process is based on matching unique tag ID numbers which correspond to individually identifiable persons. These ID numbers often remain in the data files and they can be useful for tracking vehicles for origin/destination studies. However, problems can arise due to the sensitivity of privacy issues. It is possible to assign an anonymous ID number

to each original tag ID number. This reassigned anonymous ID does not correspond to an individually identifiable account, yet it retains the ability to track vehicles for origin/destination studies. Once the anonymous file is created, the original tag ID numbers can be discarded.

5.2.5 Previous Experience

This section describes several AVI systems in the U.S. and describes actual experiences and practices of the operating agencies. The Texas Department of Transportation (TxDOT) has helped to develop the TranStar system in Houston which operates an AVI system in order to monitor traffic conditions, detect incidents, distribute travel information, and archive travel time data. TxDOT is currently developing an AVI system in San Antonio to monitor traffic conditions and detect incidents. The Washington State Transportation Center (TRAC) studied AVI use in Seattle's Puget Sound region in 1994. The TRANSCOM agency operates the TRANSMIT system in New York and New Jersey to monitor traffic conditions with AVI technology. In addition, several AVI systems are operated abroad, and system design criteria from these systems are useful for U.S. applications. The experiences of these agencies can provide useful support for designing and managing AVI systems and effectively collecting quality travel time data.

TranStar Traffic Monitoring System, Houston, Texas

Antenna installation specifications - Antennas are mounted above traffic on existing roadway overpasses, overhead sign structures, or side-mount sign structures. Antenna spacing depends on the availability of existing structures, and spacings are typically 2 km (1.2 mi). The actual range of spacings is between 1.4 km (0.9 mi) and 10.8 km (6.7 mi) with an average of about 4.6 km (2.85 mi).

Antenna capture range setting - The Houston system uses two general antenna types. One antenna type emits a directional, narrow, and long RF capture range. These narrow band projecting antennas are mounted over high-occupancy vehicle (HOV) lanes and inside freeway main lanes to prevent false reads from adjacent lanes. The second antenna type emits a broader and shorter RF capture range, and these types are mounted over outside freeway main lanes. A typical installation configuration of these two antenna types is shown in Figure 5-6.

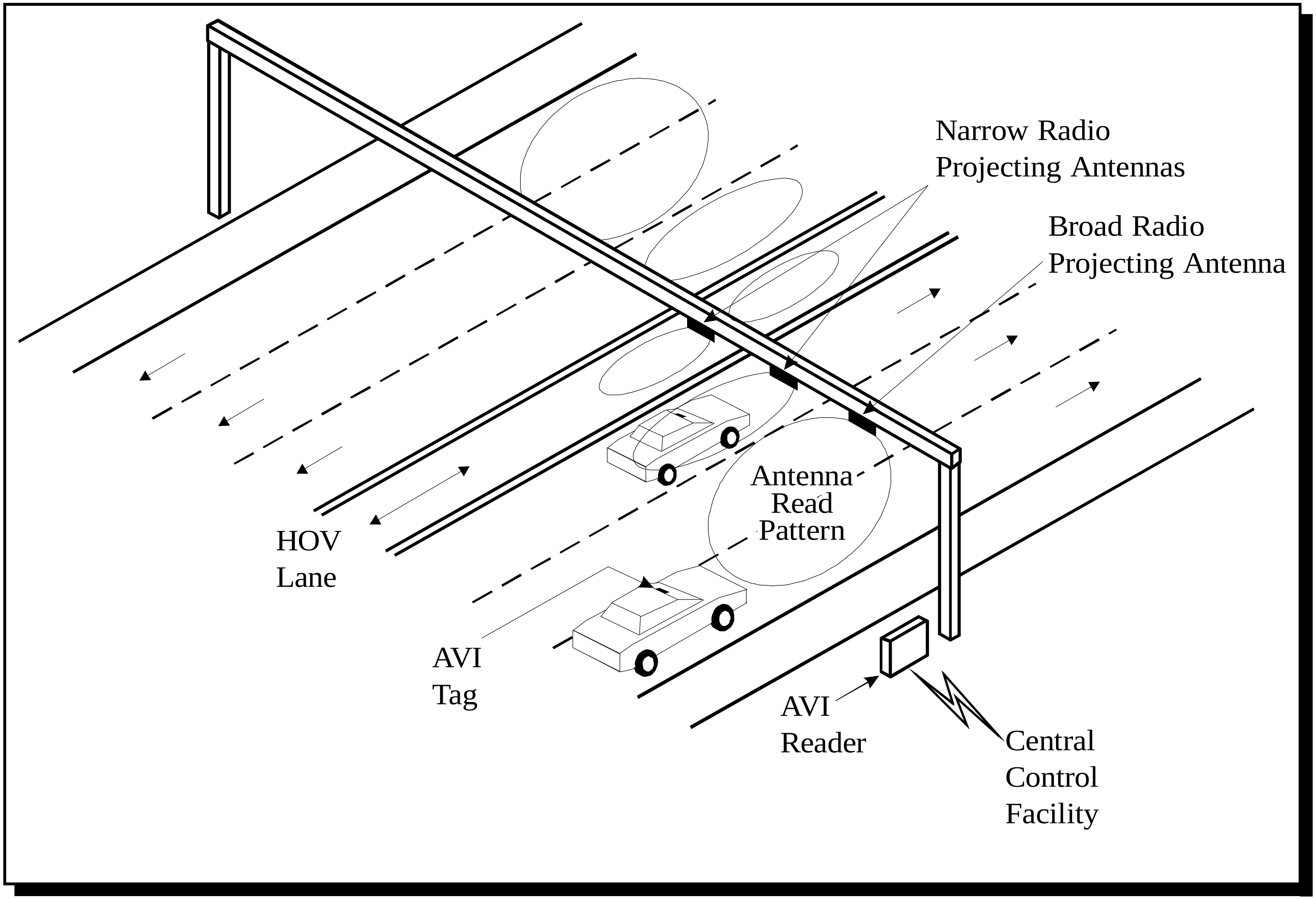


Figure 5-6. Typical AVI Antenna Mounting in Houston, Texas

AVI tag distribution - Motorists traveling during the peak period were targeted to receive electronic tags from the Texas Department of Transportation (TxDOT) through a recruitment process. The system also relied upon vehicles equipped with ETC tags from the local toll authority to supplement peak period coverage and provide for off-peak period coverage. Over 200,000 tags have been distributed through the local automated toll collection system (23) to date.

Probe vehicle driver recruitment - Citizens were reluctant to place an electronic tracking device in their vehicles. Volunteer drivers were sought through correspondence with large employers, advertising over news media, advertising on changeable message signs and trailer message signs, and advertising on the Internet. The most effective method of driver recruitment was through changeable message signs and trailer message signs along the freeways. Signs identified an appropriate telephone number to seek an explanation of the AVI system.

Probe vehicle density/tag read frequency - When planning for the system, the target rate was one probe vehicle or one tag read per antenna location per one minute. This target rate was set because it required one minute to process field data to the central facility. Approximately five percent of the total volume passing antenna locations yield tag reads. This corresponds to approximately four tag reads per minute during peak periods and about three tag reads per minute during off-peak periods. About 60 percent of the tag reads were correctly matched with tag reads at sequential antenna locations to yield a travel time data point.

Data archival - In the Houston AVI system, the travel time data are stored in an Oracle relational database. Travel time data are stored in binary files, and one binary file is created for each 24-hour period (24). Daily files can be extracted from the archive in order to analyze one day of data at a time.

Automatic Vehicle Identification System, San Antonio, Texas

The Texas Department of Transportation and the City of San Antonio are planning the development of a real-time traffic monitoring system using AVI technology.

Antenna spacing - Site selection for antennas was based partly on an analysis of volume to capacity (v/c) ratios to determine the most congested areas of the freeway system. These congested areas were ranked by congestion priority, and care was taken to ensure that antenna distribution was balanced throughout the system.

Antennas were spaced at 1.6 km (1 mi) to 3.2 km (2 mi) intervals. Travel patterns were considered to determine where the greatest number of tag reads would occur. Field evaluations were necessary to determine if antennas could be mounted on existing structures. Mounting on existing structures can significantly reduce the installation costs.

AVI tag distribution - Initially, it was decided to distribute AVI tags through the vehicle registration process. However, the process of distributing tags through the registration system and to motorists required one year which was beyond the system's schedule. Approximately 80,000 tags will be distributed. This quantity was established based upon budgetary constraints.

Tags were to be randomly distributed to large employers in the area. The system designers were attempting to target motorists who traveled the corridors within the AVI coverage area during the peak hours. No record was to exist of any particular tag placed in any particular vehicle. Tag ID numbers were to be scrambled to prevent the ability to track individuals.

Data management and reduction equipment specifications included provisions for a 167 MHZ computer, two 2.1 gigabyte hard drives, and 128 megabytes of random access memory (RAM) desktop memory.

New York/New Jersey TRANSMIT System

The TRANSCOM System for Managing Incidents and Traffic (TRANSMIT) system operates on 29 km (18 mi) of the New York State Thruway and Garden State Parkway in New York and New Jersey. About 23 antenna locations are a part of the $1.4 million system.

The TRANSMIT system follows these guidelines:

- **Antenna spacing** of 2.4 km (1.5 mi) for maximum incident detection time of five minutes;
- **Probe vehicle density specifications** of 0.9 percent of total volume for two-lane highways and 2.1 percent for three- and four-lane highways;
- **One antenna** used to cover all lanes in one direction; and
- **Antenna mounting** utilized existing overhead structures.

Puget Sound Region Study

The Washington State Transportation Center (TRAC) studied AVI use in Seattle's Puget Sound region in 1994. A combination of 50 electronic transmitters and 10 antenna units made up the infrastructure. This system used an AVI loop detection type system with the 50 in-vehicle transmitters installed underneath the vehicle.

Sequential antenna spacing was between 1 and 4 km (0.62 to 2.5 mi) with an average distance of 2.6 km (1.61 mi) (23).

European AVI Systems

Several AVI systems are operated abroad, and system design criteria from these systems are useful for U.S. applications. The Automatic Debiting Electronic Payment in Transport (ADEPT) project is an electronic toll collection (ETC) system using two-way communications between in-vehicle tags and roadside beacons (13). Type III tags, or "smart" tags contain vehicle identification, driver, financial, and other data. Toll transactions are processed within the in-vehicle tag. Since the system was designed to collect tolls, the accuracy and quality of data are very good with only one tag in 1,000,000 tags missed or incorrectly detected. Speeds as high as 140 km/h (87 mph) have been detected by the system. The main technical problem was ensuring that the system could distinguish between vehicles across multiple traffic lanes.

One estimation of AVI technology costs offered cost data based on two unique installations (13). The first installation technique requires that a single AVI antenna is required for each lane of traffic with a cost of $8,200 for site installation. It was estimated that the cost of one antenna per lane was $1,600. The second installation technique assumes that one antenna covers an entire direction of travel. For a two-directional roadway, two antennas are required per site at a cost of $3,200 in addition to the $8,200 site installation charge. Communications costs were estimated based on a theoretical AVI system (13). The theoretical system's infrastructure covered 450 directional links of multi-lane roadways carrying 75,000 vehicle per day, 750 directional links of four-lane roadways carrying 50,000 vehicles per day, and 750 directional lanes of two-lane roadways carrying 25,000 vehicles per day.

The most cost-effective method to provide communication links to antenna sites was ISDN lines. It was estimated that the annual costs of ISDN communications for the theoretical AVI system would be $1,100,000 in addition to installation fees. Annual leased-line costs for the same system were estimated at $5,400,000 plus $2,800,000 for installation. Annual radio data communications costs for the same system were estimated at $9,500,000.

An AVI system on the Oslo toll ring in Norway collects data from 400,000 probe vehicles (25). The system has been especially sensitive to Norwegian privacy legislation, such as the Personal Data Register Act of 1978. Under this law, a record of AVI tag identity is defined as a personal data register, and the unique seven digit tag ID was truncated to the last three digits. This truncation allowed the vehicles to remain anonymous and records were no longer defined as personal data files.

The Oslo toll ring AVI system tracks vehicles, calculates travel times between antennas, and averages travel times every five minutes for each section within the field reader units. The averaged travel time data are transmitted every five minutes to a traffic control center. Maximum volumes at test sites are about 1,200 to 1,400 vehicles per lane per hour, or about 100 to 120 vehicles per five-minute interval. Since one-third of the total traffic population is equipped with AVI tags, about 30 to 35 probe vehicles are recorded every five minutes during maximum volume at test sites. However, about 20 vehicles pass test sites every five minutes on average (25).

5.3 Ground-Based Radio Navigation

Ground-based radio navigation is also referred to as terrestrial radio navigation and as radio triangulation. This method involves the use of a receiving antenna network and probe vehicles which are equipped with electronic transponders. Ground-based radio navigation is commonly used by transit agencies and private companies to manage fleet operations. The ground-based radio navigation communication process is illustrated in Figure 5-7. A central computer facility solicits the location of a probe vehicle according to either a controller's request or a prescheduled location interval. Once the probe vehicle receives the location request, it transmits its unique ID code and the transmission time via a radio frequency (RF) signal. The ID code and time stamp are received by multiple antenna towers which then relay the data to the central computer facility.

These RF signals travel linearly between the probe vehicle and radio tower and at a constant known velocity. Thus, the system can calculate the linear distance of the probe vehicle from an individual tower based on the product of the signal's velocity and travel time. The probe vehicle's location is estimated by a triangulation technique. A probe vehicle's mathematically unique position may be determined if four tower sites receive transmissions from the probe vehicle (26).

Ground-Based Radio Navigation Market

Ground-based radio navigation systems are typically subscriber-based. A small number of private companies provide ground-based navigational services to primarily private companies that want to monitor their drivers or fleet vehicles. The majority of fleet management and navigational services utilize GPS technology, however, some ground-based services continue to prosper. Ground-based radio navigation infrastructure is established in several major U.S. cities including Chicago, Dallas/Forth Worth, Detroit, Houston, Los Angeles, and Miami. The ground-based navigation market is expanding into other major U.S. cities (27).

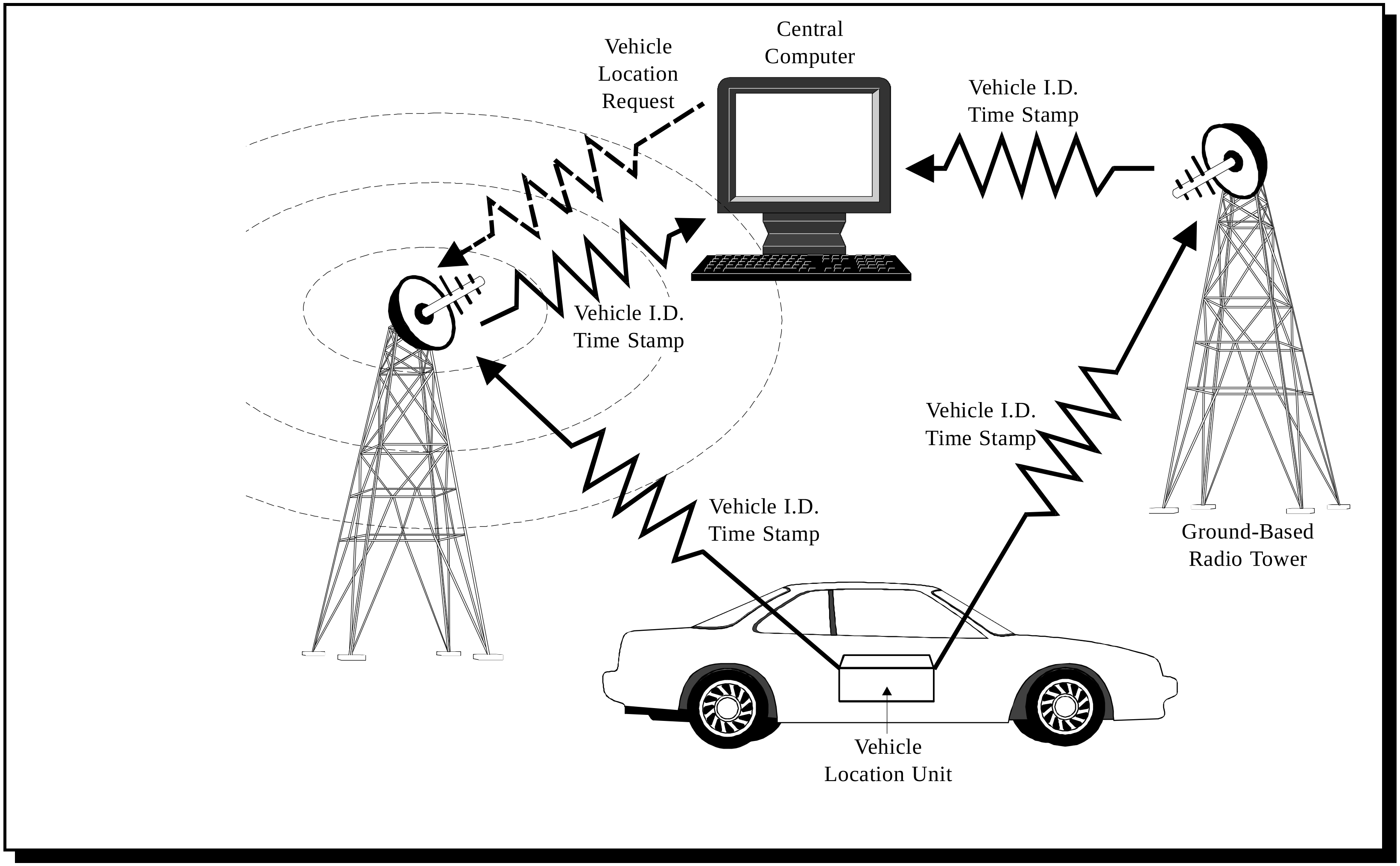


Figure 5-7. Ground-Based Radio Navigation Communication Process

5.3.1 Advantages and Disadvantages

The **advantages** of ground-based radio navigation for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Low start-up cost** data collection approach compared to other probe vehicle methods if ground-based radio navigation service is available in your area.

- **Expanding market** means more widespread use of technology.

- **Relatively simple** data collection if a ground-based location service provider is available in your area.

The **disadvantages** of ground-based radio navigation for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Low precision** - The accuracy of the locating system is between 15 to 46 m (50 to 150 ft), and errors as high as several hundred meters have been reported. Accuracy is affected by the topography of the land and mounting and power setting of the in-vehicle equipment.

- **Antiquated technology** - Ground-based radio navigation technology is less sophisticated and less precise than GPS technologies.

- **Dense urban areas** - RF signals can have difficulty penetrating in urban areas. Radio tower infrastructure can be difficult to mount in dense urban areas.

- **Non-representative data** - Technology is typically used by commercial vehicles or transit agencies. Thus, travel time data collected from these agencies may be biased towards transit or commercial drivers or vehicles and may not represent the driving population.

- **Privately-owned data** - Ground-based navigation systems are mainly operated by private companies. If you wish to utilize data collected from an outside party, the company must agree to provide data access.

- **Small market** - Ground-based radio navigation is currently available in only select cities, and is feasible in only dense urban areas with large market potential.

- **Driver recruitment** - May need to recruit volunteers to drive probe vehicles depending on the size and scope of the study.

5.3.2 Cost and Equipment Requirements

The ground-based radio navigation data collection process requires the equipment listed below. As described previously, since probe vehicle systems are often installed initially for uses unrelated to travel time data collection, other agencies interested in the system may aid in subsidizing the costs of the system.

- **In-Vehicle Transponders** - Transponders may be installed within approximately 30 minutes, depending upon the installer. The entire in-vehicle AVL unit consists of a control unit (about the size of a video cassette) and a pancake-shaped antenna. The control unit must be connected to the vehicle's ignition and is typically mounted underneath the steering column. The unit detects when a trip has begun or ended based on when the ignition has been triggered or terminated.

- **Personal Computer Workstation** - A 386 microprocessor has proven sufficient to run the proprietary software package. The personal computer must have a high-speed (14,400 bps) modem connection to the service provider.

- **Proprietary Software** - Since the service is provided by a private company, software is typically proprietary and is provided upon subscription to the service. Software requires a DOS operating system and the map database files for the coverage area. The software is typically configured to request the locations of vehicles every 30 seconds when ignition is on and every 5 minutes when ignition is off. The software can write data to an ASCII text file, and location data can be in a longitude/latitude format or in a street/nearest cross street format (26).

- **Software Training** - Relatively simple and can be done within one day.

- **Service Start-Up Costs** - A fee must be paid to the service provider to initiate service. This fee can cost as much as several thousand dollars depending upon the size of the study. However, public institutions have been given discounts.

- **Monthly Service Costs** - A monthly fee is charged in addition to the start-up costs. This fee typically runs about several hundred dollars for in-vehicle equipment rental and services.

- **Supervision and Management** - Required to obtain and reduce the data.

5.3.3 Data Collection Instructions

The ground-based navigation technique is commonly used by private agencies, such as couriers. It may be possible to obtain an agreement with an agency to utilize data collected from their fleet vehicles. However, these data will most likely be biased towards transit or commercial vehicles' atypical travel patterns. It will also be difficult to negotiate an agreement to access their data. The alternative is to establish an agreement with a service provider in your area and use probe vehicles similar to a test vehicle method. In this case, the following steps should be taken:

1. **Determine if service is available** in your area. Recall that this service is currently available in several U.S. cities, including Chicago, Dallas/Forth Worth, Detroit, Houston, Los Angeles, and Miami, and service is expanding to other cities.

2. **Obtain a service agreement** with ground-based radio navigation service provider.

3. **Establish study links** - Make sure that desired links in the study are within the provider's service area.

4. **Determine sample size** - You can select the number of probe vehicles that you wish to use for data collection. The vehicles will be instrumented with the necessary navigation equipment.

5. **Identify reliable drivers** - Determine who will be driving the probe vehicles. This may involve recruiting drivers and offering them incentives for participating.

6. **Install in-vehicle navigation equipment** in the probe vehicle fleet.

7. **Determine the polling interval** at which you wish to poll the probe vehicles for data.

8. **Archive data and process** for necessary analysis application. Depending on the size of the system (number of probe vehicles, number of link, number of trips) a typical day of data may consume several megabytes of storage space. Typically, proprietary software can automatically save daily data to a new file at the end of a day.

9. **Develop electronic report -** The proprietary software typically generates a raw data file in a useful file format, such as an ASCII text file. If this is not the case, it is necessary to configure the software to generate the report electronically.

10. **Analyze data** with a common spreadsheet or statistical analysis package.

5.3.4 Data Reduction and Quality Control

Several steps should be taken to reduce the raw data into useful travel time data. This section describes these steps which facilitate the processing of quality travel time data.

Calculate difference in sequential data points to determine the link travel time. The output contains the vehicle ID, location, and time. In order to determine the distance traveled between two locations, you must calculate the hypotenuse between sequential latitude/longitude data using Equation 5-1 or the difference between sequential cross street locations. Next, it is necessary to take the difference in time stamps from the sequential data points. Table 5-4 and Table 5-5 show replications of a typical ground-based radio navigation system software output. Table 5-4 shows the location of the probe vehicle to the nearest cross street along the traveled link. Table 5-5 shows the probe vehicle's latitude and longitude. The ASCII file report can be configured to report location data in a similar layout to the reports shown in these tables. Notice that the output contains speed data for the previously traveled link. The travel time for the previously traveled link can be determined by taking the inverse of the speed data. However, it is still necessary to calculate the distance of the link.

Table 5-4. Replication of Ground-Based Radio Navigation Vehicle Location Output Showing Nearest Cross Street

Vehicle ID	Speed/Direction	Time	Date	Route	Nearest Cross St.
1234	35 North	07:36:33 am	08/23/95	Texas Ave.	G. Bush Dr.

Table 5-5. Replication of Ground-Based Radio Navigation Vehicle Location Output Showing Latitude/Longitude

Vehicle ID	Speed/Direction	Time	Date	Latitude	Longitude
1234	35 North	07:36:33 am	08/23/95	25.74728	80.21642

$$z = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{5-1}$$

where: z = hypotenuse, or traveled distance;
x_1 = latitude at location 1;
x_2 = latitude at location 2;
y_1 = longitude at location 1; and
y_1 = longitude at location 2.

A minimum link length of less than 0.000224 geographic units, or about 24 m (80 ft), is often the limit for which a travel time can be determined. Software typically assumes that the difference in vehicle location readings less than this length is due to inaccuracies with the positioning technology and will default the distance to zero.

Avoid short link lengths when measuring travel times. Research suggests that the location accuracy of ground-based radio navigation can vary several hundred meters. For short distances, this error could skew the travel time measurement significantly. For example, for a link of 1,000 m (3,281 ft), an error of plus of minus 30 m (100 ft) could skew the travel time measurement by 20 percent.

Validate the accuracy of your data by performing simultaneous floating vehicle runs while collecting data with a probe vehicle. This can indicate whether or not the system is estimating travel times accurately. This can also verify that the system is tracking the probe vehicle on the intended link and not on an adjacent roadway.

Ensure proper installation of in-vehicle equipment. The power setting of the in-vehicle transmitter and the mounting of the in-vehicle antenna can affect the system's ability to accurately locate a vehicle. Equipment is typically installed by the service provider.

5.3.5 Previous Experience

Ground-based radio navigation technology is typically used in the commercial sector for commercial fleet management services. Two studies by public research institutions have investigated the ability of ground-based radio navigation technologies to collect accurate travel time data. The Center for Urban Transportation Research (CUTR) of the University of South Florida and the Texas Transportation Institute investigated the accuracy of the technology. Their findings are presented in this section.

Center for Urban Transportation Research Study

A study by the Center for Urban Transportation Research (CUTR) at the University of South Florida conducted 30 validation runs during a 113-day period with test vehicles. The study tested differences in speed output from the ground-based radio navigation system and the test vehicles. Study results suggested a mean difference of 1.72 km/h ± 1.38 mph (1.07 km/h ± 0.86 mph) with 95 percent level of confidence (28). Differences between the ground-based navigation speed values and the manually collected speed values followed a normal distribution.

The CUTR staff configured the proprietary software to generate an electronic report of vehicle location, time, date, and speed data in an ASCII text format. They also developed software to analyze the data and report on average speeds. The proprietary software saved the day's vehicle location data in a new file for that particular day. For a four-month period, the system logged over 4,400 trips which required about 150 megabytes of computer storage space (26).

Drivers were recruited for the study and were given an incentive of a vehicle maintenance service. This service is offered to all qualifying south Florida motorists vehicle breakdown service and stolen vehicle recovery for $300 per month, however, it was offered free-of-charge to study participants.

Texas Transportation Institute Study, Houston, Texas

A Texas Transportation Institute (TTI) study in Houston evaluated ground-based radio navigation accuracy based on its ability to locate a stationary probe vehicle in a high-density urban environment, locate a stationary probe vehicle along the periphery of the service area, and locate a moving probe vehicle (29). The location measurements were referenced to a point of known latitude and longitude.

Outside the central business district (CBD), the ground-based navigation technique located probe vehicles to within 30 m (98 ft) in 61 percent of all attempts. This satisfies the nominal global positioning system (GPS) accuracy of 30 m (98 ft). In the CBD, 26 percent of measurements were within 30 m (98 ft), as validated by differential GPS. Ninety-three percent of all measurements in the CBD and non-CBD areas were within 100 m (330 ft), and 43 percent of all measurements were within 30 m (98 ft). The range of vehicle location measurements was between one and 785 m (2,580 ft) from the reference point.

The average difference between the ground-based measurement and differential GPS measurement in CBD areas was about 56 m (180 ft) with a standard deviation of about 70 m (230 ft). In non-CBD areas, the difference was about 34 m (110 ft) with a standard deviation of about 90 m (295 ft). The test results suggested that little difference existed in the accuracy of ground-based navigation location measurements within the service area and near the periphery of the service area. In testing the accuracy of ground-based radio navigation at locating moving probe vehicles, the study suggested that accuracy remained relatively constant at speeds between zero and 80 km/h (50 mph).

5.4 Cellular Phone Tracking

Cellular telephones have been used to collect travel time data in several major U.S. cities. Two data collection techniques have been applied using cellular technology: cellular telephone reporting and cellular geolocating. The cellular reporting method has been utilized in the Boston, Massachusetts Smart Route System and as a pilot study to the Houston, Texas AVI traffic monitoring system. Cellular geolocating has been tested only once through an operational test in the Washington, D.C. area. Both methods are described, although this section emphasizes the cellular geolocation technique.

Cellular Telephone Reporting

Cellular reporting requires volunteer drivers to call a central facility when they pass checkpoints along the freeway. An operator at the central control facility records each driver's identification, location, and time (15). By monitoring the time between successive telephone calls, the travel time or travel speed between reporting locations may be determined (30).

The technique is useful for reporting a qualitative assessment of current traffic conditions (e.g., stop-and-go, bumper-to-bumper, free flow) and for collecting travel time data during delays or accidents since the incident can be visually confirmed. However, probe vehicle drivers often miss checkpoints or fail to report locations at the proper times. Further, travel times can be skewed by one or two minutes and can vary between individual probe vehicle reports. The cellular telephone reporting method is recommended for short-term studies with low accuracy requirements.

Cellular Geolocation

The cellular geolocating methodology discreetly tracks cellular telephone calls to collect travel time data and monitor freeway conditions. Use of cellular geolocating is limited to one operational test conducted in the Washington, D.C. area. This operational test was sponsored by private and public organizations under the project name Cellular APplied to ITS Tracking And Location (CAPITAL). The technique utilizes an existing cellular telephone network, vehicle locating devices, and a central control facility to collect travel time data. All vehicles equipped with cellular telephones are potential probe vehicles. The system automatically detects cellular telephone call initiations and locates the respective probe vehicle within a few seconds. Vehicles are not actively sought by the system, but vehicles initiating cellular phone calls are monitored by the system.

An illustration of cellular geolocation communications are shown in Figure 5-8. The system searches for vehicles initiating cellular telephone calls by processing the cellular reverse control channels (phone-to-tower) and identifying when a mobile telephone transmits a message. Simultaneously, the forward control channel (tower-to-phone) is examined for the assignment of communication channels to mobile telephones. The geolocating component of the system identifies when a cellular telephone transmits a call initiation message. Direction finding equipment located at multiple sites in the area determine the origin of the telephone call.

The probe vehicles' locations are determined by a combination of lines of bearing and time difference of arrival calculations by the direction finding system to geolocate a vehicle (31). Intersecting lines of bearing are used to triangulate probe vehicles' locations. Time-difference-of-arrival method calculates the location based on signal propagation times between the vehicle and nearby cellular towers. The system has the capability of tracking the cellular activity of probe vehicles even as the vehicle passes through multiple cell sites and when the telephone call switches cellular channels.

The probe vehicle's location is passed to a traffic information module. By repeating the process every five to seven seconds, sufficient data are generated in 30 to 50 seconds to provide an accurate estimate of the probe vehicle's velocity (32).

Future Direction of Cellular Technology

The Federal Communications Commission (FCC) has adopted a Report and Order which develops rules to govern the implementation of Enhanced 911 (E911) calls for wireless, or cellular, services (33). The ruling requires cellular providers to be capable of relaying the location of the base station or cell site receiving a 911 call to an appropriate Public Safety Answering Point (PSAP). They will also be required to provide the location of the mobile station, or cellular telephone, to the PSAP in two dimensions with an accuracy within a 125 m (410 ft) radius in 67 percent of all instances. These changes are to be implemented over the next several years.

The locations of the cellular telephones will be determined by time difference of arrival techniques (34). These are the techniques used in cellular geolocating methods to collect travel time data. These changes in the cellular industry can affect the feasibility of collecting travel time data cost-effectively since similar service can be used for other codes, such as 555.

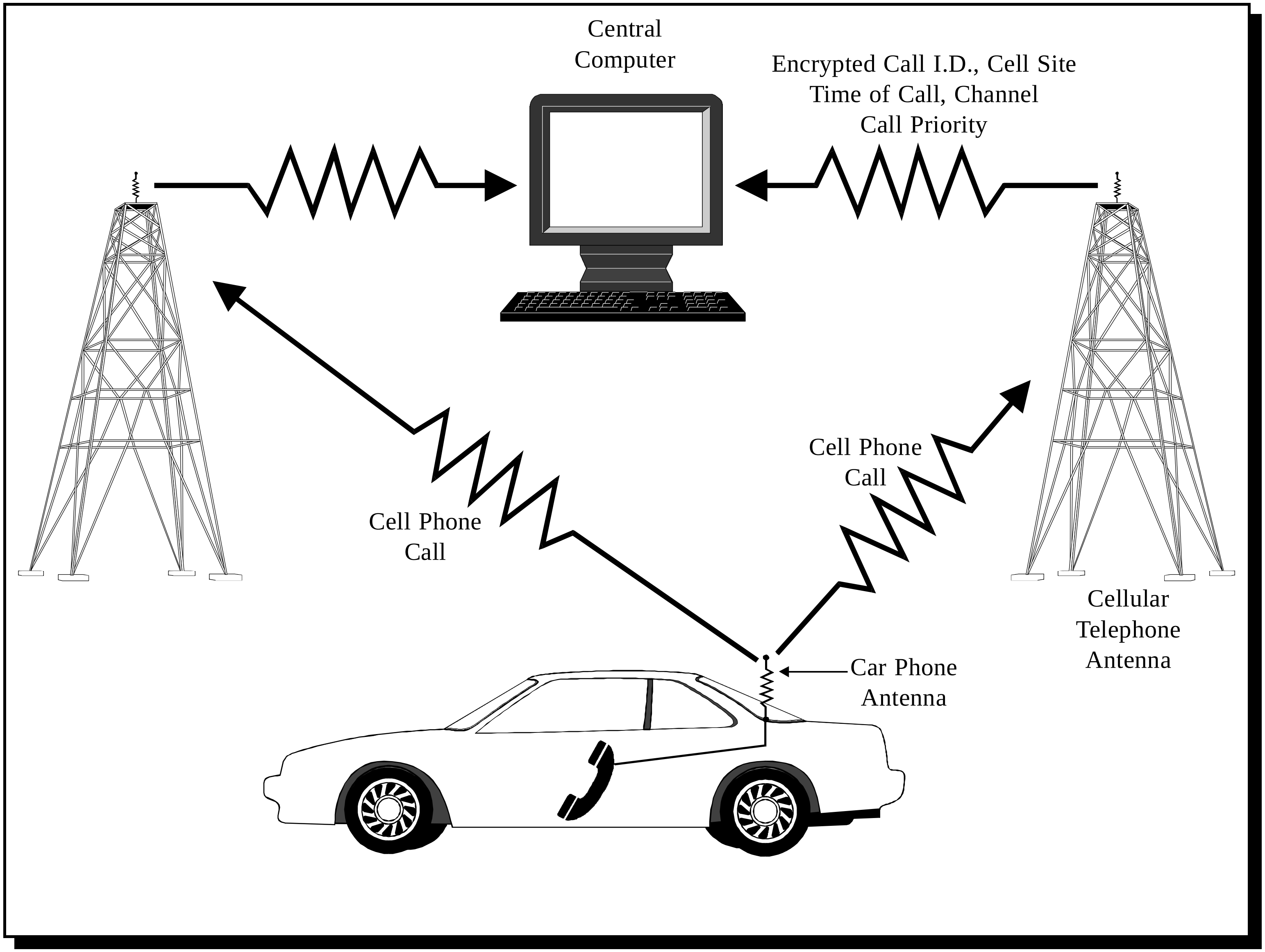


Figure 5-8. Cellular Geolocation Communications

5.4.1 Advantages and Disadvantages

The **advantages** of cellular geolocating for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Driver recruitment not necessary** - The system utilizes samples from the existing population of vehicles equipped with cellular telephones. It is not necessary to recruit volunteers or designate personnel to collect data.

- **No in-vehicle equipment to install.**

- **Large potential sample** - Studies have suggested that cellular telephone use increases as congestion increases (35). As cellular telephone ownership increases, the number of potential probe vehicles increases.

The **disadvantages** of cellular geolocating for travel time collection (relative to other ITS probe vehicle techniques) are:

- **Experimental technology** - To date, cellular geolocating has been tested only once through the CAPITAL Operational Test in the Washington, D.C. area.

- **Privacy issues** - The nature of cellular geolocating may offend persons concerned that cellular telephone calls may be monitored and that their vehicles may be tracked.

- **Infrastructure dependent** - Since the system is constrained by existing cellular infrastructure, it is impractical to readily modify the study area for data collection. Extending or adjusting the study area requires moving cellular towers and/or the geolocating equipment. Study is limited to links within the coverage area of the cellular network.

- **Cellular phone use dependent** - Travel time data collection can break down during periods of low cellular telephone use.

- **Low accuracy** - Testing of this technology has suggested it is adequate for determining if a probe vehicle is on a particular road, however, it was shown to be accurate at estimating travel times in 20 percent of all instances. Often geolocating a vehicle's position is impaired by topography and line of sight barriers. Testing of the geolocating system reported average geolocating errors between 107 to 650 meters (351 to 2,133 feet) (31).

- **Potentially biased sample -** Sample is biased towards motorists which have and use cellular telephones. There may exist personality aspects of cellular phone users which may or may not affect driving behavior.

5.4.2 Cost and Equipment Requirements

All information on the cost of equipment for cellular geolocation is based on the findings of the CAPITAL Operational Test. Much of the total system cost was attributed to research and development of the technology. The CAPITAL study assessed the capital and installation investments; however, operational and maintenance costs are not known.

A cellular geolocating system requires the presence of a cellular infrastructure of cellular towers and vehicles equipped with cellular telephones. It is also necessary to establish permission to utilize the cellular network from the cellular system operator. The CAPITAL system consisted of two primary components that were necessary to collect probe vehicle data: a geolocation component and a traffic information component.

Geolocation Component

This component is responsible for recognizing cellular calls, monitoring call switching between cellular channels, prioritizing calls, and calculating geolocations, lines of bearing, and time-differences-of-arrivals for signals. The geolocation component contains specially designed arrays of antennas and electronic equipment which monitor call initiation signals from cellular phones to provide directions from the cell towers to the telephone locations. Signals from multiple towers are used to derive latitude and longitude of phone locations. Within the geolocation component are several subcomponents, which utilize various equipment to perform the necessary geolocation component tasks. The three sub-components and the respective equipment requirements are (31):

- **Transmission Alert System** - This element was responsible for identifying new calls and alerting the geolocation control system with call data. This subcomponent costs approximately $200,000 per unit, including equipment and installation costs (31). The Transmission Alert System requires:
    - Wideband cellular call receivers; and
    - Digital narrowband cellular call receivers.

- **Geolocation Control System** - This subcomponent is needed for calculating the geolocation of probe vehicles. The installation and equipment costs for this subcomponent are approximately $150,000 (31). It requires personal computers.

- **Direction Finding System** - This subcomponent is necessary for calculating the lines of bearing and time differences in arrival of signals. One such system cost $310,000 (31). The directional finding equipment are installed at existing cellular tower sites. Some electronic equipment must be housed in an environmentally controlled structure. It requires:

- eight-element antennas;
- math processor;
- Octal digital receiver;
- synchronized system clocks (accurate within 100 nanosecond); and
- GPS receiver.

Traffic Information Component

A central facility receives all data and processes them into useful travel information. This component is responsible for determining the locations, travel times, and speeds of probe vehicles.

5.4.3 System Design Considerations

This section describes several issues which can affect the quality of travel time data. These are potentially problematic issues which should be addressed in the design of a cellular geolocation system.

Insufficient signal strengths - Cellular service providers are required to use certain amounts of the radio spectrum. A provider's usable radio spectrum is divided into channels. Each call requires two channels: receive and transmit. In areas with large cellular service demands, the cellular network is designed to reuse channels by managing the power and direction of signals from the tower to the telephone and managing the power of the signal from the telephone to the tower. An ideal power level is strong enough for calls to be interpreted yet weak enough to prevent cross-talking between phones in different cells using the same channel. Reusing channels is more critical as cellular telephone use increases. Additional antennas are installed and signal strength is further weakened to avoid cross-talk.

Insufficient tower infrastructure - If signal strength is too weak, the existing tower infrastructure may be insufficient to interpret signals for accurate geolocation. The installation of additional tower sites may be necessary. The use of directional antennas, as opposed to omni-directional, restricts the ability to interpret signals, as well.

Observe legal issues - Use of this type system should comply with the Telephone Disclosure and Disputes Resolution Act and Federal Communications Commission (FCC) Docket 93-1 which implements that act given that the phone call receiving equipment is used under contract with the federal government and in concert with licensed cellular providers.

Observe privacy issues - The identity of telephone numbers or electronic serial numbers should not be accessible to anyone operating the system. Voice conversations should not be monitored. The system can function even if transmissions are assigned random or encrypted identification numbers which do not allow specific caller information to be obtained.

5.4.4 Data Reduction and Quality Control

This section describes several problems which can occur when geolocating vehicles. These problems have been encountered in previous cellular geolocation studies (35). Data collection of quality travel time data can be impaired by:

- **Bridge structures** - it can be difficult to interpret the altitude of a probe vehicle to determine if it is atop or underneath a bridge structure.

- **Adjacent roadways** - the location system does not have pin-point accuracy, and it can be difficult to determine if vehicles are on adjacent roadways to the freeway.

- **Roadside emergency phones** - it is necessary to identify if a call is coming from a roadside emergency phone or roadside cellular phone.

5.4.5 Previous Experience

The CAPITAL operational test in the Washington, D.C. area is the only identifiable case of cellular geolocation. This section presents the data flow involved in the data collection process and also more detailed descriptions of design considerations.

In the CAPITAL project, the travel time data collection process involved four basic steps:

1. Call initiation received by geolocation control system and a message sent to the traffic information center containing the following data:

    - time stamp;
    - encrypted ID number;
    - latitude and longitude;
    - information on whether or not a 911 call was initiated;
    - flag to indicate if call was initiated within boundary of study;
    - sector number indicating specific area of cell tower; and
    - confidence factor of the latitude/longitude accuracy.

2. Traffic information center receives data. If data is within bounds, it is not discarded and the system determines if the phone is on a mapped traffic link. If the phone is not on a map link, monitoring is stopped. If the vehicle is on a map link, additional geolocating is performed to more accurately determine its location. At this point,

direction is unknown, however, it is determined that the vehicle is on either directional link.

3. The geolocation system performs additional geolocation functions and the received data are sent to the traffic information system.

4. When the traffic information system receives the second geolocation data package on an identified phone ID, the direction of the vehicle is determined and the travel speed is calculated based on the vehicle's travel time between two locations on the link.

Static geolocation accuracy tests were conducted at several locations of known latitude and longitude (U.S. Geological Survey markers and state benchmarks). With a sample of 24 static test locations tested during four days, the errors in geolocation accuracy fell between 107 m (350 ft) and 649 m (2,130 ft) (31). Differential GPS units served as a comparison to the cellular geolocation results. The error was defined as the difference between the cellular geolocation data and the differential GPS data. The poor location accuracy was attributed to topographic interference and line-of-sight problems.

The system's ability to estimate average speeds was tested in a comparison of system output to test vehicle output. Study results suggested that reasonable speeds were estimated only 20 percent of the time (31). Reasonable speeds were those determined similar to results from test vehicle runs.

University of Technology, Sydney, Australia

A recent study at the University of Technology in Sydney, Australia evaluated the use of Mobile Telephone Positioning Systems (MTPS) for vehicle positioning applications (36). The study presents the potential for success of MTPS in the future. More specifically, the study compares MTPS with the more common application of using the global positioning system (GPS) for positional information. The study describes how positional information can be supplied through a MTPS system for use in applications such as fleet operations, occasional location determination, congestion detection, navigation and route guidance, and geographic referencing.

The study makes the following points when comparing GPS and MTPS (36).

- Cellular networks in major cities operate hundreds of base stations, often with many different frequencies. This gives a far greater diversity than GPS, which may only have at best four to eight satellites visible at a particular location. This diversity is particularly important in urban areas where occlusion and multipath can seriously degrade GPS positioning.

- Many ITS applications require a communication facility as well as positioning. An MTPS can provide both facilities in a single system.

- Although the cost of GPS receivers is dropping, it will always be a finite cost. A positioning facility can be added to some cellular communication systems with no changes to the mobile handsets and relatively minor changes to the network.

Although the study presents these benefits of using MTPS, the study also discusses issues that are associated with the successful development of an MTPS. These complications include interference from co-channels or adjacent channels, equipment delay time, signal occlusion, and geometrical errors to name a few. Ingenuity and careful design are suggested to help alleviate these concerns. Privacy and security, two non-technical but equally important issues, are also discussed by the authors as critical considerations in the development and implementation of such a system.

With increasing bandwidth availability of new cellular systems, the authors expect an increase in the use of MTPS. The authors also note the anticipated increases in accuracy and coverage of MTPS in the future.

5.5 Global Positioning System

The Global Positioning System (GPS) was originally developed by the Department of Defense for the tracking of military ships, aircraft, and ground vehicles. Signals are sent from the 24 satellites orbiting the earth at 20,120 km (12,500 mi) (see Figure 3-1). These signals can be utilized to monitor location, direction, and speed anywhere in the world. A consumer market has quickly developed for many civil, commercial, and research applications of GPS technology including recreational (e.g., backpacking, boating), maritime shipping, international air traffic management, and vehicle navigation. The location and navigation advantages of GPS have found many uses in the transportation profession (37).

The reader is encouraged to review Section 3.3.1 for additional discussion of GPS including its operation and increasing usage. Chapter Three discussed the use of GPS as a test vehicle data collection technique. The test vehicle technique involves collecting data with the aid of an instrumented vehicle capable of receiving GPS signals for position information. The data are collected in the field and then downloaded to a central data storage computer after data collection is complete. The global positioning system may also be used to collect real-time positional information from vehicles. Real-time probe vehicle location information is then sent to a central control center for vehicle monitoring. The equipment requirements and set-up are similar to the test-vehicle needs, however, there is the additional need for a two-way communication link (i.e., the probe vehicle must be able to return a signal to a control center).

IMPORTANT ☞ GPS used for ITS probe vehicles has several distinct differences from GPS applications for test vehicles. These include the on-board logging capability, driving behaviors of instrumented vehicles, and accuracy levels.

Currently, there are many applications of automatic vehicle location (AVL) that employ GPS for vehicle tracking in real-time. These include emergency service vehicles (e.g., police, fire, ambulance), rental cars, commercial fleets, taxis, and transit vehicles (38). GPS has proven to be a valuable tracking mechanism for these vehicles to a central location. For emergency service vehicles, dispatching the nearest vehicles is facilitated with this technology. Further, for taxi and transit applications, the technology allows users to know the location of buses and the estimated time of arrival at bus-stops and transit centers. Many transit agencies throughout the country utilize GPS of bus fleets. One of the largest instrumented systems is the Dallas Area Rapid Transit (DART) that has approximately 1,200 buses instrumented with GPS receivers for AVL (39). These probe vehicles that are already instrumented and operating on the transportation system provide a unique opportunity for the collection of travel time data.

This section of the handbook describes the use of GPS for ITS probe vehicle applications to take advantage of vehicles that are already instrumented and operating on the transportation system for the collection of travel time information.

5.5.1 Advantages and Disadvantages

The GPS probe vehicle technique has the following **advantages** (as compared to other ITS probe vehicle methods):

- Relatively low operating cost after initial installation.
- Provides detailed data that are collected continuously along the entire travel time corridor.
- GPS is becoming increasingly available as a consumer product.
- Data collection is automated.

The GPS probe vehicle technique has the following **disadvantages**:

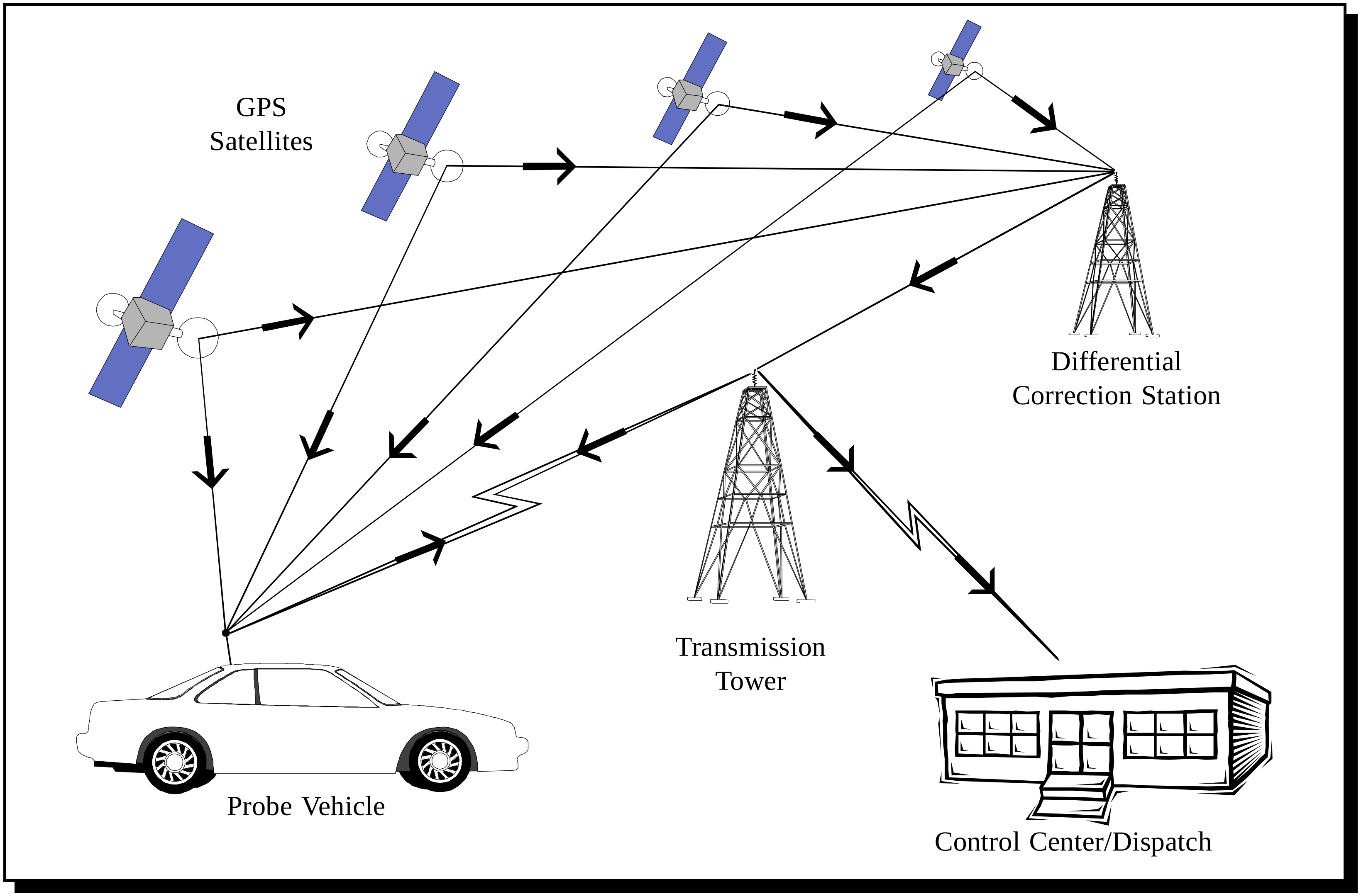
- Privacy issues become a concern when installing GPS receivers on the vehicles of volunteer motorists.
- Signals can be lost in urban areas due to large buildings, trees, tunnels, or parking garages.
- It is difficult to have consistency between drivers due to differences in driving behavior.
- It is necessary to install two-way communication systems to send and receive signals.
- Relatively high installation cost. Since the hardware investment may be initially purchased for a purpose other than travel time data collection, coordination is necessary with the agency that installed the system.

5.5.2 Cost and Equipment Requirements

This section will detail the personnel, hardware, and software needs necessary when considering the use of GPS as a probe vehicle travel time data collection method. Figure 5-9 shows a typical configuration for a GPS-based probe vehicle system. The following sequence of events describes the process of providing positional communications for a probe vehicle as shown in Figure 5-9 (40). This is how existing AVL systems utilizing GPS operate.

- The GPS receiver on the vehicle uses signals from a minimum of four satellites to determine the vehicle's position;
- This information is stored and "waits" to be processed with differential correction data;
- The differential information is then calculated at the differential correction station;
- The differential information is sent by a DGPS beacon transmitter a digital repeater on a transmission tower;
- The digital repeater then transmits this data forward to a second tower or to all probe vehicles within its range;
- The probe vehicles receive the data through a digital radio transceiver that receives and transmits data to and from the transmission tower through the digital repeater. The data are translated by the modem and passed along to the GPS receiver;
- The stored GPS information is then corrected with the differential data;
- The corrected location data is passed to the modem, translated to digital data package, and transmitted back to a digital repeater located on a transmission tower; and
- The digital repeater then verifies the data transmission, and either transmits the data to the control center or relays the data to the next transmission tower until it reaches the control center.

Dispatch and vehicle monitoring personnel would be located in the control center. It is this individual's responsibility to monitor the vehicle location information for bus operations. For emergency vehicles, the dispatcher would be responsible for ensuring that the most appropriate vehicle (generally closest) responds to the emergency.



Source: adapted from reference (40).

Figure 5-9. Typical Configuration for Satellite-Based Probe Vehicle System

For the system shown in Figure 5-9 to operate, there are several equipment needs and considerations. This figure only shows the system required to get the information to the control center. Once the data are received by the control center, reduction of the data into travel time information may also be necessary depending upon the system design.

Considerations When Using GPS Probe Vehicles

There are several additional considerations when using GPS probe vehicles for travel time data collection. As shown in Figure 5-9, the largest difference is the communication that must take place between the probe vehicle back to the control center. Many technologies exist for the transmission of position information. These include conventional radio, cellular systems, satellites, beacons and signposts, and paging systems. Conventional radio is the most commonly used communications system for AVL systems throughout the world (41).

IMPORTANT ☞ The amount of bandwidth for these systems is limited, therefore, it can often be difficult and expensive to obtain a frequency for communications, especially in large cities.

The coverage area is another consideration when developing a system, and the larger the area that must be covered with the system, the more towers that may be necessary to cover the area. It is also necessary to consider what tower will be used for setting up the antenna for the system (i.e., will a private transmission tower be used or will a locally-owned tower be rented). Further, when a conventional radio channel is desired for communication, an application for a license from the Federal Communications Commission (FCC) is required (38).

IMPORTANT ☞ The speed at which data must travel through the communication system is also an important consideration when determining the required system hardware.

For GPS probe vehicle systems, a modem combined with a conventional radio bandwidth converts data to an analog signal for transmission. Generally, modems for mobile radio operations use 2400, 4800, or 9600 baud. Some applications of GPS that are currently in use for buses or emergency vehicles, utilize several radio channels to provide more capacity. Some configurations called Time Division Multiple Access (TDMA) schemes allow for the transmission of data in a given time slot. Time slots can actually be assigned for smaller fleets. Conversely, large fleets may operate with a communication system in which the time slots are dynamically assigned to optimize the effective use of the transmissions. Generally, GPS probe vehicle systems will provide location information about a vehicle every 10 seconds (38).

Table 5-6 presents estimates of hardware, software, and personnel costs for using GPS for probe vehicle data collection. Ranges of costs are provided. Equipment costs and user fees are included except for some components that have a large variation in cost. The hardware, software, and personnel costs are further described below.

GPS Receiver - Required to process GPS signal information from the earth-orbiting satellites.

Radio Frequency (RF) Modem - Allows for two-way communication of positional information to the control center.

GPS Antenna - Required to receive GPS signals from the earth-orbiting satellites.

Differential Correction Receiver (if desired) - Receives signals from GPS satellites to determine corrected positional information. This information may be transmitted from a U.S. Coast Guard beacon or a private service (see differential signal service fee).

Differential Signal Service Fee - Fee charged for the use of the FM signal or other frequency band for obtaining differential correction information. Fees vary based upon the desired positional accuracy.

DGPS Antenna - Receives signals from the differential correction station.

Transmission Tower Costs - Towers are necessary for radio transmissions. Transmission tower costs vary depending upon several factors. If cable must be installed to the transmission tower, related costs will be incurred. The height of the transmission tower also becomes a factor. Rental fees may vary depending upon the ownership of the transmission tower. Service fees for radio frequency use can also vary. One factor that affects this cost is the availability of bandwidth.

Digital Repeater - Aids in sending radio signals from tower to tower (if necessary) and to probe vehicles or the control center.

Portable Computer - Necessary for positional data collection in the field.

Power Supply - Necessary for both the GPS receiver and the portable computer. Generally supplied through the cigarette lighter or a battery pack.

Data Storage Computer - Generally located back at the office or in the control center. This computer is used to store the positional data obtained in the field.

Table 5-6. Estimated Costs for GPS Probe Vehicle System

Equipment/Personnel	Unit Cost (1998 dollars)
Hardware	
GPS Receiver	\$300 to \$500
RF Modem	\$600 to \$700
GPS Antenna	\$100 to \$150
Differential Correction Receiver (Hardware) FM Signal Service Fee: Sub-meter accuracy 2-5 meter accuracy 10-meter accuracy	\$350 to \$500 \$700 to \$800 per year per unit \$200 to \$300 per year per unit \$70 to \$100 per year per unit
DGPS Antenna	\$30 to \$70
Transmission Tower Costs	Varies
Digital Repeater	\$1,000 to \$1,200
Portable Computer (Laptop/Palmtop)	\$1,500 to \$3,000/\$500 to \$700
Data Storage Computer	\$2,000 to \$3,000
Software	
GIS and Compatible Analyses Software	\$2,500 to \$3,500
Personnel	
Control Center Personnel	\$6 to \$10 per hour
Supervision and Management	Varies

GIS and Compatible Analyses Software - GIS software allows the positional data to be viewed on a roadway network. Compatible analyses software, generally within the GIS framework, allow for the calculation of desired measures (e.g., travel time, average speed).

Control Center Personnel - These individuals ensure that the probe vehicles are being monitored accurately in real-time on the GIS interface at the control center.

Supervision and Management - This includes management personnel who monitor the overall data collection, data reduction, and analysis of the system operation. This cost varies depending upon the size of the system, computer automation, and study needs.

There are several additional system designs to consider when developing a system for probe vehicle travel time data collection. Software packages are an integral part of the success of such a system. The GIS interface must be able to receive the GPS information in real-time for processing. Additional "packaged" software is available that is capable of placing a vehicle identifier on the vehicle that is being shown traveling in real-time on the computer screen at the control center. Analysis software is available that is able to compute real-time travel time information for predetermined routes.

In addition, dead reckoning systems may also be considered in the system design. Dead reckoning provides a means for vehicle locations to be determined when GPS satellite signals are not being received (i.e., they are being blocked by trees or buildings).

5.5.3 Data Reduction and Quality Control

Several steps are necessary in the reduction of GPS probe vehicle data:

1. **Insert necessary information into the base map at the control center**. There are several input requirements to the base map that are necessary to perform reduction of the data. These inputs include street names, cross-street information, and reference (checkpoint) locations for travel time segment definition.

2. **Convert raw GPS data from the field to a trackable vehicle on the control center screen**. With the aid of GIS software applications and related analyses software, the raw data obtained from the GPS receiver in the field is converted to a moving and labeled vehicle on the control center monitor.

3. **Adjust collected data to match base map (if desired)**. Apply map matching or appropriate software algorithms that "snap" the real-time data to the base map information.

4. **Compute travel time for a given segment**. The GIS software is capable of being programmed to calculate the travel time of vehicles traveling through predetermined links. In addition, the data being brought into the control center can be backed up for quality control and further analyses purposes. It should be noted that segment definition has caused some dispute in the profession as some professionals say that segments should be defined as a given length, while others argue that segment length should be defined in units of time since GPS data is obtained in real-time.

UNKNOWN
??

There are differing opinions about whether to aggregate GPS data into predefined roadway segments. If data storage is available, all GPS data points should be stored to permit "dynamic segmentation."

Quality Control Considerations

Several checks can be performed to ensure that adequate results are being achieved. The following quality control considerations can be applied in the data reduction stages.

- **Monitoring the course of vehicles being tracked**. The individual responsible for monitoring the vehicles being tracked in real-time can monitor the vehicles on the computer monitor. If the general routes of the labeled vehicles on the computer monitor are known, the individual watching the screen can recognize inconsistencies in vehicle trajectories if the vehicles appear to be off course.

- **Selected "spot checks" of real-time data being collected**. Although the data are being collected and transferred in real-time, data log files can be stored. These files can be randomly selected to evaluate the travel time information they are producing. Based upon the historical operation of the predetermined segments, the analyst can use this technique to determine if the results are accurate.

- **Evaluation of locations where GPS signals are temporarily lost**. In the absence of a dead-reckoning system, the path of a traveling vehicle may be lost when GPS signals are blocked. During periods when the GPS signal is lost, with or without the use dead-reckoning, it may be beneficial to check the travel time results provided for these routes.

5.5.4 Previous Experience

ADVANCE, Illinois Department of Transportation (IDOT)

The Advanced Driver and Vehicle Advisory Navigation Concept (ADVANCE) was undertaken in 1991 as a test of dynamic in-vehicle route guidance. The partners in the project include the Illinois Department of Transportation (IDOT), the Federal Highway Administration (FHWA), the American Automobile Association (AAA), Motorola, and the Illinois Universities Transportation Research Consortium (Northwestern University and the University of Illinois at Chicago) with the cooperation of the Argonne National Laboratory. ADVANCE has established a very useful Internet site where complete reports on every aspect of the project are available for the use of those interested (43).

Real-time route guidance information was provided to individuals to evaluate if they would alter their trip to avoid congestion and reduce the travel time of their trip. Many technologies were utilized in the study to provide the real-time information to travelers. These included the global positioning system (GPS), wireless communications, CD-ROM map storage, and data fusion. The Transportation Information Center (TIC) was the core of the system receiving information from several sources, processing the data, and transmitting it to users (43).

As a major effort to establish an in-vehicle real-time route guidance system to travelers, many lessons were learned from the ADVANCE project that are applicable to the establishment of travel time data collection utilizing GPS technology. The study used radio frequency communications between the vehicles and the control center through modems in the vehicles for transmission of information. Differential correction information was also supplied to the vehicles for correction of the GPS information. Although two channels were established for communication purposes, there were times when the system could become slowed down because the modems in the vehicles could not handle real time info as fast as it could be sent.

Privacy issues, such as the concern that “big brother” will be watching, is always a concern when the instrumentation of private vehicles is being considered. Although ADVANCE used project cars donated by car manufacturers, the original intent was the instrumentation of private vehicles. Therefore, experience was gained in soliciting and preparing motorists for driving the test vehicles. Very limited advertisement of the project was performed to solicit individuals to apply for the instrumentation of their vehicle for the study. However, there was a large response by individuals to test the new route guidance system. Selection criteria were established to aid in determining which individuals would be allowed to participate in the study. The participants were told of all aspects of the project including a briefing that included presentations from the partners in the project to provide information about the project including a user’s manual, quick reference guide, brochure on the ADVANCE project, and other related materials (44).

The ADVANCE project team did have a modem identification number in the database used for analysis. It would be possible to match this identification number with the individual driver with some work. Therefore, the team disclosed this information to interested drivers to ensure they were not concerned about the fact that they could be monitored. The full disclosure of exactly how the system was being used and the data being collected aided in the understanding, comfort, and interest of the volunteers in the study.

Predetermined segment links in the 780 sq-km (300 sq-mi) ranged from 0.016 to 3.2 km (0.01 to 2.0 mi) in length. Predetermined routes were also used in the study, and data collection was performed over different times of the day. Computer processing was provided in each vehicle with the aid of on-board computers. Therefore, the computation of travel time information on the predetermined links was performed in the vehicle and transmitted to the TIC. This reduced the computation that was necessary at the TIC. The TIC would then gather the information from probe vehicles and loop data from the transportation system and process it every five minutes. This information was then reported back to the probe vehicles.

The project team was satisfied with the ADVANCE in-vehicle route guidance effort. The use of the GPS technology was advantageous because it provided minimal overhead costs. This is because of the simple fact that it relied on another trustable system since GPS is maintained closely by the Department of Defense. For these reasons, ADVANCE has provided many beneficial lessons for application of future probe vehicle applications for travel time data collection.

Texas Transportation Institute (TTI), College Station, Texas

The objective of one current research effort within the Texas A&M Intelligent Transportation System (ITS) Research Center of Excellence (RCE) is to develop, demonstrate, and evaluate an AVL/GPS system for rural transit. Brazos Transit District (BTD) was selected as the transit agency to be instrumented with the AVL system. BTD presently covers 23 counties in the State of Texas. It is the largest provider of rural transit services in the state (40,42). This example is provided to describe to the reader an AVL system that is being studied in an effort to aid the practitioner in realizing the potential use of existing probe vehicle systems such as AVL for travel time data collection. The reader is encouraged to review Figure 5-9 for an illustration of such a system.

GPS technology was selected for use in determining vehicle positioning. The system was set-up similarly to Figure 5-9 except the probe vehicle was a transit vehicle. The communications system included the use of two-way UHF radio bandwidth operating in the 460 MHZ range. Differential correction improved vehicle position data from a range of 10 to 15 meters (33 to 49 feet) to 2 to 5 meters (7 to 16 feet). Real-time information is sent from the transit vehicle to a transmission tower and back to the Texas Transportation Institute (TTI) and the BTD dispatch office (42).

This study has provided several lessons learned. The first noteworthy lesson is the concern that "big brother" is watching over the transit driver. Many of the bus drivers were concerned that they were being monitored when they were traveling with the GPS receivers in the vehicle. The drivers would often shut off the GPS receivers prior to driving their scheduled route. Although the drivers were educated thoroughly that they were not being monitored while on their scheduled routes, this was a common problem. The problem could be resolved to some degree by ensuring that the GPS receiver was hidden from the view of the driver (42). Keeping the equipment out-of-sight of the driver is a valuable lesson for consideration when GPS equipment may be installed on private vehicles as well. Even when the drivers are informed that they are not being monitored, if the driver is unable to see the unit, they may not be reminded or become tempted to disconnect it. Of course, the driver must be informed that the equipment is on-board the vehicle.

The study has found that the GPS technology is applicable and effective for rural transit applications as well. Since the location was rural, there was no difficulty in obtaining RF bandwidth for the two-way communications. The critical factor is the rental fee and equipment cost for the transmission tower(s). For this study, it was necessary to install the antenna and cable into the tower for communications. As discussed previously, the coverage area will determine the number and spacing of transmission towers. One tower was able to adequately cover the Brazos County area in this study. Continued tasks in the study are evaluating the range of the transmission of the tower.

The study also describes the software packages that were used to integrate digital maps, mapping software, relational database capabilities, and GPS real-time information into one system. Further, the software that was used can track individual buses with unique identification tags (42). In addition, analysis packages compatible to the GIS software can be created that can compute real-time travel time and speed information based on the incoming real-time GPS information for predetermined links.

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See Chapter 3 for further GPS references related to test vehicle techniques.

6 EMERGING AND NON-TRADITIONAL TECHNIQUES

The technology aspects of the test vehicle, license plate matching, and ITS probe vehicle methods of travel time data collection are fairly well established. This chapter presents other methods for collecting or estimating travel time that are considered emerging and/or non-traditional techniques.

Several of the emerging or non-traditional techniques are based on using "point" vehicle detection equipment, such as inductance loop detectors or video cameras. Travel time estimation algorithms have been developed based upon measurable point parameters such as volume, lane occupancy, or vehicle headways. Image matching algorithms are used to match vehicle images or signatures captured at two consecutive observation points. For the most part, these emerging techniques are still in developmental stages.

The available information is presented here for those interested in further research, development, or testing of these techniques. Because of the rapidly changing nature of these technologies, it may be appropriate to contact the associated authors or developers for updated information. This chapter does not provide information on comparative advantages and disadvantages because of the relative infancy of these techniques. The techniques discussed in this chapter include:

- **Extrapolation Method** - estimates average travel time by assuming that spot speeds (as measured by point detection devices) can be applied for short roadway segments between detection devices. This method is simplistic but can be used for applications that do not require high levels of accuracy.

- **Vehicle Signature Matching** - calculates travel time by matching (correlating) unique vehicle signatures between sequential observation points. These methods can utilize a number of point detectors such as inductance loop detectors, weigh-in-motion sensors, video cameras, and laser scanning detectors.

- **Platoon Matching** - estimates average travel time by matching unique features of vehicle platoons such as the position and/or distribution of vehicle gaps or unique vehicles. As with correlation methods, platoon matching uses point detection devices, such as video cameras, ultrasonic detectors, etc.

- **Aerial Surveys** - estimates travel time using aerial survey methods that measure vehicle density or track vehicle movement. Fixed-wing aircraft have typically been used for aerial surveys, but newer methods propose using weather balloons, satellites, and remote controlled gliders.

6.1 Extrapolation Method

The extrapolation method is a simple way of estimating average travel times because it assumes that a spot speed is applicable over short segments of roadway (typically less than 0.8 km, or 0.5 mile). Several planning applications that do not require high levels of accuracy, like demand forecasting model validation or system monitoring, could use the extrapolation method. Spot speeds are typically collected by a number of traffic monitoring devices that are considered intelligent transportation systems (ITS) components. Traffic monitoring devices that have marketed capabilities of collecting spot speeds include (1,2):

- inductance loop detectors;
- piezoelectric sensors;
- active and passive infrared sensors;
- magnetic sensors;
- video tracking and tripline systems;
- doppler microwave;
- passive acoustic sensors; and
- pulse ultrasonic detector.

An example of the extrapolation method is shown in Figure 6-1. In the figure, the point detection devices that measure spot speed could be any of the above-mentioned traffic monitoring devices.

The most common and widely implemented point detection device is the inductance loop detector. The most accurate method to measure vehicle speed with loop detectors is to place two detectors in series, which is referred to as a "speed trap" or "loop trap." The results of a Texas Transportation Institute study indicated that the accuracy of inductance loop speed traps were dependent upon the trap length, inductance loop wire type, and consistency in design and use (3). The study found that the optimal trap length, or distance between inductance loops, was 9 m (30 ft). The study authors also found average error ranges to be about 2.4 km/h (1.5 mph) by using identical make and model detector units.

Information gathered by California PATH researchers (4) suggests that calibrated inductance loop speed traps can achieve the following accuracy ranges:

- individual wire loops: low speed, 5 to 8 km/h (3 to 5 mph);
- individual wire loops: high speed, 16 to 19 km/h (10 to 12 mph);
- multi-conductor loops: low speed, 0.3 km/h (0.2 mph); and
- multi-conductor loops: high speed, 5 to 8 km/h (3 to 5 mph).

PATH researchers also report that speed traps can be separated by a distance ranging from 2 to 20 m, with 9 m (30 ft) being the optimal spacing.

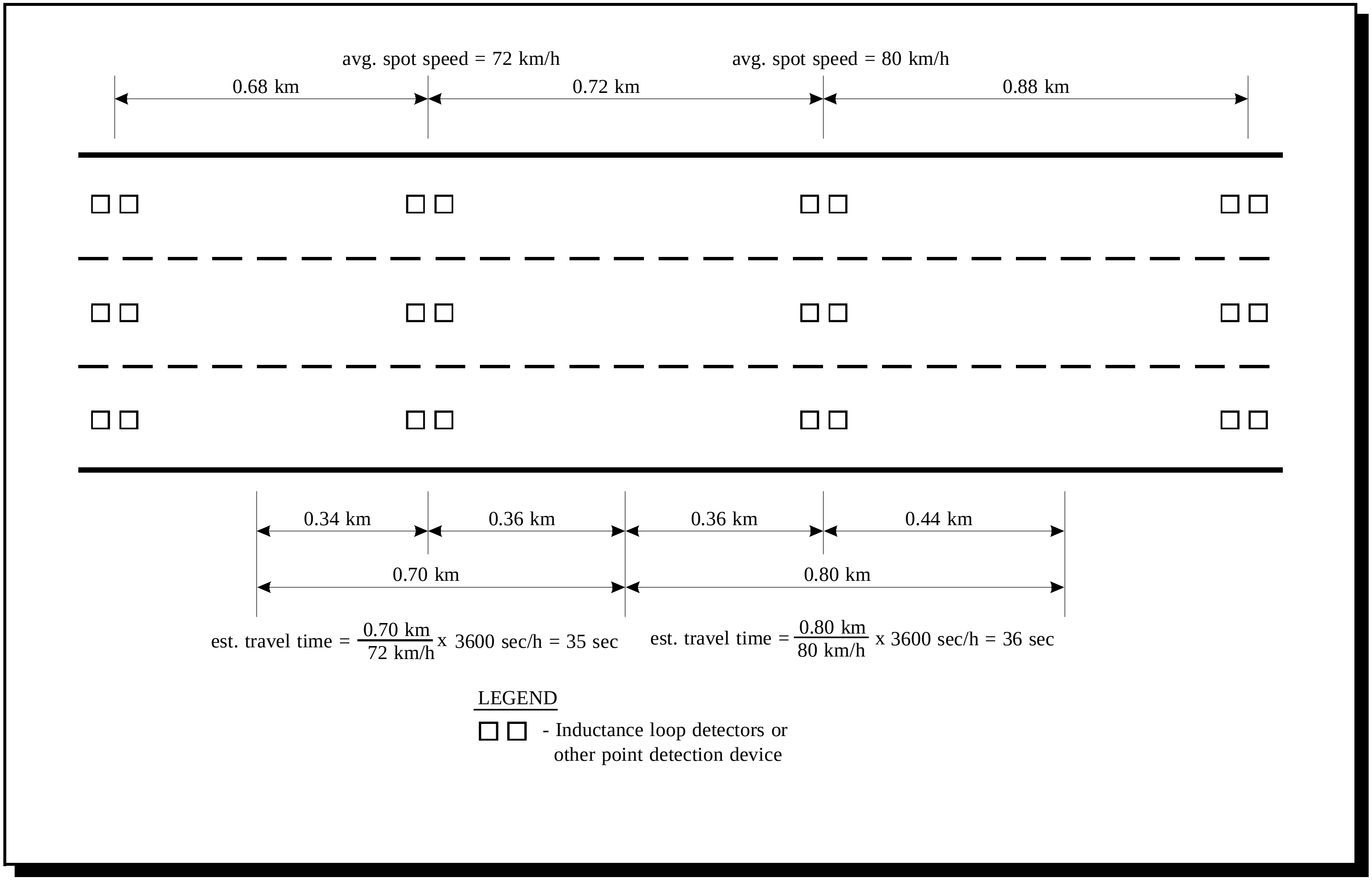


Figure 6-1. Example of Extrapolating Link Travel Times from Spot Speeds

Many inductance loop detectors currently in place are single loops primarily designed to collect vehicle counts and lane occupancy. Many attempts have been made to utilize speed-flow relationships to estimate vehicle speeds from single loop detectors. The following equations have been used to estimate spot speeds from single loop detectors:

$$spot\ speed = \frac{volume}{lane\ occupancy \times g} \tag{6-1}$$

where: g = speed correction factor (based upon assumed vehicle length, detector configuration, and traffic conditions).

The Chicago Traffic Systems Center assumes a vehicle length of 6.55 m (21.5 ft) and uses the following equation to estimate spot speed (5):

$$spot\ speed = \frac{volume \times 21.5\ ft}{lane\ occupancy \times 40.9} \tag{6-2}$$

Previous research (6,7) has identified several problems with these simplified relationships. These previous studies have shown that the accuracy of Equation 6-1 is a function of many factors, including location and weather, and may be prone to systematic bias with respect to lane occupancy.

Dailey suggests cross-correlation techniques that may provide more accurate link travel times from sequential single inductance loop detectors (8,9,10). Petty et al. also suggests correlation techniques for accurately estimating travel times from a single loop detector (11). Readers are encouraged to refer to these papers for more information about speed and travel time estimation from single inductance loop detectors.

Little or no information about the use or validation of the extrapolation method is contained in the literature, presumably because of its simplicity. The method could be easily tested for accuracy by comparing test vehicle or ITS probe vehicle travel times to travel times estimated by the extrapolation method. The accuracy of this method varies with several factors:

- type of facility (freeway versus arterial street);
- distance between point detection devices;
- traffic conditions (free-flow versus congested conditions); and
- accuracy of the device itself.

Traffic monitoring devices are often placed at 0.4- to 0.8-km (¼- to ½-mile) spacings on freeways for incident detection and devices at this spacing could be used for travel time estimation.

Inductance loop detectors on arterial streets are commonly placed at major intersections, where traffic conditions vary considerably throughout the traffic signal cycle. Mid-block system detectors on arterial streets would not include the stopped delay time associated with intersections, and would be less suitable than intersection detectors. The accuracy would presumably be less in congested traffic conditions, where stop-and-go conditions and rolling shock waves can significantly affect vehicle speeds over short segments of roadway.

Errors in measured spot speeds due to device inaccuracies would be reflected in any estimates of link travel time. There are ongoing efforts to evaluate the accuracy of various traffic monitoring devices. Minnesota DOT is testing several devices in normal and adverse weather conditions (12). Virginia Tech's Research Center of Excellence is also performing traffic sensor testing on a 9.6 km (6-mi) "Smart Road" (13). Ongoing FHWA efforts have focused on creating a National Vehicle Detector Test Center, and a Vehicle Detector Clearinghouse has been established at the Southwest Technology Development Institute of New Mexico State University (14,15).

CAUTION !!	Exercise caution when using point detection devices for estimating travel times. Freeway detectors may provide reasonable estimates in light traffic, but using detector estimates is not recommended in heavy congestion or on arterial streets.

6.2 Vehicle Signature Matching

Several research efforts are aimed at developing methods to capture unique vehicle features, or "signatures" and match these vehicle signatures between two consecutive locations to provide a link-based travel time and speed. These methods provide an anonymous alternative to ITS probe vehicle-based travel time measurement, in which a probe vehicle is identified and matched between two locations using a unique identification number. Vehicle signature matching is also regarded as implementable in the near-term using existing point detection devices. ITS probe vehicle-based systems require more extensive instrumentation and market saturation before useful results can be achieved for many areas.

Vehicle signature matching has been investigated using a number of different point detection devices, most noticeably with inductance loop detectors. Laser sensors, weigh-in-motion (WIM) sensors, and video cameras have also been tested using vehicle signature matching. Infrared and microwave radar sensors are also capable of extracting unique features of vehicles, and therefore capable of using vehicle signature matching for link travel times. The following sections discuss specific research related to the testing of inductance loop detectors, WIM sensors, and video cameras.

6.2.1 Inductance Loop Detectors

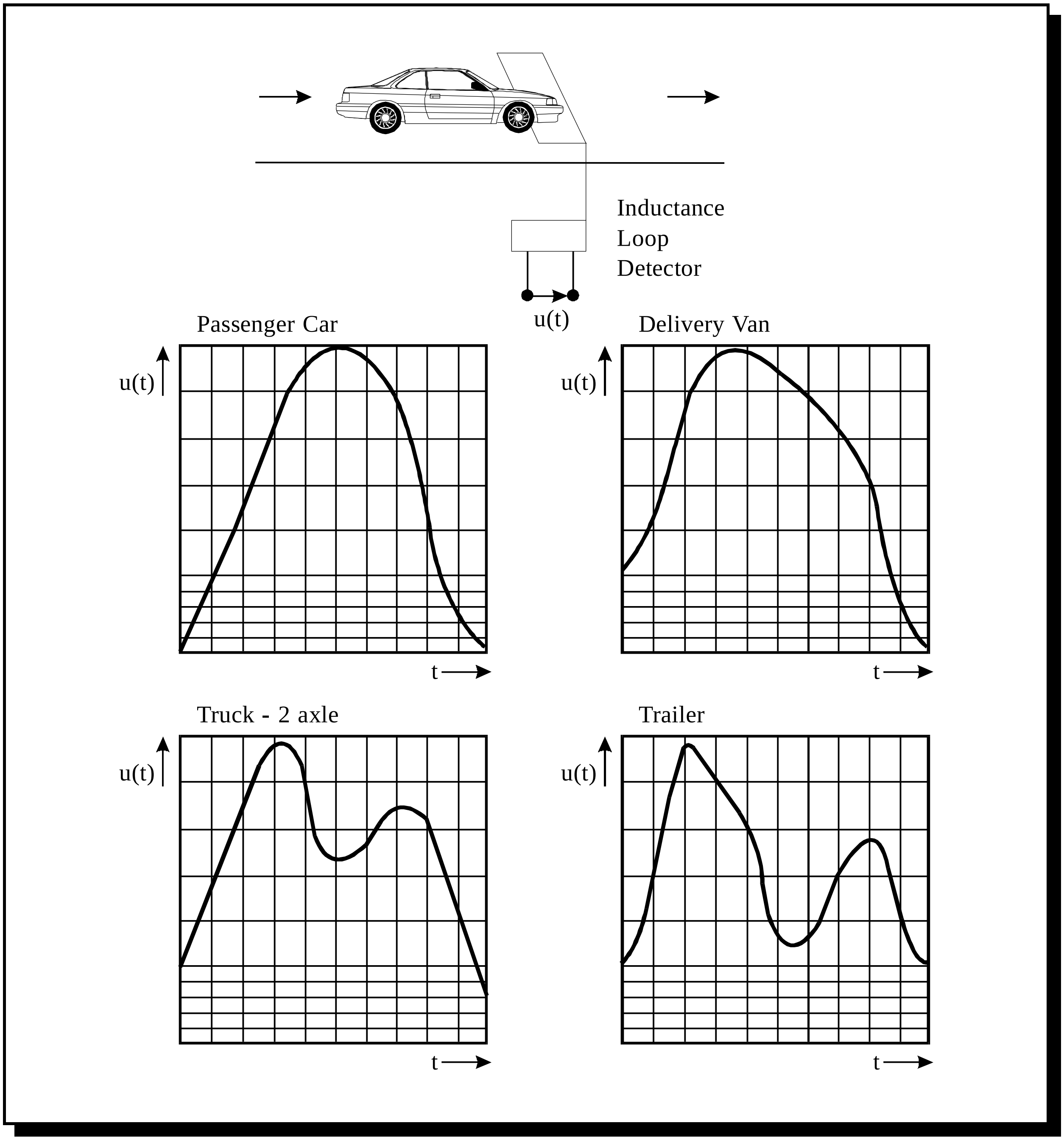
The testing of inductance loop detectors for vehicle signature matching has been thoroughly documented by Kühne et al. (see references 16,17,18,19,20,21,22). Kühne's technique relies on several algorithms to capture vehicle signatures from a loop detector frequency detuning curve. Different types and classes of vehicles provide somewhat characteristic detuning curves (Figure 6-2). The unique features of a vehicle signature (as seen in the detuning curve) are then compared to signatures within a given time frame at a downstream location. The signature is considered to be matched when a large number of feature correlations has been found within vehicle signatures at the downstream location. Figure 6-3 illustrates the features correlations, with the largest number of correlations (about 120) occurring with the matched vehicle signature. A lower number of feature correlations (less than 60) were found within other vehicle signatures, but can be discarded because of the relatively low number of feature correlations relative to the maximum correlation (about 120).

The vehicle signature matching technique does not match every vehicle signature captured, but can potentially match a large enough percentage as to be significant (estimated at 10 percent of the traffic volume). This use of inductance loop detectors has not been thoroughly tested, and no quantitative test data that details accuracy levels was available in the literature. The technique appears to be capable of providing estimates of link travel times for real-time traffic control. Vehicle signature matching appears most promising for areas that currently have an existing loop detector infrastructure with no plans for probe vehicle-based systems.

Recent research by Coifman (23) takes a slightly different approach by attempting to match a sequence of vehicle signatures between two sequential single inductance loop detectors. According to the research, the specific sequence of vehicle lengths is captured at an upstream detector and then re-identified at a downstream detector location. This vehicle length sequence method is capable of using commercially-available loop detector controllers (i.e., 170 controllers) with software developed by researchers at PATH and Caltrans. The author acknowledges that the accuracy of this method is not as great as matching actual vehicle signatures, but asserts that the necessary loop detector infrastructure is already in place. No recent field tests were available at this writing, but development on the vehicle length sequence method continues.

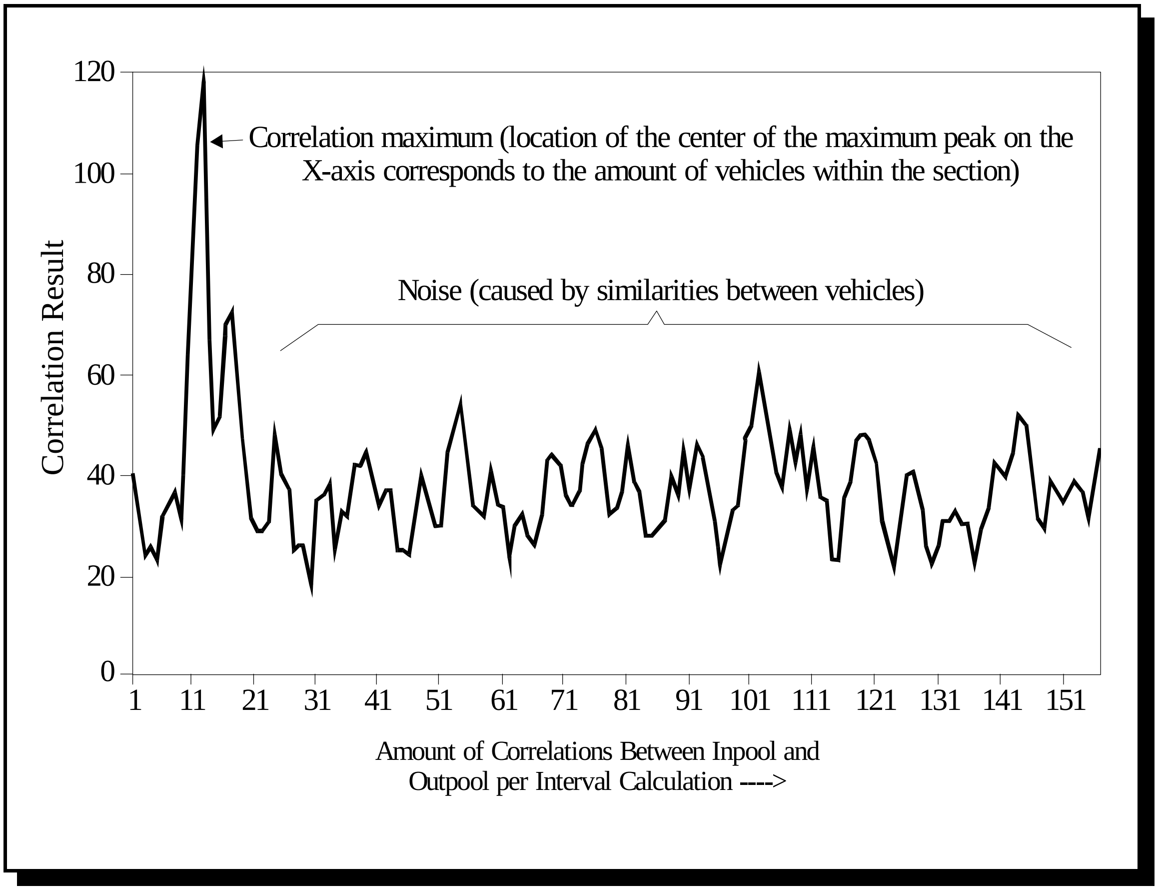
6.2.2 Laser Sensors

The vendor of a diode laser-based vehicle detector/classifier has developed matching algorithms that estimate link travel times using a laser rangefinder sensor (24). Two narrow laser beams are used to scan a moving vehicle and a three-dimensional profile is developed. The authors assert that height profiles can be obtained with considerable accuracy (± 76 mm or 3 in), and vehicle speeds can also be determined from the laser beams.



Source: adapted from reference (25).

Figure 6-2. Characteristic Detuning Curves of Inductance Loop Detectors



Source: adapted from reference (16).

Figure 6-3. Vehicle Signature Correlation Results

A structural matching algorithm is used to match the images constructed by the lasers at two consecutive locations. The algorithm reportedly can discern slight differences between similar vehicles using the spatial relationship of vehicle features. The algorithm's steps include (24):

- input image: obtain image from laser sensors;
- pre-processing: extract height and profile from image;
- develop model set: select set of vehicles from downstream location for matching;
- primitive extraction: extract characteristic features for matching;
- matching: compute a match score for all possible matches;
- matched pair pruning: select vehicle pairs with the highest matching score; and
- report: summarize matching results with link travel times.

The authors conducted a field test of this technique along SR 441 in Orlando, Florida, in which 50,000 vehicle images were collected. From these collected images, 500 sets of 100 vehicles each were chosen for matching purposes. From each set of 100 vehicles, match scores were computed for every possible vehicle combination and the matching algorithm was used to find those scores with the highest number of matching features. Then, a sample of 10 vehicles was chosen for computation of travel times. Of the 500 sets, 487 sets had all 10 sample vehicles matched correctly between the two locations. The other 13 sets had 9 of the 10 sample vehicles matched correctly. The authors reported a correct matching percentage of 99.7 percent (4,987 of 5,000 sample vehicles correctly matched).

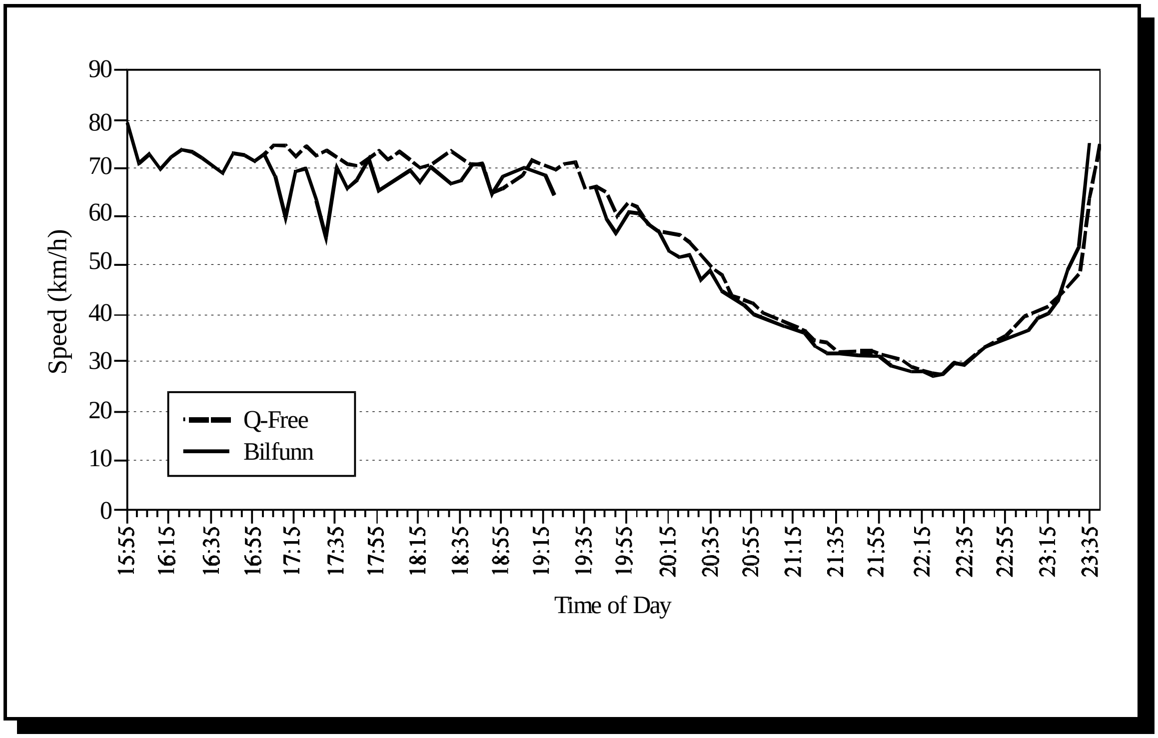
6.2.3 Weigh-in-Motion (WIM) Sensors

As with inductance loop detectors, WIM sensors also generate a vehicle signature based upon the axle weight and configuration. The Norway Public Roads Administration (NPRA) has experimented with using WIM sensors for link travel times on the Oslo Toll Ring (26,27). The Norwegian WIM system collects standard traffic parameters (e.g., volume, speed, lane occupancy) as well as axle configuration, axle distances, and axle weights. Accuracy of the WIM system is very high because the system is certified as an enforcement tool. Additionally, a prototype of the system was tested at the Winter Olympic Games in Lillehammer in 1994 and was later refined with more advanced matching algorithms.

The WIM system software uses axle configuration and axle weights to match vehicles between two different locations. Because of the high vehicle volumes and difficulty with similar vehicles, the system utilizes vehicles with unique axle configurations or weights (e.g., larger vehicles, trucks with trailers). Tracking of most standard passenger cars is difficult because of similar axle and weight configurations.

The NPRA tested the comparability of travel times collected through the WIM system to travel times collected by probe vehicles equipped with AVI transponders. WIM sensors were placed at AVI antenna locations, and travel times were compared. Figure 6-4 presents the results of AVI and WIM sensor travel times, and indicates that the two systems produce comparable travel times in both congested and uncongested traffic. The comparability was also significant because the AVI system typically measured passenger vehicle travel times, whereas the WIM system was more likely to measure travel times of large vehicles or trucks.

The Norwegian WIM system is currently being operated in real-time in an isolated fashion. Implementation of the WIM and travel time measuring system is expected in the southern parts of Norway in 1997. The NPRA hopes to be able to use the WIM system to overcome some privacy issues related to the tracking of AVI-tagged vehicles.



Source: adapted from reference (27).

Figure 6-4. Comparison of Travel Times Collected Using Norwegian AVI (Q-Free) and WIM (Bilfunn) Systems

6.2.4 Video

Video cameras are commonly used for a number of ITS applications, including incident detection and verification, sampling of traffic parameters like volume and spot speed, and monitoring traffic conditions. Several research efforts are trying to apply video cameras in the measurement of wide area traffic parameters like link travel time.

Early fundamental research examined the feasibility of capturing images of a moving vehicle, then segmenting and extracting relevant vehicle features for matching between several camera locations (28). The researchers used several steps in matching vehicle images:

- detection of moving objects: uses moving image analysis tools to detect the location of vehicle movement;

- color segmentation: divides the vehicle image into homogenous regions, or segments, using color information from the image;

- vehicle image extraction: extracts the moving vehicle from the background image based on the colorized segments; and

- matching features of individual vehicles: compute a matching score that quantifies the likelihood of a correct vehicle match.

Like other signature matching techniques, the researchers compute a match score that quantifies the likelihood of a correct match, then apply a logic algorithm to eliminate unlikely matches. In limited field tests of these techniques, it was possible to detect moving vehicles and identify unique segments of the vehicle, such as the hood, trunk, or wheels. The researchers proposed several refinements to the matching algorithms that could improve the accuracy of the technique. They also noted that multi-lane highways or congested traffic offered additional challenges because of several moving vehicles within the video camera field-of-view.

Several vendors claim they have developed a camera and machine vision system that is capable of tracking vehicles throughout the entire camera field-of-view (typically several hundred meters) (29) or calculating "wide area" travel times (30). The systems have reported capabilities of being able to "track" or correlate vehicles between several different camera locations and provide an estimated link travel time. Although no details are given on the matching algorithms, it is presumed that travel times are estimated by correlating distinguishable vehicle features between camera locations.

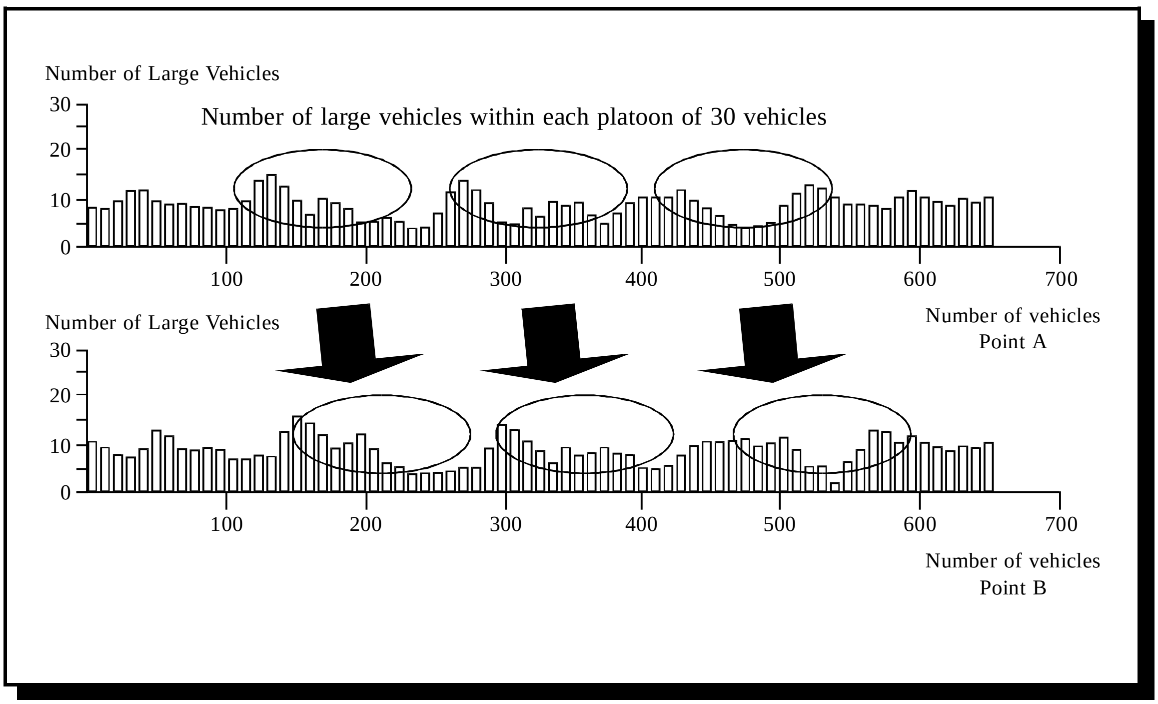
Field tests have been performed to validate point-based traffic parameters like volume and spot speed. The results of these tests have generally been comparable to other point detection devices. No documentation on the reported wide-area tracking and vehicle matching capabilities of these systems was found in the literature.

Research being conducted and coordinated by the Jet Propulsion Laboratory, California Institute of Technology, is also looking at matching techniques to measure link travel times and other traffic flow parameters (31). Color recognition technology is being used by the Massachusetts Institute of Technology and Northeastern University to identify and match individual vehicles between consecutive video camera locations. Several other commercially available video imaging detection systems will be tested and evaluated for their potential to measure and/or estimate link travel times.

6.3 Platoon Matching

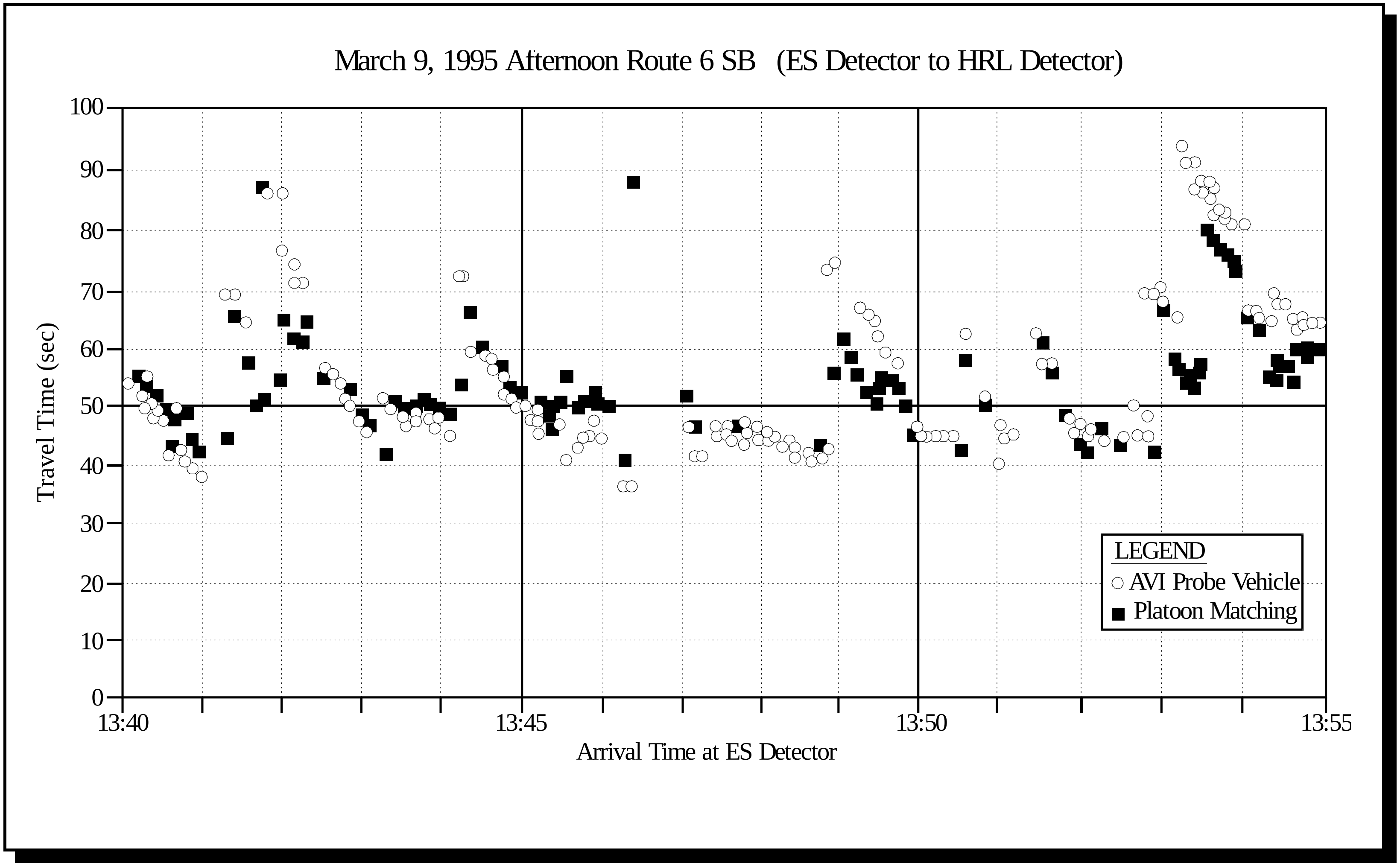
Platoon matching is similar to vehicle signature matching in that it relies on identifying, extracting, and matching unique features between two consecutive roadway locations. The underlying concept of platoon matching is based on identifying unique relationships between vehicles, whereas vehicle signature matching relies on the specific characteristics of a single vehicle or a sequence of vehicles.

Japanese researchers have conducted tests of a platoon matching system that utilizes ultrasonic traffic detectors (32). The ratio of large vehicles within a platoon was the characteristic used to estimate link travel times between ultrasonic detectors. The system algorithm selects a platoon of 30 vehicles and records the number of large vehicles within that platoon (using ultrasonic detector data). The algorithm then attempts to match the histogram of the large vehicles in the platoon between consecutive detector locations (Figure 6-5). Limited field testing on a major arterial street indicated that the matching algorithm had the greatest error (± 10 percent of AVI probe measured travel times) in free-flow traffic conditions (Figure 6-6), where platoons were less stable and vehicles had the ability to maneuver. The platoon matching algorithms did perform better in more congested traffic conditions (Figure 6-7), with an error rate of about ± 5 percent of AVI probe measured travel times.



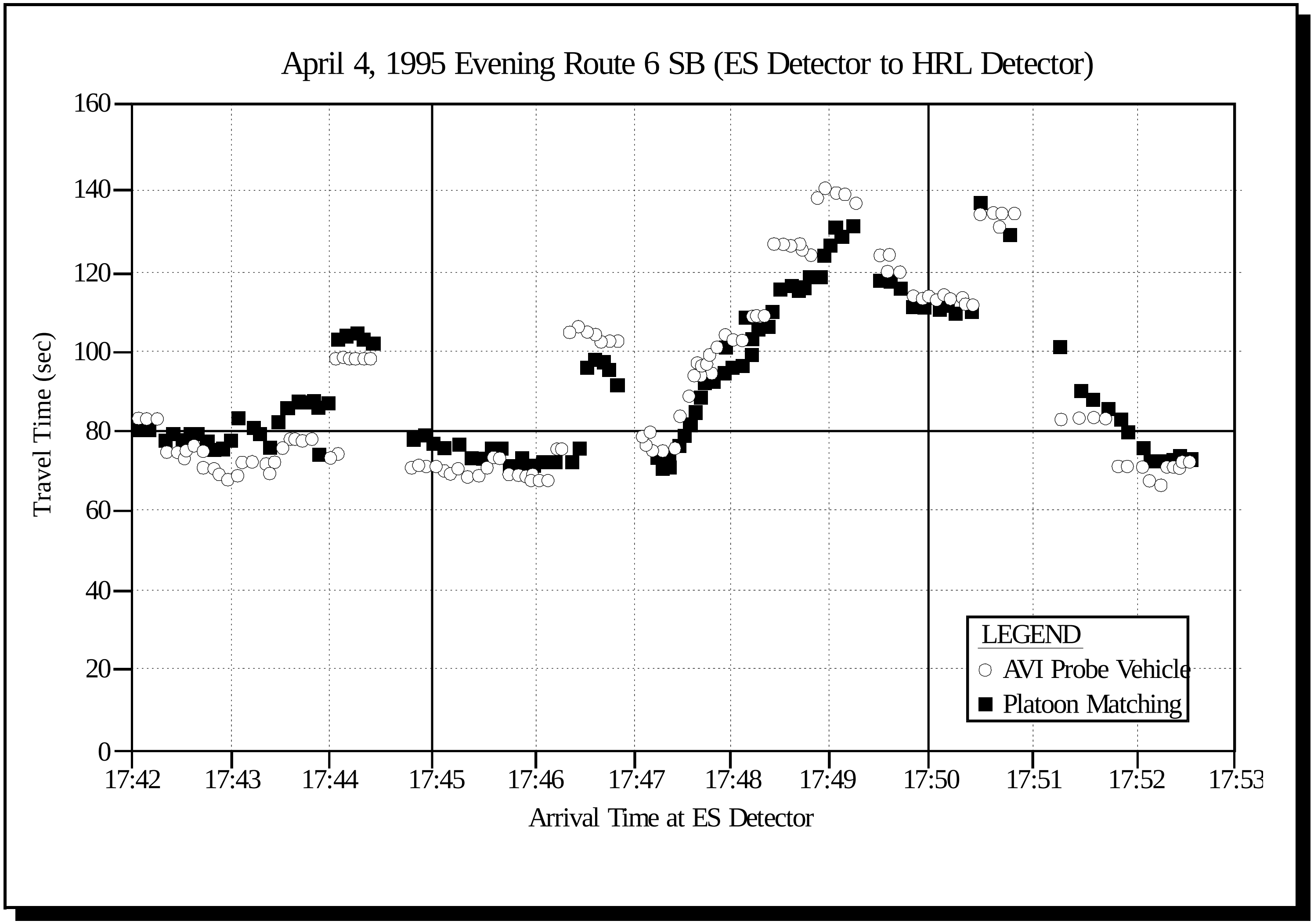
Source: adapted from reference (32).

Figure 6-5. Platoon Matching using the Ratio of Large Vehicles



Source: adapted from reference (32).

Figure 6-6. Comparison of Travel Times from Platoon Matching and AVI Probe Vehicle Systems in Free-Flow Traffic Conditions



Source: adapted from reference (32).

Figure 6-7. Comparison of Travel Times from Platoon Matching and AVI Probe Vehicle Systems in Congested Traffic Conditions

6.4 Aerial Surveys

Several types of aerial surveys have been used or tested to measure traffic flow and other parameters. These surveys can be conducted from fixed wing aircraft, helicopter, observation balloons, or even satellites. Examples of ongoing research in these techniques are discussed below.

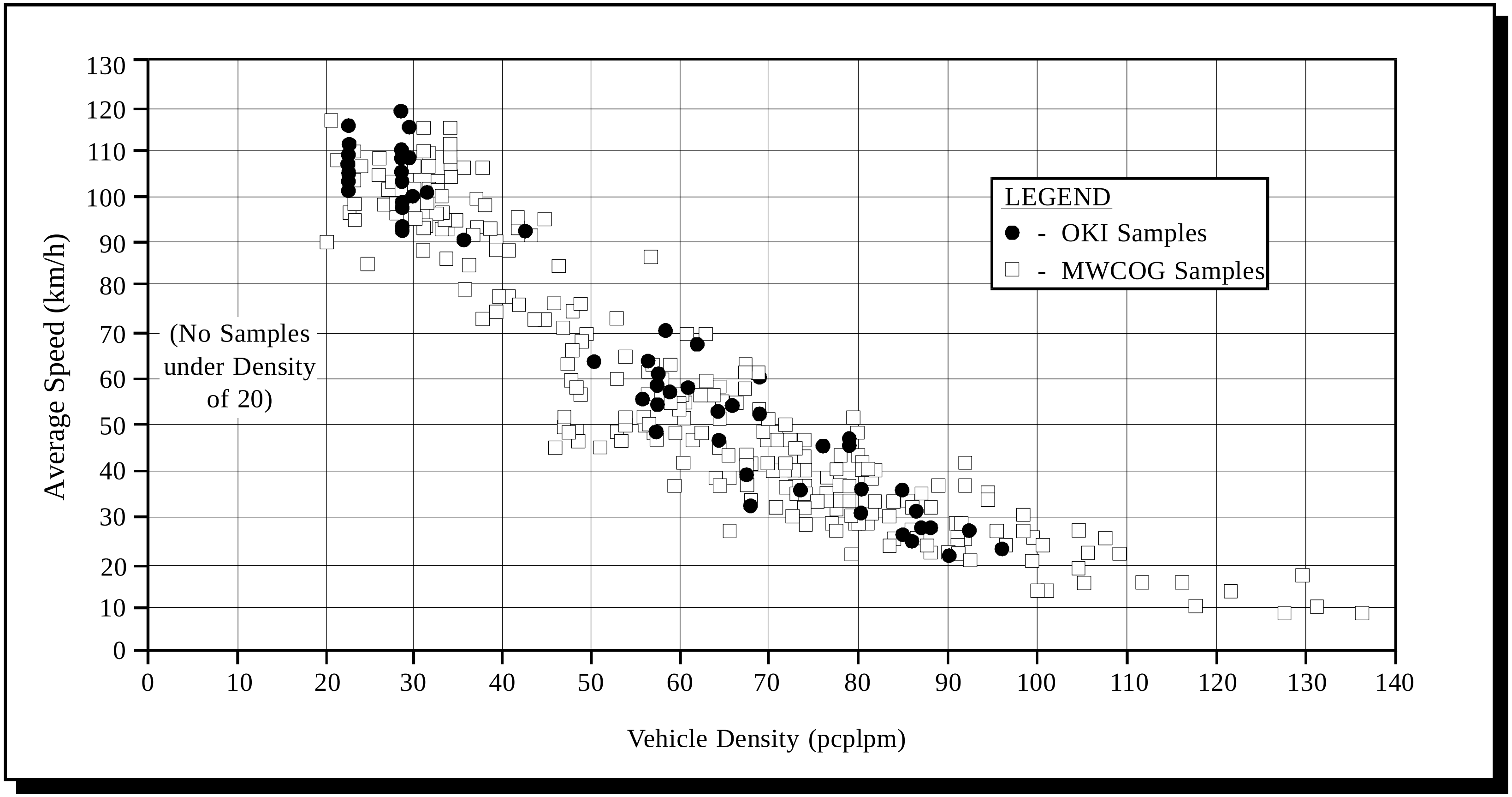
A transportation consultant in Maryland has been using a fixed-wing aircraft (and previously a helicopter) to collect congestion and traffic information as early as 1965 (33,34). In recent studies, the consultants have measured traffic densities and estimated speeds and levels of service on freeways and arterial streets. Traffic densities along freeways are easily obtained by collecting consecutive aerial photographs as the plane flies along the study corridor. Vehicles within a given section can then be counted from the aerial photos, and using known ground distances, traffic densities and corresponding levels of service can be computed. Alternatively, trained observers estimate the density and corresponding level of service without calculating actual vehicle densities.

Several efforts have focused on validating these qualitative level of service ratings collected by trained observers with satisfactory results. One such study compared aerial traffic density and estimated link speeds to average vehicle speeds being collected by test vehicles in the same traffic flow. Figure 6-8 presents the results of this comparison and shows that the aerial survey speeds correspond to vehicle speeds collected on the ground. The consultant has also considered the potential of collecting video from a fixed-wing aircraft for use in tracking vehicles along a particular section but has not pursued any extensive development or testing.

Researchers from the University of Karlsruhe in Germany examined the matching of vehicle images from aircraft in 1987 (35). The system was tested in Austria, with some problems due to curvature and slope of the area. Although the authors claim that "good results" were obtained, they suggested several improvements for the system. No recent mention of this system or subsequent research was found in the literature.

Two papers presented at the 1996 National Traffic Data Acquisition Conference discussed the potential of using observation balloons and satellite imagery for collection of traffic data (36,37). These two efforts focused primarily on collecting traffic volume and density statistics, as well as observations of congested traffic conditions. Although the papers include no mention of link travel times, the potential does exist to perform image matching and correlation. The estimation techniques and matching algorithms would presumably be similar to other methods discussed earlier in this chapter, with the exception that images would be captured from a vantage point high above the roadway.

The Georgia Tech Research Institute is testing a traffic surveillance drone that can relay video images from 8 to 16 km (5 to 10 mi) via a spread spectrum link. Prototypes will cost approximately $60,000 and be capable of 30 minutes of flight at a maximum speed of 30 knots (38,39).



Source: adapted from reference (34).

Figure 6-8. Correlation of Aerial Survey Densities (OKI Samples) to Ground-Collected Speeds (MWCOG Samples)

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7 DATA REDUCTION, SUMMARY, AND PRESENTATION

This chapter provides guidance on the reduction, summary, and presentation of travel time data. Chapters 3 through 5 contained specific data reduction and quality control procedures for each data collection technique. The procedures in earlier chapters were aimed at producing a common travel time format for each predefined roadway segment or link. The methods described in this chapter can then be used to further reduce, summarize, and/or present this travel time data. Many examples of tabular and graphical summaries of travel time data are provided at the end of the chapter.

7.1 Data Reduction

This section contains a discussion on the purposes and methods used to reduce and/or aggregate travel time data. It is assumed that appropriate data reduction and quality control measures have been applied for the specific data collection technique, and that the travel time data are in an individual link format (i.e., data contains valid individual travel times for each predefined link or segment length). Quality control procedures for each data collection technique were included in Chapters 3 through 6. The purpose of data reduction can be two-fold:

- reduce the number of data records by eliminating invalid data; or
- produce summary data and statistics at different aggregation levels for various applications.

Quality control measures applied to the data immediately after data collection should have identified data errors or invalid data. However, statistical quality control checks can be performed at this point to identify any remaining problems with data integrity. Statistical quality control procedures are available in some spreadsheet and database software programs and in nearly all statistical analysis software packages. Readers interested in statistical quality control procedures should consult a specialized statistics text.

In most cases, data reduction will be necessary to summarize or aggregate the link travel time data to a format usable in many analyses. Travel times from individual runs should be averaged to produce mean or average travel times for the peak hour or peak period. Individual travel times from license plate matching should be averaged to produce average travel times and speeds for 15- or 30-minute time periods or greater. Typical summary statistics computed with link travel time data include:

- **Mean or average travel time, speed, and delay** - These statistics provide information about the typical traffic conditions during the time period of interest. Means or averages can be computed for any time period desired, including but not limited to 15-, 30-, or 60-minute, peak hour, and peak period (Equations 7-1, 7-2, and 7-3). The selected time period typically corresponds to analysis needs and available sample sizes. For example, travel time data collected with license plate matching or ITS probe vehicle techniques can be summarized for shorter time periods because of the typically larger sample sizes. Travel time data collected using test vehicle techniques are generally aggregated to the peak hour or peak period because of smaller sample sizes (less than 10 runs per time period per direction).

$$Average\ Travel\ Time,\ \bar{t} = \frac{\sum_{i=1}^{n} t_i}{n} \tag{7-1}$$

$$Space\text{-}Mean\ (Harmonic)\ Speed,\ \bar{v}_{SMS} = \frac{distance\ traveled}{avg.\ travel\ time} = \frac{d}{\frac{\sum t_i}{n}} = \frac{n \times d}{\sum t_i} \tag{7-2}$$

where:
- $\bar{t}$ = average travel time for time period of interest
- t_i = average travel time for i-th run or vehicle
- n = total number of travel times
- d = vehicle distance traveled or segment length

$$\begin{matrix} Average\ Vehicle \\ (or\ Person)\ Delay \end{matrix} = (\bar{t} - t_{delay}) \times V\ (or\ P) = \frac{d}{|s_{delay} - \bar{s}| \times V\ (or\ P)} \tag{7-3}$$

where:
- t_{delay} = threshold travel time at which delay occurs
- s_{delay} = threshold speed at which delay occurs
- V = vehicle volume for the time period of interest
- P = person volume for the time period of interest

A more general form for an average space mean speed is presented in Equation 7-4 (1,2). This equation can be used when a different number of travel time observations exist for numerous sequential roadway links. For example, an average corridor travel speed is obtained from Equation 7-4 by computing the average travel time for each roadway link, then weighting each link travel time by the respective number of travel time observations. This approach, which weights each link travel time, has been suggested by Quiroga and Bullock as a better estimator of average corridor travel speeds. An alternative to average travel speed is the average median travel speed as shown in Equation 7-5.

$$\text{Average Space Mean Speed, } \bar{u}_L = \frac{L_T}{t_{T_L}} = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} \bar{t}_i} = \frac{1}{\sum_{i=1}^{n} \left[\frac{L_i}{L_T} \times \frac{1}{m_i} \times \sum_{j=1}^{m_i} \frac{1}{u_{ij}} \right]} \tag{7-4}$$

where:

$\bar{u}_L$ = average space mean (harmonic) speed for total length *L*
L_t = total length of roadway for calculation of average speed
t_{T_L} = total travel time for entire length of roadway *L*
L_i = length of roadway link *i*
m = total number of travel time observations for each link *i*
u_{ij} = travel speed for roadway link *i* and observation *j*

$$\text{Median Speed, } \bar{u}_L = \frac{L_T}{\sum_{i=1}^{n} t_{m_i}} = \frac{1}{\sum_{i=1}^{n} \left[\frac{L_i}{L_T} \times \frac{1}{u_{m_i}} \right]} \tag{7-5}$$

where:

t_{m_i} = median travel time associated with link *i*
u_{m_i} = median speed associated with link *i*

- **Standard deviation (or coefficient of variation) of speed and travel time** - These statistics provide information about the variability of traffic conditions throughout the time period of interest. The standard deviation and coefficient of variation are statistical measures of variability and are calculated using Equations 7-6 and 7-7, respectively.

$$\text{standard deviation, } s = \sqrt{\frac{\sum_{i=1}^{n} (t_i - \bar{t})^2}{n - 1}} \tag{7-6}$$

$$\textit{coefficient of variation, c.v.} = \frac{s}{\bar{t}} \tag{7-7}$$

- **Acceleration noise (i.e., standard deviation of acceleration)** - Acceleration noise (Equation 7-8) measures the fluctuation of speed for a typical vehicle and can only be collected with a properly instrumented test or ITS probe vehicle. The desired instrumentation should be capable of providing nearly second-by-second speeds of a vehicle traveling in the traffic stream. Acceleration noise measures the "stop-and-go" nature of congested traffic conditions or poorly timed traffic signals on arterial streets. Previous studies have linked acceleration noise to a number of dependent variables, such as accident rate, fuel consumption and mobile source emissions (3).

$$\textit{acceleration noise, a.n.} = \sqrt{\frac{\sum_{i=1}^{n}(a_i - \bar{a})^2}{n - 1}} \tag{7-8}$$

- **Level of service (LOS) based on speed or travel time criteria** - The 1994 Highway Capacity Manual (HCM) uses average speed as an LOS criteria for arterial streets and the year 2000 HCM is oriented toward similar speed/travel time criteria for most analysis modules.

The aggregation and summarization of travel time data are fairly straightforward using current computer tools. Computer spreadsheets, databases, GIS, and statistical analysis software packages can immensely simplify the data reduction and summarization process. In most cases, data reduction and summarization consists of either averaging or summing travel time or speed data. However, several notes of caution for data reduction are provided below:

- **Ensure that space-mean speeds are calculated** - Space-mean speeds are associated with a given length of roadway and are calculated using Equation 7-2. Time-mean speeds are associated with a specified point along the roadway and are calculated by simply averaging spot speeds. Chapter 1 and Table 1-1 contains a specific example illustrating the proper calculation of space-mean speeds.

- **Use vehicle or person volume to weight average speeds** - Travel time and speed data collected for a specific roadway segment also has a vehicle or person volume associated with that segment. This volume quantifies the number of vehicles or persons traveling at the corresponding average speed. This vehicle or person volume should be used to weight speeds when combining or averaging speeds for different segments or corridors (see Equation 7-9).

$$\textit{average weighted speed, } spd_w = (spd_1 \times V_1) + (spd_2 \times V_2) + \ldots + (spd_n \times V_n) \qquad (7\text{-}9)$$

- **Aggregating travel times for a long corridor** - Consider an analysis that requires an average overall travel time for a 30-km roadway corridor. The average overall travel time can be computed by simply summing the individual link or segment travel times (Equation 7-10).

$$\textit{average corridor travel time, } t_c = t_1 + t_2 + \ldots + t_n \qquad (7\text{-}10)$$

However, if the overall corridor travel time is greater than the applicable time period in which the travel times were collected, Equation 7-10 does not provide an accurate overall corridor travel time. For example, assume that average link travel times have been collected between 7:00 and 7:30 a.m. (30-minute time period), yet it required 45 minutes (as estimated by Equation 7-10) to traverse the entire 30-km length of the corridor (see Table 7-1, Scenario 1). In this scenario, at least 15 minutes of the "corridor trip" could have occurred outside of the time period in which there is valid travel time data (i.e., 7:00 to 7:30 a.m.). Three solutions exist for this dilemma:

1. Avoid the problem by equipping a test vehicle to perform travel time runs along the entire length of the corridor. Simply average the overall corridor travel time from each test vehicle run.

2. Increase the length of the analysis time period so that it is at least as long as the total time required to traverse the entire corridor (Table 7-1, Scenario 2). In this scenario, travel times were averaged from 7:00 to 8:00 a.m. so that we could simply sum the link travel times for an overall corridor travel time.

3. Collect or obtain data for several small sequential time periods and apply the average link travel time from the correspondingly correct time period (Table 7-1, Scenario 3). In this scenario, average travel times were computed from 7:30 to 8:00 a.m. If we assume that 20 minutes of the estimated 45-minute "corridor trip" occurred in the 7:00 to 7:30 a.m. time period, then we can determine how many roadway segments were traversed during that time period. We can then apply the travel times from the next time period, 7:30 to 8:00 a.m., for the remainder of the roadway segments in the corridor.

Table 7-1. Corridor Travel Time Aggregation Example

Corridor Segment	Travel Time (min:sec)			
	Scenario 1 7:00 to 7:30 a.m.	Scenario 2 7:00 to 8:00 a.m.	Scenario 3	
			7:00 to 7:30 a.m.	7:30 to 8:00 a.m.
1	6:00	5:30	6:00	~~5:00~~
2	5:20	4:40	5:20	~~4:00~~
3	4:40	4:00	4:40	~~3:20~~
4	5:40	5:20	5:40	~~5:00~~
5	6:00	5:40	6:00	~~5:20~~
6	4:30	4:00	~~4:30~~	3:30
7	3:40	3:40	~~3:40~~	3:40
8	4:00	4:00	~~4:00~~	4:00
9	2:30	2:30	~~2:30~~	2:30
10	2:20	2:00	~~2:20~~	1:40
Corridor Travel Time	**45:00** (but analysis period only 30 minutes)	**41:20** (okay since analysis period is 60 minutes)	**43:00** (okay since travel times from corresponding time period are used)	

7.2 Overview of Travel Time Data Applications

Travel time data are collected for a variety of applications and analyses. This section provides a brief overview of common applications of travel time data. The reader is encouraged to review the companion handbook on travel time applications. At press time, this guidance manual on applications of travel time data travel time was being prepared for FHWA by the Texas Transportation Institute.

Travel time data are the raw element for a number of performance measures that permeate many transportation analyses. Examples of travel-time based quantities or measures include the following:

- door-to-door travel time;
- travel time reliability/variability (i.e., standard deviations or confidence intervals);
- average speed;
- person or vehicle delay (as compared to some delay threshold);
- delay rate, relative delay rate, or delay ratio;
- speed of person movement (requires estimate of person volumes);
- travel time or congestion indices for corridors or networks; and
- accessibility to activities or opportunities (e.g., percent of population within 20 minutes of jobs, hospital, etc.).

Travel time-based measures can be used in transportation planning, design and operations, and evaluation. Examples of planning and design applications include:

- *Develop transportation policies and programs* - may rely on current and projected trends in travel time-based performance measures;

- *Perform needs studies or assessments* - may use travel time-based measures to assess transportation deficiencies and potential improvements;

- *Rank and prioritize transportation improvements* - may use numerical magnitude of travel time-based measures to set funding or programming priorities;

- *Evaluate transportation improvement strategies* - compare a number of possible alternatives using a set of travel time-based measures;

- *Input/calibration of planning models* - uses base data such as travel time or speed to compare simulated data to existing conditions, and projecting future scenarios; and

- *Calculate road user costs for economic analyses* - uses basic data as inputs to economic models that estimate costs and benefits.

Examples of operational applications include:

- *Develop historical database of traffic conditions* - an historical database of travel times and speeds can be used in numerous ITS applications;

- *Input/calibration of traffic models* - uses detailed data for model calibration relating to microscopic traffic operations, fuel consumption, mobile source emissions;

- *Real-time traffic control* - uses travel time and speed to operate dynamic message and lane assignment signs, ramp metering, and traffic signal control;

- *Route guidance and navigation* - provides travel time information and alternative routes based on current or historical databases;

- *Traveler information* - provides up-to-date travel time and speed information to the commuting public; and

- *Incident detection* - uses changes or differences in current travel time or speed as compared to historical databases.

Examples of evaluation applications include:

- *Establish/monitor congestion trends* - collect and develop historical data for trend analyses;

- *Congestion management/performance measurement* - tracking trends over time of travel time-based measures, attempt to develop cause-and-effect relationships;

- *Identify congestion locations or bottlenecks* - uses travel time data in combination with geometric or signal information to identify problems and potential solutions;

- *Measure effectiveness and benefits of improvements* - use before-and-after travel time data to gauge the effects of transportation improvements;

- *Communicate information to the public* - use non-technical travel time-based measures to communicate traffic conditions and trends to the general public; and

- *Research and development* - uses travel time data for a wide variety of research applications.

7.3 Understanding Your Audience for Travel Time Summaries

One of the first principles taught in most technical writing courses is the importance of understanding your audience. This same principle also applies to tabular and graphical data summaries. These data summaries often serve as the only interpretation of extensive data collection efforts for a wide variety of audiences. The manner in which data are presented, as well as the actual data itself, is critical for effectively communicating the results of travel time collection activities. The intended audience(s) for data summaries affects several aspects:

- **Underlying message or theme of the summary** - The intended audience directly influences the underlying message or theme of the summary. For example, a mayor of a large city is likely more interested in regional travel time and speed trends and less interested in the number of stops for a particular travel time run. Conversely, a city signal technician is likely more interested in the number and location of stops along an arterial street.

- **Manner of presentation** (e.g., table versus graph/chart) - Concise, easy-to-understand graphs or charts are best suited to non-technical audiences, whereas these concise summaries may not contain enough information for detail-oriented, technical audiences.

- **Use of technical language/terminology** - If decision-makers or elected officials will utilize data summaries, technical language should be avoided if possible. At a minimum, technical terms should be defined for unfamiliar readers.

- **Level of detail** - The level of detail should be appropriate for the intended audiences. If a wide variety of readers is expected, different types of summaries should be provided. Technical appendices can be provided for data collection details, and an executive summary can be used to present the major findings of the study in graphical or brief tabular formats.

7.4 Presenting Dimensions of Congestion with Travel Time and Speed Data

Travel time and speed data are often used to identify and evaluate traffic congestion patterns and trends. It is important to note that traffic congestion has several “dimensions,” and that data summaries should be designed to represent these four major dimensions (4):

- **Duration** - amount of time roadway facilities are congested;
- **Extent** - number of people affected or the geographic distribution;
- **Intensity** - level or total amount of congestion; and,
- **Reliability** - variation in the amount of congestion.

These dimensions of congestion can be represented with a number of travel time/speed measures, depending upon the system component as shown in Table 7-2.

Table 7-2. Measures and Summaries to Display the Dimensions of Congestion

Congestion Aspect	System Type		
	Single Roadway	**Corridor**	**Areawide Network**
Duration (i.e., amount of time system is congested)	Hours facility operates below acceptable speed	Hours facility operates below acceptable speed	Set of travel time contour maps; "bandwidth" maps showing amount of congested time for system sections
Extent (i.e., number of people affected or geographic distribution)	percent or amount of congested VMT or PMT; percent or lane-km of congested road	percent of VMT or PMT in congestion; percent or lane-km of congested road	percent of trips in congestion; person-km or person-hours of congestion; percent or lane-km of congested roadway
Intensity (i.e., level or total amount of congestion)	Travel speed or rate; delay rate; relative delay rate; minute-km; lane-km hours	Average speed or travel rate; delay per PMT; delay ratio	Accessibility; total delay in person-hours; delay per person; delay per PMT
Reliability or Variability (i.e., variation in the amount of congestion)	Average travel rate or speed ± standard deviation; delay ± standard deviation	Average travel rate or speed ± standard deviation; delay ± standard deviation	Travel time contour maps with variation lines; average travel/time ± standard deviation; delay ± standard deviation

Notes: adapted from reference (4)
VMT—vehicle-miles of travel; PMT—person-miles of travel

7.5 Examples of Data Summaries

Tabular summaries contain numerical values in a row or column format, whereas graphical summaries provide information in the form of a chart, graph, or picture. The choice of a tabular or graphical summary depends upon the intended audience and the desired message. In general, tabular summaries are best for presenting large amounts of data with some level of detail. Graphical summaries are best suited to presenting relatively small amounts of easily understandable data. Further, graphical summaries allow the viewer to quickly recognize trends and relative comparisons of data with the visual presentation. Depending upon the level of detail, tabular summaries may take longer to interpret than comparable graphical summaries. Also, technical audiences are generally more effective at interpreting tabular summaries because of their numeric orientation and format.

Travel time data summaries may be provided at several levels of detail:

- **Run summary** - summarizes data on a specific travel time run, and typically includes elapsed time and speed between checkpoints, causes of intermediate delay, and time spent in different speed ranges. Run summaries are useful in performing quality control on data collection efforts and diagnosing traffic operations problems at a detailed scale.

- **Aggregated run summary** - aggregates data for several travel time runs or vehicles along a single route, and typically includes average travel times and speeds between checkpoints and totals for delay. Aggregated run summaries provide average statistics for individual routes segments and are useful for a number of applications. Data collected from license plate matching includes average travel times and speeds for predefined roadway segments.

- **Corridor or route summary** - summarizes data for a corridor or route of consequential length, and includes average travel times, speeds, and delays. Corridor or route summaries are useful for large scale comparisons of traffic conditions and for providing information to non-technical audiences.

- **Functional classification summary** - summarizes data for all roadways within defined functional classifications (see Chapter 2), and includes average travel times, speeds, and delays. Functional class summaries are also useful at a macroscopic level for long range planning and time series trends.

- **Other summaries** - includes activity center summaries, travel time contours, accessibility plots, and other types of summaries not fitting neatly into the above categories. These types of summaries are more “system-oriented” than other summaries and help to identify the system conditions and the system effects of various transportation improvements.

The remainder of this chapter contains examples of these summaries with an interpretation of key features. These examples are a representative sample of travel time data summaries that have been used by transportation agencies. These examples are not a comprehensive inventory of all possible summaries. Two other references (4,5) contain several additional examples of tabular and graphical travel time data summaries. The figures and tables shown throughout this chapter are intended to provide the user of this handbook with examples from previous studies, with the intent of aiding the reader in identifying summaries applicable to their users and uses.

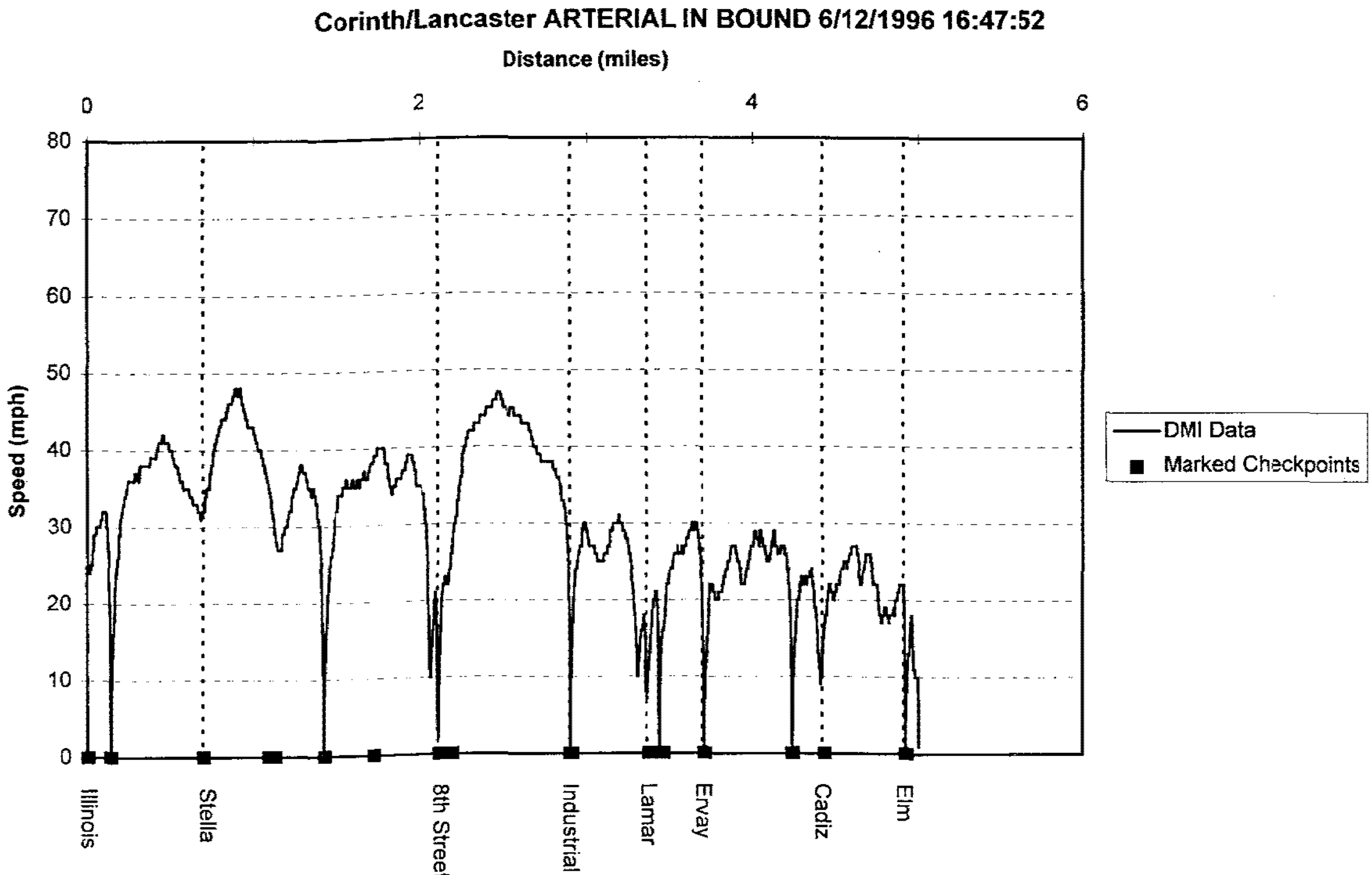
7.5.1 Run Summaries

A run summary includes data that have been collected during a specific travel time run, including elapsed time and speed between checkpoints, causes of intermediate delay, and time spent in different speed ranges. The run summaries are most common for test vehicle methods in which the vehicle is instrumented and data can be frequently collected at intermediate locations. Run summaries provide the finest level of detail for a travel time run, thereby providing a useful tool for performing quality control or diagnosing traffic operations problems.

Figures 7-1 and 7-2 show a run summary for Corinth/Lancaster Street in Dallas. The travel time and speed data shown in these figures were collected using the test vehicle method with an electronic DMI (see Chapter 3). The speed profile in Figure 7-1 illustrates the speed of the test vehicle throughout the entire length of the travel time run. Stops at intersections or mid-block speed reductions are clearly denoted by "dips" in the speed profile. Speed profiles such as Figure 7-1 provide useful information at a glance on signal coordination and progression. Also, note that the speed profile in Figure 7-1 is distance-based (i.e., x-axis is in distance units). A time-based speed profile shows more information about the duration of stops, but systematic identification of cross streets on a graph may be difficult. Graphing functions in most computer spreadsheets simplify the task of producing distance-time, speed-distance, or acceleration-distance profiles. Software macros also simplify the calculation of control delay, stopped delay, and other measures of effectiveness (6).

Figure 7-2 contains a tabular summary of the same travel time run illustrated in Figure 7-1. The tabular summary in Figure 7-2 includes intermediate and cumulative distances, travel times, and average speeds. This type of summary typically includes summary information on the cause and magnitude of stops or traffic disruptions experienced during the travel time run. The tabular summary in Figure 7-2 also contains information about the percent time spent in different speed ranges and the level of service for Highway Capacity Manual calculations.

For less automated test vehicle methods, travel times and speeds may only be available at selected intermediate checkpoints. Figure 7-3 illustrates the display of travel time, speed, and delay for a given travel time run. Note that less detail is available for the speed profile and that only average speeds are known between intermediate checkpoints. Table 7-3 contains an example of a tabular run summary of travel times, speeds, and delays between intermediate checkpoints.



Source: adapted from reference (7)

Figure 7-1. Example of Graphical Run Summary (Speed Profile) for Corinth/Lancaster Street in Dallas

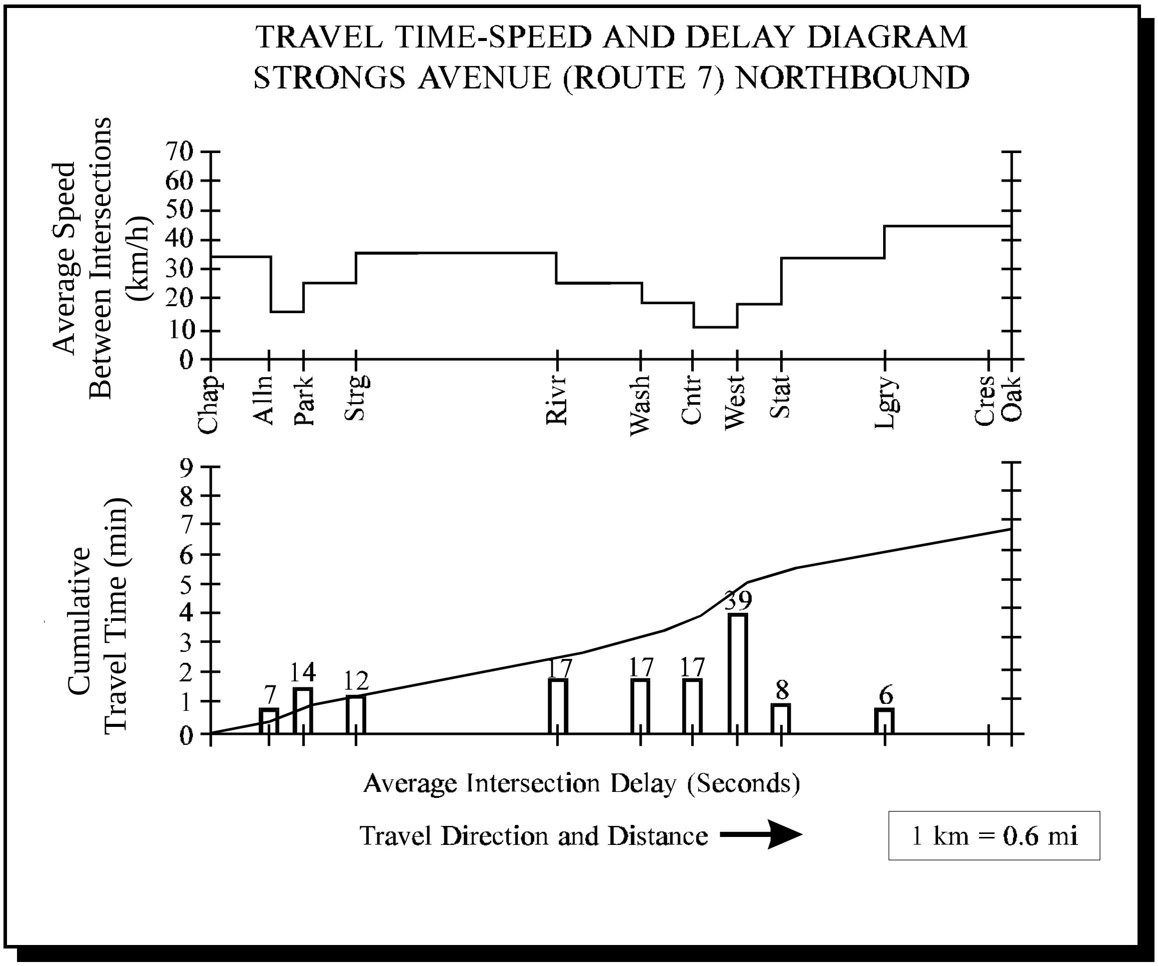
FACILITY NAME	CORINTH/LANCASTER
TRAVEL DIRECTION	IN BOUND
TTR DATE	6/12/96
WEATHER	OVERCAST
PAVEMENT	DRY
LIGHT CONDITION	NORMAL DAYLIGHT
SCHEDULED TIME	16:48
START TIME	16:47

CHECKPOINT	INT DIST (miles)	CUMM DIST (miles)	INT TIME (min)	CUMM TIME (min)	STDEV SPEED (mph)	AVG SPEED (mph)	PERCENT TIME UNDER 5 mph	PERCENT TIME BETWEEN 5-35 mph	PERCENT TIME BETWEEN 35-50 mph	PERCENT TIME OVER 50 mph	LEVEL OF SERVICE
Illinois	0.000	0.000	0.00	0.00	-----	-----	-----	-----	-----	-----	-----
Stella	0.690	0.690	1.60	1.60	14.37	25.90	19.0%	48.7%	32.3%	0.0%	-----
8th Street	1.420	2.110	2.94	4.54	13.06	28.97	10.3%	51.4%	38.3%	0.0%	-----
Industrial	0.790	2.900	1.38	5.92	12.16	34.24	5.9%	33.1%	60.9%	0.0%	-----
Lamar	0.460	3.360	1.71	7.64	11.46	16.11	27.3%	72.7%	0.0%	0.0%	-----
Ervay	0.340	3.700	1.09	8.72	8.97	18.76	12.0%	88.0%	0.0%	0.0%	-----
Cadiz	0.720	4.420	2.70	11.43	10.26	15.99	25.2%	74.8%	0.0%	0.0%	-----
Elm	0.490	4.910	1.36	12.79	3.24	21.63	0.0%	100.0%	0.0%	0.0%	-----
RUN AVERAGES						23.04	15.4%	65.2%	19.4%	0.0%	

REPORTED TRAFFIC CONDITIONS		
INCIDENT TYPE	TIME	MILE
Queue @ Signal	16:48:23	0.139
Queue Ends (Rolling)	16:48:41	0.143
One Lane Blocked	16:50:13	1.088
One Lane Blocked	16:50:14	1.101
Queue Ends (Rolling)	16:51:12	1.421
Construction Starts	16:51:46	1.727
Construction Ends	16:52:54	2.201
Queue @ Signal	16:54:00	2.903
Queue @ Signal	16:55:59	3.436
Queue Ends (Rolling)	16:56:12	3.463
Queue @ Signal	16:56:52	3.712
Queue @ Signal	16:58:25	4.241
Queue Ends (Rolling)	16:58:53	4.248
Queue @ Signal	17:00:55	4.922

Source: adapted from reference (7)

Figure 7-2. Example of Tabular Run Summary for Corinth/Lancaster Street in Dallas



Source: adapted from reference (8)

Figure 7-3. Example Summary of Travel Time, Speed, and Delay Information for an Arterial Street

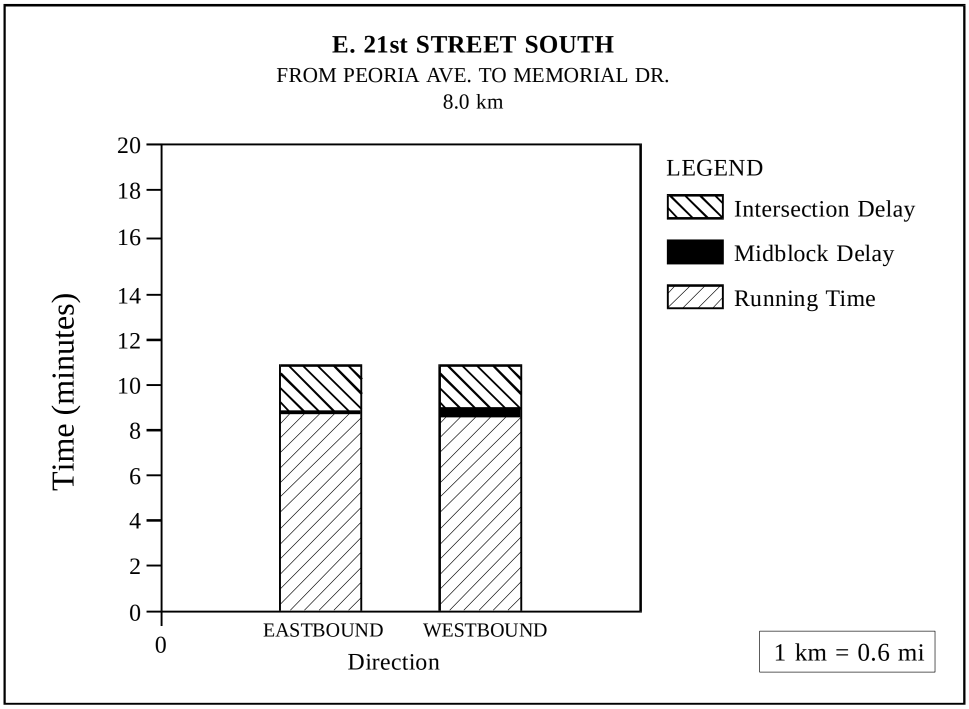
Table 7-3. Example Tabular Run Summary in Hampton Roads, Virginia

RUN SUMMARY OF: VA BEACH BLVD, FILE: VABEACHE.R10
FROM: NEWTON RD. TO: GREAT NECK DIRECTION: EASTBOUND
DATE OF RUN: 03-05-1990 TIME OF RUN: 16:19:36

Link #	Cross St. at end of link	Link Length (m)	Delay Time (sec)	Number of Stops	Travel Time (sec)	Average Speed (km/h)	Cruise Speed (km/h)
	Newtown Rd						
1	Davis St	591	22	2	81	26.2	44.3
2	Clearfield	751	38	1	97	27.9	53.0
3	Witchduck Rd	783	67	1	124	22.7	55.9
4	Dorset Ave	448	0	0	26	62.0	62.3
5	Aragona Blvd	553	0	0	32	62.3	64.7
6	Kellam Rd	352	0	0	19	66.8	66.8
7	Independence	451	25	1	62	26.2	58.6
8	Pembroke Mall	262	0	0	18	52.3	53.3
9	Constitution	249	39	1	63	14.2	47.2
10	Cox Dr	401	0	0	27	53.5	53.8
11	Thalia Rd	503	80	1	163	11.1	32.4
12	Stephey Ln	493	0	0	27	65.8	65.8
13	Lynn Shores	660	0	0	34	69.9	69.9
14	Outlet Mall	477	0	0	25	68.7	71.0
15	Rosemont Rd	511	68	1	104	17.7	71.6
16	Little Neck	619	40	1	86	25.9	63.4
17	King Richard	234	0	0	15	56.2	59.9
18	Cranston Ln	581	0	0	29	72.1	72.1
19	Kings Grant	342	0	0	23	53.5	60.1
20	Lynnhaven Rd	592	0	0	34	62.6	63.6
21	Yorktown Ave	182	18	1	36	18.2	60.4
22	Mustang Tr	393	0	0	25	56.7	58.4
23	Lynnhaven Pk	261	0	0	13	72.3	72.3
24	Byrd Ln	960	0	0	49	70.5	71.5
25	Great Neck	349	19	1	49	25.6	53.5
Route Summary:		11,998 (11.9 km)	416 (6:56)	11	1261 (21:01)	34.2	60.7

Source: adapted from reference (9)

Figure 7-4 contains an example of a run summary that combines graphical and tabular elements. The chart illustrates the travel time in relation to intersection and mid-block delay, whereas the table below contains specific travel time and delay values for the chart.



E. 21st STREET SOUTH

	EASTBOUND	WESTBOUND
Day of Week	Wednesday	Wednesday
Time of Day	Off-Peak	Off-Peak
Trip Length (km)	8.0	8.0
Travel Time (Minutes)	10:46	10:46
Intersection Delay	2:06	1:52
Midblock Delay	0:01	0:20
Running Time	8:39	8:36
Posted Speed (km/h)	55	55
Travel Speed (km/h)	44.9	44.9
Running Speed (km/h)	55.9	56.2

Source: adapted from reference (10)

Figure 7-4. Example of Combined Graphical and Tabular Data Summary from Tulsa, Oklahoma

7.5.2 Aggregated Run Summaries

An aggregated run summary includes data for several travel time runs along the same route, such as average elapsed time, average travel time and speeds between checkpoints, and totals for delay. Aggregated run summaries can be used to compare the travel times and speed for several runs that have been performed at different times or different days of the week. Most of the detail for an individual travel time run may, however, be omitted from these summaries for the sake of brevity or clarity. Data collection managers or personnel commonly use aggregated run summaries for quality control to ensure that travel time runs for the same route produced comparable results.

Figure 7-5 contains a tabular summary that includes the travel time data from three separate test vehicle runs. In this figure, one can note that the data from Figure 7-1 and 7-2 is represented in the first major column of Figure 7-5. Also note in this figure that delay and stops information from individual runs have been omitted. An average travel time and speed between each intermediate checkpoint is provided in the last column. These average travel time and speed values will then be used in subsequent facility or system summaries.

For some aggregated run summaries, it may be desirable to present only the average travel times and speeds for all runs. Figure 7-6 presents an average speed profile along an arterial street in southeastern Virginia. The average speed is shown in relation to applicable level of service (LOS) criteria. With this notation, the audience can clearly see when average speeds drop below LOS D.

Table 7-4 contains a tabular summary for a freeway corridor in Houston, Texas for both directions and three different time periods (a.m. peak, off peak, and p.m. peak). The tabular summary includes only average travel times and speeds between intermediate checkpoints. Note also that the summary provides route subtotals at major cross streets, as well as total travel times and average speeds for the entire length of the surveyed route.

Figure 7-7 shows a travel time "strip map" that was developed for the congestion management system in Baton Rouge, Louisiana. The "strip map" format correlates interchange and ramp layouts to travel time and speed data on sequential segments and also includes information about segment length and posted speed limits. Figure 7-8 contains a "speed deficit" map that illustrates the differences between measured average travel speeds and posted speed limits.

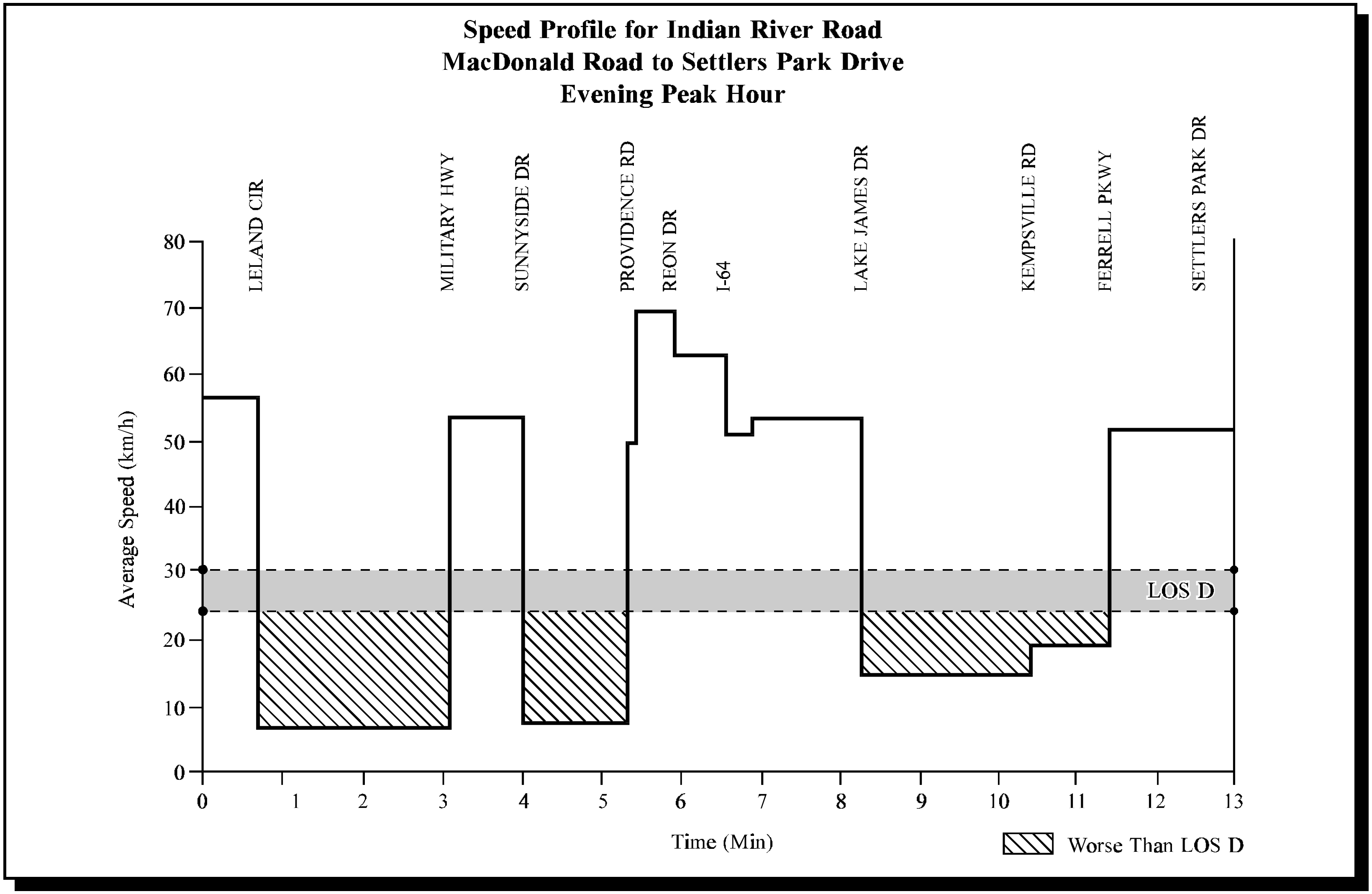
Figure 7-9 provides a graphical summary of average speeds on I-77 in Cleveland, Ohio. The figure provides average speeds for both directions and for three different time periods. Note that in this figure the average speeds appear to correspond with a single point along the corridor. Closer inspection of the accompanying report text indicate, however, that the average speeds shown correspond to six long sections of freeway.

Corinth/Lancaster
ARTERIAL
INBOUND
PM TIME PERIOD

				COAI6F12.16J 16:48 6/12/96			COAI6F12.17F 17:30 6/12/96			COAI6F10.18H 18:40 6/10/96			AVERAGE		
TRAVELED FACILITY	SEGMENT CHECKPOINT	INT DIST (miles)	CUMM DIST (miles)	INT TIME (min)	CUMM TIME (min)	AVG SPEED (mph)	INT TIME (min)	CUMM TIME (min)	AVG SPEED (mph)	INT TIME (min)	CUMM TIME (min)	AVG SPEED (mph)	INT TIME (min)	CUMM TIME (min)	INT SPEED (mph)
Corinth	Illinois	0.000	0.000	0.00	0.00	—	0.00	0.00	—	0.00	0.00	—	**0.00**	**0.00**	—
Corinth	Stella	0.690	0.690	1.60	1.60	25.90	1.04	1.04	39.88	1.43	1.43	29.05	**1.35**	**1.35**	**30.58**
Corinth	8th Street	1.420	2.110	2.94	4.54	28.97	2.60	3.63	32.83	3.13	4.56	27.21	**2.89**	**4.24**	**29.49**
Corinth	Industrial	0.790	2.900	1.38	5.92	34.24	1.44	5.08	32.87	1.47	6.02	32.32	**1.43**	**5.67**	**33.13**
Corinth	Lamar	0.460	3.360	1.71	7.64	16.11	1.05	6.13	26.17	1.89	7.92	14.57	**1.55**	**7.23**	**17.76**
Corinth	Ervay	0.340	3.700	1.09	8.72	18.76	1.31	7.44	15.57	1.27	9.19	16.08	**1.22**	**8.45**	**16.69**
Ervay	Cadiz	0.720	4.420	2.70	11.43	15.99	2.29	9.73	18.86	2.60	11.78	16.65	**2.53**	**10.98**	**17.08**
Ervay	Elm	0.490	4.910	1.36	12.79	21.63	1.29	11.02	22.73	1.37	13.15	21.50	**1.34**	**12.32**	**21.94**
				—	—	23.04	—	—	26.72	—	—	22.40	—	—	**23.91**

Source: adapted from reference (7)

Figure 7-5. Example Aggregated Run Summary for Corinth/Lancaster Street in Dallas



Source: adapted from reference (11)

Figure 7-6. Example of Aggregated Run Summary (Average Speed Profile) in Southeastern Virginia

Table 7-4. Example of a Tabular Aggregated Run Summary in Houston, Texas

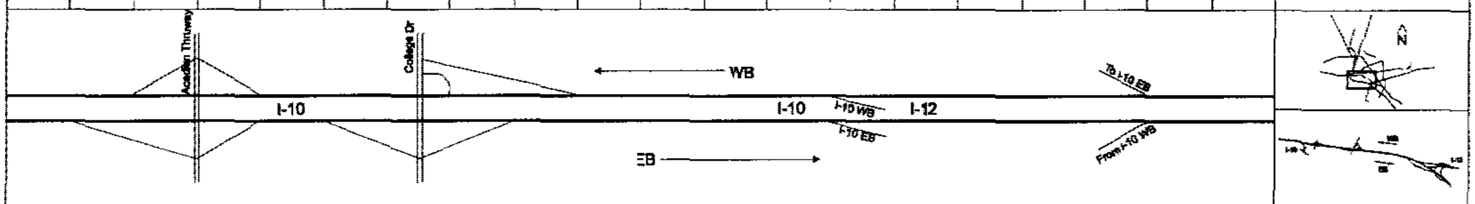
HOUSTON-GALVESTON REGIONAL TRANSPORTATION STUDY
1994 TRAVEL TIME AND SPEED SURVEY
ROADWAY NAME : US 290 (NORTHWEST FREEWAY)
FUNCTIONAL CLASS : OTHER FREEWAY OR EXPRESSWAY

SEGMENT DESCRIPTION	SEGMENT LENGTH (MILES)	A.M. PEAK (6:30 - 8:30)				OFF PEAK (9:30 - 15:30)						P.M. PEAK (16:30 - 18:30)			
		NORTHBOUND		SOUTHBOUND		NORTHBOUND		SOUTHBOUND		AVERAGE		NORTHBOUND		SOUTHBOUND	
		TIME	SPEED	TIME	SPEED	TIME	SPEED	TIME	SPEED	TIME	SPEED	TIME	SPEED	TIME	SPEED
IH 610 TO MANGUM	0.80	0.80	60.00	2.12	22.60	0.93	51.89	0.78	61.94	0.85	56.47	1.78	27.02	0.77	62.07
MANGUM TO W 34TH	0.83	0.84	59.64	1.60	31.07	0.87	57.57	0.85	58.93	0.86	58.25	1.51	33.09	0.84	59.29
W 34TH TO ANTOINE	0.42	0.47	53.90	0.74	34.19	0.45	56.63	0.42	60.00	0.43	58.27	0.90	28.16	0.44	57.27
ANTOINE TO W 43RD	0.87	0.86	61.05	1.30	40.15	0.89	58.98	0.89	58.65	0.89	58.82	1.72	30.44	0.84	62.39
W 43RD TO BINGLE	0.50	0.51	59.41	0.82	36.52	0.54	56.07	0.49	61.22	0.51	58.54	0.97	30.98	0.49	61.86
BINGLE TO PINEMONT	0.30	0.30	61.02	0.40	44.84	0.33	55.38	0.30	60.00	0.31	57.60	0.52	34.84	0.33	55.10
PINEMONT TO HOLLISTER	0.95	0.97	59.07	1.35	42.09	0.97	59.07	0.95	60.00	0.96	59.53	1.60	35.59	0.96	59.38
HOLLISTER TO TIDWELL	0.29	0.33	53.13	0.65	26.65	0.32	55.24	0.31	56.13	0.31	55.68	0.59	29.66	0.30	58.00
TIDWELL TO F-BANKS N HOUSTON	1.06	1.02	62.66	1.73	36.82	1.06	60.00	1.08	58.89	1.07	59.44	1.77	35.86	1.05	60.57
F-BANKS N HOUSTON TO GESSNER	1.13	1.12	60.54	2.13	31.81	1.12	60.81	1.13	60.00	1.12	60.40	1.48	45.86	1.12	60.45
GESSNER TO LITTLE YORK	0.49	0.51	57.37	0.56	52.50	0.49	60.00	0.48	61.89	0.48	60.93	0.50	59.00	0.48	60.83
LITTLE YORK TO SAM HOUSTON TOLLWAY	0.49	0.50	59.39	1.42	20.75	0.53	56.00	0.51	58.22	0.52	57.09	0.67	43.99	0.51	57.65
SUBTOTAL	8.13	8.19	59.54	14.83	32.89	8.45	57.73	8.17	59.71	8.31	58.70	13.98	34.88	8.13	60.02
SAM HOUSTON TOLLWAY TO SENATE	0.51	0.53	58.01	1.45	21.12	0.51	60.00	0.56	54.64	0.54	57.20	0.63	48.96	0.54	57.20
SENATE TO JONES ROAD	1.60	1.58	60.66	1.61	59.68	1.54	62.34	1.58	60.95	1.56	61.64	1.36	70.42	1.62	59.20
JONES RD TO ELDRIDGE	1.41	1.34	63.25	1.42	59.64	1.44	58.75	1.37	61.98	1.40	60.32	1.42	59.44	1.38	61.23
ELDRIDGE TO FM 1960	1.28	1.27	60.35	1.26	61.09	1.26	61.20	1.23	62.69	1.24	61.94	1.30	59.23	1.28	59.84
SUBTOTAL	4.80	4.72	61.02	5.73	50.24	4.75	60.70	4.73	60.95	4.74	60.82	4.71	61.17	4.82	59.73
CUMULATIVE SUBTOTAL	12.93	12.91	60.08	20.56	37.73	13.20	58.79	12.90	60.16	13.05	59.47	18.69	41.51	12.95	59.92
FM 1960 TO HUFFMEISTER	0.91	0.96	56.88	0.93	58.98	0.93	59.03	0.93	59.03	0.93	59.03	0.97	56.10	0.95	57.47
HUFFMEISTER TO TELGE	1.58	1.53	61.86	1.58	60.16	1.53	62.16	1.54	61.56	1.53	61.86	1.57	60.32	1.62	58.46
TELGE TO BARKER CYPRESS	1.84	1.80	61.45	1.71	64.56	1.79	61.85	1.83	60.49	1.81	61.16	1.71	64.44	1.87	59.04
BARKER CYPRESS TO CYPRESS-ROSEHILL	1.80	2.01	53.64	1.88	57.55	1.99	54.41	1.90	56.99	1.94	55.67	2.03	53.29	1.96	55.01
CYPRESS-ROSEHILL TO BECKER RD	6.90	6.69	61.88	6.75	61.33	7.03	58.93	6.52	63.55	6.77	61.15	6.45	64.15	6.62	62.57
BECKER RD TO WARREN RANCH RD	3.03	2.97	61.14	3.02	60.27	3.15	57.71	3.04	59.90	3.09	58.79	3.10	58.65	2.96	61.35
WARREN RANCH RD TO FM 2920	4.43	4.40	60.41	4.47	59.42	4.75	55.96	4.44	59.86	4.60	57.85	4.82	55.11	4.61	57.70
FM 2920 TO HARRIS/WALLER CO LINE	0.53	0.75	42.59	0.59	53.60	0.82	38.78	0.58	55.30	0.70	45.59	0.69	45.87	0.59	53.90
SUBTOTAL	21.02	21.11	59.74	20.92	60.28	21.97	57.42	20.75	60.78	21.36	59.05	21.36	59.06	21.18	59.54
TOTAL	33.95	34.03	59.87	41.48	49.10	35.16	57.94	33.65	60.54	34.40	59.21	40.05	50.87	34.13	59.68

Source: adapted from reference (12)

BATON ROUGE — CORRIDOR No. 1 – I-10 — 9/1/95 to 5/3/96

																				PM PEAK
53	51	54	54	50	47	48	48	55	55	54	55	55	57	56	57	56	55	52	47	Avg. Travel Speed (mph)
233	224	216	203	191	177	162	153	144	135	122	108	95	88	74	61	48	35	24	10	Cum. Travel Time (sec)
																				OFF PEAK
53	52	56	56	50	54	51	52	55	55	55	55	52	42	60	59	59	59	57	57	Avg. Travel Speed (mph)
227	219	211	198	187	172	159	151	142	134	120	107	94	84	67	55	43	3'	20	8	Cum. Travel Time (sec)
																				AM PEAK
43	40	49	50	44	43	39	38	36	37	38	39	40	35	37	39	47	49	41	28	Avg. Travel Speed (mph)
306	296	285	271	258	242	225	215	202	190	170	151	132	119	98	79	61	46	32	15	Cum. Travel Time (sec)
55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	Posted Speed Limit (mph)
0.12	0.12	0.20	0.18	0.20	0.20	0.11	0.13	0.13	0.20	0.20	0.20	0.15	0.20	0.20	0.20	0.20	0.18	0.20	0.12	Segment Length (mi)
14262	12412	12421	12422	12423	12428	12423	12435	12434	12439	12438	12437	12436	12448	12447	12482	12446	12445	12481	12480	Segment ID

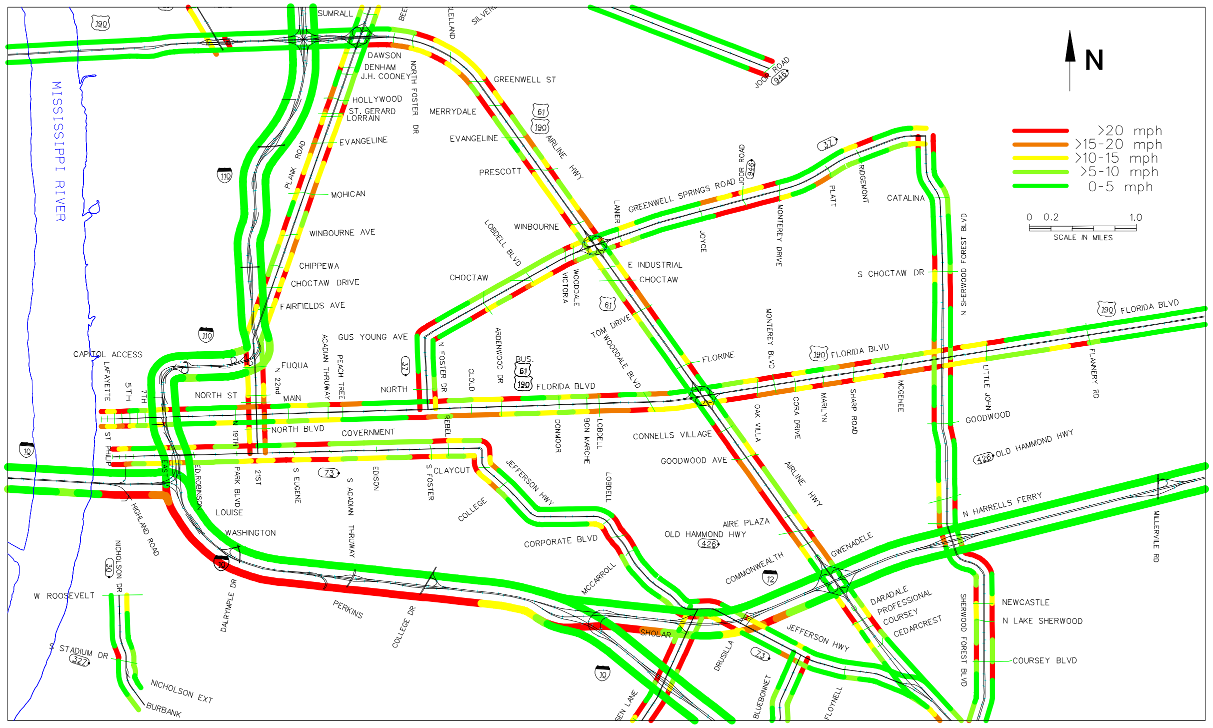


12139	12414	12420	12415	11810	12426	12429	12427	12440	12441	12442	12443	12444	12451	12450	12483	12464	12449	12478	12479	Segment ID
0.15	0.14	0.20	0.20	0.12	0.14	0.20	0.20	0.12	0.20	0.20	0.20	0.20	0.10	0.10	0.20	0.20	0.20	0.17	0.20	Segment Length (mi)
55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	Posted Speed Limit (mph)
																				AM PEAK
51	52	53	52	51	53	52	53	52	53	53	53	53	52	53	54	54	53	54	55	Avg. Travel Speed (mph)
10	19	33	47	56	66	79	93	102	115	129	143	156	163	170	184	197	210	222	235	Cum. Travel Time (sec)
																				OFF PEAK
51	56	56	53	50	54	52	52	50	53	54	54	55	57	58	62	63	63	61	61	Avg. Travel Speed (mph)
10	19	33	47	55	65	79	93	101	115	128	142	155	161	167	179	190	202	213	224	Cum. Travel Time (sec)
																				PM PEAK
21	14	12	13	22	23	22	20	23	33	37	39	41	31	17	20	21	16	22	35	Avg. Travel Speed (mph)
26	61	118	173	193	215	249	284	304	326	345	364	382	393	415	451	486	531	559	580	Cum. Travel Time (sec)

09/17/96 — Remote Sensing and Image Processing Laboratory — Avg Travel Speed/Posted Speed Limit Ratio: >0.9 | 0.8-0.9 | 0.7-0.8 | 0.5-0.7 | 0.3-0.5 | <0.3 — Section 11

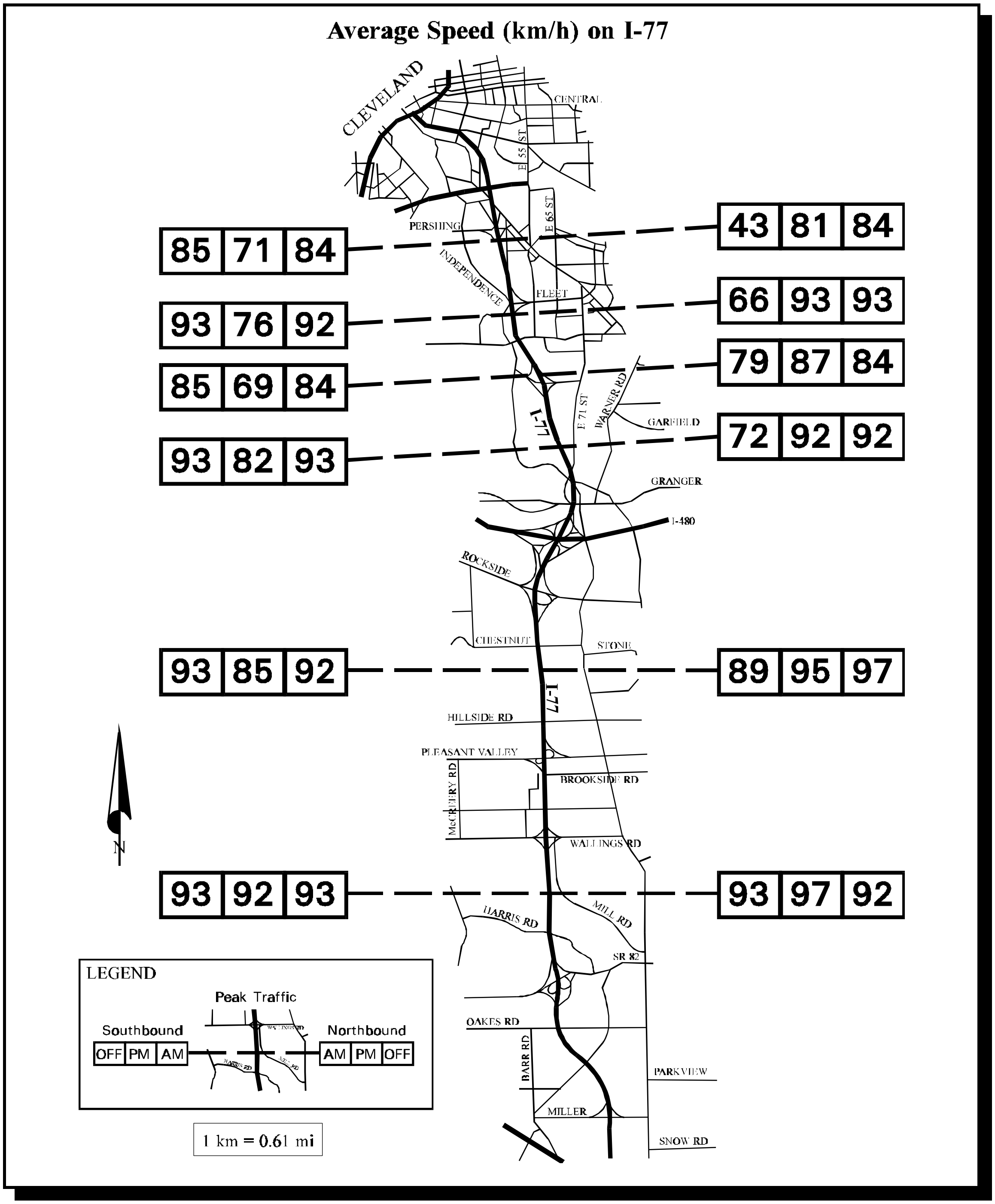
Source: adapted from reference (13)

Figure 7-7. Example of Travel Time "Strip Map" in Baton Rouge, Louisiana



Source: adapted from reference (12).

Figure 7-8. Example of a "Speed Deficit" Map in Baton Rouge, Louisiana



Source: adapted from reference (15)

Figure 7-9. Example of Graphical Aggregated Run Summary in Cleveland, Ohio

Figure 7-10 presents a speed contour diagram that shows the average speeds along a corridor for different times of the day. In this figure, the morning and evening peak periods are shown. Similar speed contour diagrams are available through computer simulation programs, such as the speed diagram shown in Figure 7-11. Note that although these two figures only show speeds to the nearest 10 or 15 mph, one can clearly see the patterns and trends of congestion and any associated bottleneck locations.

7.5.3 Corridor or Route Summaries

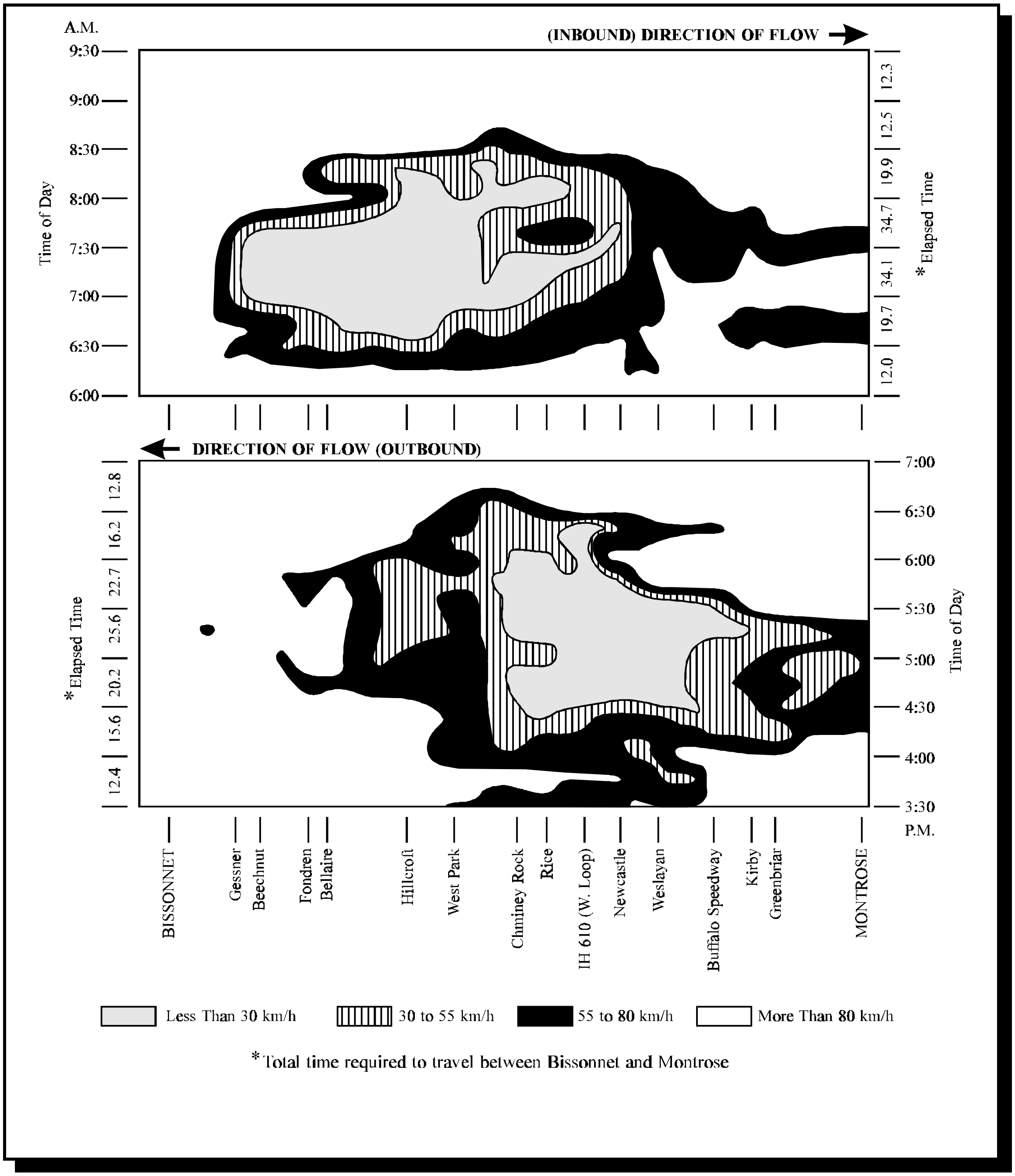
A corridor or route summary includes travel time, speed and delay data for corridor or routes of consequential length (typically eight km (five mi) or longer). The main purpose of these types of summaries is to compare travel times and speeds between several different routes or corridors.

Figure 7-12 illustrates the differences between average speeds in an HOV lane and the adjacent freeway mainlanes using travel time data collected using license plate matching techniques. The figure represents the range in travel speeds during the morning peak period on an eight-kilometer freeway section in Dallas, Texas. The large number of speed samples provides a better perspective on the variability of speeds during the morning peak and between the different roadway facilities.

The corridor summary in Table 7-5 compares the average speeds for two freeways and four arterial streets over a period of three years. Note that the addition of a fourth column containing the percentage change of average speed between 1977 and 1979 would improve the comprehension of speed trends for each facility.

Figure 7-13 and 7-14 show a similar perspective on the differences between travel times on Houston's Katy (IH-10) freeway HOV lane and the adjacent mainlanes. The travel time data shown in these figures were obtained from probe vehicles in Houston's automatic vehicle identification (AVI) traffic monitoring system. Figure 7-13 also shows the average monthly and daily travel time values, illustrating that the HOV lane offers a significant travel time savings and a more reliable travel time than the adjacent freeway mainlanes. Figure 7-14 more clearly illustrates the variability of travel times using an 85 percent confidence interval for average peak hour travel times.

The chart in Figure 7-15 compares the travel times, speeds, and delays for both directions of two arterial streets for different times of the day. Note that although the chart contains a wealth of information, it takes more time to interpret the graphics than most charts. This figure contains more detail than most typical corridor summaries.



Source: adapted from reference (16)

Figure 7-10. Example of Speed Contour Diagrams from Data Collection

```
CONTOUR DIAGRAM OF SPEED     ALL LANES
BEFORE  IMPLEMENTATION

        TIME                                                                                                         BEGIN
        SLICE .......................................................................................................  TIME
              .                                                                                                    .
            1 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. -  6:00
            2 .6666666666666666666666666666666666666666666666666666666666666666555555566666666666666666666655555555. -  6:15
            3 .6666666666666666666666666666666666666666666666666666666555555555555555555555555555555555555555555555. -  6:30
            4 .6666666666666666666666666666666666666666666666666666666555555555555555555555555555555555555555555555. -  6:45
            5 .6666666666666666666666666666644444444433333333322222222333333333555555555555555555666666666655555555. -  7:00
            6 .3333333332222222221111111111111111111122222222211111111222222222555555566666666666666666666655555555. -  7:15
            7 .1111111112222222221111111111111111111122222222222222222333333333555555555555555555666666666655555555. -  7:30
            8 .1111111111111111111111111111111111111122222222211111111222222222555555566666666666666666666655555555. -  7:45
            9 .2222222222222222222222222222222222222222222222222222222333333333555555555555555555666666666655555555. -  8:00
           10 .1111111112222222221111111111111111111122222222211111111222222222555555566666666666666666666655555555. -  8:15
           11 .2222222222222222222222222222222222222222222222222222222333333333555555555555555555666666666655555555. -  8:30
           12 .3333333332222222222222222222222222222222222222222222222444444444555555555555555555555555555555555555. -  8:45
           13 .6666666665555555554444444444433333333333333333322222222444444444555555555555555555555555555555555555. -  9:00
           14 .6666666666666666666666666666666666666666666666633333333333333333555555555555555555666666666655555555. -  9:15
           15 .6666666666666666666666666666666666666666666666666666666666666666555555566666666666666666666655555555. -  9:30
           16 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. -  9:45
           17 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 10:00
           18 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 10:15
           19 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 10:30
           20 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 10:45
           21 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 11:00
           22 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 11:15
           23 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 11:30
           24 .6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666. - 11:45
              .                                                                                                    .
              ......................................................................................................
               :        :        :          :        :        :       :        :       :          :       :
              ML     FM 1325   GAP        WBP      GAP     Howard   WBP     Howard Parmer     Yager    Parmer
            Origin     Entr    Exit       Exit     Entr     Exit    Entr     Entr   Exit       Exit     Entr

         THE DIGIT LEVELS DENOTE THE FIRST DIGIT OF THE OPERATING SPEED (EX. 4 MEANS 40-49 MPH).
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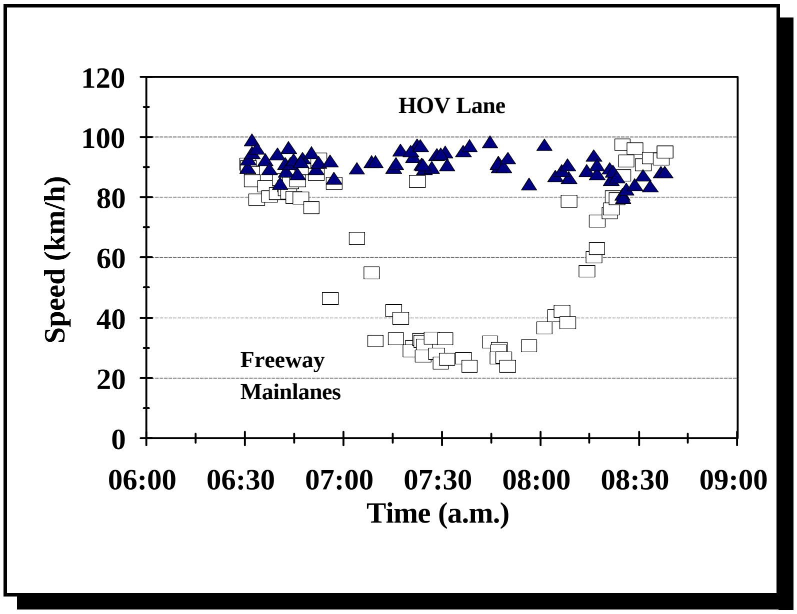
Figure 7-11. Example Speed Contour Diagram from FREQ Computer Program



Source: adapted from reference (17)

Figure 7-12. Example Corridor Summary Illustrating Variability of Travel Speeds

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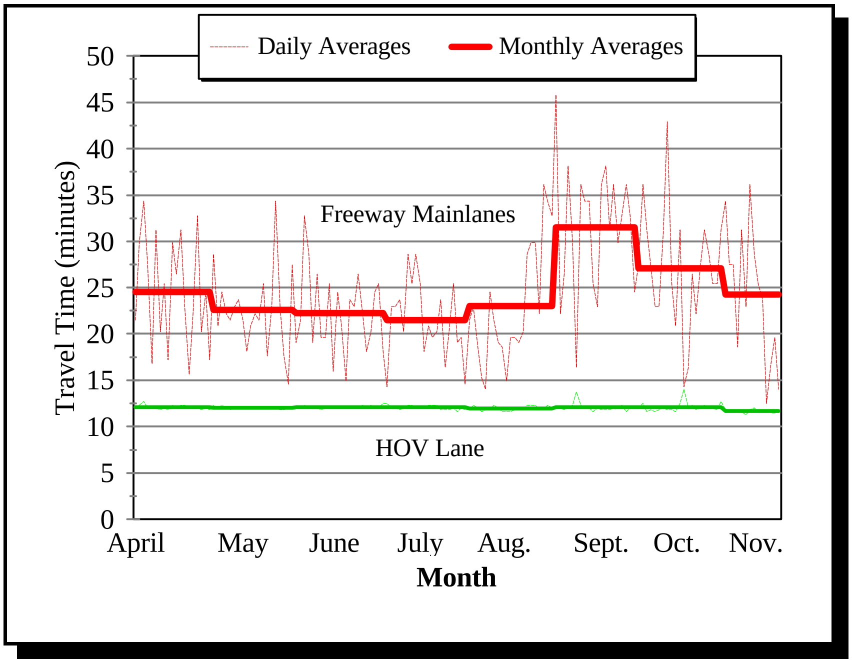
Table 7-5. Example of Tabular Corridor Summary in Tulsa, Oklahoma

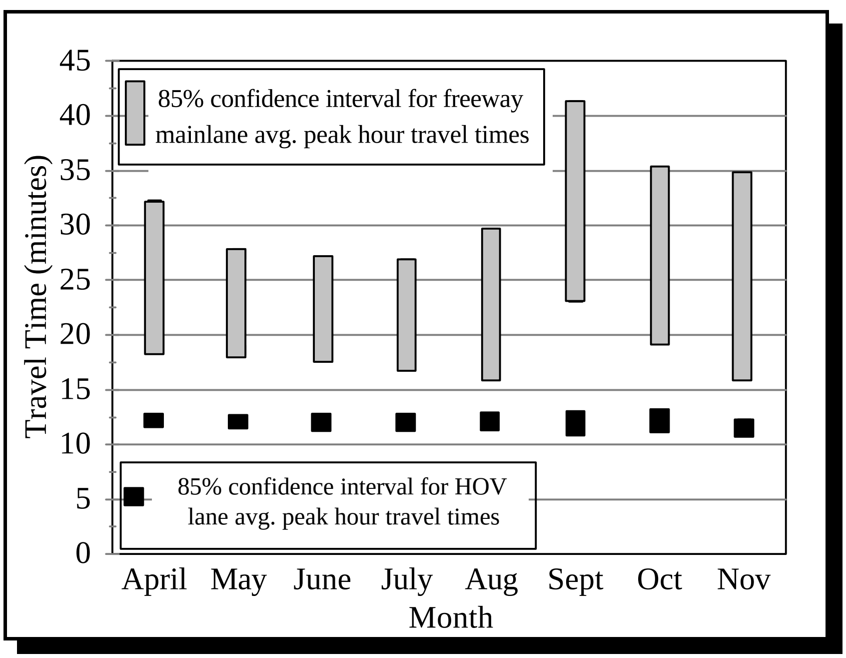
Facility	Average Speed, km/h		
	1977	1978	1979
Crosstown Expressway (I-244)	86.4	86.4	88.0
Skelly Drive (I-44)	81.5	83.6	86.4
11th Street	39.9	38.0	43.8
Memorial Drive	35.7	33.8	33.8
Riverside Drive	63.6	59.7	60.2
Union Avenue	53.3	54.2	57.5

Source: adapted from reference (18)



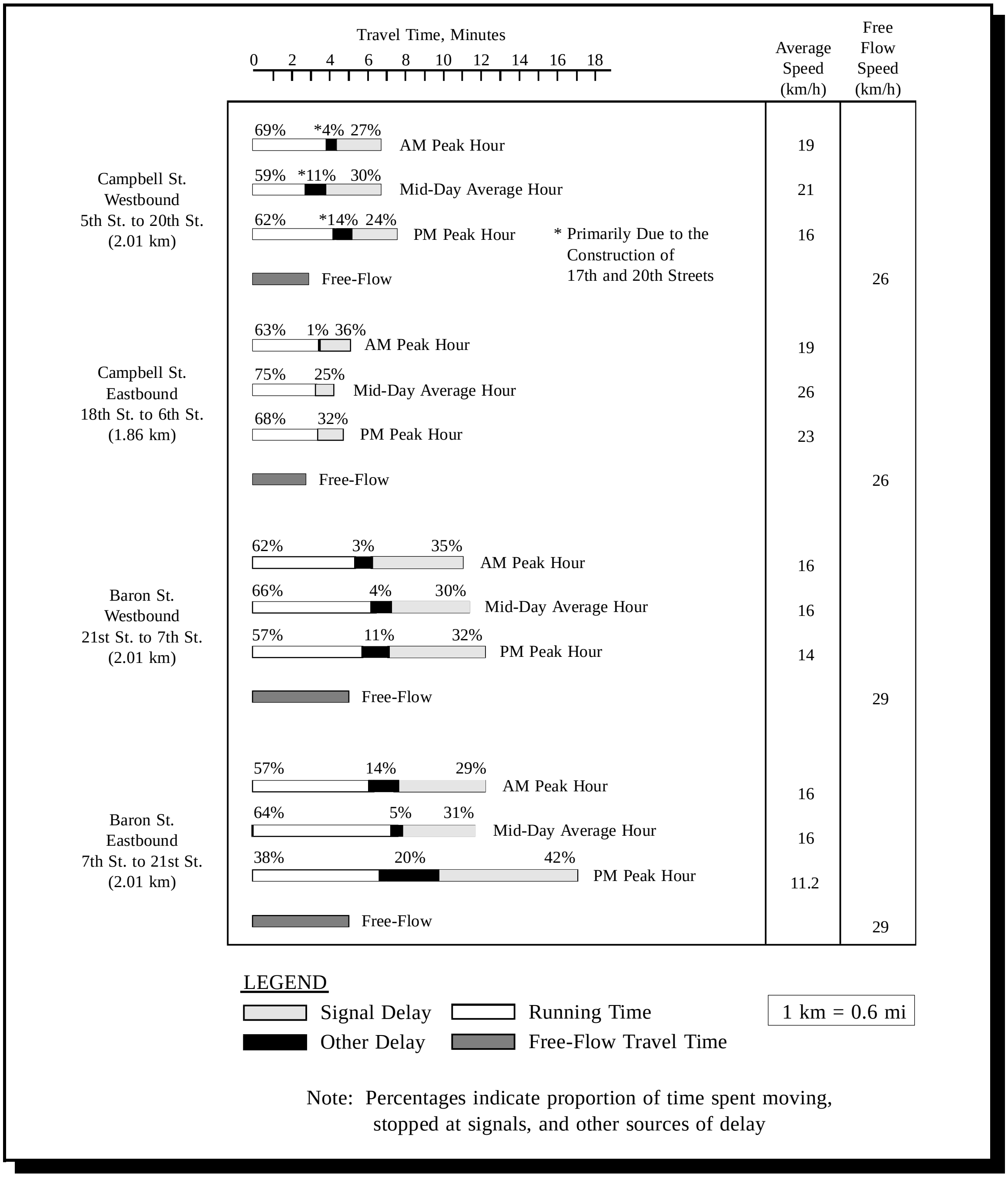
Source: adapted from reference (19)

Figure 7-13. Example Summary Illustrating Daily and Monthly Travel Time Variability



Source: adapted from reference (19)

Figure 7-14. Example Summary Illustrating Differences in Travel Time Variability



Source: adapted from reference (4)

Figure 7-15. Example of Corridor Summary with Detailed Information

Table 7-6 summarizes the average speeds for all freeways in Houston and Harris County, Texas. Note that the freeways are differentiated by their system location (e.g., radial versus circumferential) and by their proximity to downtown and major circumferential facilities. Also note that averages and totals are provided for sub-categories and all freeways.

Table 7-7 summarizes the morning peak period average speeds for freeways and arterial streets in Dallas, Texas. These average speeds served as the “before” conditions in an assessment of the effects of the light rail transit (LRT) starter system in Dallas. Note the inclusion of a control freeway and arterial street that will eventually be used to compare overall changes in average speeds.

Figure 7-16 illustrates a color-coded map of average travel speeds in the Chicago, Illinois area. Note that the map shows both directions of travel for the arterial streets, and that the color codes chosen correspond to drivers’ perception of speed (yellow equals slow speeds, red equals slowest speeds).

Table 7-6. Example of Tabular Freeway Speed Summary in Houston, Texas

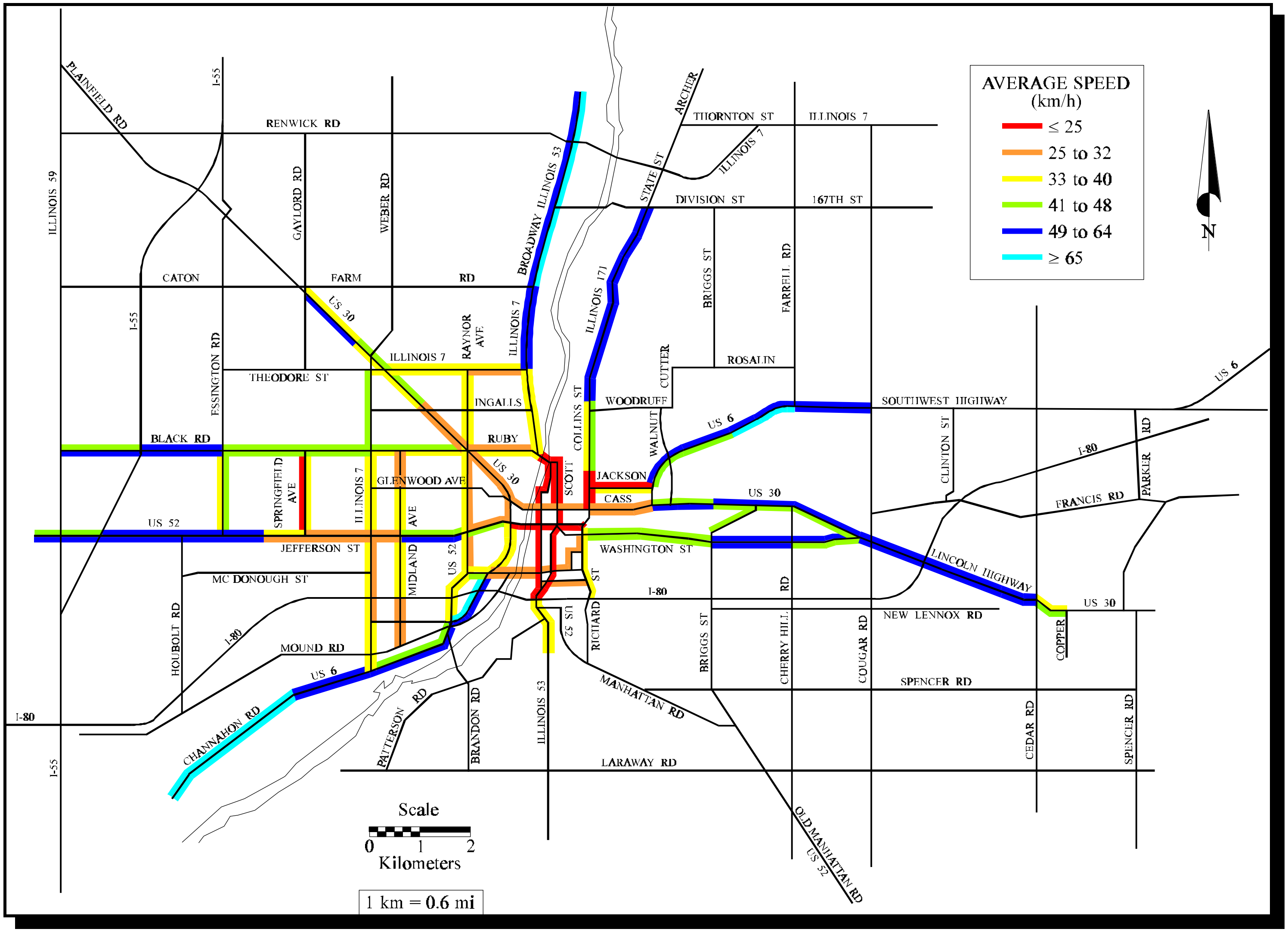
Freeways	1991 Average Speed, km/h (by proximity to downtown Houston)			
	IH-610 & Inside	IH-610 to Beltway 8	Outside Beltway 8	Total Corridor
Radial Freeways				
IH-10, Baytown East Freeway	89	93	98	95
IH-10, Katy Freeway	85	47	89	72
IH-45, Gulf Freeway	58	43	93	60
IH-45, North Freeway	77	76	72	74
US 59, Eastex Freeway	76	64	71	69
US 59, Southwest Freeway	50	45	97	48
US 290, Northwest Freeway	-	72	95	82
SH 225, LaPorte Freeway	-	93	92	93
SH 288, South Freeway	87	93	93	90
US 90, Crosby Freeway	-	-	92	92
Hardy Tollroad	-	89	92	90
Average-All Radial	**69**	**89**	**87**	**74**
Circumferential Freeways				
IH-610, East Loop	95		-	95
IH-610, North Loop	87		-	87
IH-610, South Loop	85		-	85
IH-610, West Loop	50		-	50
Beltway 8, E Sam Houston Pkwy	-	69	-	69
Beltway 8, N Sam Houston Pkwy	-	50	-	50
Sam Houston Tollway	-	84	-	84
Average- All Circumferential	**76**	**72**	**-**	**74**
Total Freeway System Average	**72**	**68**	**87**	**74**

Source: adapted from reference (20)

Table 7-7. Example of Facility Summary--Morning Peak Period Travel Times and Speeds in Dallas, Texas

Facility	From	To	Average Travel Time (min:sec)	Average Travel Speed (km/h)
Freeways				
IH-35E Northbound	IH-20	Lamar@Ross	19:28	53
IH-35E Southbound	Lamar@Ross	IH-20	12:17	84
IH-45 Northbound	IH-20	Lamar@Ross	15:26	64
IH-45 Southbound	Lamar@Ross	IH-20	14:49	68
Control Freeway				
IH-30 Eastbound	Loop 12	Lamar@Ross	9:38	72
IH-30 Westbound	Lamar@Ross	Loop 12	8:21	79
Arterial Streets				
Corinth Street Northbound	Illinois Avenue	Ervay@Elm	12:05	39
Corinth Street Southbound	St. Paul@Elm	Illinois Avenue	11:29	40
Illinois Avenue Eastbound	Cockrell Hill Road	IH-45	16:35	47
Illinois Avenue Westbound	IH-45	Cockrell Hill Road	16:20	47
Jefferson Blvd. Eastbound	Cockrell Hill Road	Zang Boulevard	9:15	43
Jefferson Blvd. Westbound	Zang Boulevard	Cockrell Hill Road	10:13	39
Kiest Avenue Eastbound	Cockrell Hill Road	Illinois Avenue	15:49	40
Kiest Avenue Westbound	Illinois Avenue	Cockrell Hill Road	13:45	45
Zang Boulevard Northbound	Saner Avenue	Lamar@Ross	11:54	43
Zang Boulevard Southbound	Lamar@Ross	Saner Avenue	14:27	35
Control Arterial Street				
Singleton Blvd. Eastbound	Loop 12	Lamar@Ross	14:29	45
Singleton Blvd. Westbound	Lamar@Ross	Loop 12	14:38	43

Source: adapted from reference (13)



Source: adapted from reference (21)

Figure 7-16. Example of Color Map Showing Average Speeds

7.5.4 Functional Class Summaries

A functional class summary contains data for all roadways within defined functional classifications (see Chapter 2) and typically includes average travel times, speeds, and delays. The functional class summary is similar to the corridor or route summary, only several facilities within a functional class are averaged together.

Figure 7-17 contains a comparison of average speeds on arterial streets in several urban areas in Arizona for 1979 and 1986. The figure provides an overall perspective on arterial street system speeds in several different locations and for two separate years. Note that the chart emphasizes general trends in average speeds and not necessarily the numerical values (which can only be estimated from the chart).

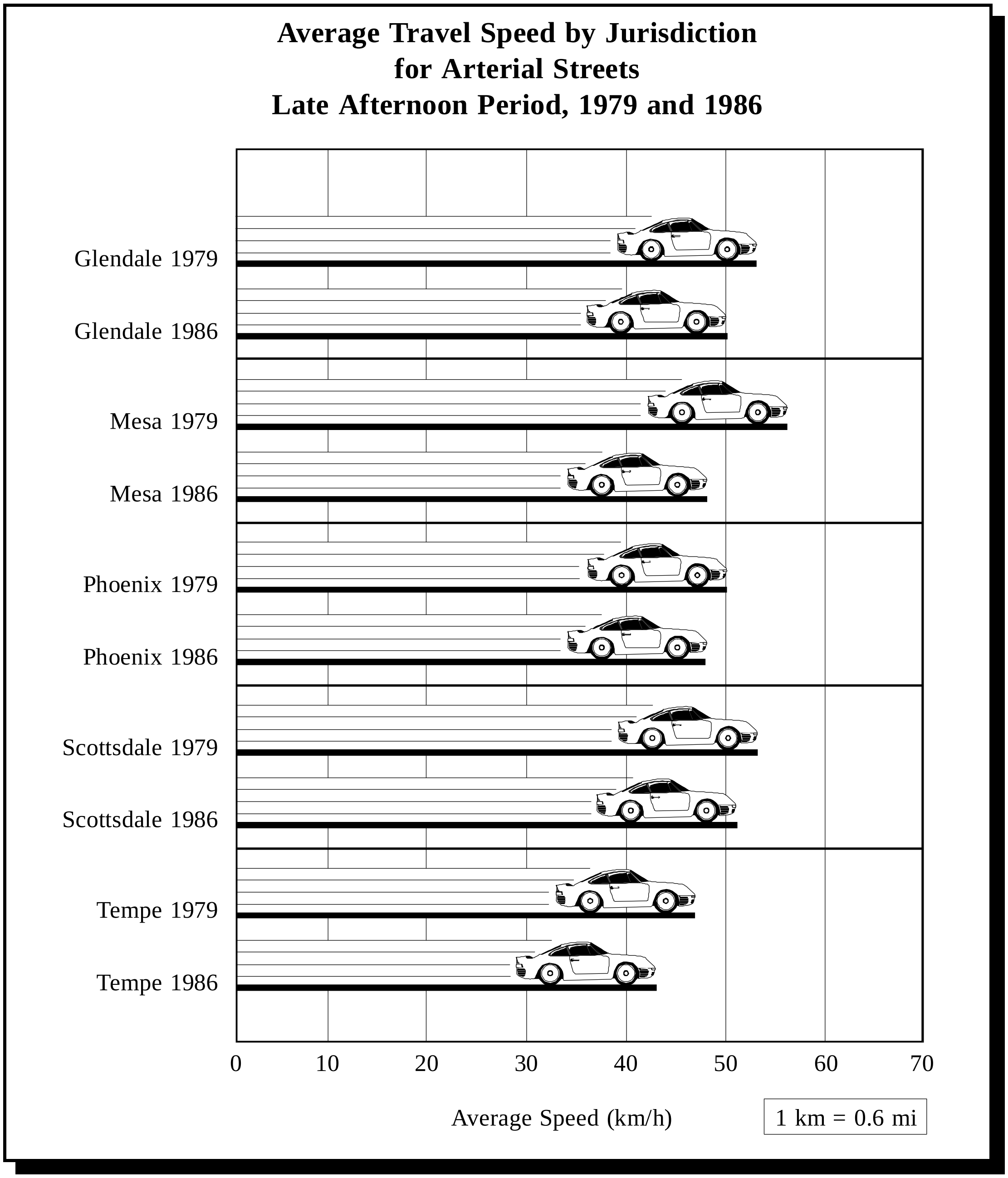
Figure 7-18 presents an historical perspective (1969 to 1994) for average speeds on freeways in Harris County, Texas with a simple bar graph. The figure clearly illustrates that average speeds dropped in the early 1980s, only to increase in the 1990s to original levels. A line graph could also be used to illustrate time series speed or travel time trend.

Table 7-8 contains average speeds for freeways and arterial streets in Albuquerque, New Mexico. The table contains the average speeds for the a.m. peak, p.m. peak, and both peak periods combined. The total facility mileage is also included in the table to indicate the extent of each functional class.

Table 7-9 presents average speeds for several different functional classes in Harris County, Texas. For each functional class, the table compares average speeds for different time periods and three study years (e.g., 1988, 1991, 1994). Note that the table also includes the percentage change in average speeds over the years illustrated. The inclusion of percent change in speed makes the time series comparison easier to interpret.

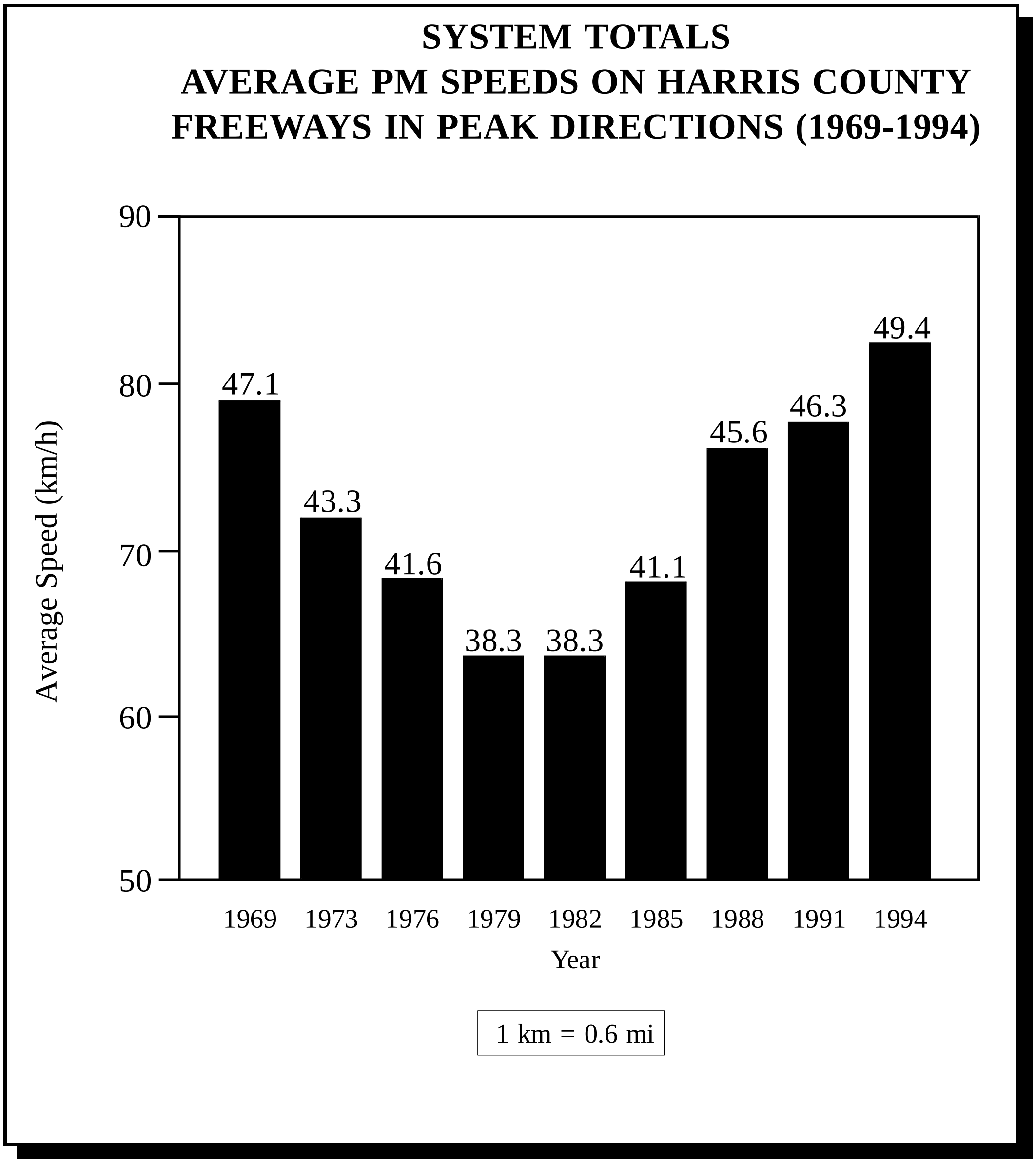
Figure 7-19 shows several regional freeway speed trends using different types of graphical presentations. Using bar graphs, the figure shows several dimension of congestion, including the miles of congested freeway, the location of congestion, the congestion trend between 1969 and 1979, and the congestion location trend between 1973 and 1979.

Figure 7-20 provides a summary of speed characteristics for all Class I arterial streets (as defined by the 1994 Highway Capacity Manual) for data collected on streets in Houston, Texas. The speed distributions presented in this figure are most appropriate for mobile source emissions modeling, in which it is necessary to project the vehicle miles traveled (VMT) for various speed ranges. An instrumented test vehicle is best suited for this application because the instrumentation is capable of recording second-by-second changes in vehicle speed and acceleration.



Source: adapted from reference (22)

Figure 7-17. Example of Functional Class Summary in Arizona Cities



Source: adapted from reference (23)

Figure 7-18. Example of Functional Class Summary in Harris County, Texas

Table 7-8. Example of Functional Class Summary for 1986 Albuquerque Travel Time Study

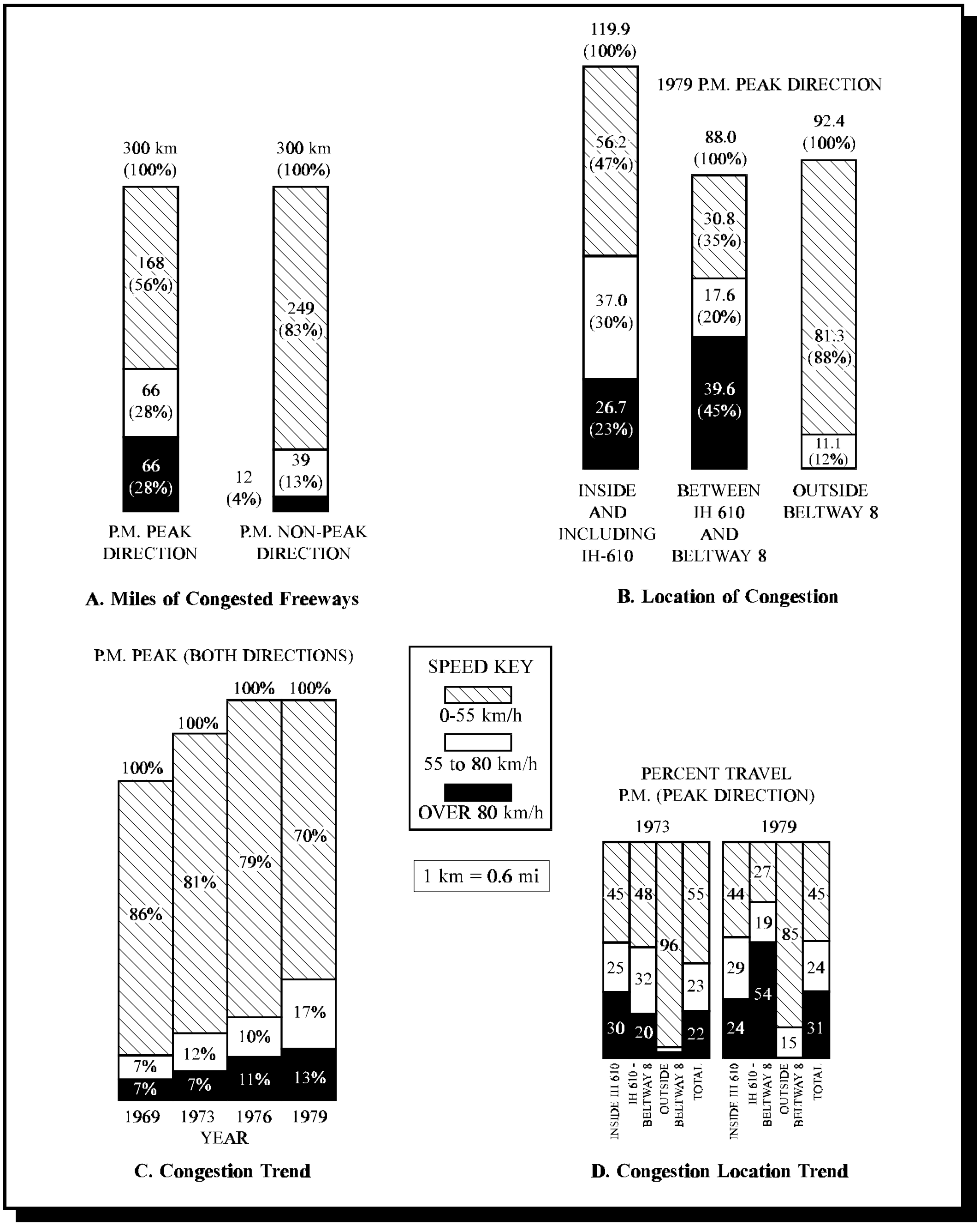
Functional Class	Average Speed, km/h		
	AM Peak	PM Peak	AM and PM Peak
All Streets Combined			
Total Length	309.4 km	305.5 km	614.9 km
Mean Speed	43.6 km/h	41.9 km/h	42.7 km/h
Median Speed	41.7 km/h	40.7 km/h	41.4 km/h
Freeways			
Total Length	58.0 km	55.9 km	113.9 km
Mean Speed	80.3 km/h	76.60 km/h	78.4 km/h
Median Speed	82.8 km/h	82.8 km/h	82.8 km/h
Arterials, Collectors, and Ramps			
Total Length	251.4 km	249.5 km	500.9 km
Mean Speed	40.6 km/h	38.7 km/h	39.7 km/h
Median Speed	40.8 km/h	39.7 km/h	40.6 km/h

Source: adapted from reference (24)

Table 7-9. Illustration of Functional Classification Summary for Harris County, Texas

Functional Class	**Roadway Extent (km)**			**Average Speeds, km/h** (for both directions of travel)															
				AM Peak				**Off Peak**				**PM Peak**				**Total**			
	1988	1991	1994	1988	1991	1994	▲, 91-94	1988	1991	1994	▲, 91-94	1988	1991	1994	▲, 91-94	1988	1991	1994	▲, 91-94
HOV Lanes	-	82	101	-	87.1	80.7	-7 %	-	94.5	86.1	- 9 %	-	83.9	82.3	-2 %	-	88.2	82.9	-6 %
Interstates	230	230	232	79.9	81.0	82.4	2 %	93.9	94.8	96.0	1 %	82.9	81.1	79.2	-2 %	85.2	85.2	85.3	0 %
Freeways	274	311	356	73.3	76.6	79.4	4 %	80.3	81.5	81.8	0 %	72.9	74.9	77.9	4 %	75.3	77.6	78.7	1 %
Principals	630	678	927	51.2	52.8	50.6	-4 %	53.3	53.9	53.6	-1 %	51.0	49.7	48.5	-3 %	51.8	52.0	50.9	-2 %
Arterials	765	407	164	44.9	46.9	44.0	-6 %	47.0	49.1	46.9	-5 %	44.3	43.8	44.9	3 %	45.4	46.5	45.2	-3 %
Totals Systemwide	1,898	1,708	1,782	49.6	54.4	55.1	1 %	52.2	56.8	58.3	3 %	49.1	51.5	53.6	4 %	50.2	54.3	55.4	-3 %

Note: "▲, 91-94" represents the percent change in average speeds between 1991 and 1994.
Source: adapted from reference (25)

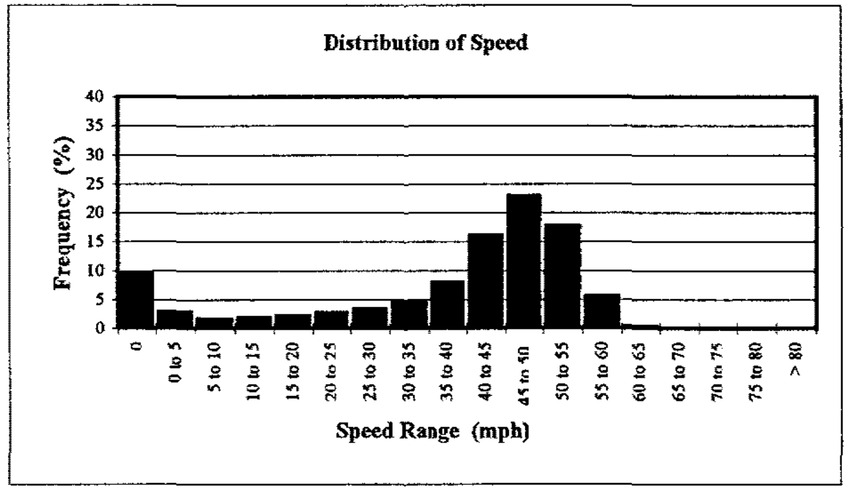


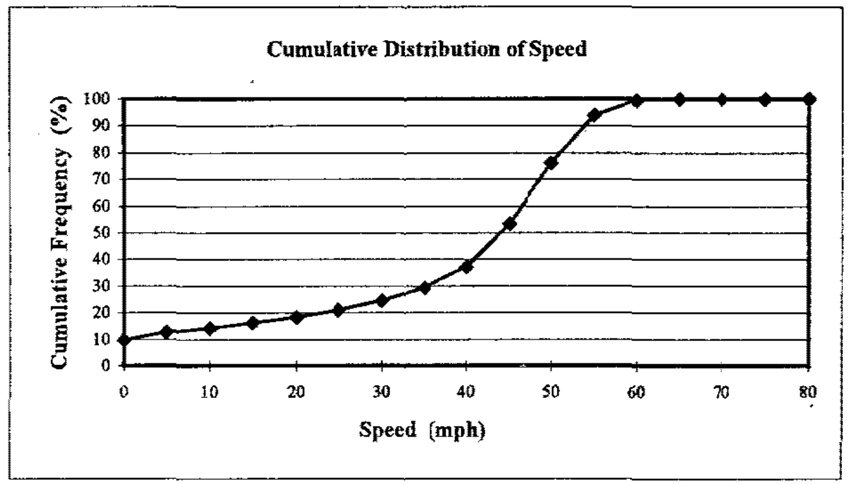
Source: adapted from reference (16)

Figure 7-19. Example Summary of Congestion and Average Speed Trends

CLASS I ARTERIAL STREETS
Morning and Evening Peak Period
(6 to 9 am, 4 to 7 pm)

Speed Frequency Distribution		
Speed Range (mph)	Range Frequency (%)	Cumulative Frequency (%)
0	9.7	9.7
0 to 5	2.9	12.6
5 to 10	1.6	14.2
10 to 15	1.9	16.1
15 to 20	2.2	18.3
20 to 25	2.7	21.0
25 to 30	3.5	24.4
30 to 35	4.8	29.3
35 to 40	8.0	37.2
40 to 45	16.1	53.3
45 to 50	22.9	76.2
50 to 55	17.7	93.9
55 to 60	5.6	99.6
60 to 65	0.4	100.0
65 to 70	0.0	100.0
70 to 75	0.0	100.0
75 to 80	0.0	100.0
> 80	0.0	100.0





Source: adapted from reference (26)

Figure 7-20. Example Summary of Regional Speed Distribution for Class I Arterial Streets

7.5.5 Other Summaries

There are several other travel time data summaries that do not fit neatly into any of the above categories. Included in this group are activity center summaries, travel time contour maps, and accessibility maps. Activity center summaries present trends or comparisons of travel time or average speed between major activity centers in an urban area. Travel time contour maps use isochronal lines (i.e., lines of equal time) to illustrate the distances that one can travel away from a selected point (e.g., central business district (CBD) or major activity center) in given time intervals. The isochronal lines are typically centered around a downtown or CBD area and are in ten-minute increments. Accessibility maps show the accessibility (in terms of time increments) of land uses, jobs, or services to transportation facilities.

In the past, the development of travel time contour and accessibility maps were considered time-consuming and labor-intensive. The advent of geographic information systems (GIS) substantially reduces the work and time required to prepare these types of graphical displays. Even if travel time data are not collected with global positioning system (GPS) units, agencies may wish to consider importing travel time data into a GIS platform for the ease of future analyses.

Table 7-10 shows an example of an activity center travel time matrix for Harris County, Texas (this table has been shortened from the original travel time matrix). The table shows travel times between major activity centers for three different time periods during the day: off peak, a.m. peak, and p.m. peak. The travel times shown are for the most direct route and may include portions of several different arterial streets and/or freeways.

Figure 7-21 illustrates average speeds between major activity centers and two airports in the Philadelphia area. The average speeds are compared for two years, 1971 and 1983. As with the activity center matrix in Table 7-10, the average speeds shown in Figure 7-21 presumably contain portions of trips on arterial streets and/or freeways.

Figure 7-22 shows an example of a travel time contour map that compares average travel times between 1980 and 1991. The decreases in mobility can be seen from the shaded areas. Travel time contour maps can be used to show many regional trends relating to mobility:

- Trends over time (e.g., historical comparisons every five years);
- Differences between peak and off-peak traffic conditions;
- Reliability of travel times;
- Comparison of transportation alternatives; and,
- Trends before and after regional transportation improvements.

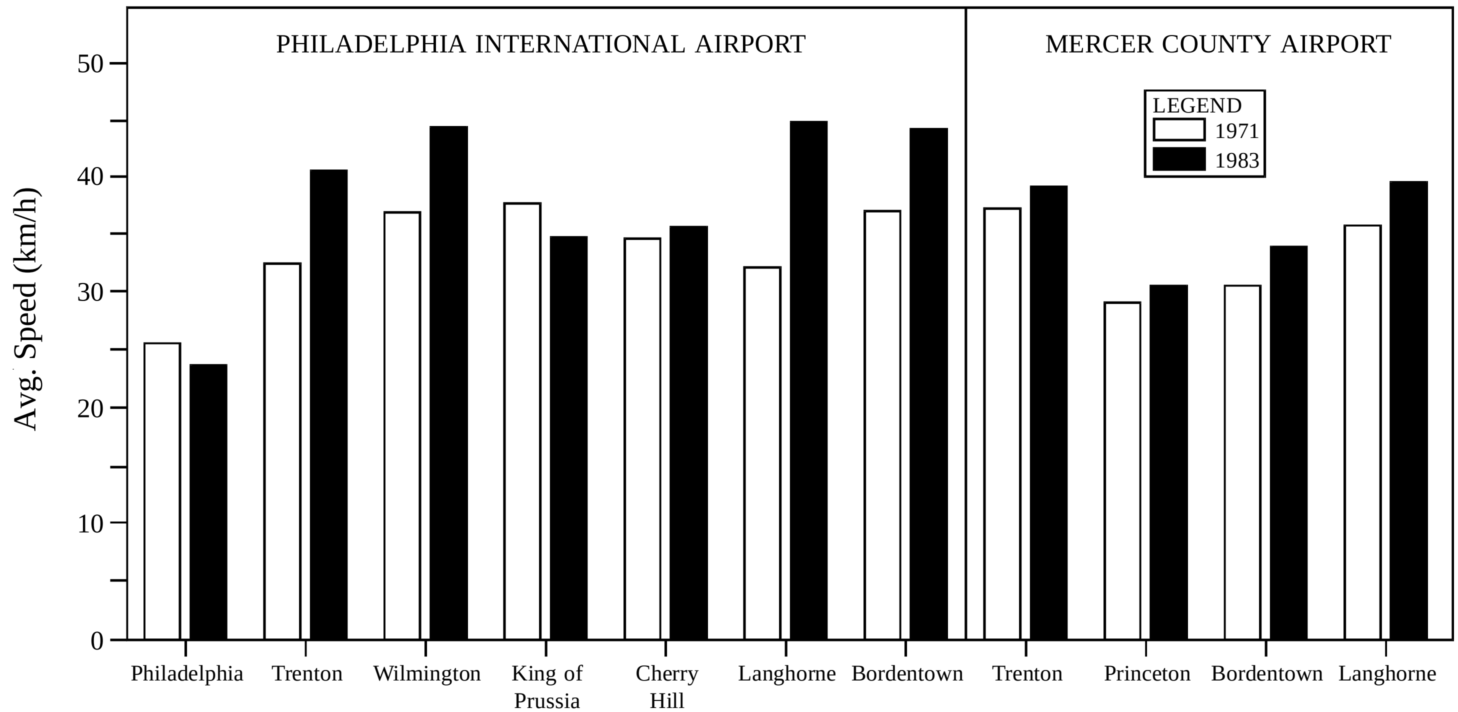
Figure 7-23 shows an example of an accessibility map for a proposed transportation improvement (i.e., Inter-County Connector) in Montgomery County, Maryland. In this example, the figures show the accessibility to jobs within a 45-minute commute, and the additional accessibility to jobs created by the transportation improvement.

Table 7-10. Example of Activity Center Travel Time Matrix

From	Time Period	Travel Time (minutes) to						
		CBD	MED CTR	ASTR	HOBBY	INTRC	CLR LK	SGLD
CBD Main @ McKinney (CBD)	Off Peak AM Peak PM Peak	- - -	11 9 10	11 13 14	17 16 24	25 25 28	26 27 38	27 27 39
Medical Center Main @ University (MED CTR)	Off Peak AM Peak PM Peak	11 8 10	- - -	6 6 8	19 19 28	31 33 39	29 29 41	24 24 34
Astrodome Kirby @ IH 610 (ASTR)	Off Peak AM Peak PM Peak	11 13 12	6 6 7	- - -	13 13 19	30 31 36	22 22 33	20 22 27
Hobby Airport Airport Entrance (HOBBY)	Off Peak AM Peak PM Peak	17 19 19	19 21 25	13 14 17	- - -	33 36 40	14 14 16	32 36 45
Intercontinental Airport Terminal B (INTRC)	Off Peak AM Peak PM Peak	25 27 25	34 37 35	30 36 31	34 35 41	- - -	43 45 52	44 47 48
Clear Lake City Bay Area Blvd@IH 45S (CLR LK)	Off Peak AM Peak PM Peak	26 33 25	28 36 31	22 29 24	15 18 15	43 51 46	- - -	41 50 51
Sugar Land SH 6 @ US 59S (SGLD)	Off Peak AM Peak PM Peak	27 37 26	26 34 24	22 28 21	34 41 40	45 48 48	43 50 53	- - -

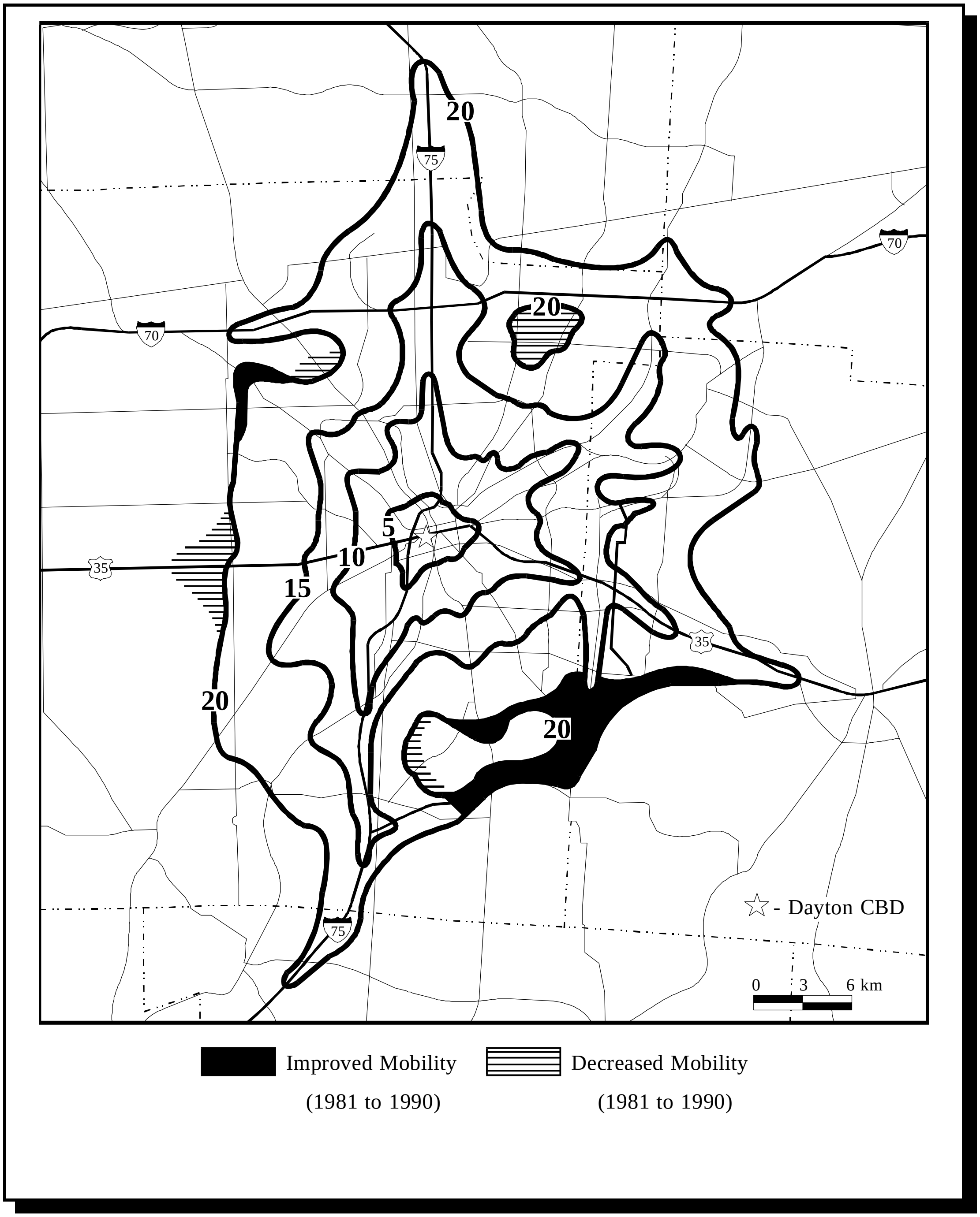
Source: Houston-Galveston Regional Transportation Study, 1991.

Peak Period Travel Speeds Between Major Regional Activity Centers and Philadelphia International and Mercer County Airports



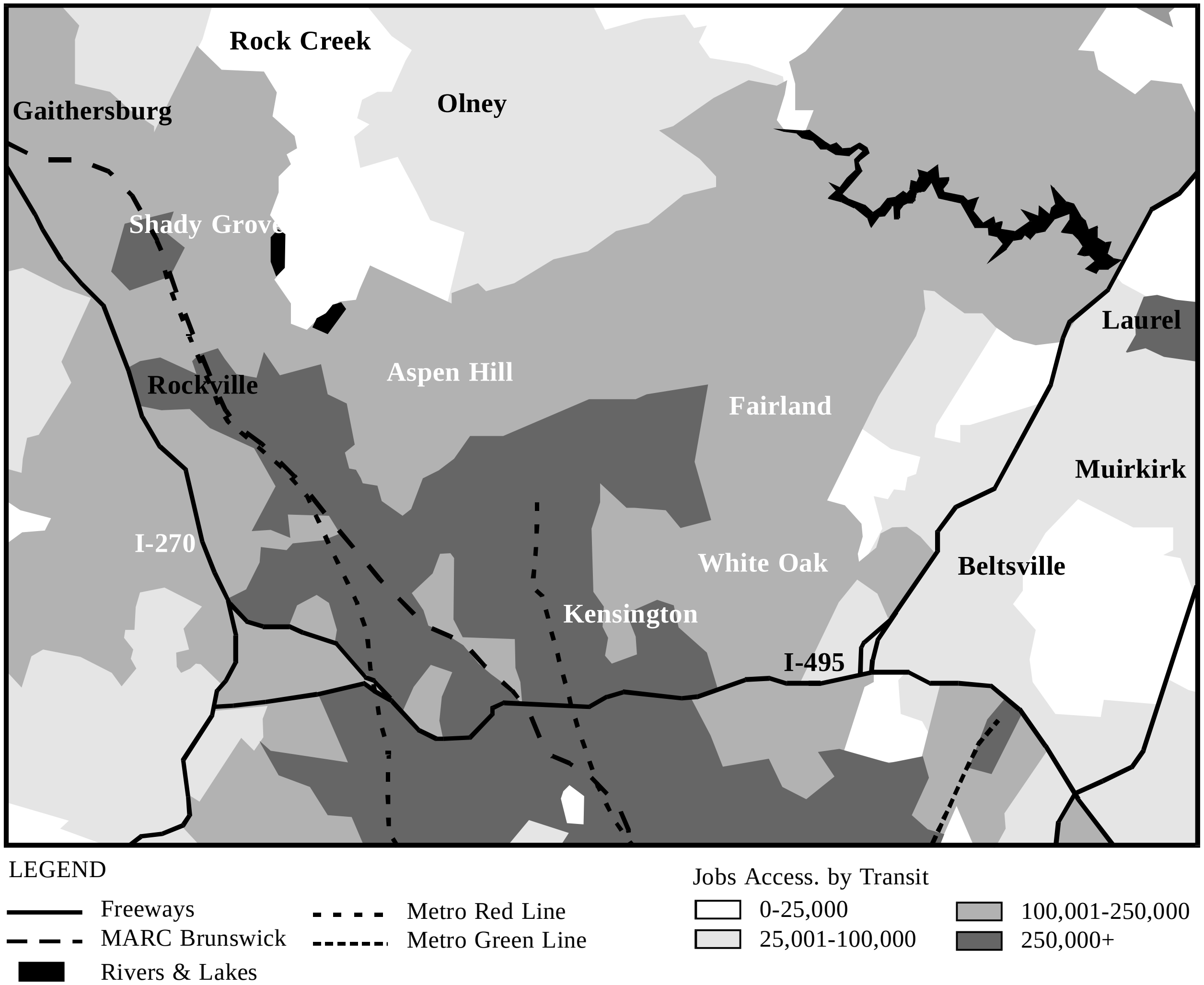
Source: adapted from reference (27)

Figure 7-21. Example of Activity Center Average Speed Comparison in Philadelphia, Pennsylvania



Source: adapted from reference (28).

Figure 7-22. Example of a Travel Time Contour Map



Source: Metropolitan Washington Council of Governments, 1996.

Figure 7-23. Example of an Accessibility Map for Montgomery County, Maryland

Other good examples of travel time or speed summaries can be found on the World Wide Web. Tens of thousands of daily commuters rely on these web page summaries for real-time information on travel times and speeds. Because of the dynamic nature of these pages, several examples are referenced below for the reader to explore. The following are examples of web pages that provide real-time travel time or speed information:

- Atlanta, Georgia: http://www.georgia-traveler.com/traffic/rtmap.htm
- Gary-Chicago-Milwaukee: http://www.ai.eecs.uic.edu/GCM/GCM.html
- Houston, Texas: http://traffic.tamu.edu/traffic.html
- Houston, Texas: http://www.accutraffic.com/accuinfo/cities/houston.tx/
- Long Island, New York: http://metrocommute.com:81/LI/#heading
- Los Angeles, California: http://www.scubed.com/caltrans/la/la_big_map.shtml
- Minneapolis-St. Paul, Minnesota: http://www.traffic.connects.com/
- Orange County, Ca: http://www.maxwell.com/yahootraffic/OC/OC_W/map.html
- Phoenix, Arizona: http://www.azfms.com/Travel/freeway.html
- San Diego, California: http://www.scubed.com/caltrans/sd/big_map.shtml

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APPENDIX A: COMPUTER SOFTWARE FOR TEST VEHICLE TECHNIQUES

This appendix contains documentation for test vehicle computer software that is used to collect travel times. Chapter 3 of the handbook describes the test vehicle methods of travel time collection that can utilize software for automating data collection and reduction. The appendix primarily documents 3 software packages that are used in conjunction with electronic distance measuring instruments (DMIs). At the time of publication, no commercially available software for global positioning system (GPS) equipment was deemed adequate for travel time data collection (although several developmental versions are in the public domain).

Software for Electronic DMI Equipment

Table A-1 summarizes commercially available electronic DMI software and hardware and the corresponding contact information. An attempt was made to evaluate all available hardware and software packages. The following sections provide the reader with an overview of the look, feel, and features of each software package. No recommendation is stated or should be implied. Notes on the ease of use and problems were observations of the drivers and opinions and experiences may vary.

Software for GPS Equipment

At the time of publication, no commercially available software for global positioning system (GPS) equipment was deemed adequate for inclusion in this appendix. However, several developmental or beta software programs do exist in the public domain. These packages have mostly been adapted to the preferences of individual users and their applications. Many GPS equipment vendors distribute proprietary data logging software with individual units, but this software does not have the flexibility to perform required travel time collection functions such as conversion to a GIS platform.

There are three primary software tasks that are required for performing GPS travel time data collection. Several vendors provide software that is capable of individually performing the GPS software tasks of logging, mapping, and analysis. However, it is still up to the practitioner to decide how to go about setting up the system with the several software tools and vendors available. For example, the data logging software is often proprietary for each GPS receiver vendor. This data must be compatible with the GIS mapping platform that is used (i.e., files must be either in the form acceptable by the GIS software or must be converted). Finally, the analysis package must be capable of analyzing the GPS data that is received. Many vendors provide software that can read the GPS data and compute travel time and speed of positional data along predetermined links. For probe vehicle applications using the GPS data, such analyses need to be performed and reported in real-time. Again, several vendors are currently available that can develop such analysis tools depending upon the needs of the practitioner.

There are also many additional considerations (e.g., the need to purchase an FM signal for differential GPS, the variety of available equipment from different vendors) that are inevitable in GPS travel time data collection. These considerations make it difficult to define a specific software or hardware specification that will be satisfactory for all practitioners. At the time of this publication, a fair amount of research is still required by the practitioner to determine the desirable software and hardware configurations.

Table A-1. Summary of Test Vehicle Software and Contact Information

Product	Hardware Requirements	Program Capabilities	Analyses/Reports	Contact Information
Computer Aided Transportation Software (CATS)	Laptop PC: 386 CPU, 4 MB RAM, 5 MB free hard drive Analysis PC: 486 DX2, 66 MHz or higher, 16 MB RAM 30 MB free hard drive space (for storage) Windows 95 or Windows 3.1 Microsoft Excel Version 5.0+ DMI equipped Vehicle,9-pin RS-232 serial port	Measures distances, speeds, and travel times. Provides access to raw data files. Offers an incident location and identification. System allows driver comments to be saved to run files. Provides an automatic file naming scheme.	Detailed statistical reports Project-level summaries Speed profiles	McTrans, Phone (352) 392-0378 http://www-t2.ce.ufl.edu/mctrans/mct.htm or PC-Trans, Phone (913) 864-5655 http://kuhub.cc.ukans.edu/~pctrans/index.html
PC-TRAVEL	Laptop or TDC-8 data collection board Analysis PC: DOS 2.2+, 512K RAM Hard disk 286 CPU class or higher Vehicle equipped with a transmission sensor	Measures speed, distance traveled, travel time, delay, fuel consumption, and emissions. Offers an incident location and identification system	Study summaries Individual & group run statistics Speed profiles HP LaserJet and PostScript output capabilities	Jamar Technologies Phone (800) 776-0940 or (215) 491-4899 151 Keith Valley Road Horsham, PA 19044
Traffic Analyzer 1988 (TA-88) Moving Vehicle Run Analysis Package (MVRAP)	Laptop PC: DOS 2.1+, 256K memory Parallel printer port Analysis PC: DOS 3.0+, 640K RAM Vehicle equipped with a DMI	TA-88 measures distance, travel time, speed, delay, stops, acceleration noise, and fuel consumption MVRAP analyzes the collected data	Average values of the measure of effectiveness for all travel time runs in a study, Speed profiles	McTrans, Phone (352) 392-0378 http://www-t2.ce.ufl.edu/mctrans/mct.htm
Nitestar Distance Measuring Instrument	not available	not applicable	not applicable	Nu-Metrics Phone (800) 346-2025 or (412) 438-8750 Box 518 University Drive Uniontown, PA 15401
Distance Measuring Instruments Microcomm Software	not available	not available	not available	Advanced Microsystems Phone (800) 628-0575 or (412) 438-7500 654 Pittsburgh Road Uniontown, PA 15401
Microfloat Software	not applicable	not available	not available	Fredric R. Harris Phone (703) 204-6395 Fairfax, VA

1 TA-88/MVRAP Speed and Delay Study Software

Traffic Analyzer 1988 (TA-88) data collection software and the Moving Vehicle Run Analysis Package (MVRAP) were developed by the University of Florida Transportation Research Center for "evaluating the performance of an arterial street in terms of travel speed, delay, fuel consumption, and driver comfort". TA-88 was accessed from within MVRAP in this report, but it can also be used independently.

1.1 Preparing to Use MVRAP

1.1.1 Equipment Required

- laptop computer with at least 256K memory, a disk drive, and a parallel printer port;
- computer for analysis with at least 640K memory, a hard disk, DOS 3.0, and a standard printer;
- vehicle equipped with a distance measuring instrument (DMI) such as the Nitestar by Nu-metrics that was used for this report; and
- cable to connect the printer port to the DMI unit.

1.1.2 Training

All personnel should be familiar with the software and hardware set-up procedure, use of the DMI, and the route being studied.

1.1.3 Configuring Files and Directories

1.1.3.1 Setting Up a Directory and Starting the Program

Set up a directory for the program files. Within this directory, type "MVRAP" at the DOS prompt. All collected data will be stored in the MVRAP directory. Follow on-screen instructions (if any) until the main menu appears (see Figure A-1).

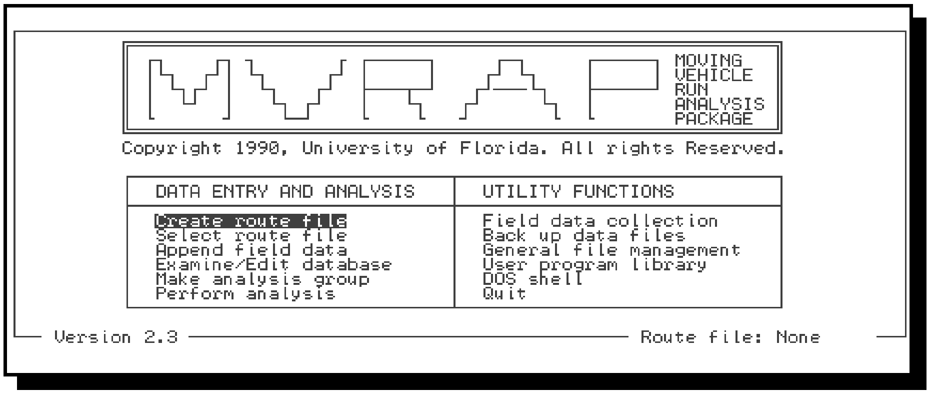


Figure A-1. MVRAP Main Menu

1.1.3.2 Creating a Route Map

Choose “Field Data Collection” from the main menu, using the arrow keys or the F key. Hit ENTER to reach the TA-88 control screen (see Figure A-2). Hit ESC to move from the *Run Description* section of the screen to the *Command List* section and type C for “Create New Route”. Type in a name for the new route map. (Note: Route maps names are a reversible pair when they differ only by E and W (for East and West), N and S (for North and South), or 1 and 2.) Then enter the route name and its starting point.

Link lengths (in ft) are entered in the office, but they may also be measured directly in the field on the first data collection run. Link ending points *must* be entered in the office before any data is collected. A maximum of eighteen links is allowed per route. Type CTRL-S to save route data.

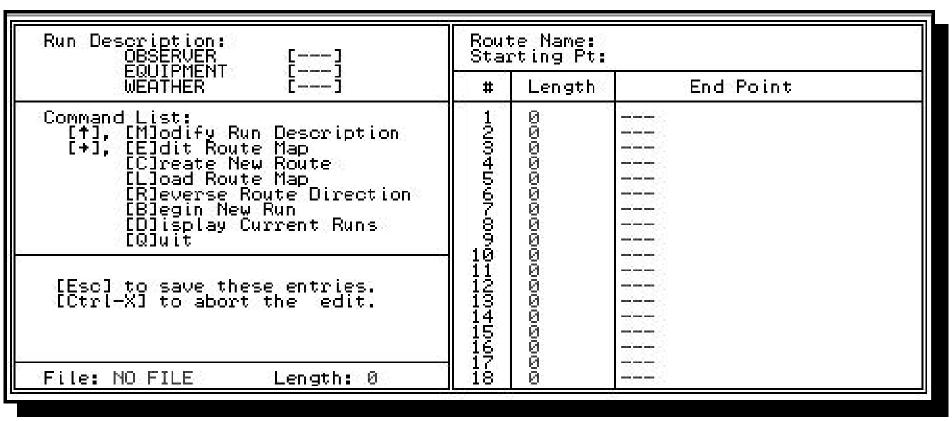


Figure A-2. TA-88 Control Screen

1.2 Collecting Field Data

1.2.1 Loading a Route Map

In the field, run MVRAP and choose “Field Data Collection”. At the TA-88 control screen, fill in the observer, equipment, and weather fields with predefined three-letter codes and hit ESC. Type L for “Load Route Map” and select the proper route map. Then type B for “Begin New Route” and begin driving.

1.2.2 Starting the Run, Marking Checkpoints, and Ending the Run

When the vehicle reaches the starting point, hit any key. Hit the space bar at each subsequent link ending point. After marking the last ending point, hit ENTER to conclude the data collection run.

1.2.3 Notes on Data Collection

- If a link ending point is not marked, TA-88 may not save any data for that run;
- Ending points can be marked no more than two percent or sixty feet off the link lengths in the route map file;
- The computer will beep whenever zero distance is traveled in any one-second interval;
- There is nothing on the screen during data collection to indicate that the equipment and software are working correctly; and
- A route map is easily reversed for return trips (provided the naming convention mentioned earlier has been utilized) by choosing “Reverse Route Direction” from the TA-88 control screen.

1.3 Data Analysis

MVRAP will organize all data collection run text files (*.txt) in its database structure. After new data is collected, it must be appended to an existing route database file (*.rdf) or stored in a new one by choosing “Select Route File” or “Create Route File” from the MVRAP main menu. (If a new *.rdf file is created, it must then be selected using “Select Route File”.)

- “Append Field Data” must then be selected in order to officially attach new data to the route database file.

- "Examine/Edit Database" allows the analyst to see route map information and a summary of collected run data, with the option to print hard copies of this information. The summary includes travel time, delay, number of stops, fuel consumption, and acceleration noise for each link in the route. (Travel speed is calculated elsewhere.)

- "Make Analysis Group" allows the analyst to select specific runs from the route database file for different time and date ranges. (Note: To choose all runs in the route database file, press ENTER and move through all the time and date fields. Pressing ESC will not select all the runs.)

- "Perform Analysis" will produce three types of output, printed either to a single file or to the printer:

  - "Summary of Run Data" table with travel time, speed, delay, number of stops, fuel consumption, and acceleration noise data averaged over each run (see Figure A-3);

  - "Evaluation Summary (By Link)" table with the same information as above except that the data is averaged over each link in each run (see Figure A-4); and

  - "Travel Speed Profile" plot of speed vs distance (see Figure A-5).

MOVING VEHICLE RUN ANALYSIS PACKAGE
SUMMARY OF RUN DATA
summtst1

ROUTE NAME: KATY FWY EB TEST
1 RUN(S) 5 LINKS

RUN#	DATE	TIME	TRAVEL TIME (sec)	DELAY (sec)	STOPS	FUEL	ACCELE-RATION NOISE
1*	03-18-97	11:37	260	0	0	0.000	0.000

* - Indicates assumed distances

Figure A-3. Example of "Summary of Run Data" Report

MOVING VEHICLE RUN ANALYSIS PACKAGE
ARTERIAL SYSTEM PERFORMANCE EVALUATION
summtst2

ROUTE NAME: KATY FWY EB TEST
STARTING AT GESSNER AVL
1 RUN(S) 5 LINKS

END POINT	LINK LENGTH (ft)	TRAVEL TIME (sec)	DELAY (sec)	STOPS	ACCELE-RATION NOISE	SPEED (MPH) AVG.	SPEED (MPH) RUN.
BUNKER HILL	1584	30.0	0.0	0.0	0.00	36.0	36.0
BLALOCK	3326	46.0	0.0	0.0	0.00	49.3	49.3
BINGLE	7181	93.0	0.0	0.0	0.00	52.6	52.6
WIRT	4330	54.0	0.0	0.0	0.00	54.6	54.6
ANTOINE	3010	37.0	0.0	0.0	0.00	55.4	55.4
TOTAL	19431	260.0	0.0	0.0	0.00	50.9	50.9

Figure A-4. Example of "Evaluation Summary (By Link)" Report

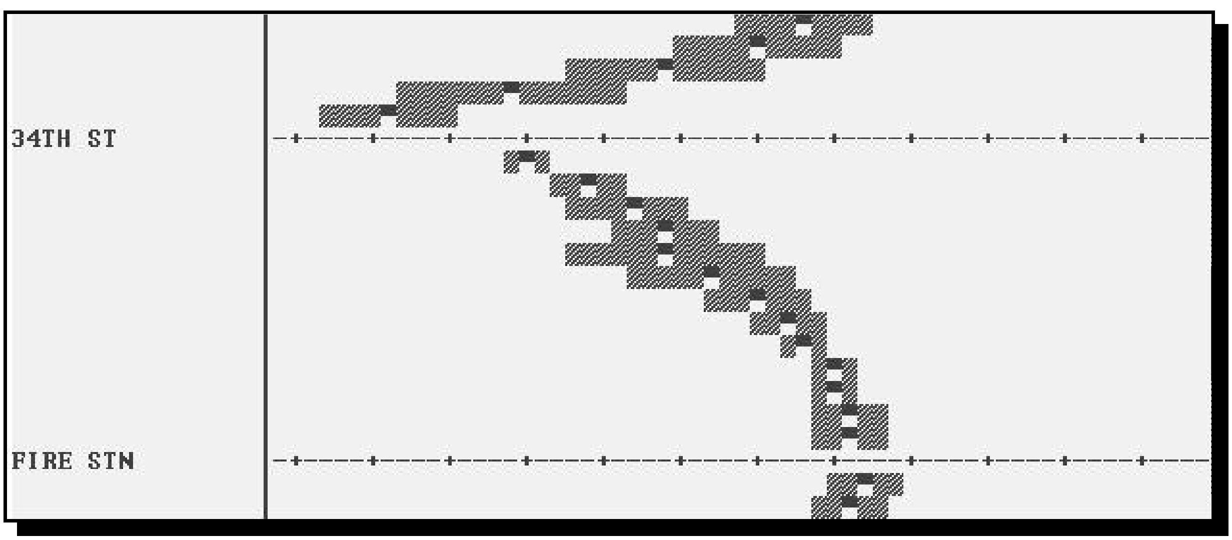


Figure A-5. Example Section of "Travel Speed Profile" Report

1.4 Comments on the Analysis

- All output reports are printed to a *single* file. For separate report files, they must be viewed in a text editor and saved separately there;

- Configuration of screen layout and report layout is extremely limited;

- The program is set up to work with dot matrix printers, although a laser printer was used for this report;

- A limited help file is found only within the analysis portion of the MVRAP program;

- Deleting a file within MVRAP renames it with a .old extension;

- The travel speed profile is plotted at 100-foot increments when the route length is less than 30,000 feet, at 200-foot increments when the route length is between 30,000 and 60,000 feet, and increases proportionally past 60,000 feet. Shading around the plot of average speeds is the 95 percent confidence interval;

- Fuel consumption is estimated from the travel speed profile;

- Acceleration noise is used to measure driver comfort;

- It is possible to tie in a user program library, access a DOS shell, and manage files from within MVRAP; and

- Run adjustments are also possible, in order to better fit run lengths to route data or take into consideration variations in DMI units.

2 PC-TRAVEL

PC-TRAVEL 2.0 is a “computerized travel time and delay analysis” software package developed by Jamar Technologies, Inc., to acquire and analyze speed and travel time data. It also provides “a completely flexible data presentation system,” and operation is “simple and intuitive.” Both fixed-route and chase car studies can be accommodated.

Jamar’s TDC-8 traffic data collection board was used in this report, but a laptop computer may be substituted in the field as noted throughout.

2.1 Preparing to Use PC-TRAVEL

2.1.1 Equipment Required

- IBM-compatible computer for analysis, with at least 512 KB RAM and a hard disk (a four-hour run will require about 30 KB of memory);
- Epson or other IBM-compatible printer (designed originally for dot matrix, but Hewlett Packard LaserJet and PostScript output are possibilities with this version of PC-TRAVEL);
- TDC-8 collection board or a laptop computer;
- Vehicle equipped with transmission/speedometer sensor; and
- PC-TRAVEL (software and hardware such as cables and connections included).

2.1.2 Training

All personnel should be familiar with the software and hardware setup procedure and the route being studied.

2.1.3 Setting Up Files and Equipment

2.1.3.1 Naming Conventions

Set up a naming convention for data files beforehand. It is very difficult to change file names later on, since analysis files refer to specific data files and will not be able to find these data files if their names are changed. The PC-TRAVEL manual describes one possible naming scheme.

2.1.3.2 Incident Descriptions (Optional)

PC-TRAVEL can record incident type and location information. Assign incident descriptions to the sixteen buttons on the TDC-8. (Sixteen more are available when using the BANK 1 key in conjunction with the numbered buttons.) If using the laptop for data collection, only ten incident keys (the number keys) are available.

The templates provided with the TDC-8 can be used as a model to assist the driver in remembering which buttons/keys correspond to which incidents.

2.1.3.3 Setting Up the Equipment

In the office, run "trsetup.exe" in DOS on the analysis computer to configure ports, printer options, display options, fuel and emissions constants, and mouse setup. Type "trav" to run PC-TRAVEL and reach the main menu (see Figure A-6).

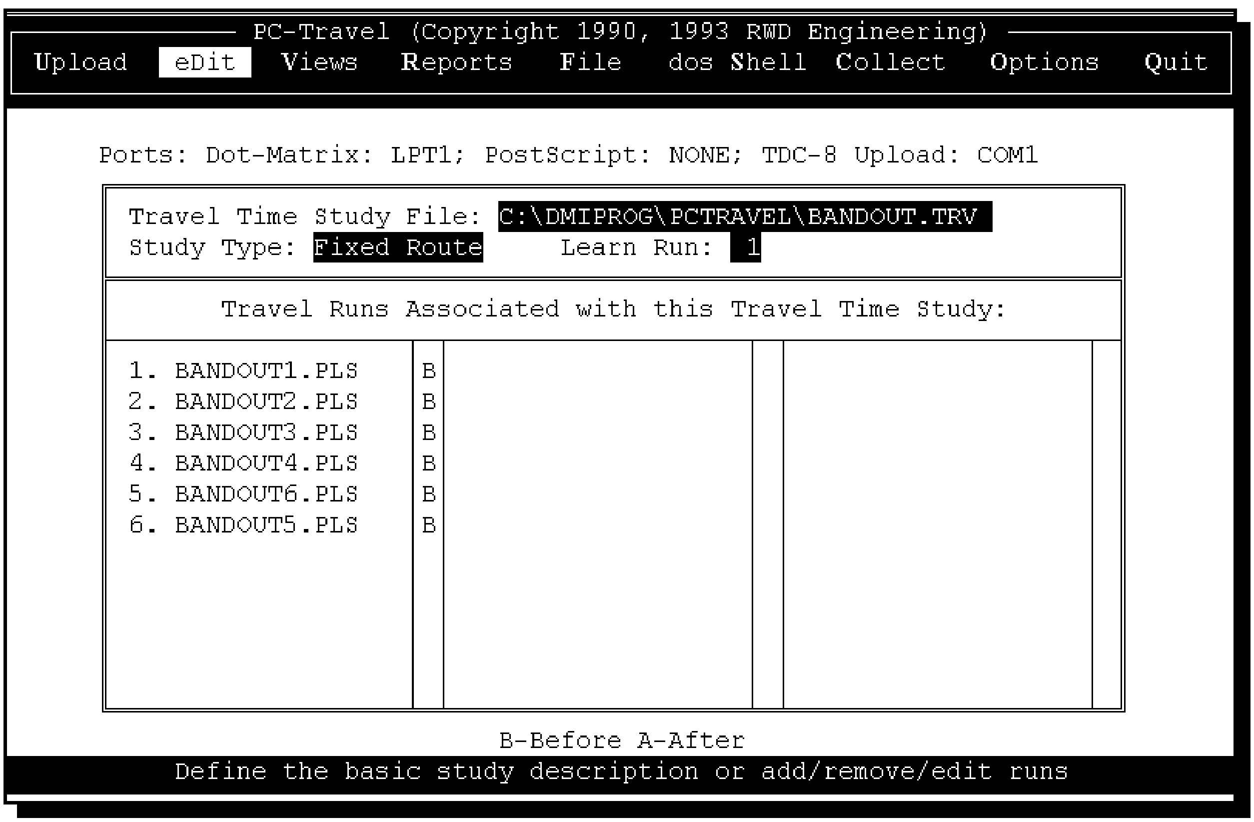


Figure A-6. PC-TRAVEL Main Menu

In the field, connect the TDC-8 (see Figure A-7) or laptop to the vehicle's transmission sensor using the appropriate Jamar cable. If using the TDC-8, connect the push-button switch to "Bank 2" on the side of the TDC-8 to provide an alternate method of marking new links in the study. The AC adaptor that comes with the software package can be used in lieu of the four AA batteries that power the TDC-8.

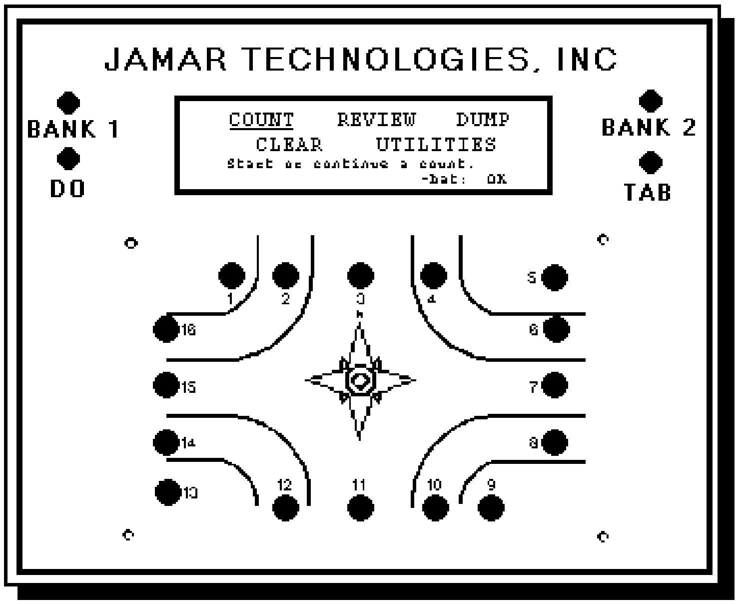


Figure A-7. Diagram of TDC-8

There is no need to predefine a route on either the TDC-8 or laptop. Collected data will be stored in the TDC-8 until manually cleared or (somewhere) in the laptop.

2.1.4 Using the Equipment

2.1.4.1 The TDC-8

The DO button is used to select entries from the display screen menu. The TAB button is used to move from one menu item to another. Pressing buttons 1 through 9 will enter those numbers as digits, and button 10 acts as a zero. The BANK 1 button is equivalent to the SHIFT key.

2.1.4.2 The Laptop

In later sections of this report, to use the laptop in place of the TDC-8, PC-TRAVEL must be running on the laptop. During data collection, utilize the following key/button equivalencies:

- DO on the TDC-8 is equivalent to ENTER on the laptop;

- "New Link" or BANK 2 on the TDC-8 is equivalent to the space bar on the laptop; and

- The numbered buttons on the TDC-8 are equivalent to the number keys on the laptop.

2.2 Collecting Field Data

2.2.1 Running the Program

Turn on the TDC-8. If using the TDC-8 with the AC adaptor, the on/off switch will not work, and the unit will have to be unplugged to turn it off later.

2.2.1.1 Calibration

To calibrate the data collection system, select COUNT, then NEW, then TT (for Travel Time Study), and then CALIBRATE from the TDC-8 menu. Enter a known constant by selecting EDIT or measure a new one by selecting MEASURE.

2.2.1.2 Collecting Data

Select COUNT, then NEW, then TT, and then TRAVEL. Choose to enter a site code (maximum of eight digits) or an alpha-numeric site description.

Begin driving. At the start of the first link, hit DO. At the start of each subsequent link, hit BANK 2 or press the push-button switch to indicate "New Link". 32 links are allowed. Press DO again at the end of the last link to end the run. Throughout, press the numbered buttons to mark incidents.

To start another run, press DO at its first checkpoint and repeat the process above.

2.2.2 Notes and Observations on Collecting Field Data

- If calibrating with the laptop instead of with the TDC-8, select *Collect* from the main menu and then "Calibrate System". Follow on-screen instructions, which are similar to those used in calibrating with the TDC-8.

- If collecting data with the laptop, choose *Collect* and then "Run Data Collection" from the main menu. Press ENTER to start the run, use the number keys as incident markers, use the space bar to mark the start of new links, and press ENTER again at the end of the run. Choose "Run Data Collection" again to start a new run.

- Entering a site code or site description is required with the TDC-8. The alpha-numeric site description is very awkward to enter.

- To run different routes out in the field, the site code must be changed before starting each one. The only way to do this is to turn off TDC-8 and restart the run setup from the beginning. “Before” and “After” designations make it unnecessary to enter a new site code before making a return trip, though. These designations can be set under “Edit Run Headers”.

- Jamar recommends including “dummy” links at the start and end of each route to minimize the distance errors inherent in using a device that records all data at the *end* of the current second. These can be ignored in the analysis.

- Jamar recommends that links be long enough that it takes more than two seconds to traverse them. This helps to reduce the distance errors mentioned above.

- The TDC-8 indicates remaining battery power and available memory.

- Run length is limited only by available memory.

- The TDC-8 can store up to 4.25 hours of data.

- All measures are in feet and mph.

- To exit from calibration or data collection routines, you must turn off the TDC-8. There is no other way to exit or cancel. This is awkward when using the AC adaptor.

- On-screen instructions are helpful and make the TDC-8 very easy to use.

- Context-sensitive help is available by pressing F1.

2.3 Data Analysis

2.3.1 Organizing Collected Data

2.3.1.1 TDC-8 Data

Connect the TDC-8 to the analysis computer using the provided cable. Turn on both devices. Run PC-TRAVEL on the analysis computer by typing “trav” at the DOS prompt. Select *Upload* from the main menu and follow on-screen instructions.

On the TDC-8, choose “Dump” and “Local” to send data directly to the copy of PC-TRAVEL running on the analysis computer. The data may also be sent via modem.

After the transfer begins, pressing ESC on the analysis computer will abort the upload.

When the transfer is complete, PC-TRAVEL will ask for file names and header information. The file name must be entered correctly now because it will be very difficult to change it later without invalidating current analyses.

All information will remain stored in the TDC-8 until specifically cleared, so the data can be uploaded again if necessary.

2.3.1.2 Laptop Data

In the directory that PC-TRAVEL is run from on the laptop, up to 32 temporary run files can be created. Before these files can be used, their data must be “finalized” by selecting *Collect* and then “Finalize Field Data” on the main menu.

2.3.2 Creating and Modifying a Study

A “study” is a collection of data files for a particular project. Select *File* and “Get Study” from the main menu. If a new study is being created, type in the new study name. Otherwise search for an existing study. Study files are merely lists of run file names, and they have a *.trv extension.

Under the *Edit* menu, select runs to add to the study. These will have a *.hdr extension. There are options to delete the run data, edit run headers, edit link lengths and names, and change the study type between fixed-route and chase car.

Under “Edit Run Headers” (see Figure A-8), selecting one run in a study as the “primary” run will use its link lengths as the basis of comparison in all the other runs. Type in incident marker button descriptions and the three speed threshold values for the primary run and they will apply to all other runs as well. Alternatively, select the option for user-defined lengths after link names are typed in under “Section Names and Lengths” (see Figure A-9). These will apply to all runs in the study.

```
═══════════════ Edit Run Information ═══════════════
                   Name of Run:
BANDOUT1.PLS

                 Run Number: 1
----------------------------------------------------
Run Title: Bandera Outbound 1
----------------------------------------------------
Date of Run:  3/ 2/91       | Ignore End Links: No
                            |
Speed Category 1:  0        | Before/After: Before
                            |
Speed Category 2: 10        | Run Type: Primary (Learn Run)
                            |
Speed Category 3: 30        | Calibration:        882
```

Figure A-8. "Edit Run Headers" Screen

```
═ Edit Cross Street Names for New Link Button in Fixed Route Study ═
        Study being edited: C:\DMIPROG\PCTRAVEL\BANDOUT.TRV
--------------------------------------------------------------------
  Cross Street Names assigned to New Link Button of Primary (Learn) Run:
--------------------------------------------------------------------
 1. I-8 Off Ramp           | 12.   | 23.
 2. Camino Del Rio North   | 13.   | 24.
 3. Camino De La Reina     | 14.   | 25.
 4. Hazzard Center Drive   | 15.   | 26.
 5. Mission Center Court   | 16.   | 27.
 6. Friars, South Ramp     | 17.   | 28.
 7. Friars, North Ramp     | 18.   | 29.
 8. Ralph's Driveway       | 19.   | 30.
 9. Mission Valley Road    | 20.   | 31.
10.                        | 21.   | 32.
11.                        | 22.   |
F2: Get names from another study. F3: Reverse names. F4: Insert. F5:Delete
```

Figure A-9. "Section Names and Length" Entry Screen

2.3.3 Analyzing the Data

2.3.3.1 Available Analyses Under the Views Menu

These are all viewed on the screen:

- Quick Summary (which provides a summary of travel time, stops, speed, and time below the three threshold speeds for all runs; see Figure A-10);

- Speed Profile (which is a plot of speed in mph vs. distance in feet for each run in the study; see Figure A-11); and

- Run Statistics (which is a report like the quick summary, but for a single run; see Figure A-12).

Summary of Study

Travel Study File: C:\DMIPROG\PCTRAVEL\BANDOUT.TRV

Section #	1	2	3	4	5	6	7	8	9	10	11
BEFORE Number of Before Runs: 6											
Travel Time	14.3	40.3	64.5	46.0	33.8	0.0	0.0	0.0	0.0	0.0	0.0
Stops	0.0	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Speed	38.1	27.9	27.5	37.4	45.8	0.0	0.0	0.0	0.0	0.0	0.0
Time Below:											
Speed 1	0.0	4.3	10.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Speed 2	0.0	8.0	14.3	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Speed 3	2.0	19.3	25.5	6.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
AFTER Number of After Runs: 0											
Travel Time	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Stops	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Speed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time Below:											
Speed 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Speed 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Speed 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PgUp/PgDn/Esc

Look at a short summary of the travel study

Figure A-10. Partial "Quick Summary"

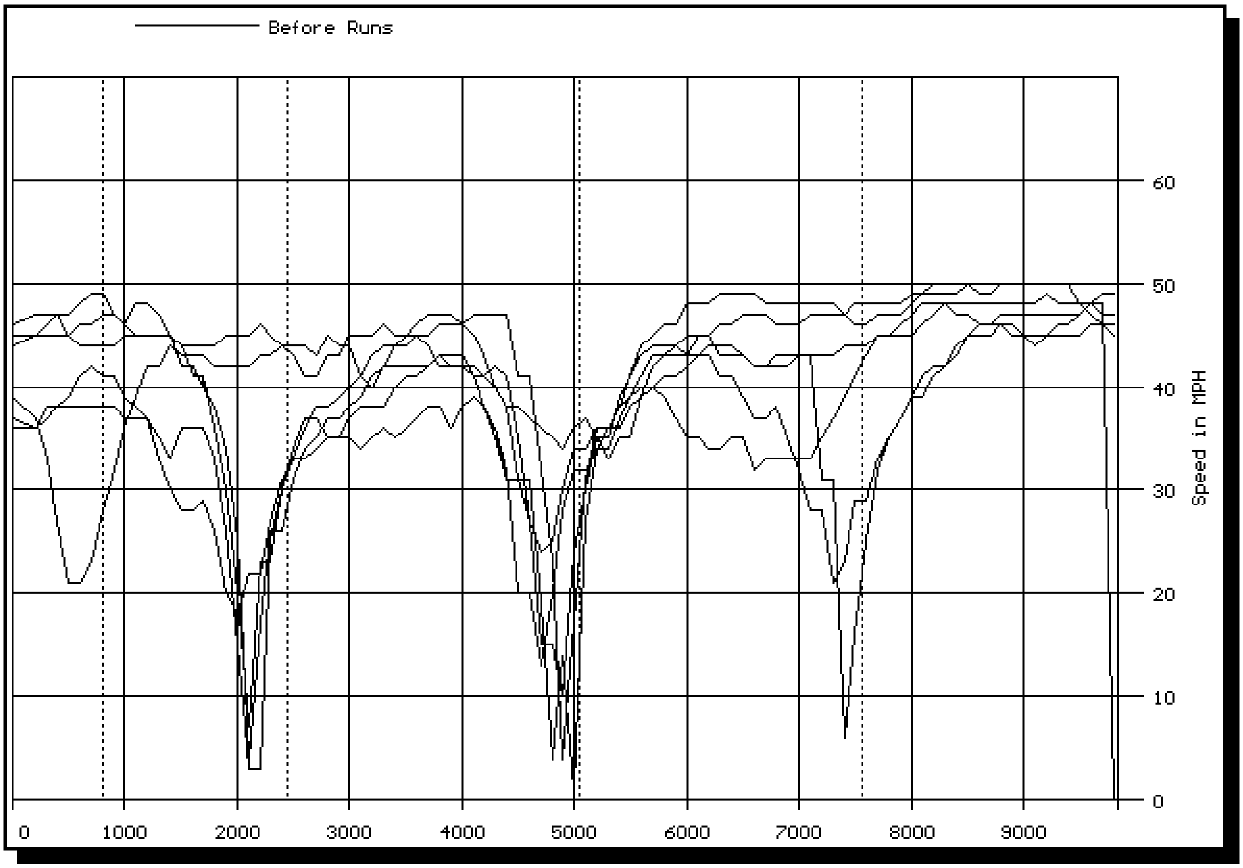


Figure A-11. "Speed Profile"

```
                          Summary of Study
        Travel Study File: C:\DMIPROG\PCTRAVEL\BANDOUT.TRV

   Section #      1    2    3    4    5    6    7    8    9   10   11

BEFORE   Detailed Statistics for Run: 1
 Travel Time     12   25  118   41   32    0    0    0    0    0    0
 Stops            0    0    2    0    0    0    0    0    0    0    0
 Speed           45   45   15   42   48    0    0    0    0    0    0
 Time Below:
  Speed 1         0    0   55    0    0    0    0    0    0    0    0
  Speed 2         0    0   67    0    0    0    0    0    0    0    0
  Speed 3         0    0   83    3    0    0    0    0    0    0    0

AFTER
 Travel Time
 Stops
 Speed
 Time Below:
  Speed 1
  Speed 2
  Speed 3

                           PgUp/PgDn/Esc
                    Display statistics for each run
```

Figure A-12. Partial "Run Statistics" Report

2.3.3.2 Available Analyses Under the Reports *Menu*

The first four reports are printed directly to the printer configured in "trsetup.exe". (This version of PC-TRAVEL will print to an HP LaserJet where the menu options describe dot matrix output.) The fifth report prints to a comma-delimited .txt file with the same name as the study. The printing options are:

- Quick Dot Matrix (which is the Quick Summary from the *Views* menu);
- Complete Dot Matrix (which includes the Quick Summary, Speed Profiles, and individual Run Statistics from the *Views* menu);
- Quick PostScript;
- Complete PostScript; and

- Spreadsheet Output (which contains summary statistics for the complete study and each run).

2.3.4 Notes and Observations on Data Analysis

- Raw (second-by-second) data can be accessed only by capturing TDC-8 uploads with a communications program.

- Report and view layouts cannot be reconfigured by the user.

- It is possible to add a run to a study multiple times. Be careful not to duplicate data in this way.

- One run *must* be designated as the primary run in order to assign incident description labels to the data, set speed thresholds, and choose whether or not end links should be ignored in analysis.

- Calibration numbers can be edited with run headers.

- “Delay” is actual travel time minus ideal travel time (the time a run would have taken at the desired speed). The desired speed is set under *Options*.

- Moving about the screen is not always completely intuitive, though it is still fairly easy. Sometimes the name of a run must be selected and sometimes only its number is necessary, the TAB and arrow keys *increment* some fields instead of moving the cursor between them, and some program features are buried within menus and not quick to access.

- Section names and links are reversible.

- Some incorrect entries can force the program to close. If a study has not been saved, it will be lost.

3 CATS

Computer Aided Transportation Software (CATS) was developed by the Texas Transportation Institute to "assist the transportation professional with all phases of corridor-level travel time and speed studies". The software records distances, speeds, and travel times, provides easy access to raw data files, offers an incident location and identification system and a file naming scheme, generates detailed statistical reports, and maintains project-level summaries and output tables.

3.1 Preparing to Use CATS

3.1.1 Equipment Required

- Laptop computer with 386 CPU class or higher, at least 4 MB RAM, and at least 5 MB free hard drive space;
- Analysis computer with 486 DX2 CPU running at 66 MHz or higher, at least 16 MB RAM, and at least 30 MB free hard drive space (large enough to store collected data);
- Windows 95 or Windows 3.1, Microsoft Excel Version 5.0 or higher;
- Vehicle equipped with a distance measuring instrument (DMI) such as the Nitestar by Nu-metrics that was used for this report; and
- Cable for 9-pin RS232 serial port.

3.1.2 Training

All personnel should be familiar with the software and hardware setup procedure, use of the DMI, and the route being studied.

3.1.3 Configuring Files, Directories, and the Program

CATS is made up of two separate program modules: the DMI_READ data collection module and the DMI_ANALYZE analysis module.

3.1.3.1 Setting Up a Project

A project can include up to twenty different roadways. The number of projects that can be set up is limited only by available computer memory.

To set up a project, run CATS from Windows. From the CATS main menu (see Figure A-13), choose **Set Up a Project**. Select *Define Project Parameters* and type in the project name, a directory name, and the path via which project files will be saved.

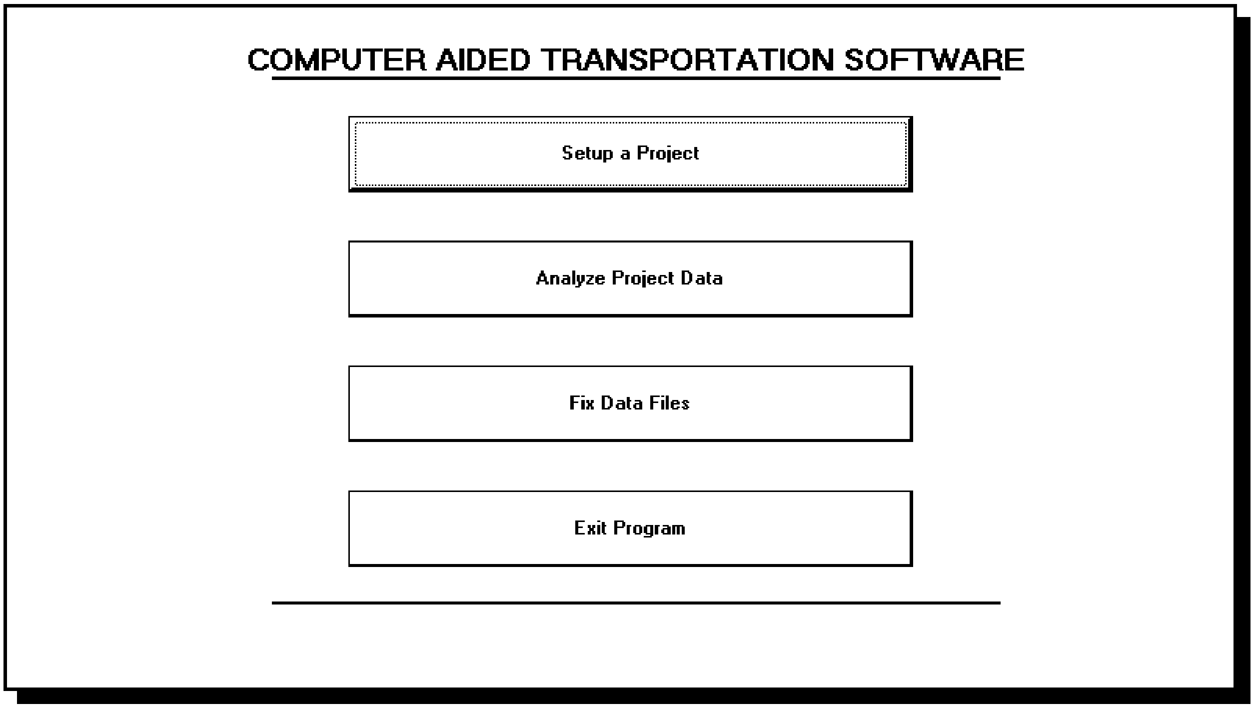


Figure A-13. CATS Main Menu

Then select *Configure DMI_READ Menus* and "Facility Menu Setup Wizard" (see Figure A-14) and type in the roadways that will be a part of the study. Each must have a unique two-character code (for the naming scheme) and an eight-character abbreviation (for a directory name). Valid travel directions must also be entered for each roadway.

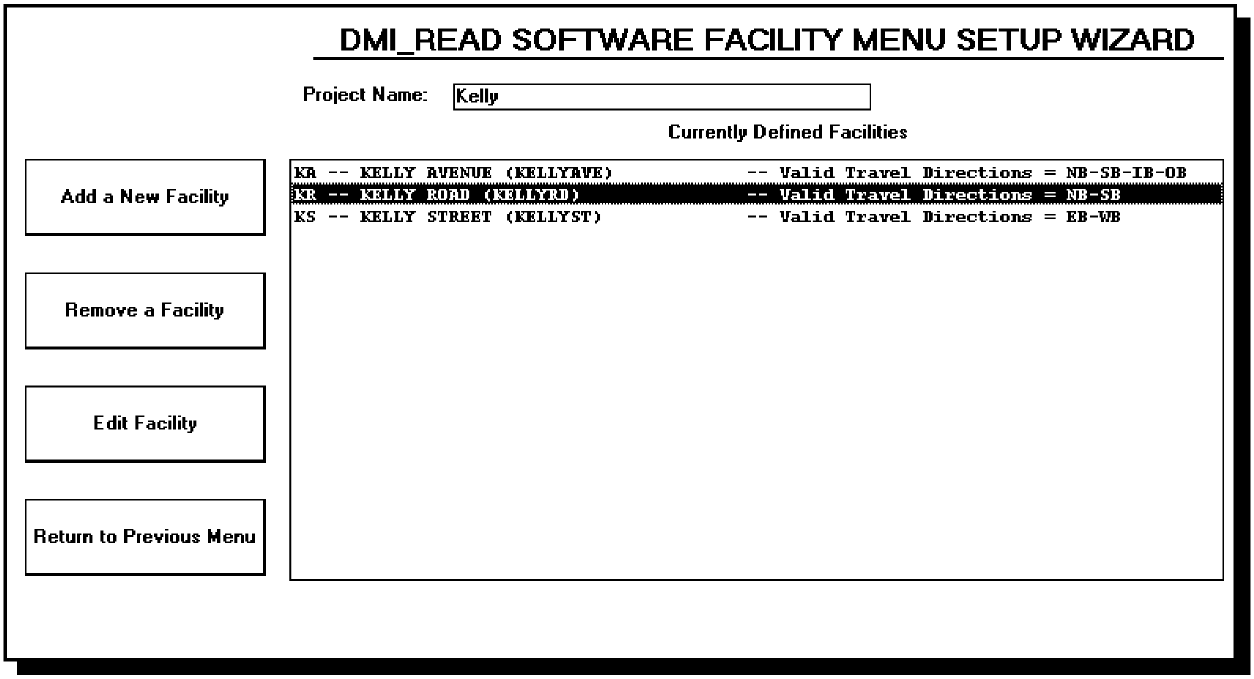


Figure A-14. DMI_READ Facility Menu Setup Wizard

One optional program feature is the ability to assign function keys to the types of incidents (such as stalled vehicles or debris) that might be encountered during the travel time run. Up to 48 incident types can be defined using the function keys, CTRL, ALT, and SHIFT. Incident descriptions are limited to 80 characters (see Figure A-15).

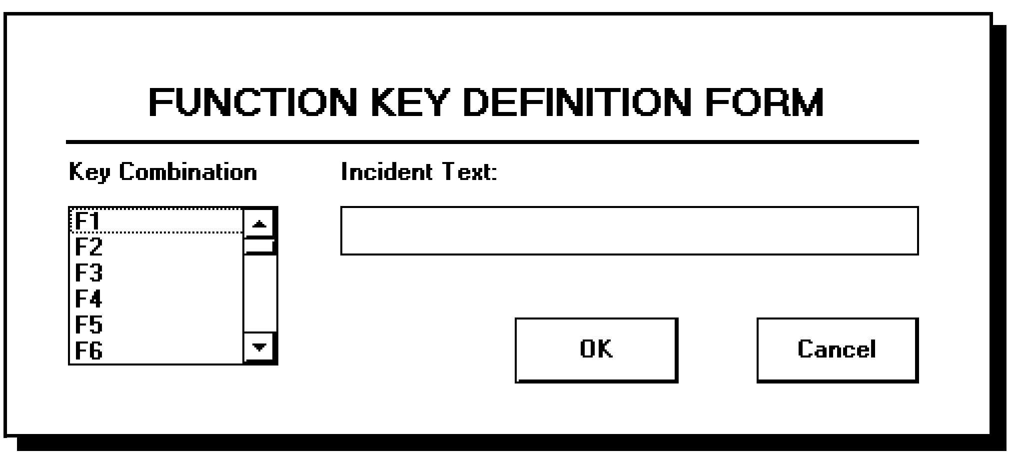


Figure A-15. Function Key Definition Form

A second optional program feature is the ability to include end-of-run questions for the driver to answer. An unlimited number of questions may be asked, but each can be no longer than 80 characters.

A final setup option is the creation of an installation diskette which can be used to install DMI_READ on the laptop used for data collection.

Another required setup element under **Set Up a Project** is *Make DMI_ANALYZE Yardstick Files* (see Figure A-16). Yardstick files contain the segment names and lengths (bounded by "checkpoints") and are compared with collected data in analysis. Up to 55 segments may be defined for a project. The yardstick file may be printed out in the form of a data collection sheet that can be taken into the field to assist the driver in locating checkpoints. This sheet lists the facility name, checkpoint names, identification landmarks, and cumulative distances between checkpoints, and it is printed automatically through Microsoft Excel.

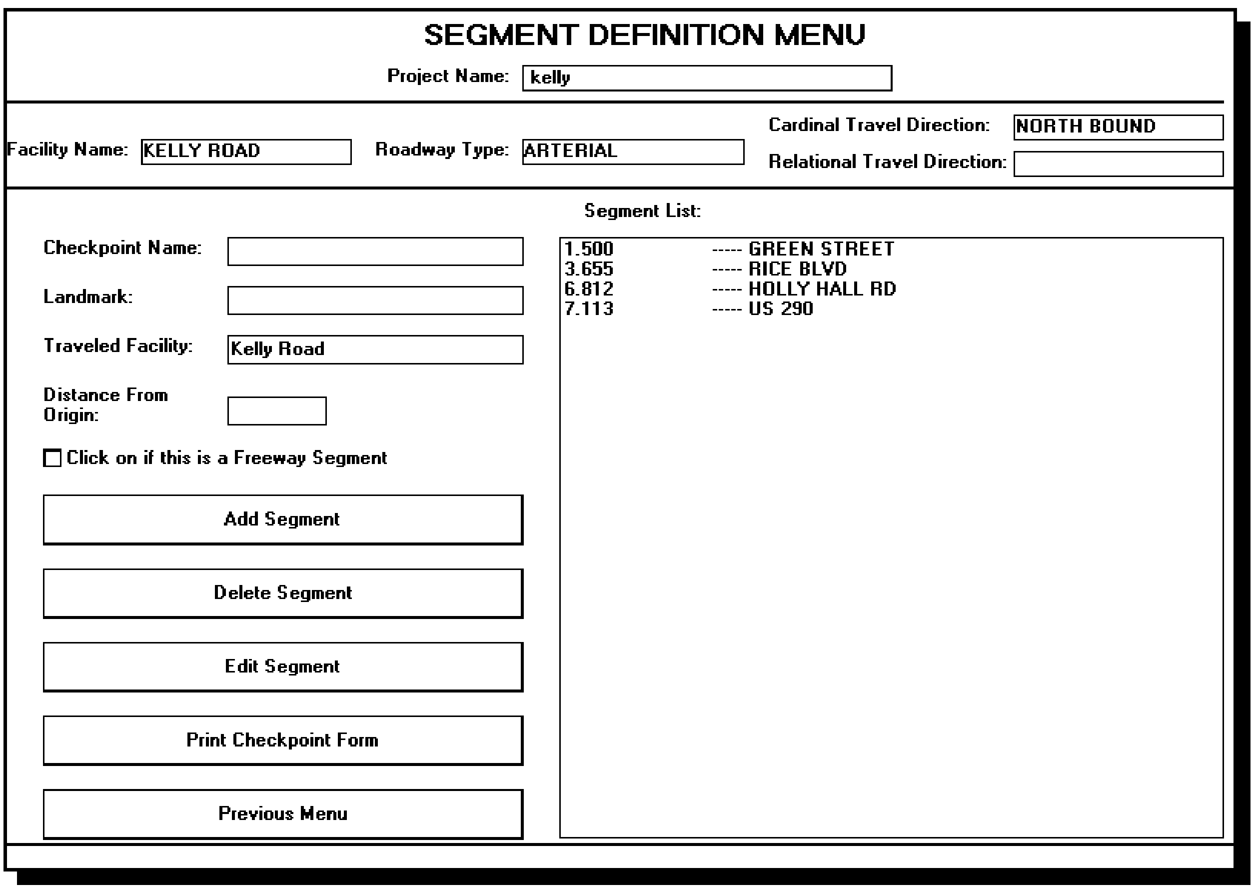


Figure A-16. Segment Definition Menu Under "Make DMI_ANALYZE Yardstick Files"

3.1.3.2 *Notes and Observations on Setting Up a Project*

- Interface is very easy to understand.

- Some input errors, such as entering an incorrect path name, will exit CATS without providing a chance to correct the error.

- The CATS setup routine operates smoothly when it is completed in one sitting. If re-entering the program at a later time to complete the setup of a project, defining the same project parameters will access the previously-entered information. However, CATS tries to create a *new* project whenever project parameters are entered and will say that the file already exists. Exit this screen--the correct project information will be still be accessed.

- Avoid assigning incident types to combinations of function keys and CTRL, ALT, and SHIFT unless absolutely necessary. It is unsafe for a driver to try to use such combinations while driving, so limit incident markers to the 12 function keys individually.

- Space for answers to the optional questions is limited to 80 characters.

3.2 Collecting Field Data

3.2.1 The CATS Main Menu

From the DOS prompt, type “dmi”, or choose the DMI icon in Windows. Follow on-screen instructions to reach the DMI_READ main menu (see Figure A-17).

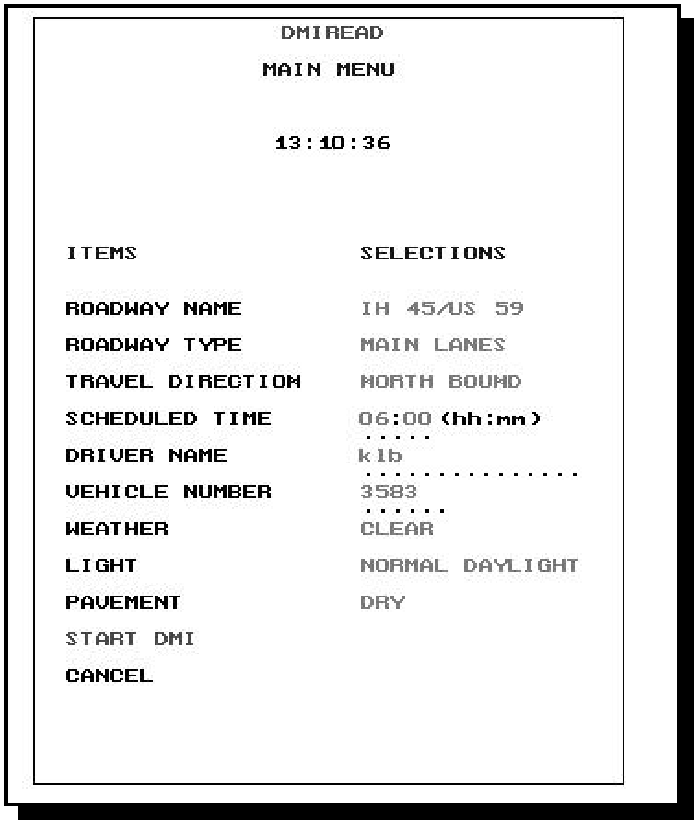


Figure A-17. DMI_READ Main Menu

3.2.2 Starting the Run, Marking Checkpoints, and Ending the Run

Select a user-defined roadway name, roadway type, and travel direction. Type in driver name and vehicle number, and then select preconfigured weather, lighting, pavement condition descriptions. To start the data collection process, highlight “Start DMI” and press ENTER. Data will begin scrolling on the screen in half-second increments, if equipment is set up properly (see Figure A-18).

```
                              DMIREAD

                 Data File --> \DMIDATA\GFMN7E06.13K
_________________________________________________________________________________
 39.,    0.028, 0.002,  12, 13:51:25.58                    | F1 = Stall on Left sh
 40.,    0.029, 0.002,  12, 13:51:26.07                    | F2 = Number one (1) l
 41.,    0.031, 0.002,  14, 13:51:26.57,!!! MARK!!!        | F3 = Number two (2) l
 42.,    0.032, 0.002,  14, 13:51:27.06,!!! MARK!!!        | F4 = Number three (3)
 43.,    0.034, 0.002,  14, 13:51:27.56,!!! MARK!!!        | F5 = Number four (4)
 44.,    0.036, 0.002,  15, 13:51:28.05                    | F6 = Stall on Right s
 45.,    0.038, 0.002,  15, 13:51:28.55                    | F7 = Multiple Lanes B
 46.,    0.040, 0.002,  16, 13:51:29.04                    | F8 = Construction Sta
 47.,    0.042, 0.002,  16, 13:51:29.53                    | F9 = Construction End
 48.,    0.043, 0.002,  16, 13:51:30.03                    | F10 = Debris in road
 49.,    0.045, 0.002,  15, 13:51:30.52,Stall on Left      | F11 = Accident in oppi
 50.,    0.047, 0.002,  15, 13:51:31.02                    | F12 = Accident on HOVL
 51.,    0.049, 0.002,  16, 13:51:31.51                    |
 52.,    0.051, 0.003,  16, 13:51:32.01                    |______________________
 53.,    0.053, 0.002,  18, 13:51:32.50                    |
 54.,    0.055, 0.003,  18, 13:51:32.99,Debris in road     | [ALT-F]=F1-F12 map
 55.,    0.057, 0.002,  18, 13:51:33.49                    | [ALT-S]=Shf F1-F12 map
 56.,    0.060, 0.003,  18, 13:51:33.98                    | [ALT-C]=Ctr F1-F12 map
 57.,    0.062, 0.003,  18, 13:51:34.48                    | [ALT-A]=Alt F1-F12 map
 58.,    0.064, 0.003,  19, 13:51:34.97                    | [ALT-END]=EXIT
                                                           |
```

Figure A-18. CATS Display Screen

Hit any key (except function keys) three times when passing the first checkpoint. "!!!MARK!!!" will appear three times in a row on the screen. Hit any key once at each subsequent checkpoint, and choose the appropriate function key to indicate any incidents passed.

To end the run, hit ALT-END. A series of preconfigured questions about the data collection run will follow (see Figure A-19). After answering the final question and hitting ENTER, the program will terminate. Repeat this process for additional runs.

```
Q.  Were there changes in the weather during the run?

A. -->Light rain at Kelly St._
```

Figure A-19. Example of CATS Comment Questions

3.2.3 Notes and Observations on Data Collection

- The data entered on the DMI_READ menu are used to define unique run file names.

- Constantly scrolling data makes it easy to check that the DMI-reported speeds match those of the speedometer and that the correct function keys have been pressed.

- Ford vehicles traveling at speeds less than eight mph do not send pulses to the DMI, and so stop and delay data may not be correct.

- The roadway names on the data collection sheets printed out from the Segment Definition Menu will exactly match those listed in the DMI_READ main menu to help the driver select the proper project roadway in the field

3.3 Data Analysis

3.3.1 Performing the Analysis

First, all data files must be moved from a subdirectory called DMIDATA on the laptop to the DATA subdirectory under the appropriate project directory on the analysis computer. The raw data is in ASCII format, and an example is shown in Figure A-20.

Run CATS on the analysis computer and choose **Analyze Project Data** from the CATS main menu. This will bring up the DMI_ANALYZE screen (see Figure A-21).

Select one or more of the available analysis options, type in the path to the project directory, and click on “Process Data!!!” to analyze the data. The available analysis options are:

- Convert From Feet to Miles;

- Update Executive Summary (which stores only segment travel time and speed data in the project’s EXEC_SUM subdirectory; see Figure A-22);

- Archive Analyzed Data (which stores statistical reports of each file in the OUTPUT subdirectory);

- Plot Speed Profiles (which prints a graph of instantaneous speed vs. distance traveled for each file; see Figure A-23);

- Print Driver Comments; and
- Print Statistical Reports.

After the analyses are finished, completed files are moved to a subdirectory called COMPLETE if the analysis identified no problems or to a subdirectory called PROBLEMS if there was an analysis error. These analysis errors might include incorrect DMI calibration or failure to mark the first checkpoint.

3.3.2 Notes and Observations on Data Analysis

- If any files other than raw data files are in the DATA subdirectory, the analysis will fail.

- Excel is opened and closed automatically by CATS, so close any running copies of Excel before running CATS.

- Other program capabilities include the ability to change calibration numbers and convert units.

```
ROADWAY NAME      : ,EAST LOOP TO I-10
ROADWAY TYPE      : ,MAIN LANES
ROADWAY DIRECTION : ,NORTH BOUND
DATE TODAY        : ,11/21/1996
SCHEDULED TIME    : ,17:30
WEATHER CONDITION : ,OVERCAST
LIGHT CONDITION   : ,DARK OR TWILIGHT
PAVEMENT CONDITION : ,DRY
DRIVER            : ,klb
MILE START        : ,3582
START TIME        : ,17:28:03.64


 79.,  0.396, 0.008,  55  ,17:28:42.26
 80.,  0.403, 0.008,  55  ,17:28:42.75
 81.,  0.411, 0.008,  55  ,17:28:43.24 ,!!! MARK!!!
 82.,  0.419, 0.008,  56  ,17:28:43.74 ,!!! MARK!!!
 83.,  0.426, 0.008,  56  ,17:28:44.23 ,!!! MARK!!!
 84.,  0.434, 0.008,  56  ,17:28:44.73
 85.,  0.442, 0.008,  56  ,17:28:45.22
 86.,  0.449, 0.008,  56  ,17:28:45.72
 87.,  0.457, 0.008,  56  ,17:28:46.21
 88.,  0.465, 0.008,  56  ,17:28:46.70
 89.,  0.472, 0.008,  56  ,17:28:47.20
 90.,  0.480, 0.008,  56  ,17:28:47.69 ,Stall on Right shoulder
 91.,  0.488, 0.008,  56  ,17:28:48.19
 92.,  0.496, 0.008,  56  ,17:28:48.68
 93.,  0.504, 0.009,  58  ,17:28:49.18
 94.,  0.512, 0.008,  58  ,17:28:49.67
 95.,  0.520, 0.009,  58  ,17:28:50.16
 96.,  0.528, 0.008,  58  ,17:28:50.66
 97.,  0.536, 0.009,  59  ,17:28:51.15
 98.,  0.544, 0.008,  59  ,17:28:51.65
 99.,  0.552, 0.009,  58  ,17:28:52.14 ,!!! MARK!!!
 100.,  0.560, 0.008,  58  ,17:28:52.64
 101.,  0.568, 0.009,  58  ,17:28:53.13
 102.,  0.576, 0.008,  58  ,17:28:53.63
<many data points deleted for this example>
3488., 21.718, 0.000,   0  ,17:56:48.91
3489., 21.718, 0.000,   0  ,17:56:49.40 ,!!! MARK!!!
3490., 21.718, 0.000,   0  ,17:56:49.90
3491., 21.718, 0.000,   0  ,17:56:50.39
3492., 21.718, 0.000,   0  ,17:56:50.88
3493., 21.718, 0.000,   0  ,17:56:51.38


Q. ,Were any incidents, stalls etc. observed?
A. ,"yes"

Q. ,Were there changes in the weather during the run?
A. ,"no"

Q. ,Did you observe any major queue build up during the run?  If so at what locations?
A. ,"yes--before cavalcade"

Q. ,Did you need to take any detours?
A. ,"no"

Q. ,Any other comments?
A. ,"construction at I-45/I-610.  construction at main in right lane."
```

Figure A-20.
Example of CATS Raw Data File (Greatly Abbreviated)

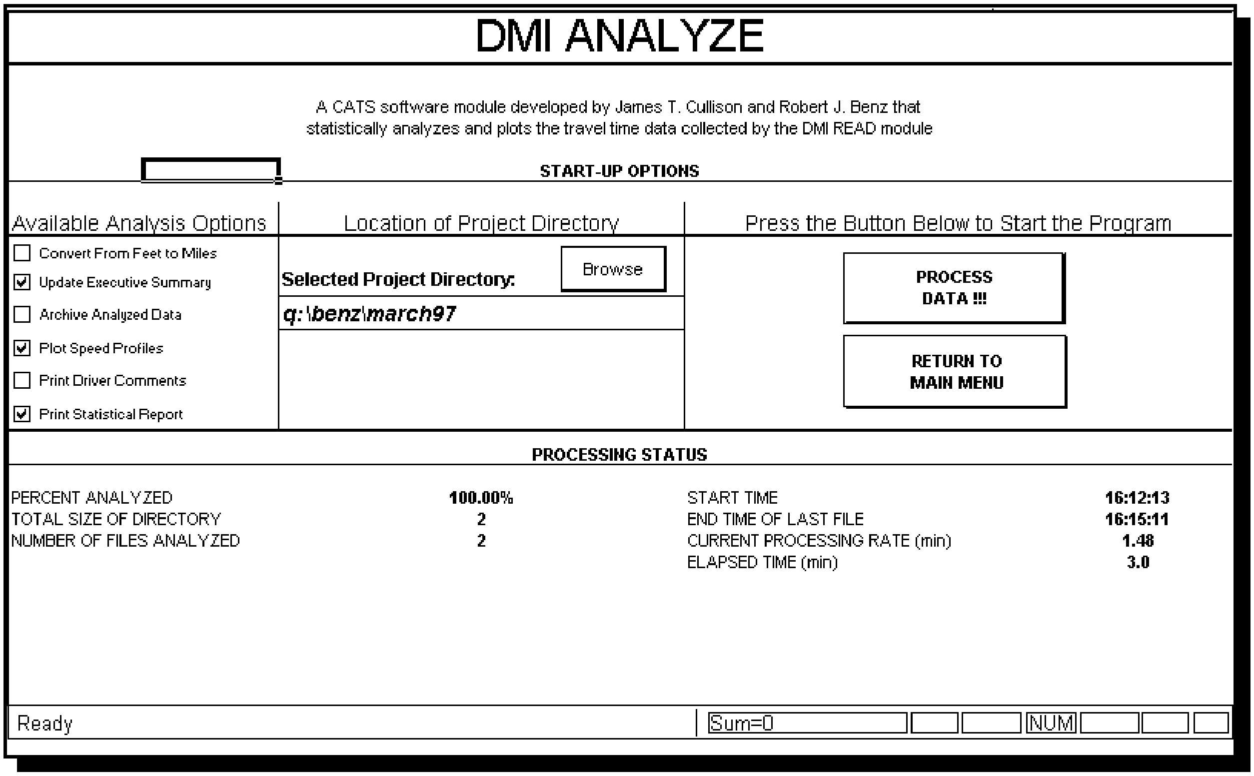


Figure A-21. DMI_ANALYZE Screen

EFME7C18.06L

FACILITY NAME	EAST FREEWAY
TRAVEL DIRECTION	EAST BOUND
TTR DATE	3/18/97
WEATHER	OVERCAST
PAVEMENT	DRY
LIGHT CONDITION	NORMAL DAYLIGHT
SCHEDULED TIME	7:00
START TIME	06:55

CHECKPOINT	**INT DIST (miles)**	**CUMM DIST (miles)**	**INT TIME (min)**	**CUMM TIME (min)**	**STDEV SPEED (mph)**	**AVG SPEED (mph)**	**PERCENT TIME UNDER 5 mph**	**BETWEEN 5-35 mph**	**BETWEEN 35-50 mph**	**OVER 50 mph**	**LEVEL OF SERVICE**
MCKINNEY	0.000	0.000	0.00	0.00	-----	-----	-----	-----	-----	-----	-----
TEXAS	0.250	0.250	1.28	1.28	11.49	11.72	46.2%	53.8%	0.0%	0.0%	-----
COLLINS/ROTHWELL	0.610	0.860	1.95	3.23	13.13	18.75	29.0%	67.6%	3.4%	0.0%	-----
EASTEX	0.950	1.810	2.38	5.62	22.45	23.91	36.6%	31.7%	17.6%	14.1%	-----
WACO	1.070	2.880	1.08	6.70	1.93	59.33	0.0%	0.0%	0.0%	100.0%	A
LOCKWOOD	0.670	3.550	0.68	7.37	0.47	59.50	0.0%	0.0%	0.0%	100.0%	A
KRESS	0.480	4.030	0.49	7.86	0.52	59.26	0.0%	0.0%	0.0%	100.0%	A
LATHROP	0.380	4.410	0.38	8.24	0.31	60.16	0.0%	0.0%	0.0%	100.0%	A
WAYSIDE	0.620	5.030	0.62	8.86	0.81	60.19	0.0%	0.0%	0.0%	100.0%	A
MCCARTY	0.460	5.490	0.46	9.32	1.43	59.83	0.0%	0.0%	0.0%	100.0%	A
EAST LOOP	1.210	6.700	1.21	10.53	0.69	59.81	0.0%	0.0%	0.0%	100.0%	A
MERCURY	1.010	7.710	1.01	11.54	1.60	60.29	0.0%	0.0%	0.0%	100.0%	A
HOLLAND	0.880	8.590	0.83	12.37	1.45	63.45	0.0%	0.0%	0.0%	100.0%	A
FEDERAL	1.180	9.770	1.18	13.55	0.61	59.96	0.0%	0.0%	0.0%	100.0%	A
UVALDE	1.670	11.440	1.68	15.23	0.80	59.62	0.0%	0.0%	0.0%	100.0%	A
FREEPORT	0.480	11.920	0.48	15.71	0.89	60.27	0.0%	0.0%	0.0%	100.0%	A
BELTWAY 8	1.480	13.400	1.44	17.15	4.05	61.47	0.0%	0.0%	0.0%	100.0%	A
SHELDON	1.800	15.200	1.55	18.70	0.68	69.73	0.0%	0.0%	0.0%	94.7%	A
CEDAR LANE	1.180	16.380	1.02	19.73	2.18	69.12	0.0%	0.0%	0.0%	95.2%	A
MAGNOLIA DRIVE	1.090	17.470	0.97	20.70	3.52	67.27	0.0%	0.0%	0.0%	81.5%	A
CROSBY LYNCHBERG	2.050	19.520	2.02	22.72	3.88	60.85	0.0%	0.0%	0.0%	100.0%	A
RUN AVERAGES						**51.55**	**8.9%**	**12.2%**	**2.1%**	**75.4%**	

Figure A-22. Executive Summary

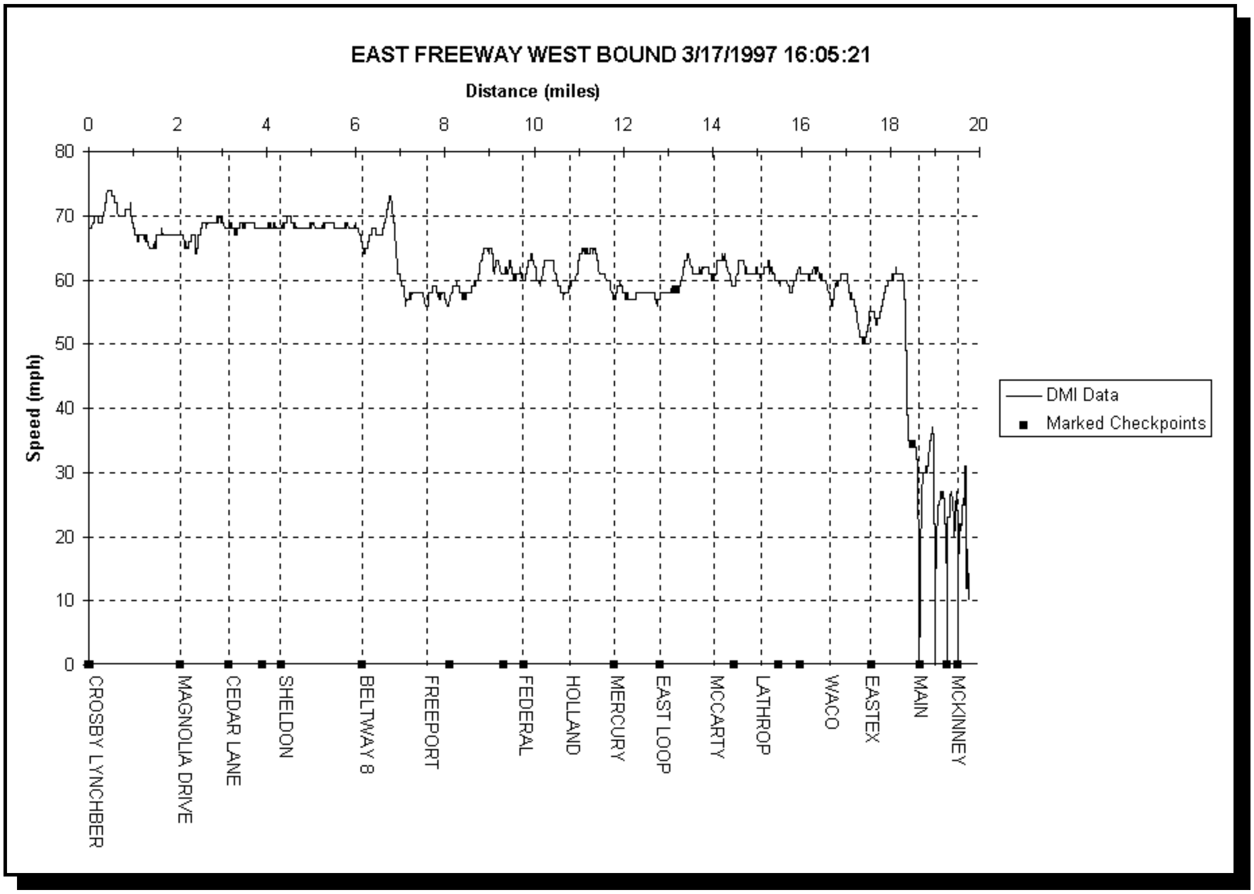


Figure A-23. Speed Profile

APPENDIX B: COMPUTER SOFTWARE FOR LICENSE PLATE MATCHING

This appendix contains documentation for license plate collection and matching computer software that is used to collect travel times. Chapter 4 of the handbook described the manual and portable computer-based methods of travel time collection that can utilize software for automating data collection and reduction.

Only a single version of license plate collection and matching software is presented in this appendix, but other versions are available at cost through the McTrans or PC-Trans software distribution centers. The license plate collection and matching functions of this and similar software can be replicated in most basic programming languages or spreadsheet/database macro languages.

1 Texas Transportation Institute's License Plate Collection and Matching Software

The Texas Transportation Institute (TTI) modified the "SPEEDRUN" and "MATCH" software developed by the Chicago Area Transportation Study (CATS) for use in NCHRP Project 7-13, *Quantifying Congestion*. The modified software programs are called "TTCOLLEC" and "TTMATCH". The software is available and freely distributed by TTI [contact Shawn Turner at (409) 845-8829].

1.1 Instructions for Using License Plate Collection and Matching Software

All data collection personnel should be familiar with the collection software and should have one to two hours of practice reading and entering license plate numbers. Observers should arrive at the designated collection site 10 to 15 minutes in advance to prepare for data collection. Depending upon the method of data collection, 30 to 60 minutes should be enough time to collect an adequate number of license plates at a particular station. As a minimum, you should expect that approximately 5 to 10 percent of the collected license plates will result in matches. A preliminary analysis of the first day's data should provide a better idea of collection times and matching percentages.

The following steps should be taken to prepare the portable computer for data collection:

1. Create a travel time data collection sub-directory on the hard disk drive of the portable computer (or floppy disk if no hard drive exists).

2. Copy the TTCOLLEC.EXE collection program into the data collection sub-directory.

1.1.1 Data Collection

The following steps should be taken to begin data collection on the portable computer:

1. Type “TTCOLLEC” from the data collection sub-directory to start the collection program. Press any key to continue past the title screen.

2. The user will be prompted for an input file name and path. If no path is typed the input data file will be created in the current data collection directory. Type a logical file name for your data file, and consider using a file name extension like “.1", “.2”, “.3”, etc., corresponding to the relative position or location of the checkpoint.

3. Answer prompts regarding the study route, direction of traffic flow (two letters only), your location, and the weather conditions or other comments. The responses to these prompts, along with the file name, will be included as a header at the beginning of the data file. This information will also be included at the top of each data entry screen.

4. After answering the “weather conditions or other comments” prompt, a plate entry screen will appear. There are three fields: one for an 8-digit plate number, one for a 2-letter state abbreviation, and one for comments (70 characters). There are several function keys in the plate entry screen:

   - “TAB” moves the cursor between fields.
   - "*" (asterisk) clears screen without saving entry (updates on-screen clock).
   - “RETURN” or “ENTER” saves the plate entry and refreshes the entry screen.
   - “ESCAPE” exits the program and saves the data file.

   In addition, the arrow keys “←”, “→”, “↑”, and “↓” can be used to move the cursor within and between fields. The “BACKSPACE” and the space bar can be used to delete an entry.

   If the TTCOLLEC program is exited accidentally during data collection (e.g., from temporary loss or interruption of power), restart the program and use the same file name as before. The program will append your new data to the original input file.

5. When data collection is complete, press “ESCAPE” to exit the program. All observers should enter plate numbers in a uniform and consistent manner (e.g., first four plate characters in upper-case type). The matching program is only capable of matching plate numbers that have been entered identically.   Data files should be copied onto a permanent storage disk (e.g., office computer or backup floppy disk) at the end of each day of data collection.

1.1.2 Data Reduction

Preliminary data reduction, like plate matching, can be performed in the field. Final data reduction and analysis should be performed in the office once the data collection for a route is complete. The computer program “TTMATCH” is used to match the license plates collected by “TTCOLLEC”. The TTMATCH.EXE file should be copied into the data collection sub-directory before proceeding.

The following steps should be taken to match license plates:

1. Copy the data files into the data collection sub-directory. The program is only capable of matching two data files at once.

2. From the data collection sub-directory, type “TTMATCH”. The program will prompt you for names of the two input data files that contain the license plates to be matched. If the data files are not in the data collection sub-directory, the path must be specified. The program will also prompt you for the name of the summary output file (use the extension "*.out"), which is user-specified. If no path is specified for the output file, it will be created in the current data collection sub-directory.

3. You will be prompted for the run distance, and whether you wish to set speed limits for the license matching procedure. The speed limits feature can eliminate most spurious matches if used properly. If the speed limits feature is used, set the limits so that practically no vehicle could have traversed the study section outside of these limits. For example, speeds above 100 mph or below 5 mph may be used on freeways, whereas above 70 mph or below 5 mph may be more appropriate for arterial streets. The speed limits should be based on local route and traffic conditions.

4. The program will proceed to match the plates in the two data files. Some spurious matches are automatically eliminated by the program (discards observations greater or less than two standard deviations from the mean), and a summary output file will be created with your specified file name in the data collection sub-directory or the user-specified path.

The output file contains summary statistics and a list of all matched plates and corresponding speeds in a text file (comma-separated values). The individual speed estimates can be examined to further eliminate any identifiable spurious matches through visual inspection, graphing, or statistical procedures. The output file can also be imported into a spreadsheet or statistical analysis software for final data reduction and analysis.

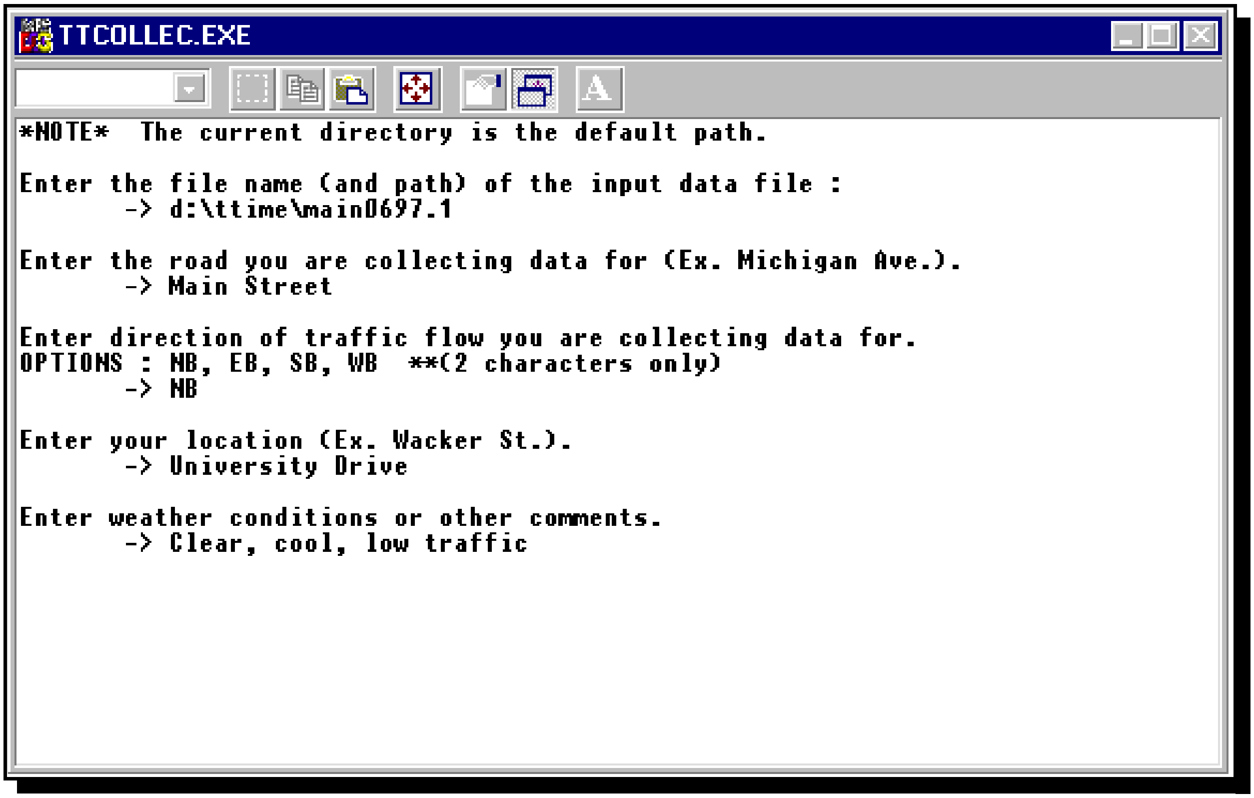


Figure B-1. TTCOLLEC Site Information Entry Screen

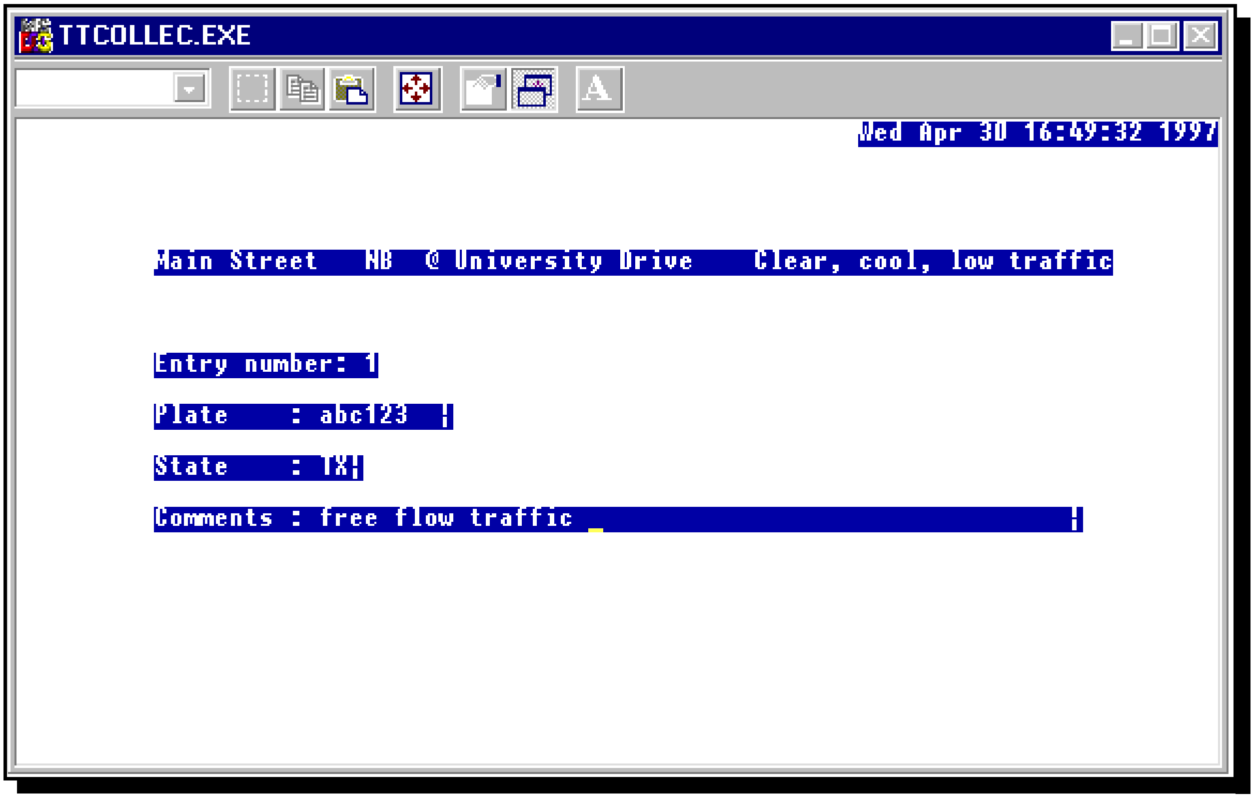


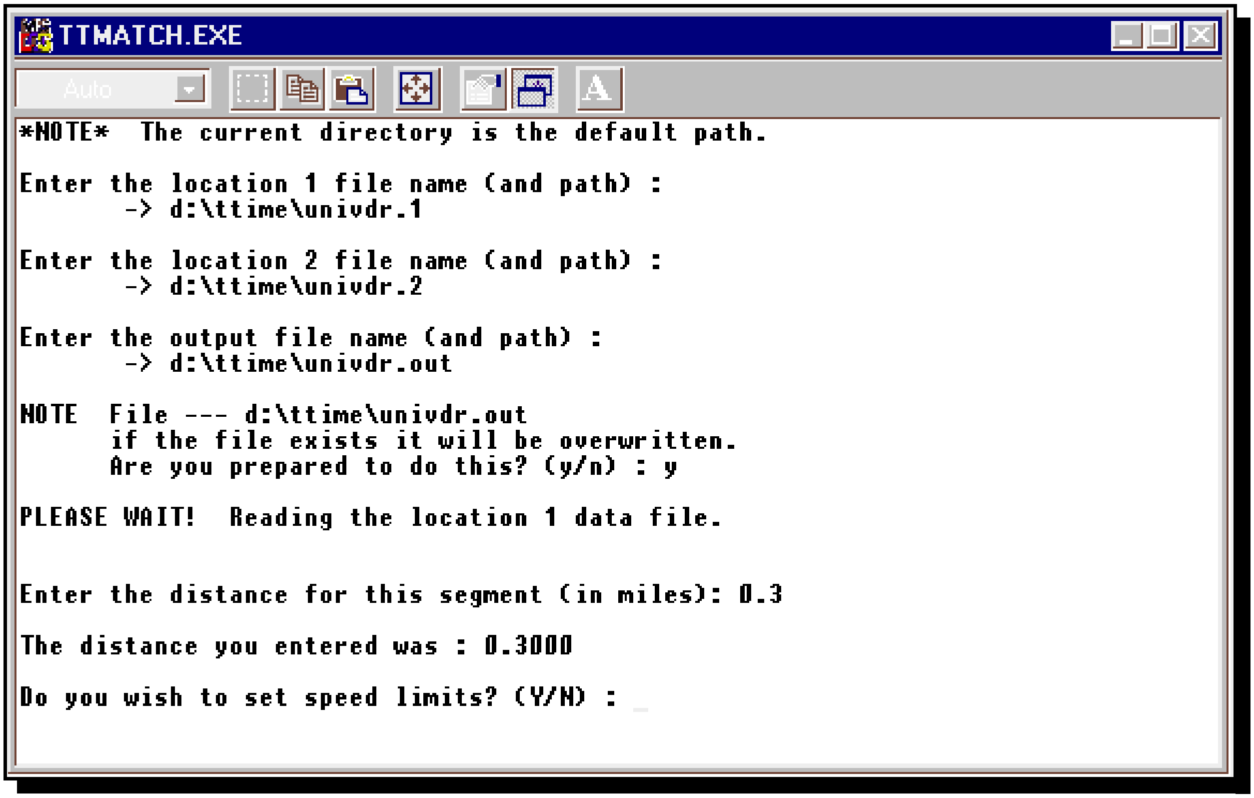
Figure B-2. TTCOLLEC License Plate Entry Screen

Univdr.1 - Notepad

File Edit Search Help

```
University Drive -- Wellborn Road to Asbury Street   Sunny and cool   Thu Nov 05 13:59:05 1992
1,13:59:12, 36ne    ,  ,
2,13:59:35, 178h    ,  ,
3,13:59:43, 25xf    ,  ,
4,13:59:48, 5868    ,  ,
5,14:00:04, 32xv    ,  ,
6,14:00:38, t72s    ,  ,
7,14:00:45, d976    ,  ,
8,14:00:51, 6m1u    ,  ,
9,14:01:07, 6865    ,  ,
10,14:01:26, 7185    ,  ,
11,14:01:44, t71r    ,  ,
12,14:01:49, 2rlo    ,  ,
13,14:01:57, 9mbw    ,  ,
14,14:02:04, s16r    ,  ,
15,14:02:17, f02d    ,  ,
16,14:02:24, 6sqb    ,  ,
17,14:02:31, 67xq    ,  ,
18,14:02:37, 8933    ,  ,
19,14:02:42, x13w    ,  ,
20,14:03:25, 8823    ,  ,
21,14:03:29, 1wzf    ,  ,
22,14:03:35, 0zha    ,  ,
23,14:03:59, 7rmn    ,  ,
24,14:04:09, x65v    ,  ,
25,14:04:16, 3hjr    ,  ,
26,14:04:21, 9074    ,  ,
27,14:04:35, 60cy    ,  ,
28,14:04:45, k61x    ,  ,
29,14:04:58, 9nxn    ,  ,
30,14:05:04, 86ew    ,  ,
31,14:05:10, 65tr    ,  ,
32,14:05:38, 39hq    ,  ,
33,14:05:45, 5qrv    ,  ,
```

Figure B-3. Example Input Text File for TTMATCH



```
TTMATCH.EXE

*NOTE*  The current directory is the default path.

Enter the location 1 file name (and path) :
       -> d:\ttime\univdr.1

Enter the location 2 file name (and path) :
       -> d:\ttime\univdr.2

Enter the output file name (and path) :
       -> d:\ttime\univdr.out

NOTE  File --- d:\ttime\univdr.out
      if the file exists it will be overwritten.
      Are you prepared to do this? (y/n) : y

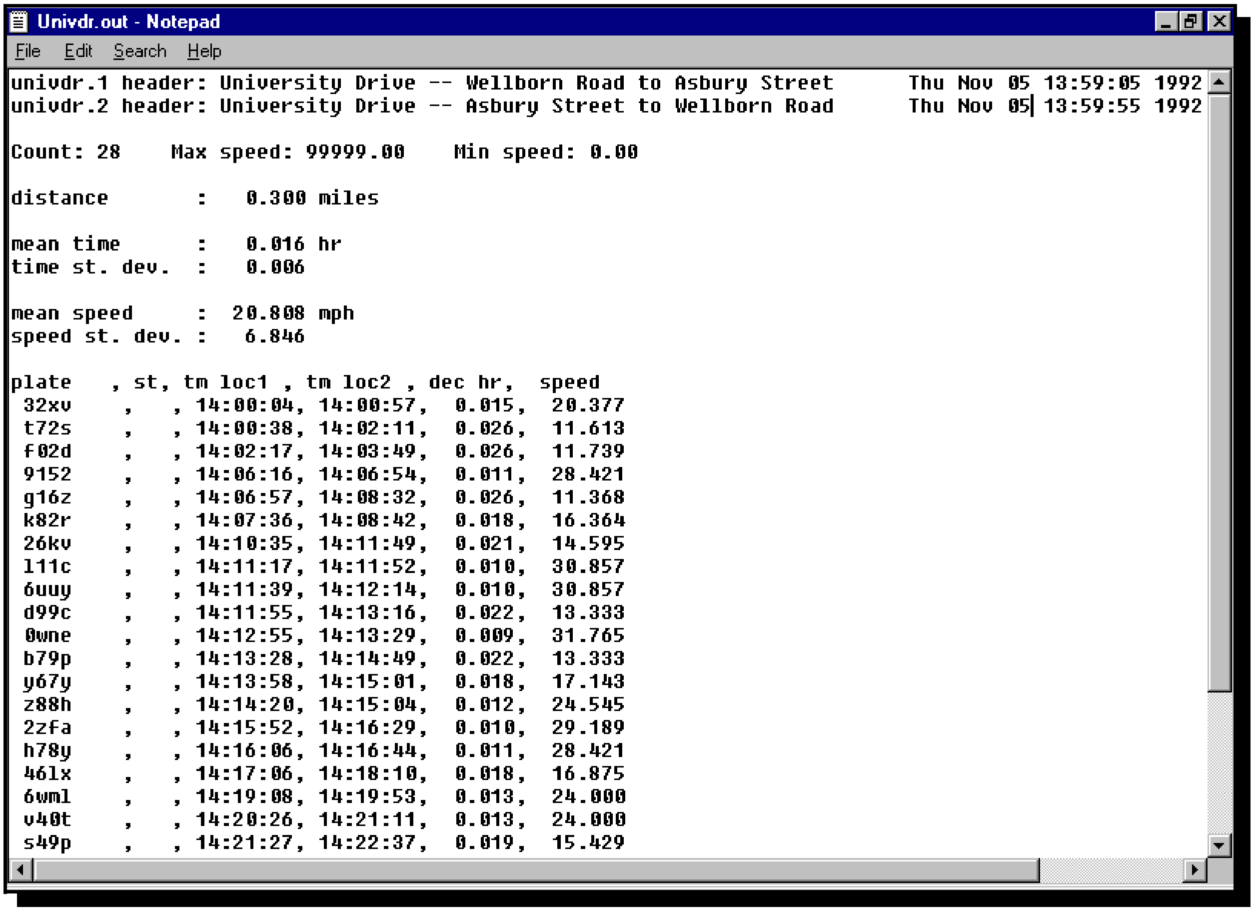
PLEASE WAIT!  Reading the location 1 data file.


Enter the distance for this segment (in miles): 0.3

The distance you entered was : 0.3000

Do you wish to set speed limits? (Y/N) : _
```

Figure B-4. Example Matching Input Screen for TTMATCH




```
univdr.1 header: University Drive -- Wellborn Road to Asbury Street      Thu Nov 05 13:59:05 1992
univdr.2 header: University Drive -- Asbury Street to Wellborn Road      Thu Nov 05 13:59:55 1992

Count: 28    Max speed: 99999.00    Min speed: 0.00

distance       :   0.300 miles

mean time      :   0.016 hr
time st. dev.  :   0.006

mean speed     :  20.808 mph
speed st. dev. :   6.846

plate   , st, tm loc1 , tm loc2 , dec hr,  speed
 32xv    ,   , 14:00:04, 14:00:57,  0.015,  20.377
 t72s    ,   , 14:00:38, 14:02:11,  0.026,  11.613
 f02d    ,   , 14:02:17, 14:03:49,  0.026,  11.739
 9152    ,   , 14:06:16, 14:06:54,  0.011,  28.421
 g16z    ,   , 14:06:57, 14:08:32,  0.026,  11.368
 k82r    ,   , 14:07:36, 14:08:42,  0.018,  16.364
 26kv    ,   , 14:10:35, 14:11:49,  0.021,  14.595
 l11c    ,   , 14:11:17, 14:11:52,  0.010,  30.857
 6uuy    ,   , 14:11:39, 14:12:14,  0.010,  30.857
 d99c    ,   , 14:11:55, 14:13:16,  0.022,  13.333
 0wne    ,   , 14:12:55, 14:13:29,  0.009,  31.765
 b79p    ,   , 14:13:28, 14:14:49,  0.022,  13.333
 y67y    ,   , 14:13:58, 14:15:01,  0.018,  17.143
 z88h    ,   , 14:14:20, 14:15:04,  0.012,  24.545
 2zfa    ,   , 14:15:52, 14:16:29,  0.010,  29.189
 h78y    ,   , 14:16:06, 14:16:44,  0.011,  28.421
 461x    ,   , 14:17:06, 14:18:10,  0.018,  16.875
 6wml    ,   , 14:19:08, 14:19:53,  0.013,  24.000
 v40t    ,   , 14:20:26, 14:21:11,  0.013,  24.000
 s49p    ,   , 14:21:27, 14:22:37,  0.019,  15.429
```

Figure B-5. Example Output Text File from TTMATCH