# Detection Technology for IVHS

# Volume I: Final Report

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# Detection Technology for IVHS

## Volume I: Final Report

Research and Development
Turner-Fairbank Highway Research Center
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McLean, Virginia 22101-2296

# FOREWORD

This report presents the results of a comprehensive study to measure the laboratory and field performance of commercial vehicle detectors under different traffic conditions on freeways and surface-street arterial sites. The detectors were installed in three states having diverse climates ranging from cold winter and snow in Minneapolis, Minnesota; humidity, rain, lightning, and heat in Orlando, Florida; warm, dry weather in Phoenix and Tucson, Arizona; and hot summer temperatures with thunderstorms in Phoenix. IVHS traffic parameter specification were developed for interconnected intersection control, isolated intersection control, freeway incident detection, traffic data collection, real time adaptive control and vehicle-roadway communications. This report assesses the best performing detector technologies by application.

Sufficient copies of the report are being distributed to provide a minimum of two copies to each FHWA regional and division office, and five copies to each State highway agency. Direct distribution is being made to division offices.

A. George Ostensen

A. George Ostensen, Director
Office of Safety and Traffic Operations
Research and Development

# NOTICE

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16. Abstract

This project identified traffic parameters and their required accuracies for characterizing traffic flow in conventional and newer intelligent transportation systems (ITS), obtained state-of-the-art detectors and installed and evaluated them in three states having diverse climates, and studied the need and feasibility of establishing a national detector evaluation facility. Task A was devoted to identifying traffic parameters and accuracies. Task B dealt with locating surface-street and freeway test and evaluation sites in Minnesota, Florida, and Arizona. Task C developed the test plans used to evaluate the detectors at Hughes and in Los Angeles before they were evaluated in the other states. Task D explained how the detectors to be evaluated were selected and then compiled specifications about detectors currently on the market. In Task E, detector setup and operation were studied as tests were performed according to the plans of Task C. Task F developed the plans and specifications for evaluating the detectors at the surface-street and freeway sites in each of the three states. Detector mounting, power availability, data recording, ground truthing, and security were addressed. Task G consisted of setting up the test sites and collecting detector performance data. The collected data were reduced as part of Task H. In Task I, the performance of the detectors was compared to the specifications developed in Task A. Task J discussed the need and feasibility of establishing permanent detector test facilities. A consensus appears to be developing for such a facility, with several universities and agencies vying for its operation. The preparation of the final report was contained in Tasks K and L. The addendum to this final report (FHWA-RD-96-109) contains additional field test results.

This project also used pooled funds from HPR-2(|57) titled "Testing and Evaluating Traffic Detectors." The states which participated are Colorado, Florida, Iowa, Maryland, Minnesota, Missouri, Nebraska, New York, Oklahoma, Oregon, Virginia, and Wisconsin.

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Detection Technology, Detectors, Sensors, ITS, Microwave, Infrared, Video Image Processing, Ultrasound, Inductive Loops, Magnetometers, Presence, Speed, Occupancy

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## ACKNOWLEDGMENTS

Many people and organizations contributed to the success of this project. We feel fortunate to have had the generous support and expertise from several city and state departments of transportation. The Minnesota Department of Transportation (DOT) was instrumental in getting the project started correctly by supplying not only cables, equipment mounting racks, and power supplies, but indispensable knowledge of how to label, wire, and keep track of the, hundreds of wires required to send power to the detectors and transmit information from them to the data logger. We followed the plans they developed at all of the test locations. The City of Minneapolis was a warm host to us as well during the Winter of 1993. They cut loops in their streets, cored holes for our magnetometers, and provided us with a test site not far from the best rib joint we found during the project. Our contacts and support in Minnesota were through Jim Wright, Ping Yi, Dave Long, and Tim Bangsund.

The Florida DOT helped us set up a unique test site along the I-4 corridor into Orlando where the same data acquisition trailer location was used for freeway and surface arterial detector evaluation. We simply moved the detectors from the freeway below to the overpass above when we were ready to switch highway types. In addition to the usual cutting of loops and coring for magnetometers, they designed a chain-link fence protective screen to shield our detectors from inquisitive onlookers. They also provided an out-of-the-ordinary technique for mounting the self-powered magnetometers under the overpass so that the vehicles above could be counted. Our Florida coordination was through George Gilhooley and Jon Cheney, with support from Steve Hull, Don Carmer, Mark Candella, and Larry Gross.

With the aid of the Arizona DOT, we selected a test site on the west side of the I-10 freeway in downtown Phoenix. We didn't use the pipe tree to support the overhead detectors at this site, but instead mounted them directly on the sign-bridge structure that spanned the westbound lanes. The cat-like ability and the fearlessness of the DOT personnel were greatly appreciated during this adventure. The Arizona DOT personnel who supported the project were Dan Powell, Sarath Joshua, Jim Shea, Larry Cummings, Andy Murray, and Sam Stubbs.

Not to be out done, the City of Tucson Department of Transportation provided a test location across the street from the largest shopping mall in the area. Only at this site did we bury our cable run from the signal mast arm and pole to the data acquisition trailer. After warding off prairie dogs and water from a spring storm, we got the detectors operating. Once more, the technicians made available to the project by the city were outstanding in their willingness and ability to aid us in mounting and diagnosing any problems with the detectors. Our appreciation is extended to Dennis Sheppard, Ray Svec, John Swanson, and Edwin Daugherty for arranging for the support of the city and assisting us in connecting and aiming the detectors.

The research division at FHWA provided an ideal technical representative. The project would not have been as successful without his many thought-provoking comments and suggestions and his general support. The efforts of the contracting officer to keep the proverbial checks in the mail were certainly appreciated. We are also indebted to the FHWA Program Manager for establishing the need for a project of this type and for his continued support throughout its many phases.

Don Savitt of Hughes Aircraft Company had the foresight to develop the strategy that led to the winning of this contract. With the assistance of JHK and Associates, we were able to develop a team that understood the need for acquiring accurate traffic parameter data and could develop methods for acquiring them. Many people at JHK helped develop one of the major outputs of the project, the Task A Report Development of IVHS Traffic Parameter Specifications. In particular, Scott MacCalden, Jr. and Craig Gardner provided the insights that are incorporated in the document.

Rick Anderson of Hughes and Steven Birch of Iron Mountain Systems designed the hardware and software used in the data logger to acquire and convert the detector output data into a user-friendly database format. Their expertise was instrumental in being able to simultaneously record and time-tag data from the approximately 20 detectors that represented the technologies under evaluation.

There is one more person to whom the project owes a great debt, Michael Kelley. As a key participant in the installation, data acquisition, and data analysis tasks, his contributions are priceless. He displayed his enthusiasm by spending long weeks and days in the field, getting up before sunrise and retiring after dark to make sure that the necessary data were recorded. With the encouragement of the Principal Investigator, he helped seek out the best ribs in each city we visited.

Lawrence A. Klein
Principal Investigator

# PREFACE

The *Detection Technology for IVHS* project, under Federal Highway Administration Contract DTFH61 -91 -C-00076, began in September 1991 and continued through April 1995. In the first part of the project, parameters used in characterizing traffic flow for conventional traffic control systems and for newer Intelligent Vehicle-Highway Systems (IVHS) applications were identified. IVHS applications may place higher accuracy requirements on traffic parameters measured by detectors and may also require the acquisition of traffic data not normally output by the more conventional detectors. The traffic parameter data accuracies developed for IVHS applications are based on available operational test data, traffic control algorithms, and performance prediction analyses. Even though an extensive effort was made to acquire traffic data accuracy requirements, there was not a great deal of this information available. We expect that the accuracies given in this report will be updated as new control algorithms and information continue to be developed.

Detector manufacturers were contacted to determine if they would make their devices available to the program. A cross section of detectors that represented different technologies were obtained, including inductive loop with conventional and high sampling rate detector amplifiers, magnetometers with relatively small detection zones, magnetometer arrays with large multilane detection zones, microwave radar, laser radar, ultrasound, acoustic microphone arrays, passive infrared, imaging infrared, and video image processing.

In the next part of the project, laboratory test plans were developed and tests were conducted for detectors that would eventually be exposed to diverse environmental and traffic conditions during the field tests. The laboratory tests demonstrated the operation and capabilities of the detectors and their limitations. These tests were performed at Hughes Aircraft Company facilities in Fullerton, CA and by the City of Los Angeles Department of Transportation on Exposition Boulevard in Los Angeles.

Once the laboratory tests were completed, the detectors were installed in three states having diverse climates that ranged from cold winter and snow in Minneapolis: humidity, rain, lightning, and heat in Orlando; warm, dry weather in Phoenix and Tucson: and hot summer temperatures with thunderstorms in Phoenix. A freeway and a surface-street arterial site were used sequentially in each state. The tests were conducted according to a test plan that described the mounting of the detectors, their power requirements, test patterns, data acquisition and reduction, ground truth procedures, and security at the test sites.

The recorded data were processed using application-specific software designed for each detector. This resulted in a database being created that contained the normal outputs from the detector when a vehicle passed through its field of view, the time of the event, videotape index number, and air temperature and wind speed and direction. By using the video index number, a specific event can be accessed and reviewed on a computer-controlled video recorder.

The feasibility of establishing a national detector evaluation facility was also studied. Letters were sent to the detector manufacturers and several universities soliciting their inputs and thoughts about such a center.

# METRIC/ENGLISH CONVERSION FACTORS

## ENGLISH TO METRIC

### LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

### AREA (APPROXIMATE)

1 square inch (sq in, in$^{2}$ = 6.5 square centimeters (cm$^{2}$)
1 square foot (sq ft, ft$^{2}$ = 0.09 square meter (m$^{2}$)
1 square yard (sq yd, yd$^{2}$) = 0.8 square meter (m$^{2}$)
1 square mile (sq mi, mi$^{2}$) = 2.6 square kilometers (km$^{2}$)
1 acre = 0.4 hectares (he) = 4,000 square meters (m$^{2}$)

### MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (Lb) = 0.9 tonne (t)

### VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft$^{3}$) = 0.03 cubic meter (m$^{3}$)
1 cubic yard (cu yd, yd$^{3}$) = 0.76 cubic meter (m$^{3}$)

### TEMPERATURE (EXACT)

[(x-32)(5/9)] $^{o}$F = y $^{o}$C

## METRIC TO ENGLISH

### LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

### AREA (APPROXIMATE)

1 square centimeter (cm$^{2}$) = 0.16 square inch (sq in, in$^{2}$)
1 square meter (m$^{2}$) = 1.2 square yards (sq yd, yd$^{2}$)
1 square kilometer (km$^{2}$) = 0.4 square mile (sq mi, mi$^{2}$)
1 hectare (he) = 10,000 square meters (m$^{2}$) = 2.5 acres

### MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

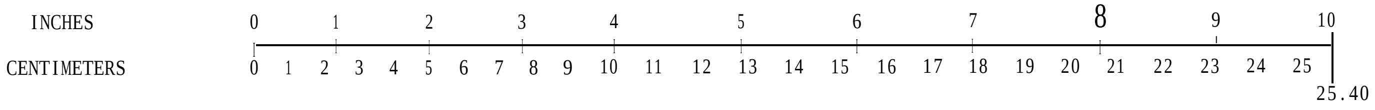
### VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m$^{3}$) = 36 cubic feet (cu ft, ft$^{3}$)
1 cubic meter (m$^{3}$) = 1.3 cubic yards (cu yd, yd$^{3}$)

### TEMPERATURE (EXACT)

[(9/5) y + 32] $^{o}$C = x $^{o}$F

## QUICK INCH-CENTIMETER LENGTH CONVERSION



## QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

| $^{o}$F | -40° | -22$^{0}$ | -4° | 14° | 32° | 50° | 68° | 86° | 104° | 122° | 140° | 158° | 176° | 194° | 212° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | -40° | -30° | -20° | -10° | 0° | 10° | 20° | 30° | 40° | 50° | 60° | 70° | 80° | 90° | 100° |

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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# 1. SCOPE OF THE PROGRAM

## 1.1 INTRODUCTION

Maximizing the efficiency and capacity of the existing transportation network is made necessary by the continued increase in traffic volume and the limited construction of new highway facilities in urban, intercity, and rural areas. Smart 'street systems that contain traffic monitoring detectors, real-time adaptive signal control systems, and motorist communications media are being combined with freeway and highway surveillance and control systems to create smart corridors that increase the effectiveness of the ground transportation network. The infrastructure improvements and new technologies are, in turn, being married to smart cars to form Intelligent Vehicle-Highway Systems (IVHS). Since the inception of this contract, Intelligent Transportation Systems (ITS) has replaced IVHS to represent the marriage of smart vehicles with smart infrastructure systems. As IVHS is included in the contract title, it is retained in this report.

Vehicle detectors are an integral part of nearly every modern traffic control system. Moreover, detectors and communications media will be major elements in future traffic monitoring systems. The types of traffic flow data, their reliability, consistency, accuracy, and precision and detector response time are some of the critical parameters to be evaluated when choosing a vehicle detector. These attributes become even more important as the number of detectors proliferate and the real-time control aspects of IVHS put a premium on both the quantity and quality of traffic flow data used in traffic surveillance and control algorithms.

Current vehicle detection is based predominantly on inductive loop detectors installed in the roadway subsurface. When properly installed and maintained, they can provide real-time data and a historical database against which to compare and evaluate more advanced detector systems. Alternative detector technologies being developed provide direct measurement of a wider variety of traffic parameters, such as density, travel time, vehicle path, volume, and speed. These advanced detectors provide more accurate data; parameters that are not directly measured with previous instruments; inputs to area-wide surveillance and control of signalized intersections and freeways; and support of motorist information services. Furthermore, many of the advanced detector systems can be installed and maintained without disrupting traffic flow.

## 1.2 PURPOSE OF THE PROJECT

The objectives of the Federal Highway Administration (FHWA)-sponsored Detection Technology for *IVHS* project are to:

- Determine the traffic parameters and their corresponding accuracy specifications needed for future IVHS applications;
- Perform laboratory and field tests with detectors that apply technologies compatible with above-the-road, surface, and subsurface mounting to determine the ability of state-of-the-art detectors to measure traffic parameters with acceptable accuracy, precision, and repeatability;
- Determine the need and feasibility of establishing permanent vehicle detector test facilities.

In performing the technology evaluations and in analyzing the data, focus was placed on the underlying technology upon which the detectors were based. It was not the purpose of the program to determine which specific detectors met a set of requirements, but rather whether the sensing technology they used had merit in measuring and reporting traffic data to the accuracy needed for present and future applications. Obviously, there can be many implementations of a technology, some of which may be better exploited than others at any time. Thus, a technology may show promise for future applications, but the state-of-the-art of current hardware or software may be hampering its present deployment.

The project consisted of 12 major tasks:

Task A. Develop a working paper that defines IVHS traffic parameter specifications for the following application areas:

- Interconnected Intersection Control,
- Isolated Intersection Control,
- Freeway incident Detection,
- Traffic Data Collection,
- Real-Time Traffic Adaptive Control,
- Vehicle-Roadway Communications.

Task B. Select sites for detector field tests. Test sites in three different regions of the country will be selected to provide a range of environmental and traffic conditions broad enough to ensure the utility of the test results on a nationwide basis.

Task C. Develop vehicle detector laboratory test specifications and a laboratory test plan.

Task D. Select and obtain vehicle detectors for testing.

Task E. Conduct laboratory detector tests and generate a report describing the results.

Task F. Develop vehicle detector field test specifications and field test plan.

Task G. Install vehicle detectors at field test sites and collect detection technology evaluation data.

Task H. Generate detection technology field test results.

Task I. Determine which of the currently available vehicle detectors meet the IVHS criteria of Task A.

Task J. Determine the need and feasibility of establishing permanent vehicle detector test facilities.

Task K. Prepare a draft final report.

Task L. Prepare the final report that incorporates comments received from FHWA and others.

## 1.3 ORGANIZATION OF THE FINAL REPORT

The final report documents the planning and the conclusions of the *Detection Technology for IVHS* program that ran from September 1991 through January 1995.

Section 1 contains an introduction to the project that outlines the various tasks that were included in the program and the contents of the final report.

Section 2 summarizes Task A by including descriptions of traffic parameters needed to characterize free flow and interrupted flow on freeways and surface streets. The accuracies of the parameters for several future IVHS applications are summarized in tables at the end of the section. The accuracies represent those needed for input data to as yet undefined future algorithms and paradigms that support the selected applications. As such, they are subject to revision as the specific algorithms, strategies, and applications become better known.

Section 3 describes the field test and evaluation site locations that were visited. The information for this section is taken from the Task B Report.

Section 4 discusses the detector selection process using information in the Task D Report. On-bench photographs of each detector and manufacturer's specifications are given.

Section 5 describes the theory of operation of the detector technologies and the types of information typically available from each. These technologies include those for above-the-road mounted detectors, namely video image processing, microwave, active (transmit and receive) and passive (receive only) infrared, imaging infrared, passive acoustic arrays, and ultrasound, as well as those for conventional and newer applications of beneath-the-surface inductive loop, magnetic, and magnetometer detectors. Communications technologies, such as those used for automatic vehicle identification, are also discussed.

Section 6 reviews the Task C report by explaining the need for laboratory tests before venturing out for field tests and by describing the types of laboratory tests conducted.

Section 7 summarizes the results from the laboratory tests that were originally published in the Task E reports. These tests were conducted in the City of Los Angeles and at the Hughes Aircraft Company facility in Fullerton, CA.

Section 8 contains a summary of the Task F field test plan and procedures. Detector installation requirements are listed. The data logger hardware and software that played a major role in the data acquisition are discussed in this section and in Appendix C.

Section 9 describes the detector technology data collection and evaluation processes. Photographs and line drawings of the field sites with the installed detectors and the detector locations are shown. The data analysis process of converting the raw data files into Paradox database format is explained as are the ground truth procedures. Tabulations of the amount of data collected at each site are given.

Section 10 describes how to access the data storage media, presents the analyzed detector output data from several runs at each test site, and interprets the results. Not all the collected data have been analyzed as a part of this phase of the project. However, representative data have been plotted to show the types of results and analyses that can be performed on the extensive data set.

Section 11 compares the detector specifications for future IVHS applications developed in Section 2 with the performance of the presently available detectors. The accuracies of the detectors that were evaluated and their application to current traffic management areas are summarized. Where possible, recommendations are made as to how to improve the detector design to bridge the gap between the data and accuracy of present detectors and those needed for some specific IVHS applications.

Section 12 gives the general conclusions from the program and makes recommendations for future research.

Appendix A documents the results of Task J, determining the need and feasibility of establishing one or more permanent vehicle detector test facilities.

Appendix B lists the detector manufacturers and contact personnel that provided detectors and information during the evaluation program.

Appendix C describes the data logger hardware and software design and the formats used to record the analog, digital, and serial information output by the detectors in the technology evaluation study.

Appendix D illustrates the concepts involved in designing a continuous wave microwave radar to detect multiple vehicles in a given lane on a roadway.

Appendix E contains the pipe tree installation and intersection plan-view drawings used at the Minneapolis field sites.

Appendix F gives the azimuth and elevation ground footprints of the detectors as a function of mounting height, azimuth and elevation aperture beamwidth, and angle of incidence (with respect to nadir).

Appendix G contains the specifications for the inductive loops installed by the states that hosted the field tests.

Appendix H documents the connections made during the field tests from the detectors to the data logger and power supplies.

Appendix I contains pipe tree installation and selected construction plans for the State Route (SR 436) overpass at Interstate 4 (I-4) that describe the design of the truss for the sign bridge and the design of the SR 436 span over I-4.

# 2. TASK A SUMMARY

## DEVELOPMENT OF IVHS TRAFFIC PARAMETER SPECIFICATIONS

A working paper was developed in Task A to define traffic parameter specifications for IVHS applications that include:

- interconnected intersection control,
- Isolated intersection control,
- Freeway incident detection,
- Traffic data collection,
- Real-time traffic adaptive control, and
- Vehicle-to-roadway communications.

Traffic parameters of value in these applications are described in this section. Projected accuracies for the measurement of the traffic parameters in support of future IVHS applications such as signalized intersection control, freeway incident detection, and freeway metering are then presented.

### 2.1 TRAFFIC FLOW PARAMETERS

Vehicle flow, speed, and density parameters are fundamental to the management of highway traffic. Over a given section of open roadway, such as a freeway, they are related through equation 2-l and their values are usually expressed on a per lane basis. Hence,

$$\text{Flow (vph)} = \text{Speed (mi/h)} \times \text{Density (vpm)} \qquad (2\text{-}1)$$

where

vph = vehicles per hour per lane,
mi/h = miles per hour, and
vpm = vehicles per mile per lane.

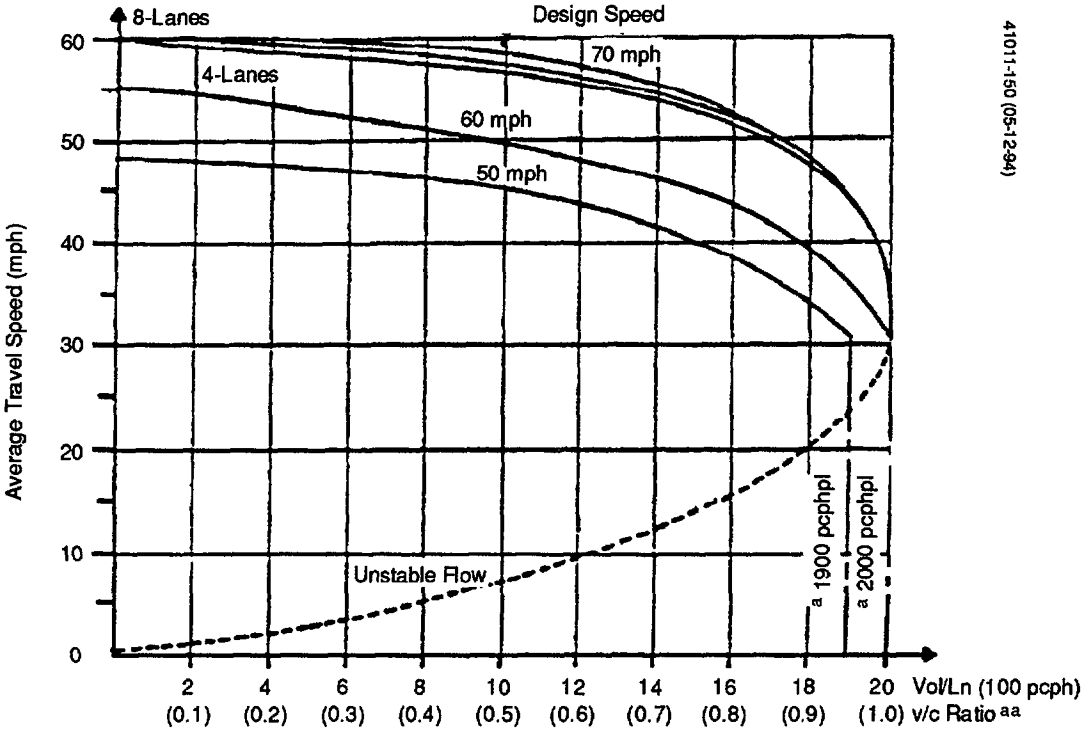
Flow or volume flow rate is the time rate of flow in vehicles per hour used to characterize traffic volume. A transition in terminology is occurring as “flow” or “flow rate” has taken the place of “ volume.“ (1) Because of the mix of old and new terminology, there is some inconsistency in the use of “volume” and “flow rate” in the literature. This can be seen in the capacity curves of Figure 2-l that illustrate the relation between speed and flow on the open roadway. Capacity is expressed as “volume/lane” in units of flow rate (passenger cars per hour). The term “flow” is also used to describe the general condition of traffic on the roadway, such as “free-flow” or “congested flaw.“ (2)

The volume flow rate data by themselves are not sufficient to define how well traffic is moving. For example, if counts show a flow rate of 1200 vehicles per hour, it is not known whether traffic is moving briskly at 55 mi/h (88.5 km/h) or is congested and creeping along at 10 mi/h (16.1 km/h).

On the other hand, by measuring density and knowing the speed-flow characteristic for a given highway type, speed-density and flow-density curves can be estimated as shown in Figures 2-2 and 2-3, respectively. When density is a performance indicator, as shown by the shape of the curve in Figure 2-2, there is no longer any ambiguity with respect to speed. If density is measured at 20 vehicles per mile per lane (32 v/km/lane), then speed is 55 mi/h (88.5 km/h). If density is 120 vehicles per mile per lane (192 v/km/lane), then speed is 10 mi/h (16.1 km/h). Likewise, Figure 2-3 shows that a flow rate of approximately 1200 vehicles per hour per lane (1920 v/h/lane) corresponds to these same density measurements of 20 and 120 vehicles per mile per lane, respectively.

### 2.2 TRAFFIC PARAMETERS FOR INTERRUPTED FLOW

Flow, speed, and density are used to characterize traffic flows on freeways and other open sections of roadway not affected by control devices such as traffic signals, stop signs, and ramp metering. When interrupted flow conditions are encountered, such as at signalized intersections, other traffic flow characteristics appear and additional



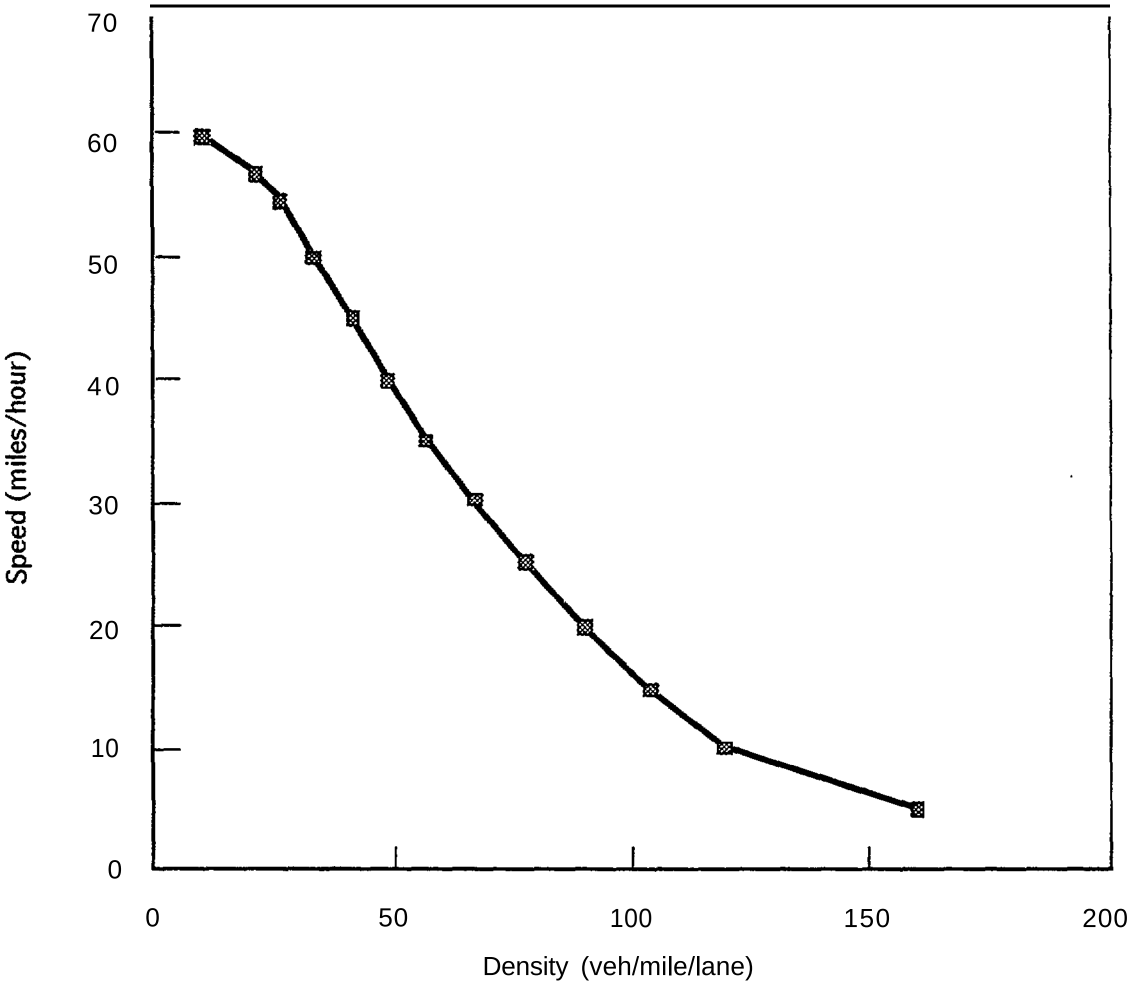
41011-150 (05-12-94)

a capacity
aa v/c ratio based on 2000 pcphpl valid only for 60 and 70 mph design speeds

Source: Highway Capacity Manual, FHWA, 1985.

1 mi/h = 1.6 km/h

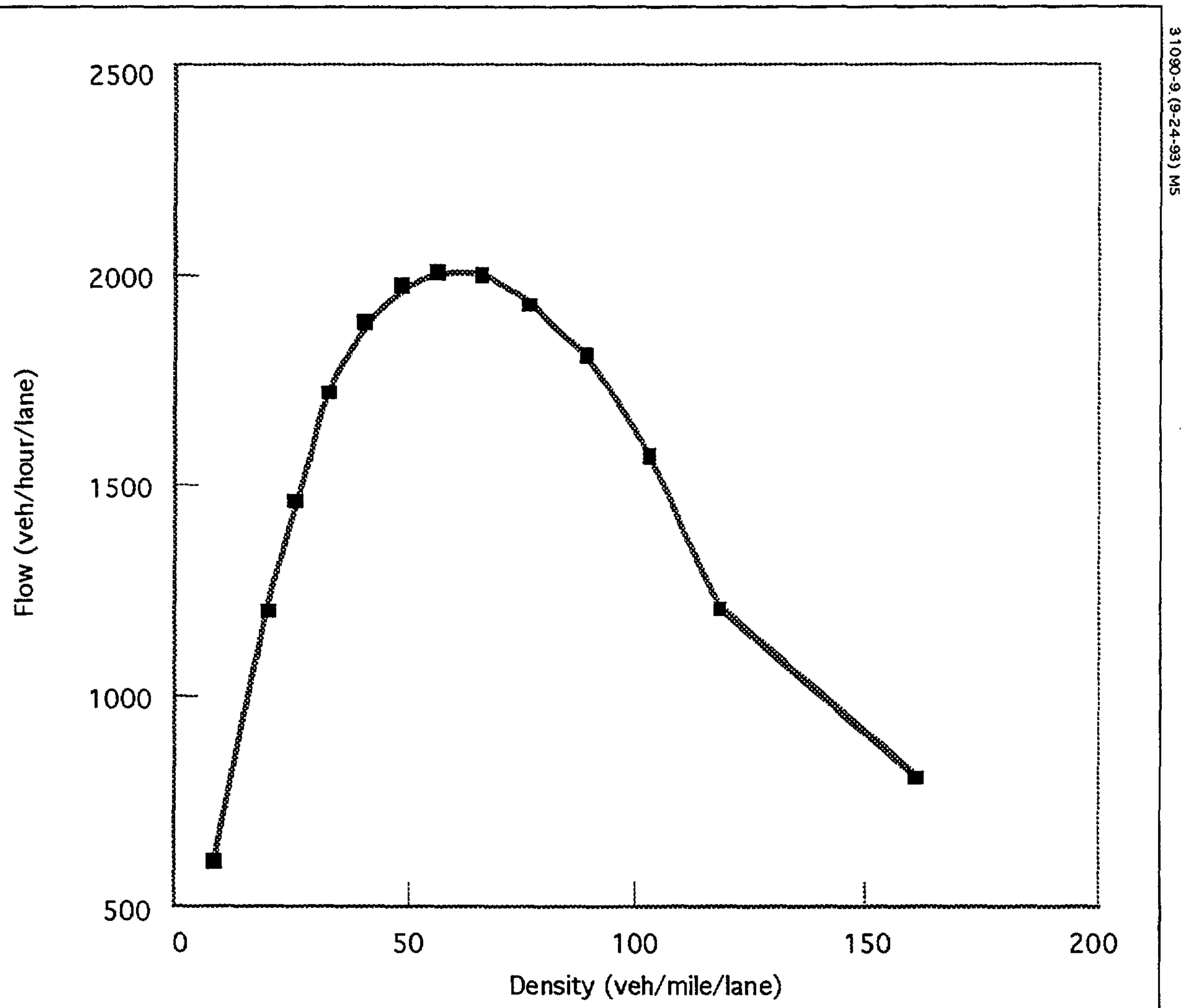
Figure 2-1. Highway Capacity Curve Showing Relation Between Speed and Flow Under Ideal Conditions



This figure was calculated using the 70 mph design speed shown in the Highway Capacity Curve of Figure 3- 1 and the application of the relation Flow = Speed x Density.

1 mi/h = 1.6 km/h

Figure 2-2. Speed-Density Curve



This figure was calculated using the 70 mph design speed shown in the Highway Capacity Curve of Figure 3-1 and the application of the relation Flow = Speed x Density.

1 mi/h = 1.6 km/h

Figure 2-3. Flow-Density Curve

measures of flow are needed. Flow, speed, and density are still required by current and future IVHS applications for efficient management of interrupted flow, but to these are added measures such as delay, stops, and turning movements.

Some of the parameters are directly measurable in real time, while others are mathematically derived or estimated from the measurable parameters. Still others must be estimated from collected historical data. A generic discussion of commonly used traffic parameters considered relevant to IVHS is presented below, although specific parameters and accuracies will be a function of the IVHS application and the detector technology deployed.

## 2.3 TRAFFIC PARAMETER DEFINITIONS

Parameters that characterize traffic flow can be classified in terms of one of the following:

- Quantify Measures: How much or at what rate is traffic moving or waiting to move?;
- Quality Assessment Measures: How well is traffic moving?;
- Movement Measures: Where is traffic coming from and going to?; and
- *Composition/Classification Measures:* What kind of traffic is moving?

Parameters which fall into each of the above categories are discussed below.

### 2.3.1 Quantity Measures

Traffic quantity measures include volume, demand, time headways, and throughput.

### *2.3.1.1 Volume*

Volume data are generally expressed in terms of flow rate. Flow rate is a temporal quantity measure defined as the number of vehicles passing a point in a given period of time, usually 1 hour. Flow rate 9 is the inverse of the average of the time headways measured over the same period such that

$$q = \frac{3600}{h} \qquad (2\text{-}2)$$

where

$q$ = hourly flow rate (vehicles per hour),

$h$ = average time headway (seconds per vehicle), and

3600 = number of seconds per hour.

Flow rates, both measured and forecasted, have many applications in traffic engineering, including developing traffic trends, analyzing accident data, determining sites for traffic signals, estimating future toll revenues, developing design requirements for new or reconstructed highways, and investigating operational improvements using capacity analysis.

On most facilities, traffic flow rates vary throughout the day and by direction. Figure 2-4 depicts these variations on the San Francisco-Oakland Bay Bridge, a 1 O-lane urban highway without shoulders. In addition, highways exhibit monthly variations in traffic flow rates that are dependent on the highway type and location. These variations are a function of urban versus rural facilities and recreational versus nonrecreational facilities, for example.

Traffic flow measurements can have different interpretations depending upon the conditions upstream and downstream of the measurement site, as well as at the detector locations. For example, if there is no congestion at the site (or upstream of it) to limit the arrival rate of the vehicles being measured, then the flow rate is equal to the existing demand. If, on the other hand, queuing exists at the site, then the measured flow rate reflects the downstream bottleneck capacity.

### *2.3.7.2 Demand*

Demand is “the amount of traffic volume (or flow rate) that occurs on a facility under some given set of travel conditions.” When not constrained by a highway’s capacity, the actual flow rate measured on the highway will equal its demand. However, in cases where highway demand exceeds capacity, some queuing will occur and actual **measured flow** rates will be less than the demand.

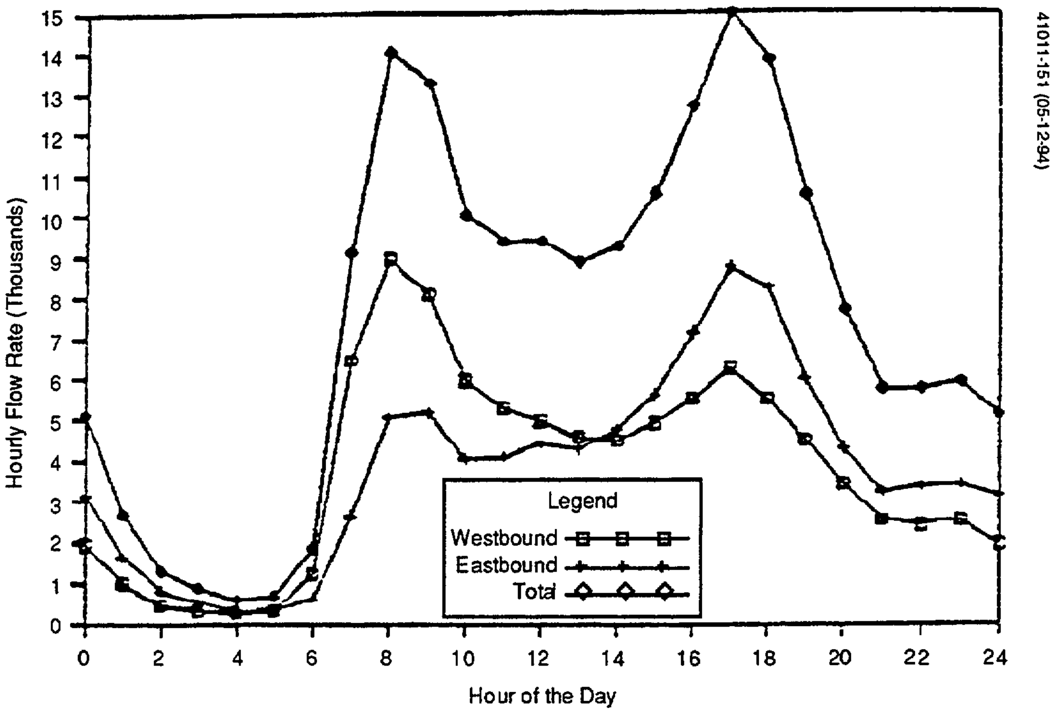


Figure 2-4. Hourly Traffic Flow on the San Francisco-Oakland Bay Bridge

Many IVHS applications make a distinction between volume and demand values. For optimal decision making, traffic control and traffic advisory subsystems often need the anticipated traffic demand for a given road at a future time (not just its current volume). For example, when advising motorists to use an alternate route around a freeway incident, an estimate of the expected demand for the alternate route is needed.

Unfortunately, demand values are difficult to obtain directly. If congestion is present either upstream of the diversion point on the freeway or on the alternate route, then measured flow rates may understate potential demand. Furthermore, the demand for a particular alternate route will vary over time and with the actual number of motorists being diverted. To predict the consequences of a routing decision, estimates for demand on the alternate route segments are projected for the future time when diverted motorists will encounter these demands along their route. Current and historic flow rate data and diversion percentage estimates are key inputs for such projections. In addition to projecting future flow rates, on-line traffic assignment techniques are used to estimate traffic demand on alternate routes.

#### *2.3.1.3 Time Headway*

Time headway between vehicles is defined as: "the elapsed time between the passage of an identical observation point by consecutive vehicles in the traffic stream." Time headway measurement can be performed manually with a stopwatch and automatically with any presence-type detector or with video image processors. Since the average of vehicle time headways past a point over some time interval is the reciprocal of the flow rate past that point, time headways present microscopic measures of flow past a point. Time headways are also frequently used as a quantitative measure of service or productivity at traffic signals and toll collection stations, that is, as a service headway expressed in terms of average number of seconds per vehicle.

The space-time diagram of Figure 2-5 shows the paths of several vehicles as they pass an observation point and the two components that make up time headway. The first component is the time it takes the vehicle to pass the observation point, or occupancy time. The second component is the time between the rear of one vehicle and the leading edge of the next, or gap time.

Highway capacity depends primarily on the gap times that individual drivers are comfortable with on the particular highway. Opportunities for passing, merging, or crossing are also determined by gaps provided by the appropriate time headway distributions. Two measures of the level of service closely associated with time headways are the percentage of time one vehicle is forced to follow another on two-lane highways and the frequency of speed adjustments that a driver makes to maintain a minimum headway.

#### *2.3.7.4 Throughput*

Throughput is defined as: "the vehicle-miles of travel carried by a given length of roadway for a given period of time." It is determined by measuring flow rates for each section of highway between points of entry or egress. It is often used to characterize the efficiency of a highway facility and to evaluate the "before-and-after" effects of operational improvements. Appropriate comparisons are obtained by calculating the throughput for each travel direction and for comparable times of day.

### 2.3.2 Quality Assessment Measures

Quality measures determine how well traffic is flowing on a given roadway. They include speed, density, delay, and stops.

#### *2.3.2.1 Speed*

Speed is one of the three macroscopic traffic flow measures, the others being volume and occupancy. Speed expresses the rate at which traffic is moving and, therefore, is a natural measure of the quality of the flow. Three types of speed measurements are described below: spot speed, time mean speed, and space mean speed.

Spot ***speed*** is defined as: "the speed of an individual vehicle as it passes an observation point of the traffic stream." As spot speeds are instantaneous speeds of individual

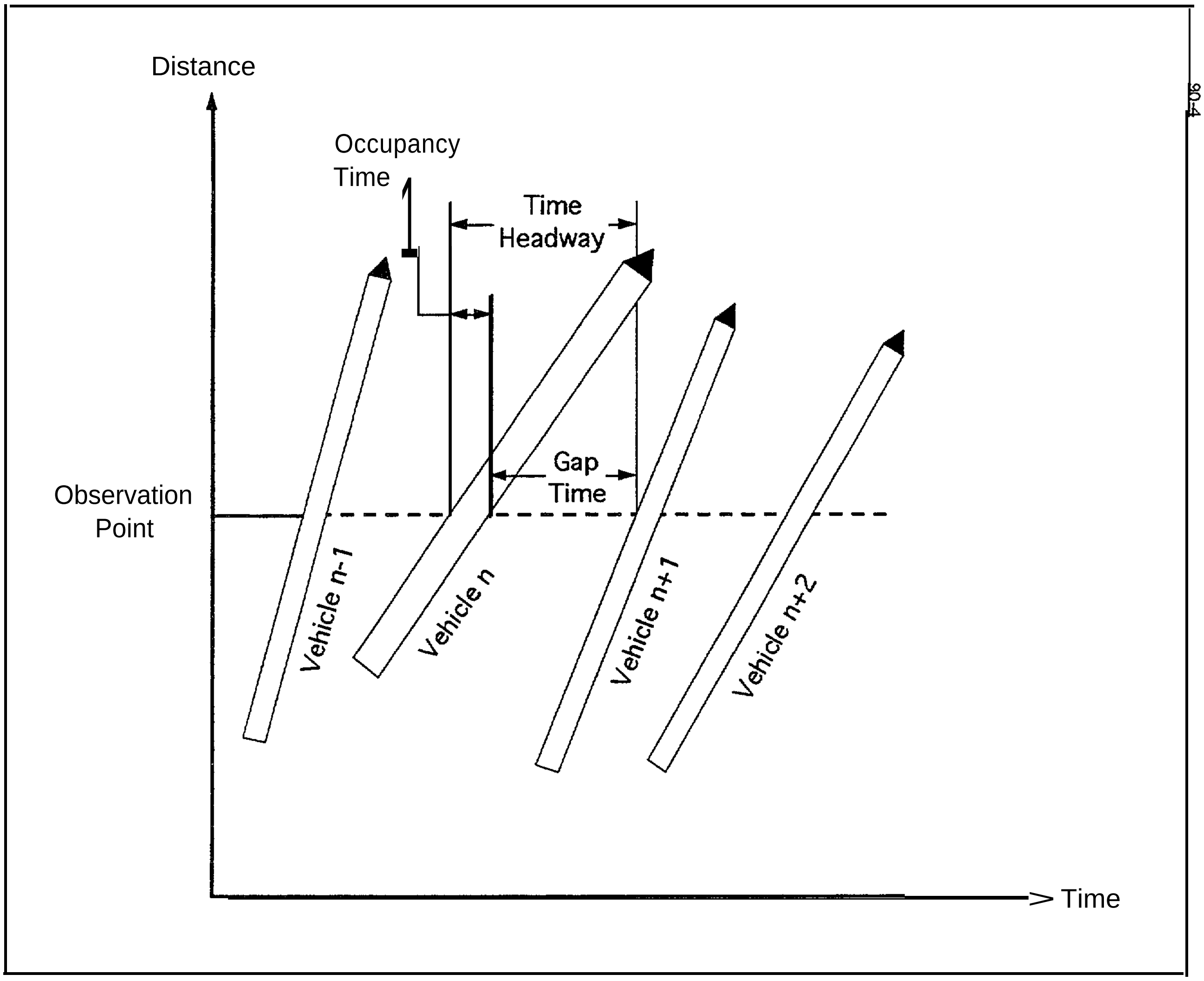


Figure 2-5. Time Headways of Consecutive Vehicles

vehicles, they can be determined from the slope of the vehicle traces on a space-time diagram such as Figure 2-5. Speed can be measured in several practical ways. First, using a speed trap station, a pair of detectors is placed on a length of roadway. Speed is calculated from the time it takes vehicles to transverse the distance between the start of the detection zones of the two detectors. Measurement accuracy depends on the distance between the detectors, the average speed of the traffic, and the detector sampling rate. Detectors used for this application include pneumatic tubes, piezoelectric strips, inductive loops, infrared, video image processors, and any other type of presence detector.

A second method for measuring spot speed is with a single-loop detector and an assumed average vehicle length. This approximate technique is employed by the Urban Traffic Control System (UTCS) to compute average speed S as

$$S = \frac{0.6818\ VC\ (LL+VL)}{0} \qquad (2\text{-}3)$$

where

S = speed in mi/h,

0.6818 = constant to convert from ft/s to mi/h,

vc = vehicle count during the time period,

**LL** = loop length in ft,

**VL** = vehicle length in ft, and

**0** = seconds of loop occupancy during the time period.

With current Inductive Loop Detector (ILD) technology, speed estimates from a single loop vary from the true value by as much as 30 percent. To obtain even these relatively crude measurements, volume, vehicle length, and occupancy must be known to within an error rate no greater than ± 10 percent. Of these, vehicle length is the most difficult to estimate accurately due to variations in the real-time vehicle mix. Its value is typically based on historical data.

Other techniques for spot speed measurement exist. Imagery from video cameras measures spot speeds based on vehicle movement across a calibrated distance in the field of view. Radar technologies, such as laser radar that transmits multiple beams and microwave radar that divides its field of view into multiple zones, determine spot speed by measuring the time it takes a vehicle to move between the beams or zones. Detector technologies such as ultrasound and Doppler microwave exploit the Doppler shift in the received signal to measure spot speed.

***Time mean speed*** is defined as: “the arithmetic mean of individual spot speeds that are recorded for vehicles passing an observation point over a selected time period.” An adequately sized sample of spot speeds is needed to ensure that the time mean speed approximates the population mean to within the desired accuracy.

***Space mean speed*** is defined as: “the harmonic mean of individual speeds which are recorded for vehicles passing an observation point over a selected time period.” The harmonic mean is calculated by converting the individual spot speeds to individual travel time rates, then calculating the average travel time rate, and finally inverting the average travel time rate to obtain an average speed.

The relationship between time mean speed and space mean speed is given by

$$\text{Time Mean Speed} = \text{Space Mean Speed} + \frac{\text{Variance of Space Speed}}{\text{Space Mean Speed}} \qquad (2\text{-}4)$$

Space mean speed can also be calculated from sample travel times gathered over a known length of highway and computing the inverse of an average travel time rate (in units of time divided by units of distance). Travel times can be obtained by matching license plates or some other distinctive vehicle feature, using image processing for example, or with floating cars used as probes. In the future, vehicles equipped with automatic vehicle identification (AVI) transponders will be another source of these data.

### *2.3.2.2 Density Characteristics*

Density, or the density rate, is a spatial measure that describes the quantity of vehicles occupying a section of roadway. The 1985 Highway Capacity Manual bases its freeway level-of-service descriptions on density rather than speed because, as previously noted, there is a wide range of flow rates where speed is relatively constant.(3) Moreover, the freedom to maneuver and the proximity to other vehicles are equally important factors that are directly related to density. Common density-related measures include density rate, occupancy, and distance headway.

***Density*** is defined as: "the number of vehicles occupying a given amount of roadway space (generally a lane-mile)." While density is a fundamental measure of traffic flow, its use in freeway traffic assessment and control has been limited due to the difficulty in obtaining and analyzing the required data. Until recently, the only way to directly measure density rates was through photographs taken from a high vantage point (usually aerial photography). The vehicles in a given section of roadway were then manually counted from the photograph image. Density can also be estimated from speed and flow measurements or from percent occupancy measurements. With the development of imaging techniques, density data may be obtained automatically for real-time application to IVHS.

***Occupancy*** is defined as: "the percent of time the detection zone of a detector is occupied by some vehicle." Occupancy and density are spatial parameters and their values are related. Both occupancy and density depend on the length of the vehicles in the traffic stream and the spacing between the vehicles.

***Distance headway*** between vehicles is defined as: "the distance between identical points on consecutive vehicles in single file." Distance headways can be thought of as a microscopic view of density. The space-time diagram of Figure 2-6 shows the distance headway components and the location of the vehicles on the highway. As with time headways, distance headways have two parts: the actual length of the vehicle and the gap distance between vehicles. Distance headways and their statistical distributions are used for developing car-following models and for investigating the stability of traffic flow.

### 2.3.2.3 *Delay Measures*

Delay measures are used for freeways and signalized intersections to evaluate the benefits of operational improvements and to estimate cost-effectiveness.

***Freeway delay*** occurs when travel speeds are less than some arbitrary "free-flow" threshold, usually 35 or 45 mi/h (56.3 or 72.4 km/h). The delay is measured in terms of flow rate and travel time in excess of the free-flow value. Delay is expressed in vehicle-hours (or person-hours).

Speed and travel time data were historically recorded on "tachograph" charts by equipment installed in floating car vehicles and were reduced manually. Newer methods record and store the data in electronic form, allowing them to be downloaded into a personal computer for easier analysis. For example, a surveillance system containing speed and traffic flow detectors spaced at 1/3-mi (1800-ft [548.6-m]) increments or less, depending on the desired accuracy of the delay estimate, can be used to construct speed profiles. With computer assistance, vehicle hours of delay can be calculated from the profiles without deploying floating vehicles. The automatic data collection approach also makes it easier to gather data samples at more frequent time intervals during a day or on more days during a week.

***Intersection delay*** can be characterized by stopped delay, time in queue delay, and approach delay. Figure 2-7 depicts the time-space trace of a vehicle that comes to a stop several times on the same signalized intersection approach. This trace might occur at a congested location during peak volumes when a queue of stopped vehicles is not completely discharged during one green phase. It also represents a situation where there is considerable compression of the queue during a red phase, or where a lane is carrying both through and left-turn movements, or stop and-go conditions exist.

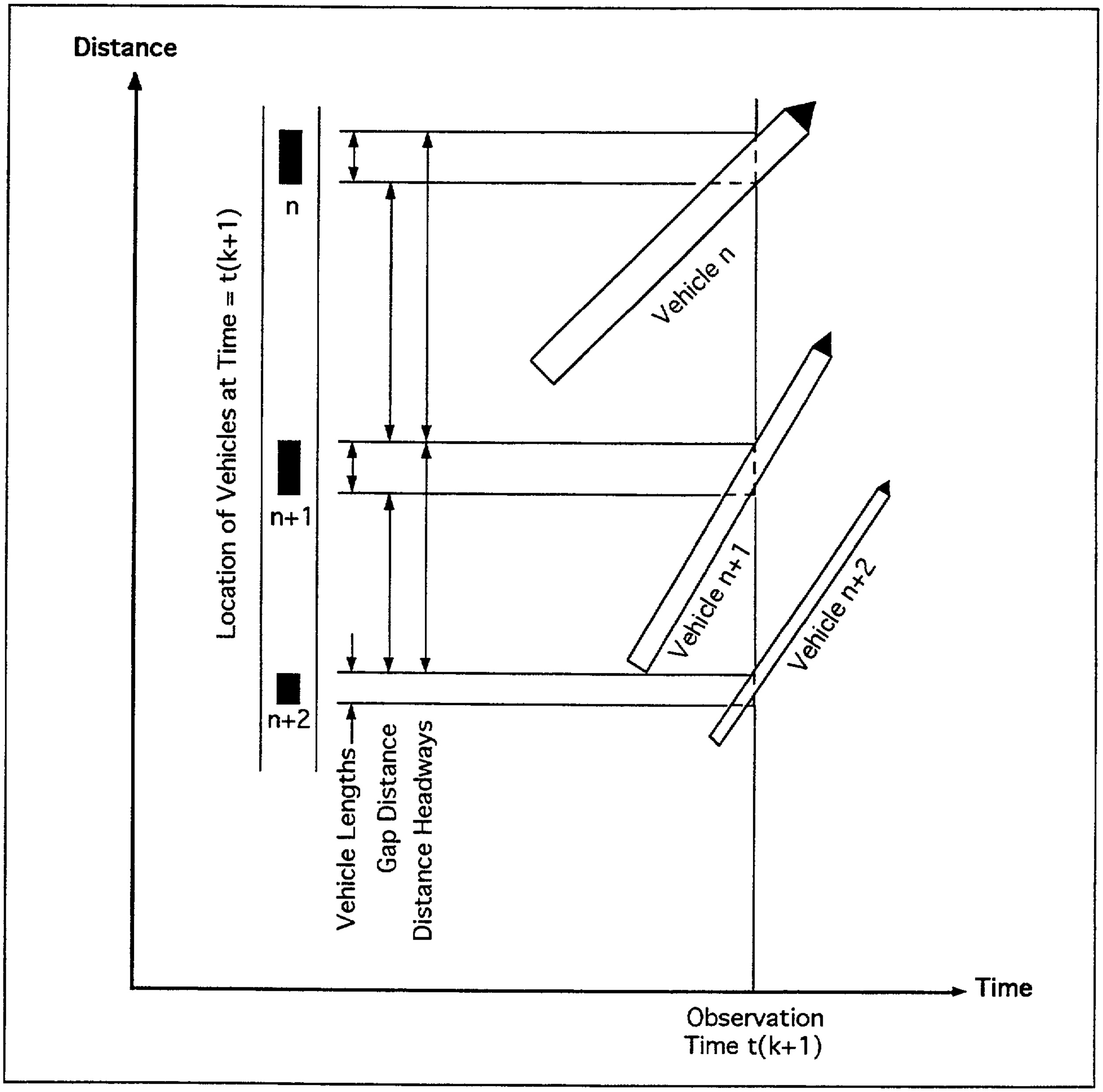
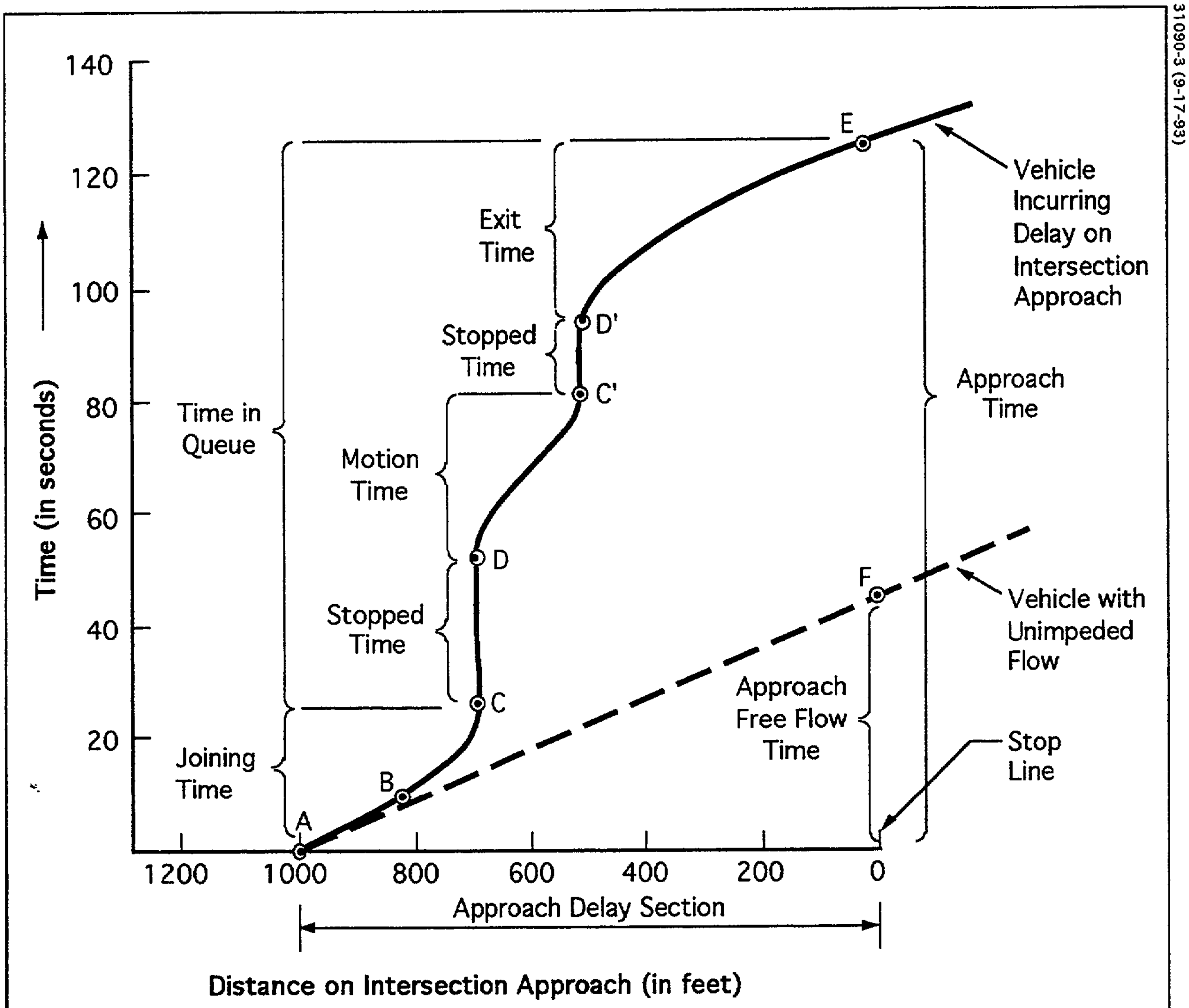


**Figure 2-6. Distance Headways of Consecutive Vehicles at a Particular Time**



Source: W.R. Reilly et al., "A Technique for Measurement of Delay at Intersections," FHWA-RD-76-135, -136, -137, 1976

1 ft = 0.305 m

Figure 2-7. Time-Space Relationship for Vehicle with Multiple Stops

- Stopped Delay: The sum of the stopped times, shown in Figure 2-7, equals the total stopped delay. Stopped delay, an obvious measure of traffic to the motorist, is also important when evaluating environmental impacts such as vehicle emissions. Comparisons of stopped delay between intersections may be misleading when one intersection is operating under conditions where the time of stop is short, but low speed movement in a long sluggish queue follows the stop. An associated parameter, percent of vehicles stopping, while not strictly a delay measure, is a useful statistic, particularly in evaluating both fuel consumption and emissions. It is defined as the number of vehicles that stop at least once, divided by the total number of vehicles using the approach, and is expressed as a percent.

- Time in Queue Delay: The time in queue is the sum of stopped time, motion time, and exit time as shown in Figure 2-7. It is equivalent to the total approach time minus the joining time. The time in queue delay is set equal to the time in queue, even though some progress is being made through the intersection during this time.

  Time in queue delay often falls between stopped delay and approach delay. Time in queue delay can also be greater than approach delay because approach delay is equal to the difference between the actual time on the approach and the free-flow time of an unimpeded vehicle over the same distance.

- Approach Delay: The approach time is the total time required to traverse the approach section under study. The approach delay is equal to the approach time less the time required for an unimpeded vehicle to travel through the same section under free-flow conditions. Approach delay can be used directly in the analysis of road-user time costs. This measure also compares the efficiency of intersections having different modes of control, such as stop or yield signs and pretimed or vehicle-actuated traffic signals.

***Delay data collection techniques*** have been primarily manual. However, the advent of area-wide traffic control and system-collected detector and signal status data have increased the information available for estimating delay at signalized intersections. Data collection techniques include point sample, input-output, and path trace.

The point sample method periodically samples the intersection approach to record the number of stopped vehicles at equally spaced time intervals. It determines the average number of stopped vehicles, calculates the total stopped time by multiplying the average number of stopped vehicles by the duration of the sample interval, and then calculates the average stopped delay by dividing the total stopped time by the number of vehicles passing the study section. It is analogous to taking a series of snapshots at regular intervals.

The input-output method samples data during intervals, rather than between intervals. It addresses the flow rates at the upstream and downstream boundaries of the approach area. The SCOOT adaptive traffic control system and the UTCS-enhanced area-wide traffic control system use the input-output technique.

The vehicle path trace method is essentially the same as the two other data collection techniques. Sample data are obtained by either running test vehicles through the approach area, measuring the various passage times of selected sample vehicles, or obtaining trace data from detector imaging techniques.

### 2.3.2.4 Intersection Stops

Intersection stops characterize the quality of traffic flow at signalized intersections. Stops are normally expressed as total stops or percent stops. Total stops are defined as the number of stops made by vehicles approaching an intersection. Percent stops is the percent of approaching vehicles making at least one stop. Both measures can be collected manually, although some traffic signal control systems estimate them using real-time flow data in combination with signal display status.

### 2.3.3 Movement Measures

Movement measures are based on data that describe the movement of vehicles in terms of the path they follow. The travel path may comprise an entire trip, as when origin-destination data are collected, or it may occur within a small area, as when intersection turning movements are studied.

#### *2.3.3.1 Origin-Destination* Data

Origin-destination (O-D) data help to specify traffic flow volumes between established geographic zones or points of origin and destination. Hence the data are useful in evaluating traffic operations strategies and in making control decisions. In the past, the data have been difficult to obtain as expensive manual methods were needed to gather information from license plate surveys or traveler interviews. In the future, two-way communications between the vehicle and the operations center, such as with automatic vehicle location technology, may allow O-D data to be collected and acted upon in real time. In-vehicle navigation equipment may also be useful for some of the latter applications.

#### *2.3.3.2 Turning Movements*

Turning movement data define the volume or percent of traffic turning left, right, or traveling straight through an intersection approach. Today, most turning movements are collected manually using either a counter board or a notebook computer. Left and right turn and through movements at each intersection are typically counted separately for each approach and for each signal phase on that approach.

Detector imaging techniques are being developed to permit automatic recording of intersection turning movements. This will allow data to be collected over many more days than is presently feasible, and may result in more accurate data than with the manual method. Potentially, the resulting real-time data can significantly enhance the value of on-line control algorithms.

### 2.3.4 Composition and Classification **Measures**

Many traffic management strategies, including those for IVHS, require the identification of individual vehicles and their length, weight, or cargo specifications as an input to a vehicle classification process. These strategies include assessing fares for automatic toll collection, as well as law enforcement actions related to stolen vehicles, high-occupancy vehicle (HOV) violations, and peak period travel restrictions in central business districts. They are also used to improve commercial vehicle operations through automatic identification, weigh-in-motion, and hazardous material tracking.

Because of requirements to provide a broad spectrum of vehicle data, classification data can best be obtained through automatic vehicle identification and vehicle-to-roadside communications. However, until these technologies are more universally deployed, other means of vehicle detection and data gathering will continue to be used. Three types of vehicle classification categories are currently employed: function, configuration, and weight.

#### *2.3.4.7 Functional Classification Data*

Vehicles are frequently classified according to their function, such as passenger cars, vans, trucks, and buses. Some inductive loops, coupled with specially adapted digital detectors, can distinguish among these various types of vehicles from the unique signatures they produce while passing over the detector. Traffic signal systems with a bus priority feature have demonstrated this application.

The number of passengers per vehicle is another type of vehicle function data that may be required for HOV planning, lane enforcement, and transit operations. Loop detectors cannot provide this information, but it is conceivable that a future type of in-vehicle sensor-transmitter combination could sense the number of seats occupied and transmit the data via vehicle-to-road communications. The persons-per-vehicle count can be transmitted from the vehicle to a roadside communications device and, hence, to the operations center. Another approach to obtaining the number of passengers per vehicle may be with video image processing technology. By properly situating cameras, the number of passengers could be conceivably ascertained, while simultaneously observing privacy considerations that may be demanded by the public.

#### *2.3.4.2 Configurational Classification*

Tolls are often assessed based on the configuration of the vehicles passing through the toll plaza. Historically, separate schedules are developed for passenger vehicles and trucks, and these are further classified according to the number of axles. Overheight, overwidth, and overweight vehicles also need to be identified for safety and structural reasons. By tradition, these data are collected at truck inspection stations for commercial vehicles. With automatic vehicle identification tags, automatic classification and billing is technically feasible, especially for commercial vehicles. Because of the monetary aspects of toll collection, vehicle classification accuracy requirements can be greater for these than for other IVHS applications.

Improved commercial vehicle operations (CVO) are also obtained by expediting vehicle identification, for example, by using optical detectors to measure vehicles and weigh-in-motion equipment to speed trucks through weigh stations. Advantage I-75 and Crescent are two projects evaluating methods for improving CVO. The technologies demonstrated include vehicle-to-roadside communications to minimize the number of inspections requiring stops and the amount of paper work for trucks traveling between regions covered by the system.

Advantage I-75 uses a decentralized management approach and automatic vehicle identification to allow mainline preclearance of commercial vehicles. The Crescent Project is the demonstration phase of HELP (Heavy Vehicle Electronic License Plate), a long-term program to develop and use automatic vehicle classification, weigh-in-motion, onboard computers, and beacon technologies. Crescent uses a centralized system to electronically verify operating credentials and to monitor vehicle weights.

#### *2.3.4.3 Weight Ciassifica tion Data*

The primary uses of vehicle weight information are to ensure the safety of roadway structures such as bridges and viaducts and to ensure that heavy, overweight trucks do not break down the pavement. These enforcement functions have traditionally required that data be obtained at truck inspection stations operated by highway police. Since enhanced commercial vehicle operations is a goal of IVHS, weigh-in-motion sensors are being deployed in these programs.

The same weight data required for enforcement are also valuable in updating planning and design information related to bridge live-load specifications and in establishing the required strength of highway pavements.

## 2.4 TRAFFIC PARAMETER AND ACCURACY SPECIFICATIONS FOR FUTURE IVHS APPLICATIONS

The traffic parameter accuracy specifications shown in this section are believed to be representative of requirements for selected IVHS applications. However, no claim is made as to their widespread applicability since traffic parameter specifications will necessarily vary with the particular traffic management system architecture, implementation strategies, selected components and signal processing algorithms, and system operational procedures.

The traffic parameter measurement accuracy specifications for a given management strategy must primarily take into account the data processing and traffic control algorithms for which these parameters serve as inputs. Specification of traffic parameter accuracy, therefore, cannot be separated from the overall system-level analysis and design process. For each contemplated IVHS service, there are likely to be many different system algorithms, procedures, and detection subsystem design options. Evaluating alternative implementations for a particular service is the responsibility of system analysts and designers. This discussion cannot serve as a substitute for a thorough systems analysis and design effort. Nonetheless, a suggested process for the development of traffic parameter specifications, including data types, collection interval, and accuracy, is proposed.

To structure the discussion and presentation of detector performance specifications, three general categories of traffic parameters are defined based on their intended use and the required timeliness of their input for the real-time traffic management strategy. These categories are *tactical, strategic,* and *historic.* While the same raw inputs may often feed each of the categories, each presents a somewhat different set of detection performance and sampling requirements. In fact, these differences can result in a detector technology or product being adequate for some applications and not for others.

The traffic parameter input ranges and accuracies identified are for some of the more common IVHS services, including signalized intersection control, freeway incident management, and freeway metering control. Traffic parameter range and accuracy requirements are derived or inferred from the values needed for use in a particular algorithm (when it is known) and from practical experience with operating systems. Many of the historic and strategic category parameters may also be applicable to a host of other static and dynamic trip/route planning-related IVHS services. However, for these and other services where established strategies and algorithms are less commonly applied, a system-specific parameter requirements analysis is suggested. Such analysis is beyond the scope of this document.

Factors that may drive future IVHS traffic parameter and algorithm specifications are discussed at the end of the section. To a large extent, current traffic management systems are input constrained. That is, a complete microscopic (vehicle-by-vehicle) view of the traffic stream is not available in today's systems because of the lack of applicable real-time input data, even though the accelerating advances in computer processing and distributed system designs make possible advanced traffic optimization modeling and control in near real time. In this case, current systems rely heavily on prestored turning movement and origin-destination (O-D) data to supplement incomplete real-time data. In real-time control, the analysis and response to external events are performed and determined within specified time limits, usually on the order of seconds or milliseconds. In near real-time control, the feedback response is calculated within longer time intervals that are not small enough to respond to the stimuli in real time, but are sufficiently small to still have a positive impact on the events caused by the stimuli.

Future applications will not likely require a whole new set of traffic parameters. Rather, advanced detector technologies will provide greater area coverage with better vehicle characterization (e.g., presence, speed, classification, and turning movements), increased reliability, and reduced costs. Advanced control systems with vehicle tracking capabilities are also being developed and tested. These technology trends will be key enabling factors in the widespread deployment of control algorithms that may include neural network and expert system techniques. The net result will be an increased emphasis on tactical type inputs and on requirements for increased accuracy and precision.

### 2.4.1 Detector Specification Development

Figure 2-8 shows a formal process for development of traffic detector specifications. The first phase requires a detailed up-front systems analysis to properly specify all the subsystems that are part of the IVHS architecture. Among these is the detection subsystem highlighted by Figure 2-8. The critical first step in defining traffic parameter specifications, such as signal processing algorithms, types of output data (count, speed, occupancy, etc.), parameter accuracies, sample interval, and spatial resolution, is the identification of the overall IVHS requirements, shown as inputs to the systems analysis process. These are normally based on a higher level evaluation of system goals and objectives.(s)

To meet the requirements for a particular traffic management application, a number of subsystem architectures, algorithms, and traffic parameters can be selected to function either singularly, or in combination with one

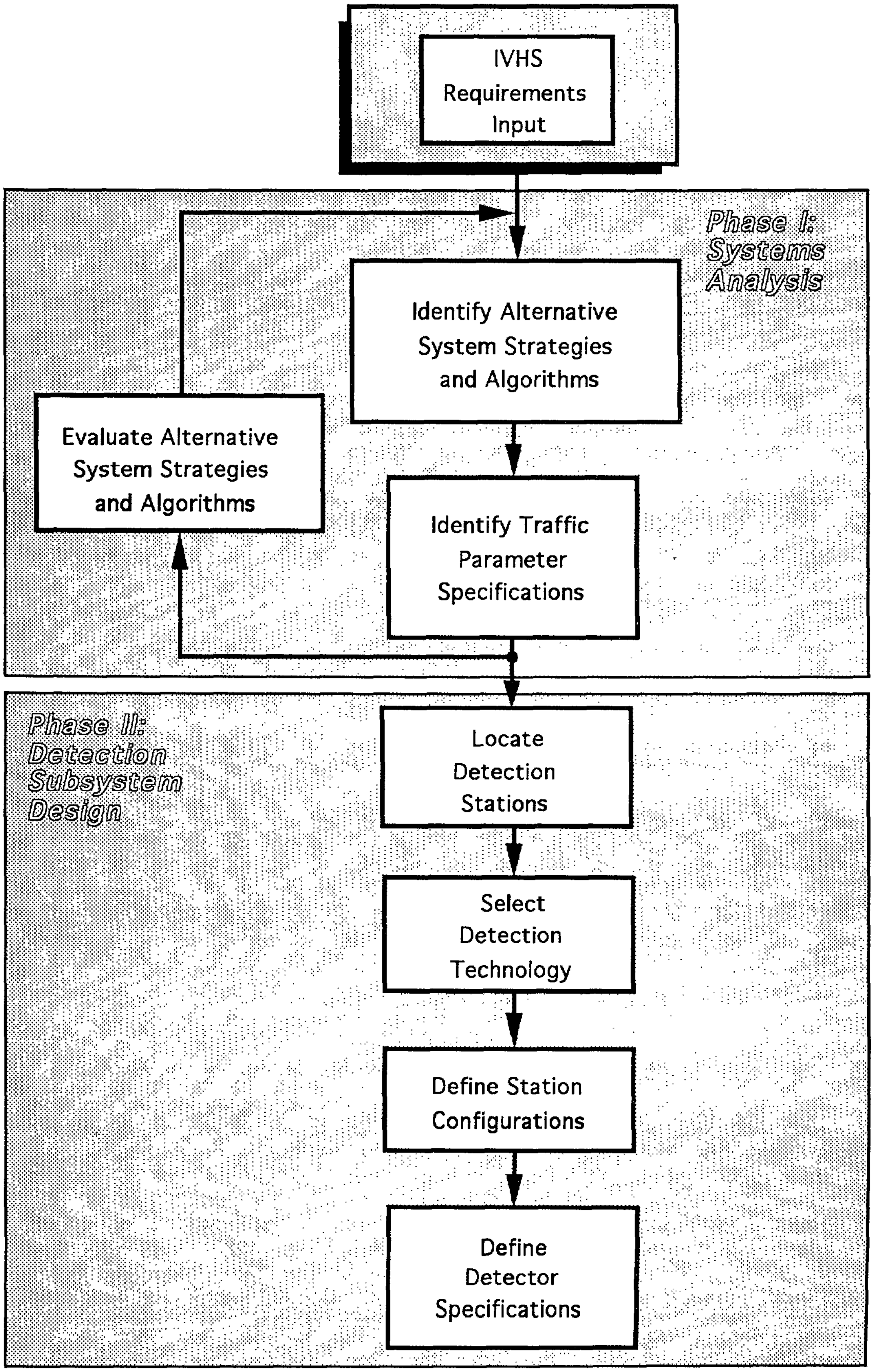


Figure 2-8. IVHS Detector Specification Process

another. The alternatives must then be analyzed and their performance compared with the overall system goals and objectives. The analysis of the alternatives not only requires a knowledge of the basic system requirements, but also a detailed understanding of the system's targeted operating environment and the constraints imposed by the available technologies that are a part of the solution. Knowledge of key technical specialty areas is needed so that they may be applied effectively in the development and implementation of traffic management systems. These specialties include traffic surveillance and control algorithm design, traffic flow theory, statistics and sampling theory, computer technology, communications technology, and detector technology.

Once the systems analysis phase is complete, the detection subsystem design phase can begin. The major components of this phase are location of the detector stations, selection of detector technologies (there may be more than one), definition of station configurations, and definition of detector specifications.

### 2.4.2 Traffic Parameter Categories

The definition of traffic parameter specifications for IVHS takes into account three categories of parameters: tactical, strategic, and historic. Each suggests different usage of the data by a traffic management application that, in turn, generally dictates a different set of parameter specifications, including data collection time interval, range, and accuracy.

#### *2.4.2.7 Tactical Input Parameters*

Tactical parameters are those utilized in tactical decision making. For this discussion, tactical decisions are defined as the expedient decisions made by a control system in response to real-time traffic parameter inputs. Tactical decisions are typically based on rote logic embedded in a predefined algorithm. One example is the real-time adjustment of a traffic adaptive controlled signalized intersection in response to the measured cyclic traffic flow profiles on each approach. Another example is the decision to declare a freeway "incident" condition in response to a mainline lane parameter value exceeding a prescribed threshold.

Because tactical decisions are made in quick response to changing real-time traffic variables, tactical parameters are generally collected over short time intervals (usually on the order of a few seconds). They may also be event driven, as, for example, a vehicle detected by a presence detector. Since tactical parameters are collected on these shorter intervals, fewer vehicles are included in each sample. Variation from sample to sample will be exhibited due to the random nature of vehicle arrivals. The limited sample size will usually impose increased accuracy and precision on the measurement of tactical parameters. For example, the measurement of approach speed as an estimate of travel time for vehicles approaching a signalized intersection requires increased accuracy and precision when traffic signal offset decisions are being made, as compared to measuring average approach speeds for strategic background "plan-based" decision making.

#### *2.4.2.2 Strategic Input Parameters*

Strategic input parameters support strategic-level decisions. These traffic control and management decisions generally operate at a higher level in the system hierarchy than do tactical decisions. Strategic decisions are typified by the activation of a preplanned management strategy in response to broad indicators of traffic flow conditions.

Strategic-level decisions are often broader in geographic scope than tactical ones and often change the mode of an entire system or a large subsystem. Strategic decisions can be expert system rule-based, as in the Los Angeles Smart Corridor Management System, or algorithm-based, as used in UTCS plan selection. They frequently employ predefined scenarios and operator confirmation and approval processes.

Strategic traffic parameters are usually collected over a period of minutes rather than seconds; as a result, samples are larger. Most currently deployed freeway management and centralized traffic signal control systems use running averages and other filtering techniques to smooth out short-term variations in the traffic stream data. Strategic traffic parameters are often input to maintain on-

on-line databases of current traffic conditions used by the management systems.

One example of a strategic-level decision process is the selection of an incident management plan in response to a detected incident on a surface street network. When an incident is declared, the strategic decision process might monitor overall network conditions and implement an appropriate control plan overriding or adjusting the tactical-level decision-making process.

Under conditions of light to moderately heavy congestion, adaptive traffic signal network optimization methods, such as SCOOT and SCATS that operate largely at the tactical-level, provide excellent results. (4-10) However, in cases of very heavy congestion, such as those caused by an incident where severe blocking of intersections results and natural or controlled route diversion occurs, these tactical-level procedures begin to break down. Strategic-level decision logic is successfully used to solve such problems.

#### *2.4.2.3 Historic Input Parameters*

Historic input parameters are those used to maintain or update on-line historic traffic databases. These data bases typically include traffic data collected over periods of 5 minutes or greater and are archived by time of day and day of week, or by time of day and date. The primary purpose of these historic databases is to provide information for off-line planning and design operations. However, historic data are also commonly used as inputs to on-line tactical and strategic decision processes. For example, most freeway management systems maintain a file of historic flow-rate data. This file is regularly used on-line as input for predicting future near-term traffic demands. In addition, some UTCS applications use historic flow-rate data as input to on-line detector failure monitoring logic.

### 2.4.3 Matching Traffic Parameter Needs to Selected IVHS Services

Individual traffic parameters and accuracies required for a given application are specified by the algorithms, strategies, and operating procedures used to implement that application. A list of criteria which can help select traffic parameters for use in a particular IVHS application includes:

- Convenience of parameter measurement;
- Amenability of resultant data to real-time processing;
- Existence of significant differences in parameter values within the range of traffic conditions that must be monitored.

Traffic parameters are identified below for signalized intersection control, freeway incident management, and freeway metering. Parameter range, collection interval, and accuracy specifications for these services are given in Tables 2-l through 2-3. Unfortunately, the search of the available literature uncovered little universally applicable information regarding the required accuracy of traffic parameters for these or other IVHS services. Consequently, the specifications are based on: (1) the data that were located, (2) operating experience, and (3) sensitivity analyses developed during the study or found in the literature. The estimates are considered representative of those for the selected traffic parameters and are consistent with the general requirements of the particular application. However, a detailed analysis is recommended to derive parameter specifications for a specific system design or for IVHS services not covered. Such analyses are outside the scope of this report.

### 2.4.4 Signalized Intersection Control

Table 2-l gives selected traffic parameter specifications for advanced signalized intersection control applications. Parameters are listed for the tactical, strategic, and historic categories. Tactical parameters include those relating to flow, speed, and occupancy measurements. For advanced signal control systems, typical flow-related parameters may include cyclically collected intersection approach flow rates, flow profile data, and turning volumes.

Tactical information related to intersection control is often collected on a cyclic basis and normalized to hourly rates. This minimizes the short-term parameter fluctuations caused

## Table 2-1. Signalized Intersection Control Traffic Parameter Specifications

### Tactical Parameters

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Approach Flow Profiles | vehicles | 0-3 | 1 second | ± 2 veh/signal cycle |
| Turning Movement Vol | vehicles | 0-200 | 1 cycle | ± 2 veh/signal cycle |
| Average Link Travel Time | seconds | 0-240 | 1 cycle | ± 2 seconds |
| Average Approach Speed | mi/h | 0-100 | 1 cycle | ± 2 mi/h (0-55 mi/h) |
| Queue Length | vehicles/lane | 0-100 | 1 second | ± 2 vehicles |
| Demand Presence | Yes/No |  | 10Hz (minimum) | No missed vehicles |
| Average Approach Delay | s/veh | 0-240 | 1 cycle | ± 2 seconds |
| Approach Stops | stops | 0-200 | 1 cycle | ± 5% of stops |

### Strategic Parameters

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Flow Rate (Volume) | veh/h/lane | 0-2500 | 5 min | ± 2.5% @ 500 veh/h/lane |
| Occupancy | %/lane | 0-100 | 5 min | ± 5% |
| Average Speed | mi/h | 0-100 | 5 min | ± 2 mi/h (0-55 mi/h) |
| Average Delay | s/veh | 0-240 | 5 min | ± 2.5 seconds |
| Percent Stops | % | 0-100 | 5 min approx. | ± 5% |

## Table 2-1. Signalized Intersection Control Traffic Parameter Specifications (continued)

### Historic Parameters

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Turning Movement Vol | Veh/movement | 0-2000 | 15 min | ± 2.5% @ 500 veh/h |
| Flow Rate (Volume) | veh/h/lane | 0-2500 | 15 min | ± 2.5% @ 500 veh/h |
| Occupancy | % | 0-100 | 15 min | ± 5% |
| Average Speed | mi/h | 0-100 | 15 min | ± 2 mi/h (0-55 mi/h) |

1 mi/h = 1.61 km/h

by data collection intervals being inconsistent with whole multiples of the cycle length. Fluctuations can also be minimized by maintaining weighted running averages and other smoothing techniques.(11)

Speed-based parameters are also of benefit to advanced signal control algorithms. From a tactical viewpoint, vehicle approach speeds can be used to estimate link travel time. However, speed accuracy is critical here because a small difference in measured speed can have a significant effect on calculated travel time. (This depends, of course, on the length of the approach section.) An error in calculated travel time of only a few seconds can have an adverse effect on operations if travel time is used as the basis for offset calculations. Another useful speed measure is the distribution of approaching vehicle speeds. The standard deviation of the measured speed can be an important input to the modeling of platoon dispersion from one signalized intersection to another.

Occupancy-based measures such as queue length, delay, and percent of stops collected on a cycle basis can also be tactical inputs to advanced signal control algorithms. Data from traditional inductive loop traffic detectors on an approach to a signalized intersection provide estimates for these parameters using an input-output model that receives the current green state of the traffic signal. These parameters provide feedback on the effectiveness of the current traffic control operation. Stop bar demand presence and queue overflow presence are two other occupancy-related parameters used by some signal control algorithms. The strategic-level parameters most often used by intersection control logic include smoothed volume, occupancy, and average speed indicators. Some systems also tabulate average approach delay and percent of vehicles stopping or total stops by approach. Strategic data are normally kept as smoothed values (weighted running averages) with collection intervals ranging from 1 to 5 minutes. In most instances, the purpose of strategic volume data collection is to tabulate current demands for network links. Similarly, occupancy parameters are often used to monitor the extent of current congestion on the roadway network. As discussed in a previous example, strategic traffic parameters can be useful for implementing incident management strategies designed for surface-street applications.

Historic parameters used in intersection signal control applications include link-based volume, occupancy, and speed. Turning movement and O-D pattern information are also important as inputs to demand prediction algorithms. These data are currently available from manual studies.

### 2.4.5 Freeway Incident Management

Table 2-2 identifies selected parameter specifications for freeway incident management. Tactical parameters serve as key inputs to automated incident detection algorithms. Basic tactical inputs include lane-specific mainline flow rate, occupancy, and average speed. Other tactical parameters derived from these basic parameters include spatial occupancy differential and spatial average speed differential. For incident detection logic based on California-type algorithms, the spatial differential parameters provide measures of the difference in lane-specific values of occupancy or speed between successive upstream and downstream detection stations for a given direction of travel. These types of algorithms rely on the identification of an incident between mainline stations from significant differences in the measured values of parameters between the two stations. Another algorithm uses the standard deviation of vehicle speed to predict when freeways are reaching capacity and to initiate strategies such as speed limit reduction or metering .(12)

Strategic-level parameters are important as traffic monitoring inputs to the overall incident management process. Strategic-level parameters include mainline lane-specific flow rate, occupancy, average speeds, and freeway on-ramp and off-ramp flows. Alternative route data are also collected when applicable. As a minimum, flow rates and link speed or travel times should be maintained for significant alternate routes in the system. Strategic parameters are generally maintained on-line as S-minute running averages.

## Table 2-2. Freeway Incident Detection and Management Traffic Parameter Specifications

### Tactical Parameters (Detection)

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Mainline Flow Rate | veh/h/lane | 0-2500 | 20 s | ± 2.5% @ 500 veh/h/lane |
| Mainline Occupancy | % (by lane) | 0-100 | 20 s | ± 1% |
| Mainline Speed | mi/h (by lane) | 0-80 | 20 s | ± 1 mi/h |
| Mainline Travel Time | min |  | 20 s | ± 5% |

### Strategic Parameters (Incident Management)

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Mainline Flow Rate | veh/h/lane | 0-2500 | 5 min | ± 2.5% @ 500 veh/h |
| Mainline Occupancy | % | 0-100 | 5 min | ± 2% |
| Mainline Speed | mi/h | 0-80 | 5 min | ± 1 mi/h |
| On-Ramp Flow Rate | veh/h/lane | 0-1800 | 5 min | ± 2.5% @ 500 veh/h/lane |
| Off-Ramp Flow Rate | veh/h/lane | 0-1800 | 5 min | ± 2.5% @ 500 veh/h/lane |
| Link Travel Time | seconds | - | 5 min | ± 5% |
| Current O-D Patterns | veh/h |  | 5 min | ± 5% |

## Table 2-2. Freeway Incident Detection and Management Traffic Parameter Specifications (continued)

### Historic Parameters (Planning)

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Mainline Flow Rate | veh/h/lane | 0-2500 | 15 min or 1 hour | ± 2.5% @ 500 veh/h/lane |
| Mainline Occupancy | % | 0-100 | 15 min or 1 hour | ± 2% |
| Mainline Speed | mi/h | 0-80 | 15 min or 1 hour | ± 1 mi/h |
| On-Ramp Flow Rate | veh/h | 0-1800 | 15 min or 1 hour | ± 2.5% @ 500 veh/h |
| Off-Ramp Flow Rate | veh/h | 0-1800 | 15 min or 1 hour | ± 2.5% @ 500 veh/h |
| Link Travel Times | seconds | | 15 min or 1 hour | ± 5 % |
| Current O-D Patterns | veh/h | | 15 min or 1 hour | ± 5 % |

1 mi/h = 1.61 km/h

As with intersection control, historic parameters play a major role in many, if not most, freeway incident management systems. Parameters which parallel the strategic parameters described above are typically stored as historic files. Data are often maintained for a particular time of day and day of week for each detection station. New data are smoothed with data for the corresponding time interval of the previous week. In this way, files are maintained that represent typical time of day and day of week conditions on the highway network. These files are used for on-line demand estimation and are often archived for planning and design purposes. Historic parameters are typically collected in 1 S-minute intervals, although S-minute and l-hour intervals are also used. Some systems, such as the Burlington Skyway in Ontario, Canada and the Denver, CO Freeway Traffic Management System, store S-minute values, but can derive 1 S-minute and 1 -hour values upon request.

### 2.4.6 Freeway Metering Control

Table 2-3 contains selected parameter specifications for freeway metering control. Tactical parameters for this application include queue length, demand presence, passage count, approach volume, and queue overflow presence. When a queue length is used in current applications, it is typically estimated based on approach and passage volumes or is derived from data produced by one or more presence detectors on the approach to the metering signal. Other tactical inputs to the metering control algorithm include mainline occupancy, speed, and flow rate as described under freeway incident management.

Strategic parameters for metering include mainline and metered traffic flow rates. Mainline values are generally lane-specific and include volume, occupancy, and average speeds. Derived average freeway speeds based on volume and occupancy data from a single inductive loop detector will give reasonable results for strategic decisions because collection intervals are typically 5 minutes or longer and smoothing procedures are normally used.

Historic parameters of value in freeway metering include those already identified as strategic plus on-ramp and off-ramp flow rates. The collection interval for historic data is lengthened to 15 minutes or 1 hour, to correspond to the intervals used with freeway incident detection and management.

### 2.4.7 Future Traffic Parameter Specifications

It is difficult to calculate the accuracy required of traffic parameters for applications where algorithms do not exist or where improved algorithms are being sought. Nonetheless, one can speculate that increased measurement accuracy will be required as advanced algorithms are deployed. These advanced algorithms will place a heavier reliance on tactical-type inputs for real-time control decisions. Future algorithms will not likely require new traffic parameters sets per se. Advances in detection technology will decrease data collection costs and, in some cases, will allow parameters such as queue lengths and origin-destination patterns to be more directly measured or estimated in real time.

Two technologies that will enable advanced algorithms to be deployed are imaging detectors and probe vehicle sampling, including AVI. Imaging detectors that track individual vehicles through a traffic scene have the advantage of monitoring actual vehicle traffic movements as they happen, thus allowing algorithms to be more demand responsive. Furthermore, stopped vehicle counts and standing queues can be directly monitored with imaging methods. Since queue buildup directly impacts delay, number of stops, fuel consumption, and emissions output, improved data and, therefore, control optimization will be possible.

AVI readers and other vehicle probe-based detection technologies are now being operationally tested. These have the potential to statistically monitor travel movements through a roadway network and provide automated collection of O-D data and travel time samples on a link-specific basis. Up-to-the-minute O-D data will enable improved incident and congestion management

## Table 2-3. Freeway Metering Control Traffic Parameter Specifications

### Tactical Parameters (Local Responsive Control)

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Ramp Demand | Yes/No | - | 0.1 s | 0% (No missed vehicles) |
| Ramp Passage | Yes/No | - | 0.1 s | 0% (No missed vehicles) |
| Ramp Queue Length | vehicles | 0-40 | 20 s | ± 1 vehicle |
| Mainline Flow Rate | % | 0-100 | 20 s | ± 2% |
| Mainline Occupancy | veh/h/lane | 0-2500 | 20 s | ± 2.5% @ 500 veh/h/lane |
| Mainline Speed | mi/h | 0-80 | 20 s | ± 5 mi/h |

### Strategic Parameters (Central Control)

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Mainline Flow Rate | % | 0-100 | 5 min | ± 2% |
| Mainline Occupancy | veh/h/lane | 0-2500 | 5 min | ± 2.5% @ 500 veh/h/lane |
| Mainline Speed | mi/h | 0-80 | 5 min | ± 5 mi/h |

### Historic Parameters (Pretimed Operations)

| Parameter | Units | Range | Collection Interval | Allowable Error |
|---|---|---|---|---|
| Mainline Flow Rate | % | 0-100 | 15 min or 1 hour | ± 2% |
| Mainline Occupancy | veh/h/lane | 0-2500 | 15 min or 1 hour | ± 2.5% @ 500 veh/h/lane |
| Mainline Speed | mi/h | 0-80 | 15 min or 1 hour | ± 5 mi/h |
| On-Ramp Flow Rate | veh/h | 0-1800 | 15 min or 1 hour | ± 2.5% @ 500 veh/h |
| Off-Ramp Flow Rate | veh/h | 0-1800 | 15 min or 1 hour | ± 2.5% @ 500 veh/h |

strategies. The availability of link travel time data in real time should significantly improve the performance of automated incident detection algorithms by reducing detection times and false alarm rates.

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# 3. TASK B SUMMARY

## SELECT FIELD SITES FOR DETECTOR FIELD TESTS

### 3.1 TEST SITE SELECTION AND CRITERIA

Freeway and surface-street field test sites were selected in Minneapolis, Minnesota; Orlando, Florida; and Phoenix and Tucson, Arizona. In Minnesota and Florida, both types of sites are in the same cities. In Arizona, the freeway site is located in Phoenix and the surface-street site in Tucson. By choosing test sites in different climatic regions of the country, a variety of environmental test conditions were encountered as described by Table 3-1.

Test sites were selected to meet the following criteria:

- Mounting structures available for installing above-the-road detectors over the central portion of the lanes at heights prescribed by the manufacturers;
- Mounting available or easily put in place on the side of the road to install side-looking detectors;
- Power available for the detectors under test;
- Communications in place, or readily installed, for transmitting traffic data and video to a central processing facility (traffic operations center or traffic management center) or another environmentally controlled data collection location;
- Inductive loop detectors in place or capable of being installed;
- Traffic flows that range from light to heavy during a 24-hour period;
- Weather-protected roadside controllers available in which to install detector amplifiers and other signal processing equipment.

### 3.2 MINNESOTA TEST SITES

Seven potential field test sites were visited in Minneapolis and St. Paul, four suitable for monitoring traffic flows on freeways and three for surface-street arterials. The detector installation and intersection plan-view drawings for the selected Minneapolis sites are contained in Appendix E. The Minneapolis freeway test site was located on I-394 at the Penn Avenue crossing. I-394 is an east-west freeway linking the western suburbs with Minneapolis and is built along the U.S. Highway 12 right-of-way. The freeway has two unrestricted lanes in each direction at this location, as well as two reversible high-occupancy vehicle (HOV) lanes that are used during morning and evening rush hours. The HOV lanes are located between the normal eastbound and westbound lanes. Inductive loop detectors are installed at 0.5-mi (0.8-km) spacing to monitor traffic on I-394. The bridge crossing at Penn Avenue has a changeable message sign (facing westbound traffic) and various exit signs installed.

The eastbound lanes and the HOV lane closest to the eastbound lanes were used as the test bed. The photograph in Figure 3-1 was taken from the Penn Avenue Bridge looking west at eastbound traffic into Minneapolis. The photograph in Figure 3-2 shows the area that was monitored by the detectors on the east side of the bridge. The above-ground detectors were installed to observe downstream traffic moving away from the detectors into Minneapolis, as there is no obstruction on the east side of the bridge over the eastbound lanes. Similarly, detectors were mounted over the HOV lanes to monitor the westbound traffic out of Minneapolis during the afternoon and evening rush hours. Speed-measuring inductive loop detector pairs were installed in the three monitored lanes to obtain vehicle count and speed data to compare with those from radar, infrared, ultrasonic, acoustic, and video image processor (VIP) detector technologies. A camera was placed on the Penn Avenue bridge structure along with the overhead detectors to

Table 3-l. Test Conditions Satisfied at Proposed Test Locations

| Test Condition | Minnesota |  | Florida |  | Arizona |  |
|---|---|---|---|---|---|---|
|  | Freeway | Surface Street | Freeway | Surface Street | Freeway | Surface Street |
| Times of Day |  |  |  |  |  |  |
| Daylight | x | x | x | x | x | x |
| Dawn | x | x | x | x | x | x |
| Dusk | x | x | x | x | x | x |
| Night | x | x | x | x | x | x |
| Vehicles |  |  |  |  |  |  |
| Passenger cars | x | x | x | x | x | x |
| Trucks | x | x | x | x | x | x |
| Semi-trailers | x | x | x | x | x | x |
| Buses | x | x | x | x | x | x |
| Emergency vehicles | x | x | x | x | x | x |
| Motorcycles | x | x | x | x | x | x |
| Bicycles |  | x |  | x |  | x |
| Road equipment | x | x | x | x | x | x |
| Traffic patterns |  |  |  |  |  |  |
| Multiple lanes | x | x | x | x | x | x |
| Normal traffic | x | x | x | x | x | x |
| Turning vehicles |  | x |  | x |  | x |
| Congestion | x | x | x | x | x | x |
| Long queues* | x | x | x | x | x | x |
| Stopped vehicles | x | x | x | x | x | x |
| Adjacent-lane vehicles | x | x | x | x | x | x |
| Lane straddlers | x | x | x | x | x | x |
| Weather |  |  |  |  |  |  |
| Clear | x | x | x | x | x | x |
| Overcast | x | x | x | x | x | x |
| Fog |  |  | x | x |  |  |
| Abrupt lighting changes (luminaries, lightning) |  |  | x | x | x | x |
| Cold temperature extremes | x | x |  |  |  |  |
| Hot temperature extremes |  |  | x | x | x | x |
| Heavy snow | x | x |  |  |  |  |
| Heavy rain |  |  | x | x | x | x |
| Smog* |  |  |  |  | x |  |
| Haze |  |  | x | x |  |  |
| Artifacts |  |  |  |  |  |  |
| Shadows | x | x | x | x | x | x |
| Sun glare | x | x | x | x | x | x |
| Electromagnetic interference | x | x | x | x | x | x |
| Wind sway and vibration | x | x | x | x | x | x |

* **Long queues: For freeway application, on-ramps and mainline during congested hours.**
For surface-street application, at traffic signals.

** Experienced also during the laboratory tests of available detectors conducted in Los Angeles **during Summer 1992.**

Figure 3-1. I-394 Freeway Test Location Photograph Looking at Eastbound Traffic Into Minneapolis Approaching Penn Avenue

Figure 3-2. I-394 Freeway Test Location Photograph of Eastbound Lanes Of East Side of Penn Avenue Bridge as Seen by Detectors obtain imagery of the traffic flow for ground truth and to serve as an input to the VIPs.

A trailer located on the southeast corner of the Penn Avenue/I-394 intersection was used for recording the outputs of the detectors. Type 170 controllers are used by the Minnesota Department of Transportation (MnDOT).

The selected Minneapolis surface-street site was located on Olson Highway (TH-55) between Lyndale Avenue North and Oak Lake Avenue just east of the I-94 overpass. A sign bridge spans the westbound lanes of TH-55 as shown in Figures 3-3 and 3-4. Detectors were mounted on the rear of the sign to monitor downstream traffic.

Westbound Olson Memorial Highway has three through-traffic lanes and a left and right turn pocket as it approaches Lyndale Avenue as shown in the figures. Fifty-foot (15. Z-m) light poles were also available to install detectors for side-looking configurations. A set of single loops were already installed for signal control. The city installed a second loop in each lane to measure vehicle speed during the tests. National Electronic Manufacturers Association (NEMA) controllers are used by the City of Minneapolis.

A trailer located on the south side of Olson Highway was used for recording the outputs of the detectors.

## 3.3 FLORIDA TEST SITES

Several freeway test sites along Interstate 4 were explored in the Orlando area. The I-4 and SR 436 intersection in Altamonte Springs, north of Orlando, was selected because it accommodated both freeway and surface-street data acquisition and, thus, potentially minimized the setup time. It has an excellent alignment of the overpass with respect to the interstate for mounting the detectors. The detector installation and SR 436 overpass construction plans are contained in Appendix I.

The freeway contains three lanes in both the east and west directions at this location, with the innermost lanes reserved for car pools during peak traffic hours. The SR 436 bridge provides a mounting structure for the detectors overlooking the freeway. The three lanes of I-4 westbound traffic into Orlando, shown in Figure 3-5, were monitored from this vantage point where data from upstream (approaching) vehicles were acquired. A camera was mounted directly over the middle of the monitored freeway lanes to obtain ground truth of the freeway traffic and imagery for the VIPs. Double-loop inductive detectors were installed in all three westbound lanes to measure vehicle count and speed.

The westbound SR 436 surface-street test location, shown in Figure 3-6, has three through lanes and two left-turn lanes that lead to an entrance ramp for I-4 West toward Orlando. The sign bridge for mounting the overhead detectors is located directly over the freeway median. The signal controller cabinet is located on the Northwest corner at the end of the I-4 West off-ramp for SR 436. Double-loop inductive detectors were installed on the SR 436 through lanes to measure vehicle count and speed. A camera was mounted on the pipe tree over the middle lane to view the stop bar and traffic moving away from the overhead detectors.

## 3.4 ARIZONA TEST SITES

Two freeway sites were visited in Phoenix. The selected test site location, shown in Figures 3-7 and 3-8, is the east-west stretch of I-I 0 called the Papago Freeway near Thirteenth Street, just east of the tunnel.

There are three mainline westbound lanes and one high occupancy vehicle lane as shown in the figures. A changeable message sign hangs over lane 3 (the rightmost lane). The overhead detectors were mounted directly on the sign bridge structure without using the pipe trees. This was the only test location where the pipe trees were not used. Figure 3-9 shows the build plan for the freeway at the test site location. Double-loop speed measuring inductive detectors were installed in the three mainline lanes to assist in the technology evaluation.

Figure 3-3. Olson Memorial Highway Surface Street Test Location Photograph Of Westbound Traffic Lanes - Front of Sign Bridge

Figure 3-4.Olson Memorial Highway Surface Street Test Location Photograph Of Westbound Traffic Lanes - Back of Sign Bridge

Figure 3-5. I-4 at SR 436 Freeway Test Site Photograph Showing Traffic on I-4 Westbound into Orlando

Figure 3-6. SR 436 Surface Street Test Site Photograph Showing Westbound Traffic

Figure 3-7. Phoenix Freeway Test Site Photograph Showing I-10 Traffic at Thirteenth Street

Figure 3-8. Phoenix Freeway Test Site Photograph Showing Westbound I-10 Traffic Leaving Deck Tunnel and Heading Toward Thirteenth Street

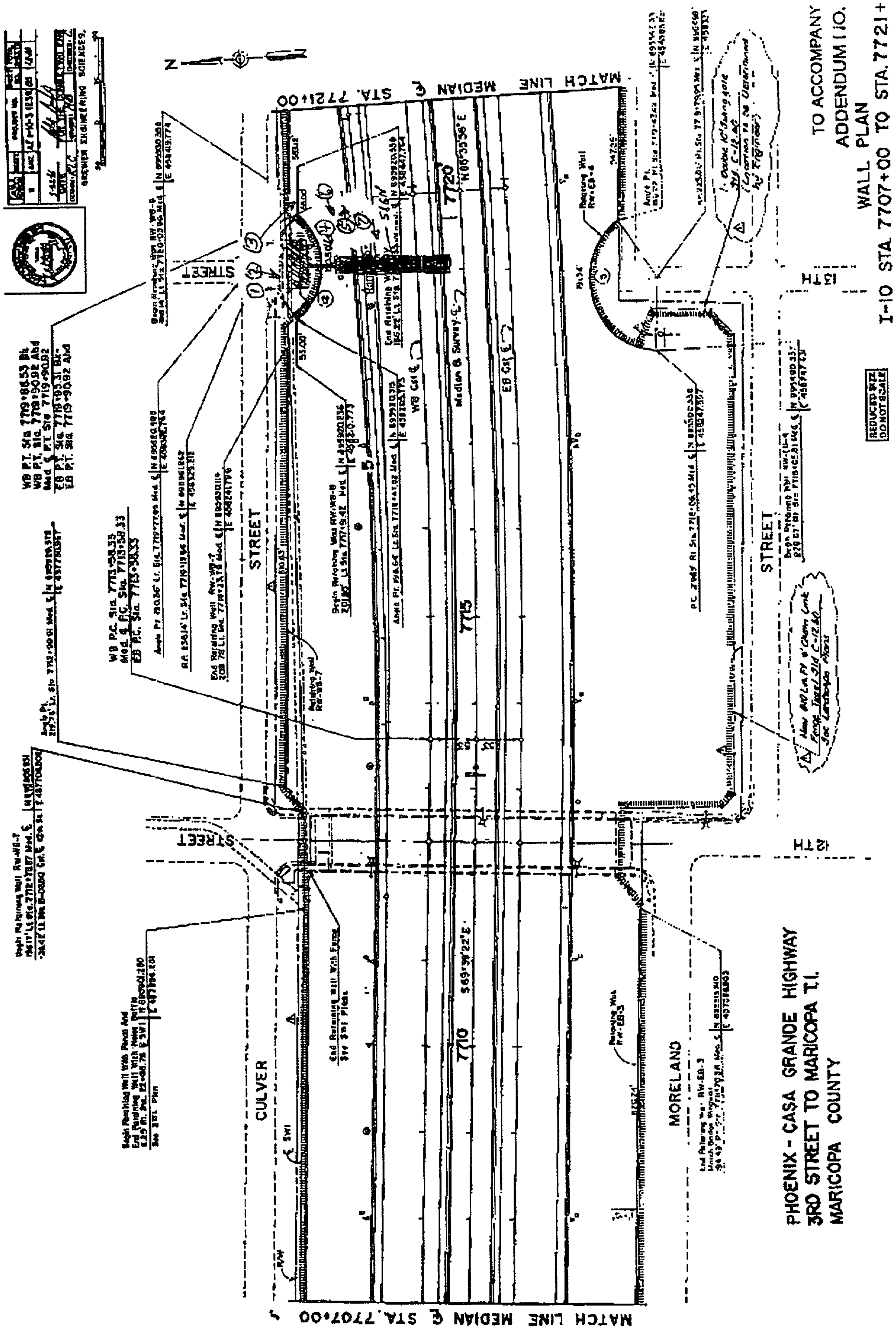

Figure 3-9. Plan-View Drawing for I-10 Freeway Near Thirteenth Street Showing Location of Sign Bridge

Six surface-street arterial test sites were visited in Tucson. The selected site was along Oracle Road at the intersection with Auto Mall Drive and across the street from the largest shopping mall in Tucson. Three lanes in each direction support north-south traffic. According to the City of Tucson, the traffic is well funneled into these lanes by the stoplight on the north side of the intersection. The overhead detectors were mounted on pipe trees and were supported by the signal light mast arm that controls southbound traffic as shown in the southbound view in Figure 3- 10. Oncoming traffic southbound on Oracle Road is shown in Figure 3-11.

Double 6-ft by 6-ft (1.8-m by 1.8-m) rectangular loops were installed in the curb and center lanes, round loops in the curb lane, and pairs of microloop detectors in the curb and center lanes in order that these types of loop data may be compared against one another, as well as against the overhead detector data. A trailer situated on the southwest corner of the intersection housed the data recording and analysis equipment.

The city-owned controller cabinet was used to supply the green phase signal for the southbound Oracle Road traffic. Temperatures in the cabinet can reach 170°F (77°C) without a fan during hot weather. The City of Tucson requires equipment to be specified for 80°C (176°F) operation. 115 VAC power came from the pole that supports the traffic signal mast arm.

# 4. TASK D SUMMARY

# SELECT AND OBTAIN VEHICLE DETECTORS

## 4.1 SELECTION CRITERIA

The criteria used to select vehicle detectors for use in the laboratory tests of Task E and the field tests of Task G were:

- Availability,
- Demonstrated capability,
- Compatibility with controllers in place at the field test locations,
- Representative of current technology, and
- Vendor support.

Availability implies that one or more units would be supplied by the vendor in time to support the field tests beginning in October 1992. This criterion was tightened to include delivery to support the laboratory tests scheduled to begin in May 1992 when possible.

Demonstrated capability implies that the detectors have either been tested by a municipality or Department of Transportation (DOT), or have undergone substantial testing by the vendor.

For compatibility with the controllers used at the test sites, an appropriate interface between the detector or amplifier and the controller must exist, or the interface must be capable of being easily put in place by personnel working for the DOTs.

To be representative of current technologies, a detector must contain design features that allow it to respond to moving and/or stationary vehicles of different sizes and colors; operate in light and heavy traffic flows under most weather conditions; be capable of day and night operation; and be immune to artifacts such as shadows and glint, and false detections from shoulder or adjacent lane objects and vehicles. The effects of these scenarios on each technology is different, as addressed in Section 5.

Vendor support implies cooperation in supplying requested data and operating and mounting instructions, and in resolving problems that arise during the tests.

These criteria were applied to vehicle detectors representative of the following technologies:

- Ultrasonic,
- Infrared (Passive and Active),
- Microwave,
- Video Image Processing,
- Acoustic Arrays,
- Inductive Loop, and
- Magnetic.

## 4.2 SELECTION PROCESS

Two general paths for selecting detectors for the field tests were considered. The first is an ideal path shown in the upper part of Figure 4-1. It is suitable if present-day detectors meet the IVHS requirements of the future as specified in Section 2.

The ideal detector selection path begins by establishing user requirements through discussions with city, county, state, regional, and federal transportation agencies and other major interested parties such as equipment manufacturers. These requirements are then analyzed and consolidated into categories that represent the IVHS applications and services surfaced through the discussions. Detectors that meet the requirements undergo further screening in laboratory tests, checking for operational compatibility with field site support services and anticipated traffic conditions (e.g., mounting configuration, communications, and weather and traffic volume environments), and verifying non-interference with the operation of other detectors. Finally, those detectors that pass the screen are chosen for further evaluation in the field tests.

In our case, it was found that none of the available detectors would meet all of the requirements developed in Section 2. Therefore, the detector selection path shown in the lower part of Figure 4-1 was used. Here the capabilities of currently available detectors are determined from the Federal Highway Administration (FHWA), user evaluations, vendors, conferences, journals, and other personal contacts. Instead of eliminating detectors that do not pass all IVHS requirements, all detectors are allowed to enter the screening process. Those that perform to the vendor's specifications are selected for further evaluation in the field tests.

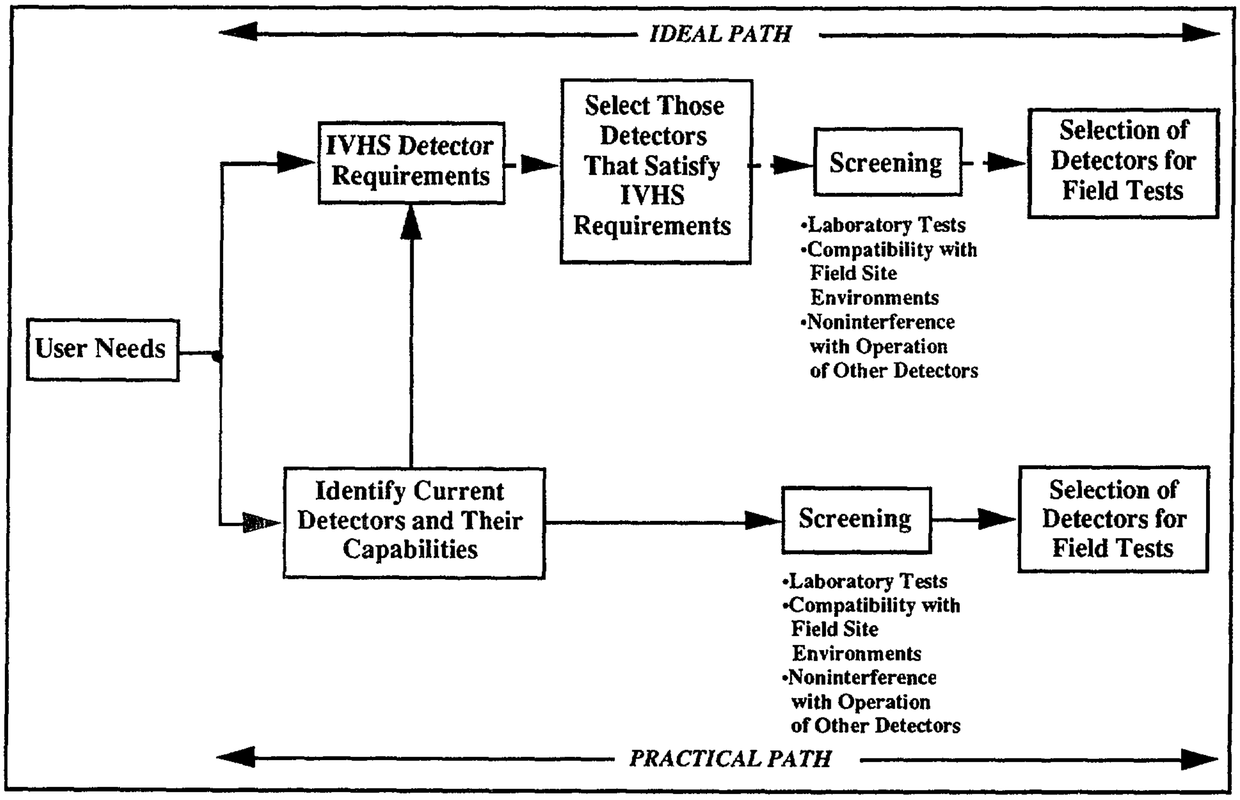

Figure 4-1. Detector Selection Processes

In applying the process just described, municipalities such as the City of Los Angeles; DOTs in Minnesota, Florida, Arizona, and California; and other user organizations such as the Enterprise Group were contacted to gather information about potential manufacturers and test results on their products. These contacts sometimes led to studies that evaluated detector performance, such as those conducted by the Institute of Transportation Studies at Berkeley and the Transportation Research Group at the California Polytechnic State University at San Luis Obispo.(1,2) As the *Detection Technology for IVHS Program* progressed, other manufacturers were made known to the principal investigator by the Contracting Officer's Technical Representative (COTR) and personnel within Hughes Transportation Management Systems. Still other sources of detectors were gathered from reviews of industry journals, such as those published by the Institute of Transportation Engineers (ITE), and from attendance at conferences sponsored by the Transportation Research Board (TRB), IVHS America, American Society for Testing and Materials (ASTM), and ITE. Manufacturers also contacted the principal investigator at technical meetings and exhibits where they were present.

Lists of detector models and specifications by technology are shown in Tables 4-1 through 4-8 for above-the-road and in-ground

Table 4-1. Specifications of Ultrasonic Vehicle Detectors Evaluated

| Detector | Detectable Objects | Transmit Frequency | 3 dB Beam-width | Speed Measure-ment Range | Speed Measure-ment Accuracy | Detection Range | Min Vehicle Sepa-ration | Peak Output | Pulse Repetition Period ($T_o$) | Pulse Width ($T_p$) | Signal Hold Time ($T_h$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sumitomo Vehicle Speed Detector SDU-200 | Subcompact cars and larger | 25.5 KHz ± 1 KHz | 15 deg | 4-120 km/h (2.5-75 mph) | ± 10% | 8 m (26 ft) | < 10 m (33 ft) | 14 ± 3 $V_{pp}$ | Not Applicable | Not Applicable | Not Applicable |
| Sumitomo Vehicle Detector SDU-300 | Subcompact cars and larger | 26 KHz ± 1 KHz | =13 deg | Not Applicable | Not Applicable | 1.5 to 8 m (4.9 to 26 ft) | 1.2 m + vehicle speed in m/sec x 0.15 sec | <10 watts | 33 ± 3 msec | 2 ± 0.5 msec | 115 msec ± 10% |
| Microwave Sensors TC-30C | Pedestrians, bicycles, and all motorized vehicles | 49.7 KHz | ~20 deg | Not Applicable | Not Applicable | 7 m (23 ft) | 1.5 m (5 ft) at 70 mph | Transmitted acoustic energy Is 110 dB at 20 ppascals at 1 m | 100 msec | 0.02 msec | 0.25 to 10 sec |

Table 4-2. Specifications of Active Infrared Detectors Evaluated

| Detector | Instantaneous Field of View (FOV) | Vehicle Classification | Speed Measurement Range | Detection Range | Response Time | Flow | Presence Hold Time |
|---|---|---|---|---|---|---|---|
| Schwartz Electro-Optics 780D1000 | ·2 beams, each 1 mrad (El) by 9.5 deg (Az)<br>·Beam separation in El = 10 deg | Auto or truck | 0 to > 80 mi/h with ±1 mi/h accuracy up to 70 mi/h | 1.5 - 15 m (5 - 49 ft) | =10 ms | 0 to >1800 veh/h | For as long as vehicle is in FOV of detector |

1 mi/h = 1.61 km/h

Table 4-3. Specifications of Passive Infrared Detectors Evaluated

| Detector | Detectable Objects | Detection Range and Footprint | Response Time | Maximum Speed at Which Vehicles Are Counted | Hold Time |
|---|---|---|---|---|---|
| Eltec 842* | Bicycle and any motorized vehicle | 6.4 - 16 m (21 - 54 ft) slant range with corresponding footprints (El x Az) of 93.2 x 99.8 cm to 237.0 x 490.5 cm (36.7 x 39.3 in to 93.3 x 193.1 in) | <250 ms | >100 mi/h (160.9 km/h) | True presence detector with 6 minutes maximum hold time for vehicles in FOV of detector |
| Eltec 833* | Bicycle and any motorized vehicle | 5 - 30 m (16 - 98 ft) down range with corresponding footprint diameters of 0.4 to 2.2 m (1.3 to 7.2 ft) | 50 to 100 ms | 85 mi/h (136.8 km/h) | Pulse-type counting operation with count held for up to 4 seconds |

* Photon-sensitive elements made of lithium material). Spectralantalate (a type of pyroelectric material. response used is from 8 to 12 micrometers.

Table 4-4. Specifications of Microwave Detectors Evaluated

| Detector | Detectable Objects | Transmit Frequency | Power Output | Polarization (Transmit & Receive) | 3dB Beam-width | Speed Measurement Range | Speed Measurement Accuracy | Detection Range | Response Time |
|---|---|---|---|---|---|---|---|---|---|
| Microwave Sensors TC-20 | Mopeds and larger traveling at speeds > 2 mph at signal-controlled intersections | 10.525 GHz | -18 dBm (56,234 µV/m at 30 m distance) | Horizontal | 16 deg Az, 15 deg El (Ant Gain = 16.4 dB) | Not Applicable | Not Applicable | 1-30 m (3-100 ft) | 0.165 sec |
| Microwave Sensors TC-26 | Mopeds and larger traveling at speeds > 3 mph on city arterials and freeways | 10.525 GHz | -18 dBm (56,234 µV/m at 30 m distance) | Horizontal | 16 deg Az, 15 deg El (Ant Gain = 16.4 dB) | 5-106 km/h (3-66 mph) | •Speed is segregated into 1 of 5 bins which together cover the range 5 to 106+ km/h<br>•Speed is also available in terms of Doppler frequency shift to within ± 1 mph | Up to 61 m (200 ft) for autos; up to 107 m (350 ft) for trucks | 0.165 sec |
| Whelen TDN-30 | Any licensed motor vehicle separated by one car length and traveling at speeds > 5 mph | 10.525 GHz | < 2.5 $mW/cm^2$ | Horizontal | 7 deg (1st sidelobe at -10 dB) | 8 - 137 km/h (5 - 85 mph) | Within ± 2 mph at all speeds | Designed to project an ≈6-ft-diameter footprint at a mounting height of 32 ft | Not applicable since detector gives a direct speed measurement |
| Whelen TDW-10 | Multiple-lane coverage of any licensed motor vehicle traveling at speeds > 5 mph | 10.525 GHz | < 2 $mW/cm^2$ | Horizontal | 25 deg (1st sidelobe at -3 dB) | 8 - 137 km/h (5 - 85 mph) | Within ± 3 mph at all speeds | Up to 30.5 m (100 ft) | Not applicable since detector gives a direct speed measurement |

## Table 4-4. Specifications of Microwave Detectors Evaluated (continued)

| Detector | Detectable Objects | Transmit Frequency | Power Output | Polarization (Transmit & Receive) | 3dB Beamwidth | Speed Measurement Range | Speed Measurement Accuracy | Detection Range | Response Time |
|---|---|---|---|---|---|---|---|---|---|
| Electronic Integrated Systems Remote Traffic Microwave Sensor (RTMS) | Presence and speed detector for motorcycles and larger | 10.525 GHz | < 2.5 V/m at 3 m distance | Horizontal | 15 deg Az, 25 deg El<br>• Beam shaping results in a user-definable azimuth footprint of 10 to 15 ft at a range of 100 ft<br>• Beam shaping results in an effective elevation beamwidth of 50 deg | 0 - >160 km/hr (0 - >99 mph) | Within ± 10% | • Sidefire: Up to 12 lanes covered<br>• Up to 60 m (200 ft) with resolution of 2 m (7 ft) in 12 detection zones<br>• Overhead: 1 lane covered<br>• Occupancy of a zone at < 2% error<br>• Traffic volume in a zone at < 5% error | < 20 msec |

## Table 4-5. Specifications of Video image Processors Evaluated

| Manufacturer/ Model | Number of Traffic Lanes Monitored[a] | Speed Measurement Range | Speed Measurement Accuracy[b] | Detection Range | Vehicle Tracking |
|---|---|---|---|---|---|
| Econolite/ Autoscope 2003[d] | 8 | 0 to > 80 mi/h | ±2 mi/h | 46m (150 ft)[c] | No |
| Computer Recognition Systems/ Traffic Analysis System[e] | 4 | 0 to > 80 mi/h | ±2 to 5% | 46 m (150 ft)[c] | Yes |
| Traficon/ CCATS-Vi P 2[f] | 4 | 0 to 112 mi/h | | 46m (150 ft)[c] | Yes |
| Sumitomo/ IDET-1 00[g] | 4 | 0 to 100 mi/h (3 lanes),<br>0 to 75 mi/h (4 lanes) | ±5% | | Yes |
| EVA/ 2000[h] | 4 | 0 to 155 mi/h | | 29 m (95 ft)[h] | Yes |

1 mi/h = 1.61 km/h

a. Per camera.

b. Function of frame rate, camera resolution, vehicle speed, and camera mounting height.

c. Based on vehicle occlusion as a function of camera mounting height, intervehicle gap, and vehicle height. Value in table reflects mounting height = 25 ft (7.6 m), intervehicle gap = 30 ft (9.1 m), and vehicle height = 5 ft (1.5 m).

d. Typical traffic data reported by Autoscope include volume (number of vehicles/time interval), lane occupancy (time vehicle is in detection zone divided by the time interval), headway over time (average number of seconds between consecutive vehicles during the time interval), speed of a single vehicle, average speed of all vehicles during the time interval, classification of a single detection based on vehicle length (three classes are available), and classification of time interval data.(3)

e. Typical traffic data reported by the Traffic Analysis System include mean speed of vehicles in each of three classes; overall mean speed; length of the vehicle; area of the vehicle; number of vehicles in each of the three classes; total number of vehicles; density of vehicles; occupancy; and per lane parameters that include number of vehicles, average speed, density, and occupancy.(4)

f. CCATS-VIP 2 incorporates a graphical data interpretation and display package that outputs total number of vehicles and number per lane, gap time between vehicles, occupancy per lane, vehicle classification (up to three types) based on length, mean length of all detected vehicles, and alarms at lower and upper thresholds set by user.(5)

g. Traffic data is reported by the IDET-100 by lane over an RS-232 interface. Data include vehicle detection with a 90 percent accuracy; vehicle type as small or large; velocity in km/h; vehicle motion as moving, recently stopped, or parked; and the pulse width of the detection signal. The maximum length of the detection zone is 20 meters. The speed measurement accuracy of ± 10 percent is based on a field test of approximately 250 units in Japan.(6,7)

h. EVA 2000 provides volume, average speed, density, occupancy, average spatial headway, and count, each on a per lane and vehicle type (two types are supported) basis. Tracks individual vehicles, even when they cross lanes,(8)

Table 4-6. Specifications of Passive Acoustic Detectors Evaluated

| Manufacturer/ Model | Number of Traffic Lanes Monitored | Detection Frequency Band | Detection Beam Pattern | Detection Range | Response Time |
|---|---|---|---|---|---|
| AT&T/ SmartSonic TSS-1 | Single detection zone in 1 lane from overhead mount | 4kHz to 6 kHz | 6 deg (3 dB)<br>20 deg (10 dB) | 20 to 35 feet (6.1 to 10.7 m) | 50 ms |

## Table 4-7. Inductive Loop Detector Specifications

| Parameter | NEMA TS-1<br>1989 | California<br>July 1989 | Connecticut<br>1991-1992 | Florida<br>May 1991 |
|---|---|---|---|---|
| Reference to NEMA specifications made | Not Applicable | No | No | No, but many NEMA sections included |
| Type of vehicle detected | Class 1:<br>small motorcycle<br>Class 2:<br>large motorcycle<br>Class 3:<br>automobile | All motor vehicles that can be licensed in California | Not specified | Class 1:<br>small motorcycle<br>Class 2:<br>large motorcycle<br>Class 3:<br>automobile |
| Speed Range | 5 to 80 mph | Not specified | Parked and speeds greater than 0 mph | 5 to 80 mph |
| Sensitivity | A minimum of 3 settings<br>Shall be able to detect Class 1, 2, or 3 vehicle when connected to any test loop described below | A minimum of 7 selectable sensitivity settings<br>Shall detect vehicle with minimum change in inductance of 0.02% at setting 6 | Not specified | A minimum of 3 settings<br>Shall be able to detect Class 1, 2, or 3 vehicle when connected to any test loop described below |
| Response Time | For Class 1 vehicle, less than 126 msec;<br>For Class 3 vehicle, less than 51 msec | 5 ± 1 msec for sensitivity setting 2 | Not specified | For Class 1 vehicle, less than 126 msec;<br>For Class 3 vehicle, less than 51 msec |
| Detection zone | 3 feet maximum beyond loop | 3 feet maximum beyond loop | Not specified | 3 feet maximum beyond loop |
| Pulse Mode | Output between 100 - 150 msec when test vehicle enters detection zone | Output pulse of 125 **± 25** msec when test vehicle enters detection zone | Output pulse not specified | Output between 75 to 150 msec when test vehicle enters detection zone |

## Table 4-7. Inductive Loop Detector Specifications (continued)

| Parameter | NEMA TS-1 1989 | California July 1989 | Connecticut 1991-1992 | Florida May 1991 |
|---|---|---|---|---|
| Presence Mode | When a Class 2 vehicle is over a test loop, the detector output shall be maintained for at least 3 minutes if vehicle remains that long | At sensitivity setting 6, the minimum duration of the detector output shall be 3 minutes if vehicle remains that long | Detection shall persist up to at least 10 minutes | When a Class 2 vehicle is over a test loop, the detector output shall be maintained for at least 3 minutes if vehicle remains that long |
| Recovery from sustained occupancy | Detector shall recover 90% of normal sensitivity within 1 sec after vehicle leaves detection zone | Detector shall recover normal sensitivity within 1 sec after vehicle leaves detection zone | Not specified | Detector shall recover 90% of normal sensitivity within 1 sec after vehicle leaves detection zone |
| Environmental change | Detector shall automatically adjust for changes in loop/ lead-in properties which might be reasonably expected | Detector shall compensate for a change in inductance of 0.001% per sec, up to a total change of + 5.0%<br>Temperature changes of up to 1 deg C per 3 minutes shall not affect detector operation | Detector shall compensate for environmental drift<br>Detector shall operate properly between -30 deg F and 150 deg F | Detector shall automatically adjust for changes in loop/ lead-in properties which might be reasonably expected |
| Delay Operation | Detector output delayed from 0 to 15 sec in 1-sec increments, and from 16 to 30 sec in 2-sec increments | Not specified | Detector output delayed from 0 to 31 sec in 1-sec increments | Detector output delayed from 0 to 30 sec |
| Extended Operation | Detector output extended from time vehicle leaves loop by 0 to 7.5 sec in 1/2-sec increments | Not specified | Detector output extended from time vehicle leaves loop by 0 to 15.5 sec in 1/2-sec increments | Not specified |

## Table 4-7. Inductive Loop Detector Specifications (continued)

| Parameter | Georgia | Missouri | New York June 1990 | Oklahoma |
|---|---|---|---|---|
| Reference to NEMA specifications made | Not mentioned | Not mentioned | No | Yes |
| Type of vehicle detected | Not specified | Not specified | All licensed motor vehicles except mopeds | Not specified – see NEMA spec |
| Speed Range | 0 to 80 mph | 0 to 80 mph | Not specified | 0 to 100 mph |
| Sensitivity | Shall detect a vehicle with minimum change in inductance of 0.02% | Not specified | A minimum of 7 selectable sensitivity settings<br>Shall detect vehicles with minimum change in inductance of 0.02% at setting 6 | Not specified – see NEMA |
| Response Time | Not specified | Not specified | 5 ± 1 msec for sensitivity setting 2 | Not specified – see NEMA |
| Detection Zone | Not specified | Not specified | 3 feet maximum beyond loop | Not specified – see NEMA |
| Pulse Mode | Output pulse not specified | Output pulse not specified | Output pulse of 125 ± 25 msec when test vehicle enters detection zone | Required,but not specified – see NEMA |
| Presence Mode | When a Class 2 vehicle is over the test loop, the detector output shall be maintained for at least 3 minutes.if vehicle remains that long | At sensitivity setting 6, the duration of the detector output shall be 3 minutes if vehicle remains that long | Detection shall persist up to at least 10 minutes | When a Class 2 vehicle is over a test loop, the detector output shall be maintained for at least 3 minutes if vehicle remains that long |

## Table 4-7. Inductive Loop Detector Specifications (continued)

| Parameter | Georgia | Missouri | New York June 1990 | Oklahoma |
|---|---|---|---|---|
| Recovery from sustained occupancy | Detector shall recover 90% of normal sensitivity within 1 sec after vehicle leaves detection zone | Detector shall recover normal sensitivity within 1 sec after veh. leaves detection zone | Not specified | Detector shall recover 90% of normal sensitivity within 1 sec after vehicle leaves detection zone |
| Environmental change | Detection shall automatically adjust for changes in loop/ lead-in properties which might be reasonably expected | Detector shall compensate for a change in inductance of 0.001% per sec, up to a total change of ± 5.0%<br>Temperature changes of up to 1 deg C per 3 minutes shall not affect detector operation | Detector shall compensate for environmental drift<br>Detector shall operate properly between -30 deg F and +150 deg F | Detector shall automatically adjust for changes in loop/ lead-in properties which might be reasonably expected |
| Delay Operation | Detector output delayed from 0 to 15 sec in 1-sec increments, and from 16 to 30 sec in 2-sec increments | Not specified | Detector output delayed from 0 to 31 sec in 1-sec increments | Detector output delayed from 0 to 30 sec |
| Extended Operation | Detector output extended from time vehicle leaves loop by 0 to 7.5 sec in 1/2-sec increments | Not specified | Detector output extended from time vehicle leaves loop by 0 to 15.5 sec in 1/2-sec increments | Not specified |

## Table 4-8. Magnetometer Specifications

| Parameter | Value |
|---|---|
| Operation Modes | Two, Pulse and Presence |
| Vehicle Types | Auto, trucks, buses, motorcycles, motor bikes, bicycles |
| **Vehicle Speed** | 0 to 100 mi/h (160.9 km/h) |
| Selectivity | High steel concentrated area shall not affect operation |
| Output Signal | Pulse Mode: Relay contact closure of 25ms minimum (Connecticut); 125 ± 25 ms (California)<br>Presence Mode: Relay contact closure for duration of presence of the vehicle (Connecticut); same for California except add that indication shall cease within 100 ms |
| Detection Area | 18 inches (457.2 mm) minimum on either side of sensing head |
| Distance Between Control Unit and Sensing Head | 3000 feet (914.4m) minimum |
| Power Interruption | The control unit shall return to normal operation within 3 minutes following a power interruption |

detectors. The above-the-road models were evaluated during the laboratory and field tests. Inductive loops and magnetometers were evaluated with the above-the-road technology models during the field tests. The specific inductive loop detector amplifier models and magnetometers used in the field tests were selected in consultation with the host cities and states and the manufacturers. Inductive loops were cut using state-of-the-art installation techniques. The detector amplifiers were supplied by the host agency and were representative of state-of-the-art signal processing technology. Loop and magnetometer manufacturers and distributors, including Indicator Controls Corporation, Detector Systems, Saratec Traffic, and 3M, were contacted to obtain copies of specifications and performance data for their most current products.

## 4.3 TECHNICAL JUSTIFICATION

The technical justification for detector selection and rejection in the field tests was based on:

- Detector performance in freeway and surface street demonstration tests conducted by Hughes, DOTS, and other evaluation projects funded by states or FHWA;
- Detector design criteria that allow operation in anticipated weather environments;
- Availability of detectors in time to meet laboratory and field test and evaluation schedules;
- Manufacturer support to help interpret specifications and evaluation data, and make available RS-232 serial data protocols that describe the data output by the detector.

Detector performance was judged against the specifications provided by the manufacturer. If the laboratory or other demonstration test performance met the manufacturer's specifications and the specifications represented state-of-the-art performance, then the detectors were used in the field tests.

The manufacturers design criteria and test data helped determine if the detectors operated in cold, hot, fog, and wet weather environments and in electrical disturbances, such as lightning, anticipated for the field tests.

Availability of detectors became a consideration because of the lead time needed to set up equipment and build required mounting brackets and interface electronics. Some of the detectors are new development models whose production-model runs do not yet exist.

Manufacturer support in making available specifications, operating procedures, and test procedures not normally supplied with the detectors made the laboratory and field testing of these devices easier and more meaningful.

A selection matrix showing which of the technical criteria are satisfied by the detectors selected is given in Table 4-9.

All detectors that met these criteria were used in the field tests. As none of the detectors met all of the future IVHS requirements listed in Section 2, the field tests were instead used to verify performance of the current state-of-the-art detectors and to make recommendations for future improvements.

## 4.4 ON-BENCH PHOTOGRAPHS OF DETECTORS

Pages 4-16 through 4-26 contain photo graphs of the detectors that represent the technologies evaluated in the project. The detectors not shown were not available during the photography sessions. The manufacturers and specification summary corresponding to each detector model can be found in Tables 4-1 through 4-6. A brief description of each detector is given in Section 10.6.

## Table 4-9. Detector Output Data and Operating Environments

| Traffic Parameter / Detector Technology and Model | Data | | | | | | | Environment | | | | | | Mount | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Count | Presence | Speed | Speed Binning | Occupancy | Vehicle Length | Incident Detection | Adequate Range | Rain | Fog | Snow | Day | Night | Overhead* | Side Looking |
| *Ultrasonic* | | | | | | | | | | | | | | | |
| Sumitomo SDU-200 (RDU-101) | x | | x | | I | x | I | x | x | x | x | x | x | U | |
| Sumitomo SDU-300 | x | x | | | x | | I | x | x | x | x | x | x | N | |
| Microwave Sensors TC-30C | x | x | | | I | | I | x | x | x | x | x | x | N | |
| *Infrared (Active)* | | | | | | | | | | | | | | | |
| Schwartz Electro-Optics | x | x | x | | I | x | I | x | ? | ? | ? | x | x | U,D | |
| *Infrared (Passive)* | | | | | | | | | | | | | | | |
| Eltec 842 | x | x | | | I | | I | x | ? | ? | ? | x | x | U,D** | |
| Eltec 833 | x | | | | | | I | x | ? | ? | ? | x | x | U,D | |
| *Microwave Radar* | | | | | | | | | | | | | | | |
| Microwave Sensors TC-20 | x | | | | | | | x | x | x | x | x | x | U,D | x |
| Microwave Sensors TC-26 | x | | | x | | | I | x | x | x | x | x | x | U,D | |
| Whelen TDN-30 | x | | x | | | | I | x | x | x | x | x | x | U,D | |
| Whelen TDW-10 | x | | x | | | | I | x | x | x | x | x | x | U,D | |
| Electronic Integ. Systems RTMS | x | x | x | | x | | I | x | x | x | x | x | x | U,D | x |
| *Video Image Processing* | | | | | | | | | | | | | | | |
| AutoScope 2003 | x | x | x | x | x | x | x | x | ? | ? | ? | x | x | U,D | x |
| Computer Recog. Systems TAS | x | x | x | x | x | x | x | x | ? | ? | ? | x | x | U,D | x |
| Golden River Traffic C-CATS | x | x | x | x | x | x | x | x | ? | ? | ? | x | x | U,D | x |
| Sumitomo IDET-100 | x | x | x | x | x | x | x | x | ? | ? | ? | x | x | U,D | x |
| EVA 2000 | x | x | x | x | x | x | x | x | ? | ? | ? | x | x | U,D | x |
| *Acoustic Array* | | | | | | | | | | | | | | | |
| AT&T TSS-1 | x | x | | | x | | | x | ? | x | ? | x | x | D | |
| *Inductive Loop Detectors* | x | x | I | | x | | I | x | x | x | x | x | x | | |
| *Magnetometers* | x | x | I | | x | | I | x | x | x | x | x | x | | |

* U = functions when viewing upstream, D = functions when viewing downstream, N = functions when viewing in nadir direction.

** Manufacturer recommends that Model 842 be mounted at an oblique angle to the traffic flow.

*x* represents either (1) data that are measured directly, (2) acceptable operating environments, or (3) side-mounted operation.

*I* represents information available through processing of detector data, i.e., indirectly available information.

*?* represents a possible degradation in performance dependent on the severity of the environment.

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8. EVA 2000 Vi[illegible] Image Processor for Measuring Traffic Variables, Copyright 1993 by EVA, Inc.

# 5. THEORY OF OPERATION OF DETECTOR TECHNOLOGIES

The quest for a reliable and cost-effective vehicle detection and tracking system that can be installed and maintained with safety and minimal disruption of traffic, and can provide traffic data at least as accurate as the loop detector has been underway for some time.(1,2)Not only are detectors used to actuate traffic control devices and detect incidents, but they are also appearing in automatic vehicle identification applications associated with electronic toll and traffic management (ETTM) as discussed at the end of this section. Still other applications include sensing of vehicle presence, turning movements, and speed for advanced vehicle control systems.

This section reviews above-the-road and below-the-surface detector technologies. The above-the-road devices have the potential to replace inductive loop detectors for intersection control, traffic surveillance, and incident detection. Many of these technologies are in limited application in demonstration projects where their potential to supply accurate data is being evaluated.@) The lessons learned are anticipated to lead to further enhancements. The section concludes with a discussion of automatic vehicle identification applications.

## 5.1 VIDEO IMAGE PROCESSORS

Video cameras were first introduced to provide roadway surveillance. They transmitted closed circuit television (CCTV) imagery to a human operator for interpretation. More advanced techniques now use video image processing to automatically analyze the scene of interest and extract information for traffic surveillance and control. Typically, the imagery is digitized in hardware that is hosted in a personal computer (PC) architecture. The PC also accommodates application-specific software used to calculate the desired traffic parameters. Video image processors (VIPs) can replace several in-ground inductive loops by a single above-the-road camera and signal processing that provide area-wide detection of vehicles and the promise of lower maintenance costs. Some VIP systems process data from more than one camera and thus increase the data collection area even further.

VIPs have the potential to classify vehicles and report vehicle presence, volume, occupancy, and speed for each class and for each lane observed. Other potentially available traffic parameters are density and link travel time.

### 5.1.1 Operation

Most current video image processors analyze imagery transmitted to them at full frame rates of 30 frames/s. Some can conserve transmission bandwidth by performing image processing in the camera or at the roadside controller and transmitting only low-bandwidth numerical traffic data to the operations center as shown in Figure 5-l. In addition to the traffic parameters, the detector interface module can transmit information that allows icons to be displayed on monitors in the traffic management center by using a combination of computer hardware and software located at the center. The icons represent the real-time traffic flow occurring on the freeway and the tracks of vehicles within the field-of-view of the camera. Different shaped and colored symbols can be created to represent automobiles, buses, trucks, motorcycles, etc. The icon representation of traffic flow, as compared to the display of full bandwidth video imagery, allows lower bandwidth transmission media to be used. The full bandwidth imagery is still available on demand for transmission to the operations center to verify and identify incidents and recurring congestion. By multiplexing video images from several cameras on one transmission line and sending the video only when requested, operating costs associated with leased transmission media are further reduced.

New generation VIPs are being developed to process high-resolution visible and infrared camera imagery with embedded algorithms

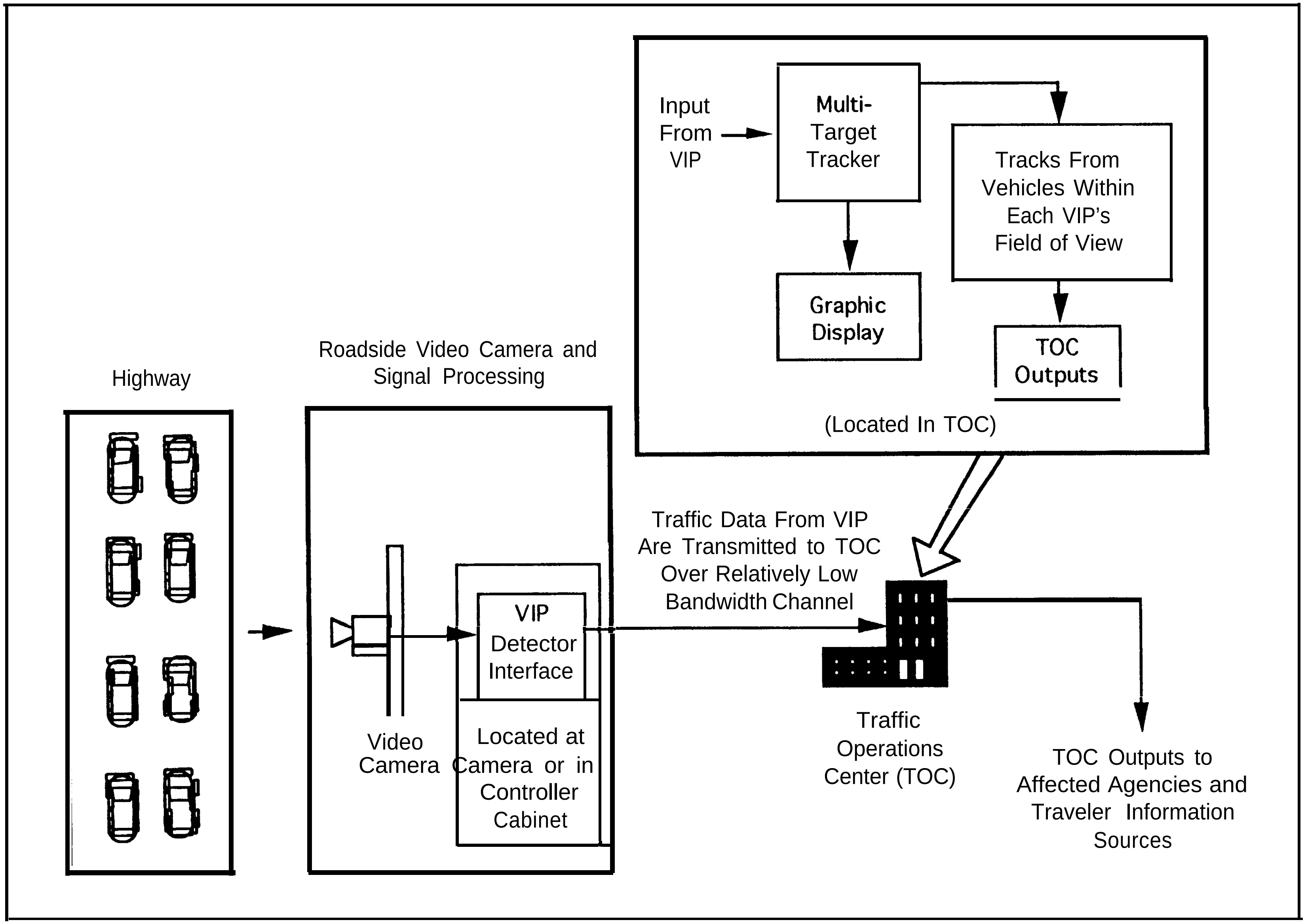


Figure 5-1. Modern Video Image Processor Incorporating Roadside Signal Processing

that are not susceptible to variations in ambient light, shadows, or other artifacts that can otherwise corrupt the traffic data. Several VIPs identify and track vehicles and then estimate the future position of the vehicle. These VIPs have the potential to transmit information to roadside displays and radios that alert drivers to factors that can lead to an incident. Other VIPs use information from a combination of sensors sensitive to visible, infrared, and ultraviolet wavelengths to detect vehicles and remove artifacts.

### 5.1.2 Mounting and Traffic Viewing Considerations

Table 5-1 shows how processing of upstream or downstream imagery influences VIP performance. The primary advantage of upstream viewing is that incidents are not blocked by the resulting traffic queues. However, tall trucks may block the line of sight and headlights may cause blooming of the imagery. Downstream viewing offers advantages of camera concealment so that driver behavior is not altered, easier identification and tracking of vehicles using information contained in the tail lights, and better acquisition of vehicle tracks because the vehicles are closer to the camera at track initiation.

Based on line-of-sight considerations, the detection distance at which a VIP can differentiate two closely spaced vehicles along the surface of a road is a function of camera mounting height, inter-vehicle distance or gap, and vehicle height as shown in Figure 5-2. The maximum detection distance $D_{max}$ along a roadway without a grade is given by

$$D_{\max} = h \frac{Vehgap}{Vehheight} \qquad (5\text{-}1)$$

**where**

$h$ = camera mounting height,

$vehgap$ = inter-vehicle gap, and

$Vehheight$ = vehicle height.

Other factors to be considered when installing cameras used in VIP systems include: (4)

- Vertical and lateral viewing angles,
- Number of lanes observed,
- Stability with respect to wind and vibration,

and

- Image quality.

VIPs tolerate an oblique view of the highway if the mounting height is high, say 45 to 50 feet (13.7 to 15.2 m). For lower heights in the vicinity of 18 to 25 feet (5.5 to 7.6 m), a mounting location centered over the area of interest may be required. However, the lower the camera, the greater is the error in vehicle speed measurement, as the measurement error is proportional to the vehicle height divided by the camera mounting height.

The number of lanes of imagery analyzed by the VIP becomes important when the required field of view is larger than the VIP's capability. For example, if the VIP provides data from detection zones in three lanes, but five must be observed, that particular VIP may not be appropriate for the application.

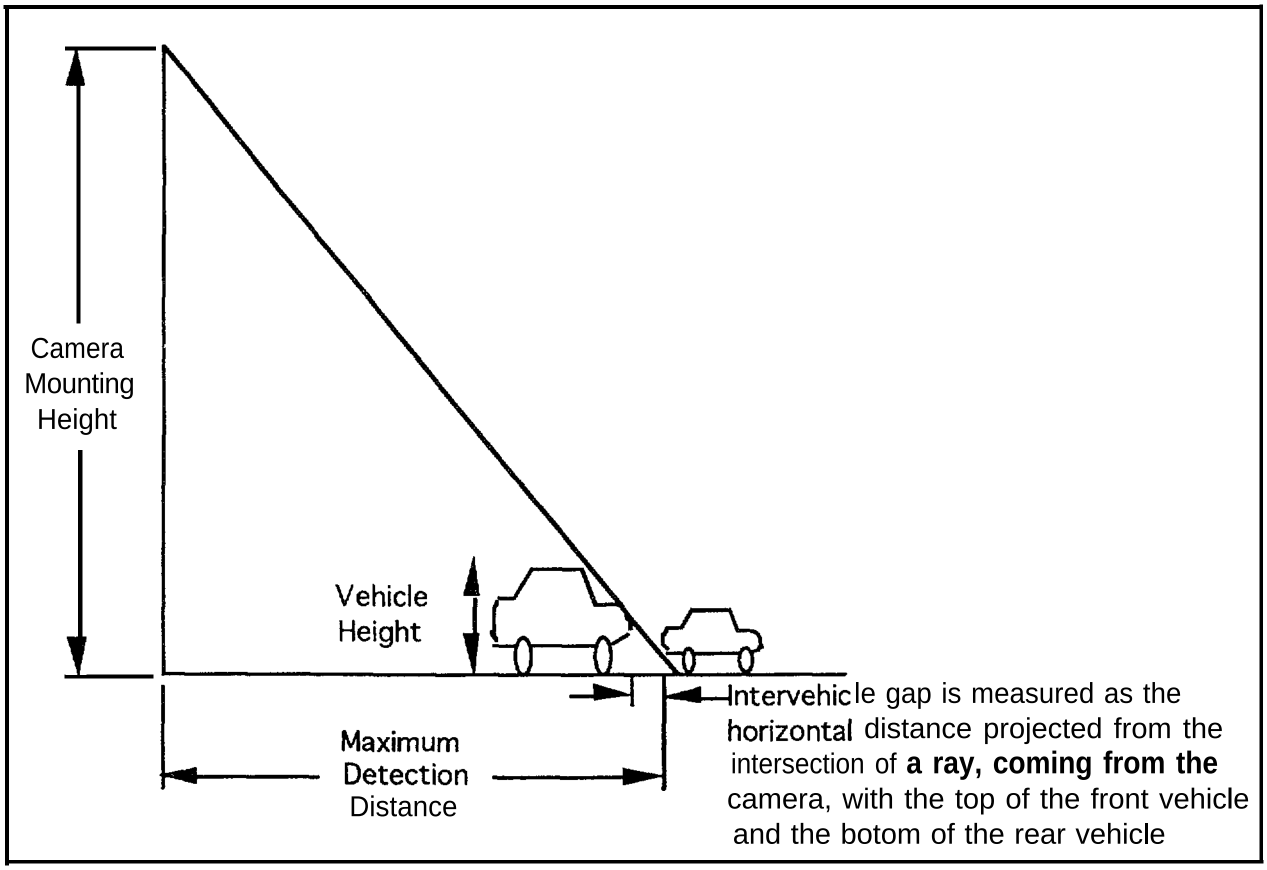
VIPs sensitive to large camera motion may be adversely affected by strong winds. Algorithms that predict the future path of a vehicle (such as a Kalman filter) and smooth its track may reduce sensitivity to camera motion.

Image quality and interpretation can be affected by cameras that have automatic iris and automatic gain control. In tests conducted by California Polytechnic Institute at San Luis Obispo, these systems were disabled.(4) In still other VIPs, the signal processing is tailored to take advantage of automatic light control systems.

Using the same camera for automatic vehicle detection with a VIP, and video surveillance with pan, tilt, and zoom features requires the camera to be repositioned for each application. If the field of view is not returned to the calibrated value for VIP operation, the performance of the VIP is adversely affected. It may be technically feasible, however, to reposition the camera at previously established VIP detection zones after it has been panned, tilted, or zoomed to view an incident location for verification and identification. In this case, one camera can be used for both applications. If the remote control of **cameras** and their return to calibrated fields of view is

**Table 5-1. Video Image Processor Characteristics as Used in Upstream and Downstream Viewing**

| Upstream Viewing | Downstream Viewing |
|---|---|
| - Headlight blooming and glare from wet pavement | • Camera concealed from drivers |
| - More blockage from tall trucks | • More information from tail lights available for braking indication, vehicle classification, and turning **movement** identification |
| - With infrared imagery, there is no difference in information obtained from headlights or tail lights when a tracking algorithm is used | - With visible imagery, more information is available to a tracking algorithm from tail light viewing |
| - Traffic incidents are not blocked by resulting traffic queues | • Easier to acquire vehicles that are closer to the camera for the tracking algorithm application |



Intervehicle gap is measured as the horizontal distance projected from the intersection of **a ray, coming from the** camera, with the top of the front vehicle and the botom of the rear vehicle

**Figure 5-2. Video Image Processor Line-of-Sight Detection Geometry**

not feasible, then separate cameras may be required to performautomated traffic data collection and video surveillance. When two cameras are used, a lower cost camera system will generally suffice for the VIP mission as the pan, tilt, and zoom features are not required.

### 51.3 Signal Processing

The data reduction and image formatting are performed with firmware that allows the algorithms to run in real time. The data reduction hardware is commonly implemented on a single formatter card in a personal computer. Once the data are digitized and stored by the formatter, spatial and temporal features are extracted from the vehicles in each detection zone with a series of image processing algorithms as illustrated in Figure 5-3. A detection process that establishes one or more thresholds is used to limit and segregate data passed on to the rest of the algorithms. It is undesirable to severely limit the number of potential vehicles during detection, for once data are removed they cannot be recovered. Therefore, false vehicle detections are permitted at this stage since the declaration of actual vehicles is not made at the conclusion of detection processing. Rather, algorithms contained in the steps still to come are relied on to eliminate false vehicles and retain the real ones.(5) Image segmentation is used to divide the image area into smaller regions where features can be better recognized. The features are analyzed to generate vehicle presence, speed, and classification data. Alternatively, neural networks can be trained to recognize and count different classes of vehicles and detect incidents.(G) Once individual vehicles are identified, they can be tracked by applying Kalman filter techniques. Tracking offers the potential ability to warn of impending incidents due to abrupt lane changes or weaving.

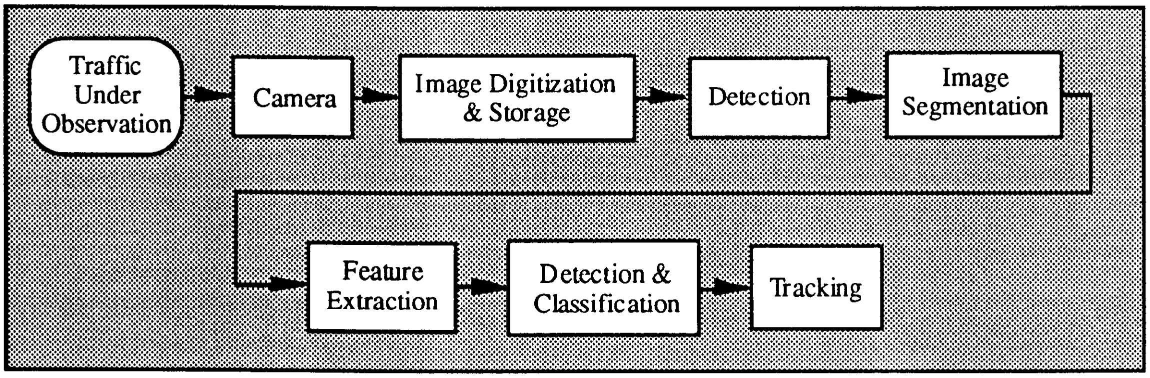


**Figure 5-3. Conceptual** Vehicle Detection, Classification, **and Tracking System**

There are two algorithmic approaches employed in image processors. In the first, VIPs detect vehicles at **a** number of fixed locations within the field of view of the camera by having the operator use interactive graphics to place the detection areas or zones. The zones can be oriented perpendicular, parallel, or at an oblique angle to the roadway lanes. Ideally, a signal is generated when a vehicle enters a detection zone. Some zone orientations, such as those parallel to a lane, **were found to be less sensitive** to vehicles than zones perpendicular to the travel direction. Newer software has apparently remedied this problem. Since a single camera and VIP can provide detection zones across several lanes, the VIP system can replace many loops and provide wide-area vehicle detection.

VIPs employing the second approach track vehicles continuously through the field of view of the camera. Multiple detections of the vehicle along a track are used to validate the detection. Once validated, the vehicle is counted and its speed is measured.(7)

The detection zone approach estimates vehicle speed by using relatively closely spaced pairs of zones to measure the time between the signals generated by a vehicle traversing the adjacent zones. This is similar in concept to speed traps implemented with two inductive loop detectors. The tracking algorithm associates a series of detections with a vehicle to predict its future position and to calculate link travel times. The more advanced VIPs that track individual vehicles can directly calculate speed from the algorithm that tracks the vehicles.

VIP algorithms have been improved to ignore artifacts produced by shadows, illumination changes, and reflections, and to minimize effects of adverse weather. In addition, the heavy congestion that degraded early VIPs does not appear to present a problem to more modern systems. Combined results for clear and inclement weather show vehicle volume, speed, and occupancy measurement accuracies in excess of 95 percent using a single detection zone.(8) VIPs with single detection zones in a lane are useful for monitoring traffic volumes on a freeway. For signalized intersection control, where vehicle detection accuracies of 100 percent are desired, the number of detection zones in the field of view is increased to between two and four, dependent on the camera mounting and road geometry.

## 5.2 MICROWAVE DETECTORS

The use of microwave radar for detecting objects had its beginnings before and during Word War II. In fact, the word radar was derived from the functions that it performs: RAdio Detection And Ranging. The term ***microwave*** refers to the wavelength of the transmitted energy, usually between 1 and **30** cm corresponding to a frequency range of 1 GHz to 30 GHz. The prefix ***giga (G)*** represents $10^9$. Radar operating at frequencies above **30** GHz is referred to as millimeter-wave radar, again corresponding to the wavelength of the transmitted energy.

**Unlicensed operation of microwave detectors** for traffic data collection and monitoring is limited to frequencies in bands near 10.5 GHz and 24.0 GHz under Part 15 of Federal Communications Commission (FCC) regulations for microwave devices. Part 15.245 of the FCC rules for Field Disturbance Sensors allows unlicensed operation at frequency bands between 10.500 and 10.550 GHz and 24.075 and 24.175 GHz if the electrical field strength 3 meters from the transmitting antenna is 2.5 V/m or less. The field strength of harmonics present in the transmitted signal must be no greater than 25 mV/m at 3 meters distance. The signal must also be at least 50 dB down from its in-band value outside this band. Field disturbance sensors cannot carry information in their transmitted signal.

Part 15.209 of the FCC rules for general radiation emissions allows transmission in the 1- to 40-GHz frequency range if the field strength is limited to $500 \times 10^{-6}$ V/m at 3 meters.

Licensed transmission in the 33.4- to 36.0-GHz band is allowed under Part 90 FCC regulations for local government radio service. The output power is specified in the authorization. Transmission is secondary to U.S. government service. Both the manufacturer and the user need licenses. The telephone number for the Gettysburg, PA, FCC office that has jurisdiction for this service is (717) 337-I 212.

As shown in Figure 5-4, microwave detectors transmit energy toward an area of roadway from an antenna mounted overhead that illuminates approaching or departing traffic, or in a side-looking configuration that views traffic across several lanes. When a vehicle passes through the beam, a portion of the transmitted energy is reflected back to the antenna. The energy then enters a receiver where the detection is made.

Microwave detectors currently used in traffic applications transmit two types of waveforms. The first is a continuous wave of electromagnetic energy whose frequency does not change with time. A detector that uses this waveform is capable of detecting only moving vehicles. It measures the speed of vehicles in **its field of view using the Doppler principle.** Here the frequency of the received signal differs from that of the transmitted **signal *f*** by an amount ***fD*** equal to the Doppler frequency produced by the vehicle speed. The frequency shift thus denotes the passage of a vehicle. The relation between $f_D$, $f$, and vehicle speed $v$ is

$$f_D = \frac{2v}{c} f \cos\theta \qquad (5\text{-}2)$$

where $\theta$ is the angle between the direction of propagation of radar energy and direction of travel of the vehicle, and $c$ is the speed of light ($3 \times 10^8$ m/s). If the vehicle is traveling directly toward the detector, the Doppler shift is maximum and positive in value. At 10 GHz, the Doppler frequency shift is approximately 30 Hz per statute mile per hour of vehicle radial speed, which is calculated as ($v \cos\theta$). Doppler detectors that do not also include range measuring capability cannot detect motionless vehicles.

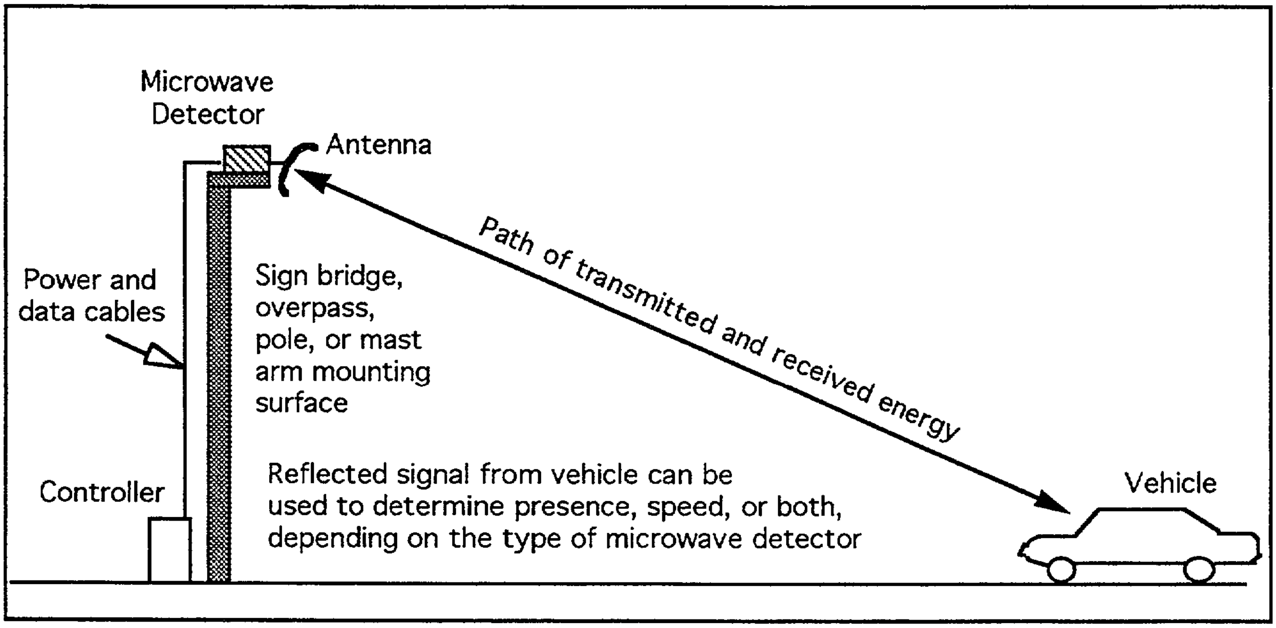


Figure 5-4. Microwave Detector

The second waveform is *sawtooth*, also called FMCW (frequency-modulated continuous wave), in which the transmitted frequency is constantly changing with respect to time, as shown in Figure 5-5.

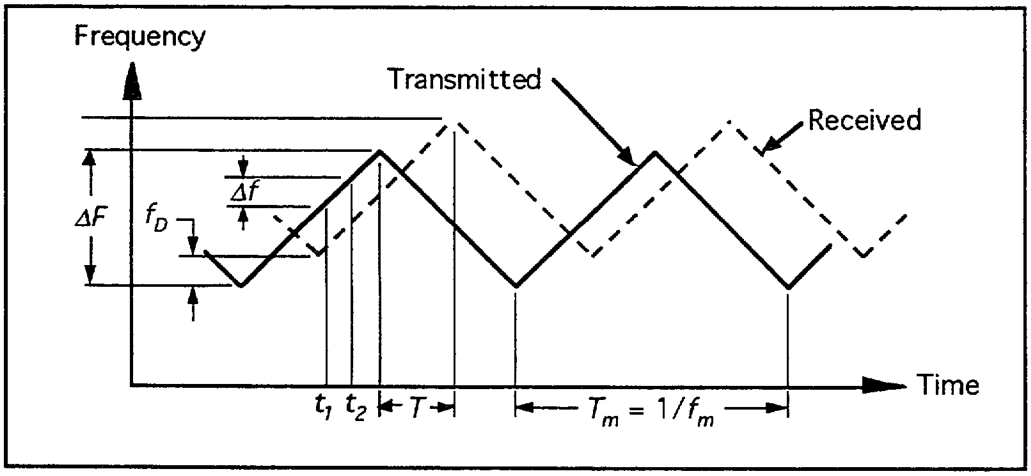


Figure 5-5. FMCW Waveform Parameters

Since the FMCW radar measures the range to the vehicle, it functions as a presence detector and can detect motionless vehicles. Range $R$ is proportional to the difference in the frequency $\Delta f$ of the transmitter at the time $t_1$ the signal is transmitted and the time $t_2$ at which it is received, as shown by

$$R = \frac{c\Delta f}{4\Delta F f_m} \qquad (5\text{-}3)$$

where

$\Delta f$ = instantaneous difference in frequency, in Hz, of the transmitter at the times the signal is transmitted and received,

$\Delta F$ = RF modulation bandwidth in Hz,

and

$f_m$ = RF modulation rate in Hz.

Alternatively, the range may be calculated by measuring the time difference $T$ between consecutive peaks in the transmitted and received signals, as shown in Figure 5-5, such that

$$R = cT/2 \qquad (5\text{-}4)$$

when the transmitter and receiver are collocated.

The FMCW radar measures vehicle speed in two ways. The first method is used when the radar's field of view in the direction of vehicle travel is divided into range bins as shown in Figure 5-6(a). A range bin allows the reflected signal to be partitioned and identified from smaller regions than the entire antenna footprint.

Speed $v$ is calculated from the time difference $\Delta T$ corresponding to the vehicle arriving at the leading edges of two range bins a known distance $d$ apart as shown in Figure 5-6(b) and is given by

$$v = \frac{d}{\Delta T} \qquad (5\text{-}5)$$

where $d$ = distance between leading edges of the two range bins and

$\Delta T$ = time difference corresponding to the vehicle arrival at the leading edge of each of the range bins.

The second method in which an FMCW radar measures speed is through the Doppler shift in frequency caused by the motion of a vehicle.(9) Referring to Figure 5-5, the instantaneous frequency difference between the two curves when they have positive slopes (upsweep) is given by

$$\delta f_u = \frac{4\Delta F f_m R}{c} - f_D \qquad (5\text{-}6)$$

and by

$$\delta f_d = \frac{4\Delta F f_m R}{c} + f_D \qquad (5\text{-}7)$$

when they have negative slopes (downsweep). Equation 5-3 is still valid when Doppler is present, as $\Delta f$ in equation 5-3 represents the average frequency difference measured when the slopes are positive and negative. The radial vehicle speed $v_R$ is

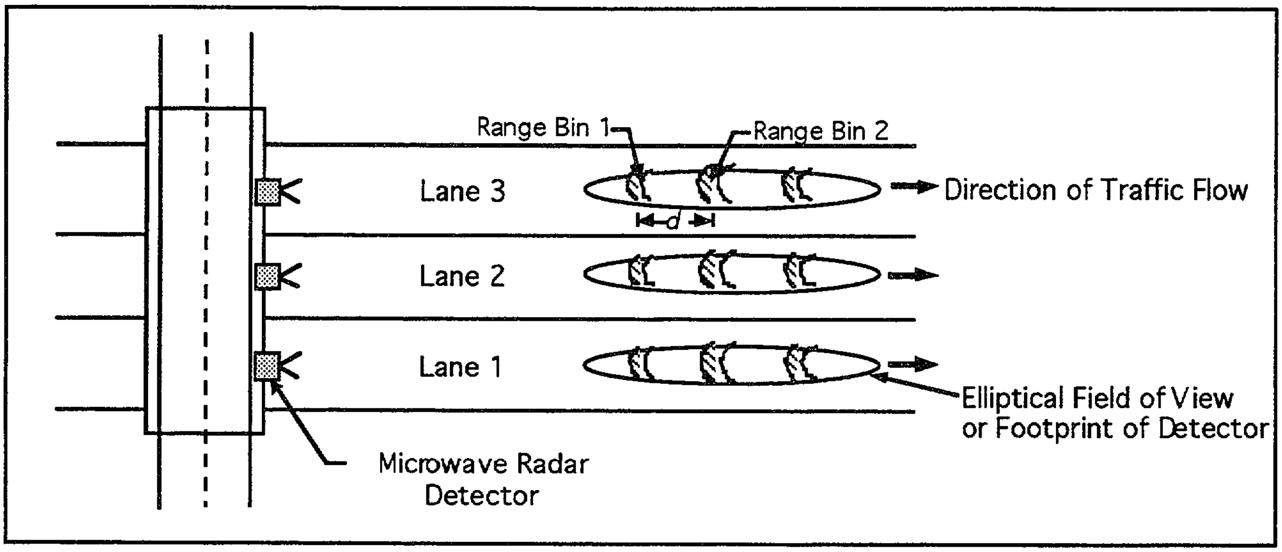
$$v_R = \frac{c}{4f}\,(\delta f_d - \delta f_u) \text{ or} \qquad (5\text{-}8a)$$

$$v_R = \frac{\lambda}{4}\,(\delta f_d - \delta f_u) \qquad (5\text{-}8b)$$

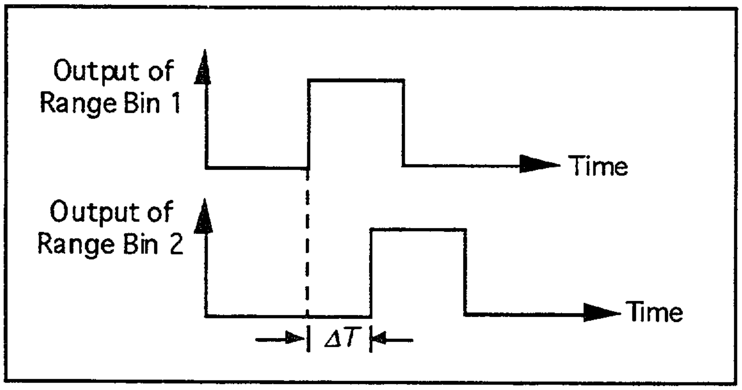
where $c = \lambda f$ and $\lambda$ is the wavelength of the transmitted energy. If the radar is forward looking, radial speed is equal to the vehicle speed toward or away from the radar multiplied by the cosine of the angle between the direction of propagation of radar energy and direction of travel of the vehicle.

To differentiate between multiple vehicles in the radar footprint, an FMCW radar can be designed with a three-segment waveform such as the one in Figure 5-7. $T_s$ represents the time duration of each segment.

An independent measure of radial speed $v_R$ is produced by the unmodulated horizontal portion of the waveform where $df/dt = 0$. The remainder of the frequency versus time curve is identical to the linear FM discussed above. Therefore, the differences in frequencies, $\delta f_u$ and $\delta f_d$, between the transmitted and received



(a) Range-Binned Footprints of Radar Detectors in Traffic Lanes



(b) Time-Phased Outputs of Range Bins

**Figure 5-6. Range-Binned Radar Footprint**

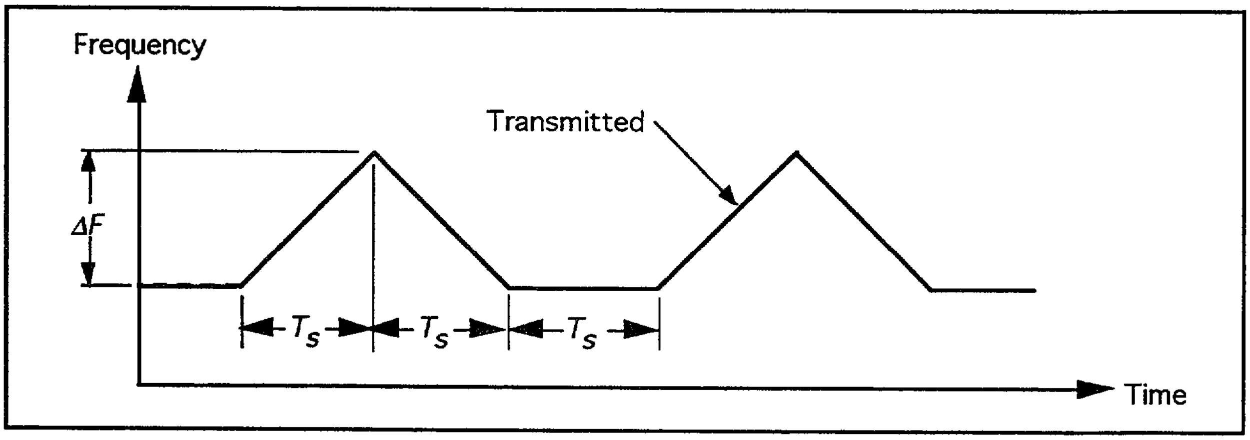


**Figure 5-7. Segmented Linear FM Waveform**

waveforms are identical to those given above. Since $f_D$ has already been found from the unmodulated portion of the curve, $\delta f_u$ and $\delta f_d$ can be used to find the unambiguous range and speed of multiple vehicles that appear in the radar footprint as described in Appendix D.(10)

Range resolution $\delta R$ of an FMCW radar is

$$dR = \frac{c}{2\Delta F} \qquad (5\text{-}9)$$

Therefore, if the radar operates in the 10.500- to 10.550-GHz band where bandwidth is limited to perhaps 45 MHz to ensure that the field strength is down by 50 dB outside the band, the range resolution is, at best, 3.3 m (10.8 ft).

Speed or Doppler resolution is given by

$$\Delta f_D = 1/T_s \qquad (5\text{-}10)$$

Presence-measuring radars can be used to control left-turn signals and monitor traffic queues. Radars that detect only moving vehicles from their Doppler frequency can be used to measure vehicular speed on both city arterials and freeways.

## 5.3 INFRARED DETECTORS

Infrared detection devices currently marketed consist of both *active* and *passive* models. Detectors are available for overhead mounting to view approaching or departing traffic or traffic from a side-looking configuration. In the active system, detection zones are illuminated with low-power infrared energy supplied by light-emitting diodes (LEDs) or with higher levels of energy supplied by laser diodes. None of the LED type of infrared detector was available for this study. The infrared energy reflected from vehicles traveling through the detection zone is focused by an optical system onto a detector matrix mounted on the focal plane of the optics. With infrared devices, the word *detector* takes on a new meaning, namely the energy-sensitive element(s) that converts the reflected energy into electrical signals. Real-time signal processing is used to analyze the received signals and to determine the presence of a vehicle. Changes in received signal levels caused by environmental effects, such as weather and shadows, can be accounted for by the signal processing.

Active infrared detectors provide vehicle presence at traffic signals, vehicle counting, speed measurement, length assessment, and queue measurement. Active infrared detectors can be designed with different fields of view when required for stop-line presence detection and for presence detection in the intersection approach (e.g., a detection zone 68 to 100 feet (20.7 to 30.5 m) in advance of the stop line). The units accommodate mounting heights of between 15 and 30 feet (4.6 to 9.1 m). Multiple units can be installed at the same intersection without interference from transmitted or received signals.

Passive infrared detectors supply similar traffic parameters except for speed. They use an energy-sensitive element located at the optical focal plane to measure the thermal energy emitted by objects in the field of view of the detector and do not transmit energy of their own. The source of the emitted energy is gray-body radiation due to the non-zero temperature of emissive objects as illustrated in Figure 5-8. When a vehicle enters the field of view, the change in emitted energy from the scene is used to detect the vehicle.

An equation can be written for the difference in energy corresponding to a vehicle entering the detector's field of view. The emissivity of the vehicle and road surface in the wavelength region of interest are denoted by $\varepsilon_V$ and $\varepsilon_R$, respectively, and their surface temperatures in degrees kelvin by $T_V$ and $T_R$. The apparent temperature $T_B$ of the vehicle, as sensed by the passive infrared detector, is

$$T_B(\theta,\phi) = \varepsilon_V T_V + (1 - \varepsilon_V)\, T_{Sky} \qquad (5\text{-}11)$$

$T_{Sky}$ is a function of atmospheric and cosmic emission. $\theta$ and $\phi$ are the incident angle with respect to nadir and the angle in the plane of the road surface (the *x-y* plane), respectively.

One can write a similar expression for the apparent temperature of the road surface as

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Alternatively, the range may be calculated by measuring the time difference $T$ between consecutive peaks in the transmitted and received signals, as shown in Figure 5-5, such that

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when the transmitter and receiver are collocated.

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and by

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when they have negative slopes (downsweep). Equation 5-3 is still valid when Doppler is present, as $\Delta f$ in equation 5-3 represents the average frequency difference measured when the slopes are positive and negative. The radial vehicle speed $v_R$ is

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$$v_R = \frac{\lambda}{4}\,(\delta f_d - \delta f_u) \qquad (5\text{-}8b)$$

where $c = \lambda f$ and $\lambda$ is the wavelength of the transmitted energy. If the radar is forward looking, radial speed is equal to the vehicle speed toward or away from the radar multiplied by the cosine of the angle between the direction of propagation of radar energy and direction of travel of the vehicle.

To differentiate between multiple vehicles in the radar footprint, an FMCW radar can be designed with a three-segment waveform such as the one in Figure 5-7. $T_s$ represents the time duration of each segment.

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## 5.4 ULTRASONIC DETECTORS

Ultrasonic vehicle detectors can be designed to receive range and Doppler speed data, the same information used by the radar detectors. Ultrasonic detectors transmit sound waves, at a selected frequency between 20 and 65 kHz, from overhead transducers into an area defined by the transmitter's beamwidth pattern. A portion of the energy is backscattered or reflected from the road surface or a vehicle in the field of view. The preferred viewing configurations for range-measuring (presence) ultrasonic detectors are downward (at a nadir incidence angle) and side viewing. The speed-measuring ultrasonic detector is forward-looking, facing approaching traffic. The transducers in both the presence and speed-measuring ultrasonic devices convert the received sonic energy into electrical energy that is fed to signal processing electronics, either collocated with the transducer or located in a roadside controller.

The range-measuring detector transmits a series of pulses of width $T_p$ (typical values range between 0.02 and 2.5 ms) and repetition period $T_o$ (time between bursts of pulses), typically 33 to 100 ms, as shown in Figure 5-9. The detector measures the time it takes for the pulse to arrive at the vehicle and return to the transmitter. The receiver is gated on and off with a user-adjustable interval that helps to differentiate between pulses reflected from the road surface and those reflected from vehicles. The detection gate is usually set to allow detection of an object at a distance greater than approximately 0.5 m above the road surface. This is accomplished by closing the detection gate several milliseconds before the reflected signal from the road surface arrives at the detector. Automatic pulse repetition frequency control is used to reduce effects of multiple reflections and to improve the detection of high-speed vehicles. These goals are met by making the pulse repetition period as short as possible by transmitting the next pulse immediately after the reflected signal from the road is received.(11) A hold time $T_h$ (composite values from manufacturers range from 115 ms to 10 s) is built into the detectors to enhance presence detection.

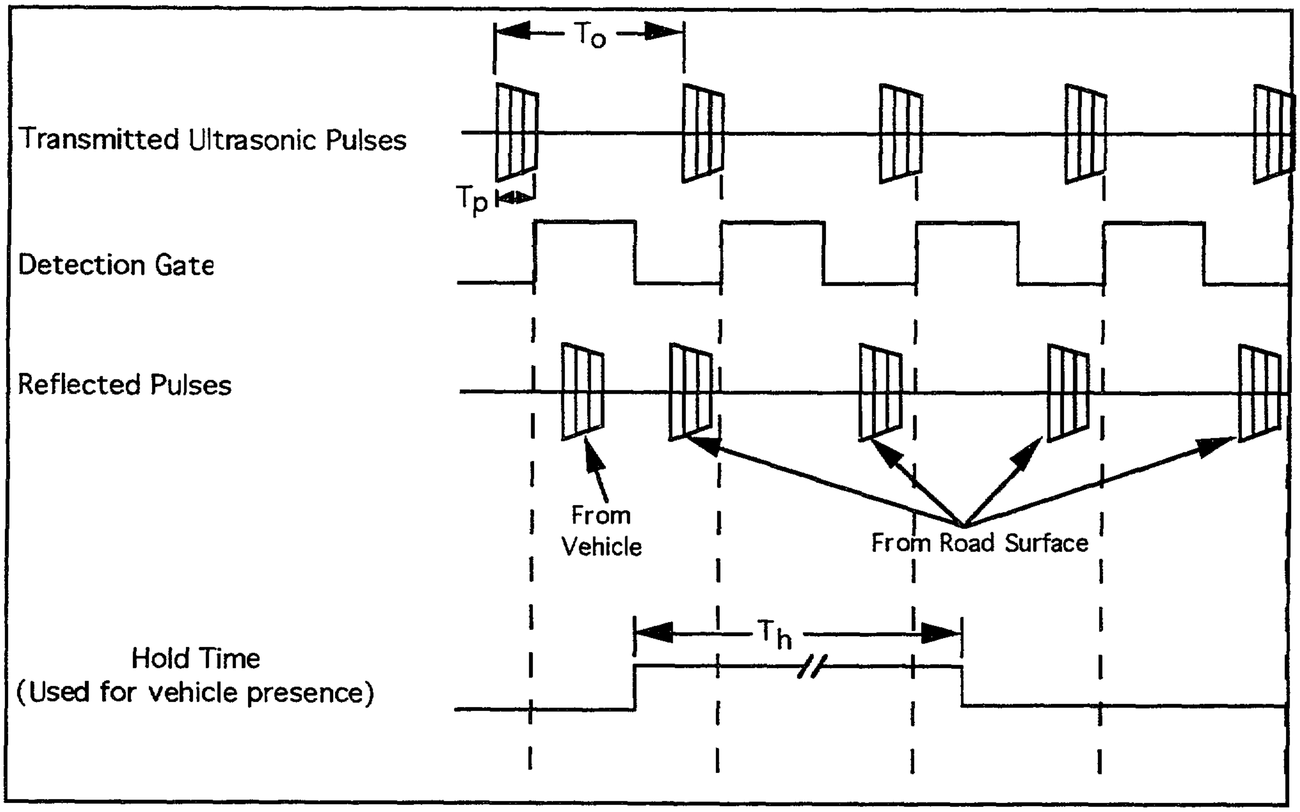

Figure 5-9. Operation of Range-Measuring Ultrasonic Detector

The speed (Doppler) measuring detector transmits a continuous wave of ultrasonic energy. It detects the passage of a vehicle by a shift in the frequency of the received signal. Vehicle speed can be calculated from the pulse width of an internal signal, generated by the detector's electronics, that is proportional to the speed of the detected vehicle.

## 5.5 PASSIVE ACOUSTIC DETECTOR ARRAYS

Vehicular traffic produces acoustic energy or audible sounds from a variety of sources within each vehicle and from the interaction of the vehicle's tires with the road. Although unintentional, the radiated sound acts as a beacon signal containing information that can be extracted by roadside acoustic energy detectors.

Arrays of passive acoustic microphones provide spatial directivity from which sounds are continuously detected and processed from a specific location along the highway. Sounds from locations outside the detection zone are rejected or attenuated. The size and shape of the detection zone are detemined by the aperture size, processing frequency band, and installation geometry of the acoustic array.

When a vehicle passes through the detection zone, an increase in sound energy is detected by the signal processing algorithm and a vehicle presence signal is generated. When the vehicle leaves the detection zone, the sound energy level drops below the detection threshold and the vehicle presence signal is terminated. Passive acoustic arrays can replace magnetic induction loops by providing vehicle presence outputs in the form of contact closures. Using this input, a traffic signal controller can calculate various traffic flow measures, such as volume, occupancy, and average speed.

## 5.6 INDUCTIVE LOOP DETECTORS

The data supplied by inductive loop detectors are vehicle passage, presence, count, and occupancy. The principal components of an inductive loop detector are one or more turns of insulated wire buried in a shallow cutout in the roadway, a lead-in cable which runs from a roadside pull box to the controller, and an electronics unit located in the controller cabinet. The wire loop is excited with a signal ranging in frequency from 10 kHz to 200 kHz and functions as an inductive element in conjunction with the electronics unit. When a vehicle stops on or passes over the loop, its inductance is decreased. The decreased inductance increases the oscillation frequency and causes the electronics unit to send a pulse to the controller, indicating the presence or passage of a vehicle.

The introduction of digital signal processors has allowed more reliable, accurate, and precise measurement of the change in oscillation frequency or period associated with the loop output that is produced when a vehicle passes over the loop. The improved capability of the detector, in turn, has increased the accuracy of the presence, count, and occupancy measurements. The data processed in the electronics unit can be either the changes in frequency or period that are measured, or the ratio of the change to its initial value.(12) The processing techniques are called:

- Digital frequency shift,
- Digital ratio frequency shift,
- Digital period shift, and
- Digital ratio period shift.

The inductive loop detector represents a mature technology. Reliability of the loop has been improved through better packaging and installation techniques. These include delivery of loops already encased by the manufacturer in protective materials, more thorough cleaning of debris from the sawcut, and the use of better sealants in the installation process.

The output of most current inductive loop detectors is a simple relay or semiconductor closure, signifying the presence or absence of a vehicle. In advanced detector processing systems, some vehicle classification and fault detection can be performed by digitizing the detector output and feeding it to a microprocessor containing embedded signal processing algorithms. These match the detector output to stored signatures for specific vehicle types or fault conditions. Digital codes can be output to identify the type of vehicle detected or report detection faults to a central processing unit.

In the past two decades, loop detector technology has become the most widely used and accepted traffic detector technology in America today. The loop detector system, however, may still suffer from poor reliability, primarily from improper connections made in the pull boxes and in the application of sealants over the sawcut. These problems are accentuated when loops are installed in poor pavement or in areas where utilities frequently dig up the roadbed. Reliability can be improved by installing loops using newer procedures and loop wire protective enclosures developed by manufacturers and user agencies. Improved traffic system operation can be obtained by holding daily loop status meetings at which the malfunctioning loop detector locations are identified and repair teams are dispatched. Another disadvantage of loops is their inability to directly measure speed. If speed is required, then a two-loop speed trap is employed or an algorithm involving loop length, average vehicle length, time over the detector, and number of vehicles counted is used with a single loop detector.

## 5.7 MAGNETIC DETECTORS

Magnetic detectors indicate the presence of a metallic object by the disruption it causes in an induced or natural magnetic field. These detectors may be active devices, as with magnetometers, or passive devices, as with magnetic detectors. An example of a magnetometer is the 1 -inch (25.4-mm) diameter by 4-inch ( 10 1.6-mm) long (approximate) detector that is buried about 12 to 18 inches (304.8 to 457.2 mm) below the surface of a road. Two types of passive magnetic detectors exist. One is subsurface-mounted and the other is mounted flush with the roadway. The primary use of magnetic anomaly detectors is to supplement or enhance data from other types of traffic detectors, although they are sometimes used in stand-alone applications.

### 5.7.1 Magnetometers

Magnetometers are active devices, excited with an electrical current in windings around a magnetic core material. They measure the passage of a vehicle when operated in the pulse output mode and give a continuous output as long as a vehicle occupies the zone of detection when operated in the presence mode. They are used where point or small-area location of a vehicle is required, such as on bridge decks and viaducts where inductive loops are disrupted by the steel support structure or can weaken the existing structure.

The Self-Powered Vehicle Detector (SPVD), developed with FHWA support, is a magnetometer detector with a self-contained battery and transmitter that broadcasts passage or presence information to a receiver that can be located remotely in a controller cabinet. A direct connection (lead-in cable) is not required. An antenna is built into the housing that encloses the magnetometer electronics and battery. The current SPVD model fits into a cylindrical hole 6 inches (152.4 mm) in diameter and 22 inches (558.8 mm) deep. Most of the volume is occupied by the battery. SPVDs have applications where temporary installations are needed or where they can be easily mounted under bridges or viaducts. Their suitability for permanent installation is a function of traffic volume and battery type. Telemetry-based traffic counters can also use spread-spectrum transmission to broadcast vehicle-count data to a receiver that can be located several miles away from the detector.

### 5.7.2 Passive Magnetic Detectors

Passive magnetic detectors sense perturbations in the Earth's magnetic flux produced when a vehicle passes over the detection zone. They require some minimum vehicle speed for detection, usually 3 to 5 mi/h (4.8 to 8.0 km/h) and, hence, cannot be used as a presence detector.

The two types of passive magnetic detectors differ only in their installation and size. One type is installed by tunneling under the roadway and inserting it into non-ferrous conduit. The other type is installed flush with the pavement. The first is 2 inches (50.8 mm) in diameter by 20 inches (508.0 mm) long. The second is approximately 3 inches by 5 inches by 20 inches long (76.2 mm by 127.0 mm by 508.0 mm long), encased in a cast aluminum housing and flush-mounted with the road surface. Passive magnetic detectors are responsive to flux changes over a large area, covering up to three lanes. If the lanes are considerably wider than 12 feet (3.7 m), several detectors may be required to get a response from small vehicles and motorcycles.

### 5.7.3 Selection Criteria and Future Trends

The criteria for selecting a magnetic sensor include the desired occupancy and traffic flow accuracy, detector sensitivity, output data rate, minimum required vehicle speed, and cost.

The infusion of new digital processing technology in the area of magnetic anomaly detection promises to significantly improve the performance of existing magnetic detectors, justifying a reassessment of their supplementary role in vehicle detection. In addition, the ability to assemble a group of magnetometers into an array sharing a common signal processor promises the ability to locate, track, and classify vehicles in a multilane scenario using a row of above-ground detectors.

## 5.8 RELATIVE COST OF DETECTORS

A satisfactory cost comparison between various detector technologies can only be made when the specific application is known. For example, a relatively inexpensive ultrasonic, microwave, or passive infrared detector may seem to be the low-cost choice at first glance for instrumenting a surface-street intersection if inductive loop detectors are not desired. But when the number of detectors needed is taken into account along with the limited amount of directly measured data that may be available (e.g., speed is not measured directly by a passive infrared detector), a more expensive detector such as a video image processor may be the better choice. For example, if it requires 12 to 16 conventional inductive loop detectors (or ultrasonic, microwave, or infrared, etc. detectors) to fully instrument an intersection, the cost becomes comparable to that of a VIP. Furthermore, the additional traffic data and visual information made available by the VIP may more than offset any remaining cost difference. In this example, the VIP is assumed to meet the other requirements of the application, such as the desired 100 percent detection of vehicles at the intersection.

Similar arguments can be made for freeway applications using multiple detectors and requiring information not always available from the less expensive detectors.

Still other applications, such as simple monitoring of multilane freeway or surface-street vehicle presence and speed, may be performed by two microwave radars mounted in a side-looking configuration. In this case, the radar detectors replace a greater number of loops that would otherwise need to be installed in the travel lanes. Furthermore, the radar poten-tially provides direct measurement of speed at a greater accuracy than provided by the loops.

Other factors that affect the cost and selection of detectors are the maturation of the designs and manufacturing processes for detectors that use the newer technologies, the attainment of reduced prices through quantity buys, and the availability of mounting locations and communications links at the application site.

## 5.9 AUTOMATIC VEHICLE IDENTIFICATION

Automatic vehicle identification (AVI) aids automated toll collection in many applications in North America, Europe, and Asia. Vehicles equipped with AVI transponders are used to determine travel times between fixed points as the vehicles move across a roadway network. As electronic toll collection continues to increase, the large universe of equipped vehicles will produce a secondary benefit by enabling automated measurements of travel time and congestion.

In the New York/New Jersey region, the TRANSCOM program uses AVI observations to track individual vehicles for real-time measurement of travel time. The transponder-equipped vehicles are identified by AVI readers along the roadway. The data are used to determine speed and travel times for incident and congestion management.

Merging this technology with a beacon system can provide true two-way communication with the vehicle. With this capability, real-time traffic data such as origin-destination pairs, travel time, and spot speeds can be collected from the vehicle, while the driver obtains motorist information such as congestion delays, parking availability, and alternative route choices. There are a number of projects being conducted in the Commercial Vehicle Operations sector of IVHS that anticipate the use of Automated Vehicle Identification, Automated Vehicle Location, and Automated Vehicle Classification for fleet operations and regulatory uses. These include the HELP (Heavy Electronic License Plate)/Crescent Project and the Advantage I-75 Project which promise reductions in the time it takes freight to move across the participating regions of the United States and Canada.

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# 6. TASK C SUMMARY
# DEVELOP VEHICLE DETECTOR LABORATORY TEST SPECIFICATIONS AND LABORATORY TEST PLAN

## 6.1 LABORATORY TEST SPECIFICATIONS FOR VEHICLE DETECTORS

This section reviews the performance specifications and presents a test plan for state-of-the-art, above-the-road detectors that were evaluated in the laboratory tests conducted at the Hughes Aircraft Company, Fullerton, CA, facility and in the City of Los Angeles. These include ultrasonic, microwave, active infrared, passive infrared, and video image processors (VIPs). Although VIPs were not evaluated during the laboratory tests because they were not made available by the manufacturers at that time, they were later included in the field evaluations. The purposes of the laboratory tests were to have Hughes verify the performance of the detectors, with manufacturer assistance where needed, before field deployment and to train Hughes personnel in installing and operating the detectors.

### 6.1.1 Ultrasonic Detectors

Presence-only and speed-measuring ultrasonic detectors are currently manufactured. These enable direct measurements of vehicle presence, occupancy, and speed (depending on the detector type) to be made.

The following are the current performance characteristics of ultrasonic detectors.(1,2,3)

1. Detectable objects. Detect subcompact cars and larger vehicles. Future applications will require detection of motorcycles and bicycles as well.
2. Waveform. Presence-measuring ultrasonic detectors transmit a pulse waveform, while speed (Doppler)-measuring detectors use continuous wave (CW).
3. Frequency. The frequencies transmitted are between 25 kHz and 50 kHz, depending on the manufacturer and model.
4. Beamwidth. The beamwidth is designed to detect vehicles in single lanes. The upper limit to the beamwidth and sidelobe levels is driven by the requirement to reject vehicles in adjacent lanes. The lower limit is driven by the need to detect lane straddlers. The beamwidth is thus a function of vehicle width, lane width, transducer sidelobes, and mounting height. Typical beamwidths establish patterns on the road surface that are 4 feet (1.2 m) wide at the specified mounting height.
5. Speed measurement range. Speed-measuring ultrasonic detectors presently respond to vehicles traveling between 2.5 and 75 mi/h (4.0 and 120.7 km/h).
6. Speed measurement accuracy. Two types of vehicle speed are required: microscopic or spot vehicle speed and macroscopic or composite speed of a group of vehicles. Required accuracy for microscopic speed measurements is between 3 and 5 percent for signalized intersection applications and ±1 mi/h (1.6 km/h) for microscopic and macroscopic freeway incident detection applications.
7. Minimum distance between vehicles. Current detectors will detect two separate vehicles when they are 1.5 to 10 meters apart, depending on detector design and speed of the vehicle.
8. Detection Range. The required detection range is 8 to 20 meters for vehicle counting, occupancy, and speed measurements. Ultrasonic detectors may not be suitable for longer range surveillance applications as may be required for freeway incident detection.
9. Installation configuration. Both overhead and side-looking operations

are accommodated within the performance limits discussed above.

10. Power requirements. Must meet NEMA and Type 170 controller standards. These are 120 VAC, 60 Hz, with current draw not to exceed the capacity of the particular controller and installation. Some controllers have DC voltage available; however, the voltage and current availability vary and must be confirmed with the operating agency.

### 6.1.2 Microwave Detectors

By appropriate processing of the information in the received energy, direct measurements of vehicle presence, occupancy, and speed (depending on detector capability) can be obtained.

Current performance characteristics include:(4)

1. Detectable objects. Detectors sense subcompact cars and larger motorized vehicles. It is desirable to detect motorcycles and bicycles as well.

2. Detection pattern. The antenna pattern may be designed to illuminate single or multiple traffic lanes. Some multiple-lane applications, such as vehicle counting, require signal processing to differentiate between vehicles detected in the different lanes. If designed for intersection traffic management, single-lane coverage is required for measurement of left-turn lane occupancy. Multiple-lane coverage may be acceptable for detecting through-lane occupancy.

3. Detection angle. Microwave detector incidence angles can be adjusted in both the azimuth and elevation planes.

4. Response time. The response time is defined as the time for an input, generated by a vehicle in the field of regard, to be processed by the detector and registered as an output in the form of a presence, count, or other appropriate indication. A response time is also defined for the time required by the detector to drop an output when the vehicle leaves the field of regard. The response time of current models is <0.3 seconds. The upper limit may be unacceptable for counting high-speed vehicles in high-density traffic.

5. Hold time. Detector hold times are designed to eliminate dropout of vehicle detections as may occur when towing vehicles with long tongue couplings. A hold time retains vehicle presence during a potential dropout period until new data are received and averaged into the next vehicle presence or velocity calculation. Current detection hold times vary with the application, ranging from continuous for Doppler detectors to 1 second for detectors that respond to vehicle presence.

6. Mounting configuration. Microwave detectors are mounted above the roadway in forward-looking, rear-looking, and side-looking configurations.

7. Speed measurement range. The minimum vehicle speed measured is approximately 3 mi/h (4.8 km/h) for Doppler motion detectors and the maximum is 65 mi/h (104.6 km/h) to greater than 85 mi/h (136.8 km/h), depending on the model. True presence microwave detectors can detect stopped vehicles.

8. Speed measurement accuracy. Two types of vehicle speed measurement are required: microscopic or spot vehicle speed and macroscopic or composite speed of a group of vehicles. Required accuracy for microscopic speed measurements is ±3 to 5 percent for signalized intersection applications and ±1 mi/h (±1.6 km/h) for microscopic and macroscopic freeway incident detection applications. Current microwave Doppler detectors measure speed within ±2 to 3 mi/h (±3.2 to 4.8 km/h). One true presence microwave radar specifies

its speed measurement accuracy at ±10 percent.

9. Power requirements. Must meet NEMA and Type 170 controller standards. These are 120 VAC, 60 Hz, with current draw not to exceed the capacity of the particular controller and installation. Some controllers have DC voltage available; however, the voltage and current availability vary and must be confirmed with the operating agency.

10. FCC approval. The operator does not need FCC approval as the manufacturer has obtained this and has marked the radar with the proper identifier, e.g., meets requirements of FCC Rules, Part 15. These rules specify the center frequency, bandwidth, and output power of the radar.

### 6.1.3 Active Infrared Detectors

Active infrared (IR) detectors transmit a beam of light and detect a portion of it that is reflected back to the detector by the objects in the field of view. They provide presence, speed, count, and occupancy data in day and night operation. When a laser diode is used as the transmitting energy source, the detector can also provide vehicle profile and shape data, and, hence, be used for vehicle classification.

Specifications for the IR detector that uses a laser diode as the active transmitting element are:(5,6)

1. Detection indication. In addition to using LEDs as potential transmitters of infrared energy, high-intensity LEDs are also used as indicators of the output state of the detector, i.e., to alert the operator as to whether there is a vehicle in the field of view of the detector.

2. Detection pattern. The footprint on the road surface should emulate a 1.8-m x 1.8-m (6-ft x 6-f-t) loop at a range of 9.2 m (30 ft) for signalized intersection control and freeway incident detection. It is also desirable to emulate a 4.3-m x 1.8-m (14-ft x 6-ft) loop and have a detection range of over 15.2 m (50 ft) for signalized intersection control and freeway ramp-metering applications.

3. Warmup time. The detector is operational within 10 seconds after application of power.

4. Stability. The detector must respond only to changes in scene reflectivity. Atmospheric effects, such as those caused by clouds shadowing the field of regard, shall not produce false vehicle detections in excess of those allowed for a particular IVHS application.

5. Response time. The response time is defined as the time for an input, generated by a vehicle in the field of regard, to be processed by the detector and registered as an output in the form of a presence, count, or other appropriate indication. A response time is also defined for the time required by the detector to drop an output when the vehicle leaves the field of regard. The response time of laser diode type IR detectors is =10 ms when a vehicle enters or leaves the field of regard.

6. Presence hold time. IR detectors using laser diode transmitters hold the presence for as long as a vehicle is in the field of view. This specification can be tailored, however, to meet individual operations requirements of the cognizant agency.

7. Speed measurement range. Currently available detectors measure speeds between 0 and >80 mi/h (128.7 km/h).

8. Speed measurement accuracy. The calculated accuracy for vehicle speed measurement is ±1 mi/h (±1.6 km/h) up to 70 mi/h (112.7 km/h).

9. Detection range. The vehicle detection range is 1.5 to 15 meters.

10. Power requirements. Must meet NEMA and Type 170 controller standards. These are 120 VAC, 60 Hz, with current draw not to exceed the capacity of the particular controller and installation. Some controllers have DC voltage available; however, the voltage and current availability vary and must be confirmed with the operating agency.

### 6.1.4 Passive Infrared Detectors

Passive infrared detectors sense objects through the energy that they emit. The detectors currently on the market usually have a single detector element that provides signals giving vehicle presence, occupancy, and count.

Characteristics of current passive infrared detectors include:(7)

1. Presence hold time. The presence signal is held as long as a vehicle remains in the field of view of the detector, up to 6 minutes maximum. This parameter can be designed to have other values as required.

2. Response time. Response times of current detectors are a maximum of 500 ms.

3. Speed measurement range. State-of-the-art passive infrared detectors detect stopped vehicles and those traveling at freeway speeds.

4. Stability. For the scene under observation, the detector must respond only to changes in the temperature and emissivity of the vehicles which are to be detected. Atmospheric effects, such as those caused by clouds shadowing the field of regard or rain-induced cooling of the background, shall not produce false vehicle detections in excess of those allowed for a particular IVHS application.

5. Sensitivity. An operator-controlled sensitivity adjustment may be required to give adequate dynamic range to detect vehicles under the anticipated weather conditions. The sensitivity must allow operation without continually changing settings to accommodate changing input levels due to varying climatic conditions.

6. Detection range. The vehicle detection range is 6.4 to 15 meters.

7. Power requirements. Must meet NEMA and Type 170 controller standards. These are 120 VAC, 60 Hz, with current draw not to exceed the capacity of the particular controller and installation. Some controllers have DC voltage available; however, the voltage and current availability vary and must be confirmed with the operating agency.

### 6.1.5 Video Image Processors

A video image processor is a combination of software and hardware components that extract desired information from the output of an imaging sensor, such as a conventional TV camera or an infrared camera. The combination of imaging hardware, processor, and software forms a VIP detector.

The following represent current VIP specifications.(8,9)

1. Detectable objects. Current VIPs sense motorcycles, subcompact cars, and larger motorized vehicles.

2. Number of lanes observed. Current systems provide vehicle data over at least three lanes. It is desirable to extend the coverage to the equivalent of five lanes in order to monitor emergency areas (such as highway shoulders), ramps for freeway applications, higher capacity freeways that have additional through-lanes, and multiple-lane surface-street intersections.

3. Speed measurement range. VIP detectors are capable of measuring speeds between 0 and 160 mi/h (257.5 km/h).

4. Speed measurement accuracy. Two types of vehicle speed measurement

are required: microscopic or spot vehicle speed, and macroscopic or composite speed of a group of vehicles. Required accuracy for microscopic speed measurements is ±3 to 5 percent for signalized intersection applications and ±1 mi/h (±1.6 km/h) for microscopic and macroscopic freeway incident detection applications.

5. Vehicle count accuracy. Counts are generally accurate to within ±5 percent.

6. Minimum distance between vehicles. VIP detectors are required to detect vehicles separated by 1/3 to 2/3 of a meter (1 to 2 feet) for the city arterial application. In freeway applications, the intervehicle spacing may be different (e.g., 10 to 30 m) depending on the comfort time of the driver (the time required or anticipated by the driver to stop the vehicle) and traffic congestion. In fact, in heavy congestion, the minimum vehicle separation may be the same as on an arterial. The maximum detection distance of a VIP along the surface of a road is a function of mounting height, inter-vehicle distance or gap, and vehicle height as described in Section 5.

7. Detection Range. The detection range is 8 meters to 20 meters for applications requiring traffic data close to the mounting location, and a minimum of 92 meters (300 feet) for adaptive, real-time signal control at city intersections and for freeway incident detection and traffic management.

8. Power requirements. Must meet NEMA and Type 170 controller standards. These are 120 VAC, 60 Hz, and current draw not to exceed the capacity of the particular controller and installation. Some controllers have DC voltage available; however, the voltage and current availability vary and must be confirmed with the operating agency.

9. Operator intervention requirements. The detector shall function without operator adjustments during setup or normal operation to account for:

   a. Day-night transitions.

   b. Shadows on the roadway.

   c. Reflections from vehicles or pavement during rain.

   d. Weather changes.

   The following conditions do require operator intervention:

   e. Repositioning the field of view.

   f. Initialization.

   g. Resetting the vehicle detection zone.

### 6.1.6 Inductive Loop Detectors

The specifications for the inductive loop detector amplifier models actually used in tests coordinated with the City of Los Angeles Department of Transportation and the state transportation departments supporting the field tests are included in Appendix G. Catalog pages were provided in the Task D Report.

### 6.1.7 Magnetometers

The specifications for the models actually used in tests coordinated with the City of Los Angeles Department of Transportation and the state transportation departments supporting the field tests are included in the Task D Report.

### 6.1.8 Interface, Cost, and Environmental Requirements

The following requirements apply to all of the detectors.

1. Communications data rates.

   a. Video imagery:

   A maximum of 128 KB/s (112 KB/s desirable) shall be used for imagery transmission with a VSAT communications link. Bandwidth may also be limited by the capacity of available leased lines or spread-spectrum radio channels.

b. Detector status data:

(1) Urban application: 88 bytes/30 s from each intersection.

(2) Freeways: 250 bytes/30 s from each site.

(3) Identification and location of each vehicle equipped with a sensor/radio: 30 bytes/30 s.

2. Cost.

a. Must be competitive with the life-cycle cost of multiple inductive loop detectors as used in the desired application.

b. Periodic maintenance is acceptable. The time interval between maintenance operations should be as large as possible. A 2-month interval may be satisfactory for some applications. Maintenance requirements should be verified by consultation with the end customer.

3. Mounting configuration for city arterial application.

The following are preliminary guidelines for mounting detectors:

a. Desirable to accommodate side mounting from a light pole or other utility pole. Detector should also be capable of being mounted at an intersection (on traffic light support pole) and looking 83 to 167 meters (250 to 500 feet) back toward oncoming traffic.

b. Desirable for detectors to sense vehicles in multiple lanes to minimize the number of detectors needed to view the roadway. Utilization of a fish-eye lens to scan an intersection may help achieve this result with VIPs. (These comments also apply to freeway use of detectors.)

c. Detector mounting height of 17 feet (5.2 m) is compatible with all utility poles.

d. Traffic lanes are 10 to 12 feet (3.0 to 3.7 m) wide.

e. Parking lane (lane nearest curb) is 17 feet (5.2 m) wide.

f. Setback of traffic light from curb is 2 feet (0.6 m).

g. Number of lanes to be monitored is one, two, or three.

4. Interfaces.

The interfaces depend on whether the test site uses a Type 170 or NEMA controller. The specific controller specification shall be used to define the interface between the detector, amplifier, and controller. General information about the amplifier/controller interface is given below.

a. Type 170 controller:(10)

(1) 6800 microprocessor-based.

(2) Cards are 6-1/2 inches by 4 inches (165.1 mm by 101.6 mm).

(3) Contact closure needed from detector.

(4) Input/output lines typically available are: ±24 volts, reset, two pair field connections, two pair controller connections.

b. NEMA controllers: Some use an 8085, 8-bit processor. Use NEMA Pub. TS-1 for detailed interface specifications.

5. Voltage.

Per Type 170 and NEMA controller specifications.

6. Temperature.

The outside temperature extremes for the detectors are determined from the following considerations:

The NEMA range for outside ambient temperature extremes is -30°F (-34°C) to +165°F (+74°C).(11) Some application sites may require the full military specification temperature range of -30°C to +125°C; however, colder states such as Minnesota may require designs that accommodate lower minimum outside operating temperatures. Heaters in weatherproof enclosures may be needed to control the operating environment of the electronic and mechanical components. Conversely, agencies operating in desert environments may require components capable of operating at higher outside temperatures. Here coolers or fans may be needed in the enclosures.

7. Humidity.

The detectors shall be designed to operate under conditions where the relative humidity complies with Table 2-I of the NEMA Pub.. TS- 1 (1989) for Traffic Control Systems.

8. Lightning protection.

Lightning protection is recommended for all types of detectors.

9. Vibration and shock.

Vibration and shock hardening are needed to withstand swinging from poles during high winds and earthquakes. The following NEMA standards may have to be improved to meet these goals. Also, some detectors, such as nonimaging IR and ultrasound, work best when they do not swing.

a. The NEMA vibration standard [paragraph 2.2.5 of TS-1 (1989)] requires the detector to maintain all of its functions and physical integrity when subjected to a vibration of 5 to 30 cycles/s up to 0.5g applied in each of three mutually perpendicular planes.

b. The NEMA shock standard [paragraph 2.2.6 of TS-1 (1989)] specifies that the detector shall suffer neither permanent mechanical deformation nor any damage that renders the unit inoperable when subjected to a shock of 10 g's ± 1 g applied in each of three mutually perpendicular planes.

10. Electromagnetic energy health hazard.

The detector shall present no health hazard from emitted radiation. As a minimum, use current standards set by professional organizations and government agencies for safe levels of microwave and electromagnetic radiation power densities. The current standard is <1 mW/cm$^2$ (10 W/m$^2$ ) for indefinitely prolonged exposure. A factor of 10 less exposure may be desirable for large-scale public applications to further reduce anxiety in the public.

11. Other operating and storage conditions,

Use NEMA Publication TS-1 (1989) as a guide.

12. Vendor notification of extreme field test conditions.

The vendors will be notified of the anticipated outside temperature, humidity, wind, and vibration levels at each field test site, and will be required to make recommendations for proper operation of their detectors.

### 6.1.9 Summary

Table 6-I compares the ability of the various overhead-mounted detector technologies to provide key traffic parameters such as presence, occupancy, flow, and speed on single and multilane roads. However, all detectors based on a given technology may not provide all of these parameters. The data available are a function of how the technology was implemented and the requirements set by the manufacturer or the transportation agency for measuring and transmitting particular data.

Table 6-l. General Qualitative Capabilities of Current Detector Technologies

| Detector Technology | Presence | Occupancy | Volume | Speed | Multilane Coverage |
|---|---|---|---|---|---|
| Ultrasonic | Direct | **Direct** | **Direct** | Direct & Indirect | No |
| Microwave | Direct | **Direct** | **Direct** | **Direct** | Direct |
| Active Infrared | Direct | **Direct** | **Direct** | **Direct** & Indirect | Direct |
| Passive Infrared | Direct | **Direct** | **Direct** | Indirect | No |
| Video Image Processor | Direct | **Direct** | **Direct** | **Direct** | Direct |

**Key:** **Direct = Via direct measurement of data**
Indirect **= Via calculations** based on measured **data**

## 6.2 LABORATORY TEST PLAN

The laboratory test plan and equipment were used to confirm the performance of the overhead-mounted traffic detectors described in Section 1. These detectors were previously tested by the manufacturer before delivery to Hughes. Therefore, the tests described below are in the nature of end-to-end system evaluation tests that confirm proper detector operation, rather than more detailed tests that evaluate the performance of subsystems within each detector.

The specific objectives of these tests were:

- [] Verify that detector operation conforms to vendor specifications.
  - . The specifications measured under this objective are those that do not require the use of special manufacturer-specific test equipment, unless it is normally supplied with the detector.
  - ● The intent of these tests is not to confirm all manufacturer specifications, but rather to verify those most critical to detector operation for the state field tests. Those specifications not directly verified at Hughes will be confirmed using manufacturer test data and reports.
- [] Identify and measure other detector performance characteristics that affect traffic parameter values.

### 6.2.1 Ultrasonic Detectors

The ultrasonic detector test procedures for vehicle presence and speed detectors are based on information obtained from the detector vendors.

The first three tests and measurements below apply to Sumitomo detectors.(12)

1. Transmit frequency and output power of the presence detector.
   a. With the Sumitomo ultrasonic presence detector, the measurement of transmit frequency and output power is performed by connecting the transmitter-receiver to the input/output (I/O) terminal of the detector cabinet. Other manufacturers' equipment may require the use of transducers (i.e., special microphones) to convert the transmitted ultrasonic energy into electrical energy in order to perform these measurements.
   b. The ultrasonic transmit frequency and peak output power will be within the tolerances specified by the vendor.

2. Field of view (FOV) of the presence detector.

   a. The Sumitomo ultrasonic transmitter-receiver feeder will be connected to the I/O terminal of the detector cabinet. A cylinder will be placed in front of the transmitter-receiver as a standard reflection object, simulating a vehicle. The cylinder is approximately 0.2 m in diameter and 2 m in length. The distance between the cylinder and the transmitter-receiver is approximately 5 m.

   b. The measured FOV will be 1.2 m ±0.12 m (i.e., ±10 percent) and the detection lamp on the detector cabinet will be on when the cylinder is within the FOV of the detector.

3. Speed measurement accuracy of the speed detector.

   This test measures the Doppler frequency shift and the received signal amplitude using the transmitter-receiver of the ultrasonic speed detector.

   a. Connect the ultrasonic receiver cable to the input/output (I/O) terminal of the detector cabinet. A pinwheel type of reflector will be placed in front of the transmitter-receiver as a standard reflection object to simulate the return from a vehicle. The reflector's turning fins simulate vehicle movement. The distance between the reflector and the transmitter-receiver will be about 2 m.

b. The received amplitude and frequency of the Doppler signal will be measured at the detector unit and verified to be within the range prescribed by the vendor.

The following end-to-end operational test applies to the ultrasonic detectors built by Microwave Sensors.(13)

4. End-to-end operational test.

a. Test equipment.

(1) Square reflector target at least 6 inches (152.4 mm) on a side.

(2) 10 to 24 VDC, 0.15-amp (min) power supply.

b. Operational test.

(1) Remove the enclosure cover.

(2) Connect power supply.

**(3)** Place square reflector 3 feet (0.9 m) from transmitter.

**(4)** Turn transmitter on after equipment warm-up time has elapsed.

**(5)** Verify that appropriate LED indicator is on.

5. Range test.

a. Objectives. This test applies to all ultrasonic detectors. The objectives are to learn how to optimally install the detectors for the field tests and to examine their detection capabilities against real vehicles. Range testing will verify the detection range versus different size and shape motorized vehicles, speed (if the detector is designed to measure this parameter), and minimum spacing for differentiating between two vehicles in the same lane. The boresight direction of the ultrasonic speed and presence detectors will be determined before they are mounted on tower, light pole, and overhead sign structures used in these tests. A laser range finder may be used to aid in measuring the footprint on the ground.

Video imagery of the tests will be recorded to help document the results. To aid in data evaluation, markers will be placed on the test track at regular intervals. Data sheets will be prepared in advance of the tests to ensure that all required data are recorded and test equipment identified. Test procedures may be expanded as needed to ensure test integrity and repeatability.

b. Detection zone. The size of the detection zone will be measured by rolling a vehicle or moving the standard reflection object through the field of view and noting when the detector gives an output.

c. Minimum spacing between vehicles. The minimum spacing for differentiating between vehicles will be found by parking a vehicle at one end of the detection zone and rolling another towards it from the other end. The distance recorded when the detector no longer distinguishes between the two vehicles is the minimum spacing. For detectors that respond to vehicles traveling above a minimum speed, a vehicle simulator, such as a metal plate, will be towed behind the first vehicle. The spacing between the vehicle and the plate will gradually be decreased from run to run to determine the minimum spacing required for vehicle differentiation. Alternatively, a second vehicle may be towed behind the first at a preset distance.

d. Detection range. To characterize detection range versus vehicle type and speed, tests will be performed at the minimum and maximum operating ranges of the detectors. Automobiles and pickup trucks will be driven through the field of view of the detectors at speeds between 5 and 55 mi/h (8.0 and 88.5 km/h), in 10-mi/h (16.1-km/h) increments.

e. Sensitivity to vehicle density. As time permits, the performance of the detectors will be verified against low-density (<800 vehicles per hour per lane) and high-density (> 1800 vehicles per hour per lane) traffic flows. These data will aid in establishing optimal use of the detectors during field testing. The speed measurement accuracy of applicable detectors will be verified during these tests by using speed surveys performed by the host agency, e.g., the City of Los Angeles Department of Transportation. Techniques to be used include radar speed guns, infrared speed guns, and vehicles traveling at predetermined speeds through the detection zones.

### 6.2.2 Microwave Detectors

These tests for microwave vehicle presence and speed detectors supplement the signal-to-noise, speed calibration, and output level adjustment tests performed by the vendors. The end-to-end operational test applies to microwave detectors built by Microwave Sensors.(14) Microwave radar detectors built by other vendors may require modifications to this test.

1. End-to-end operational test.

   a. Test equipment.

      (1) Square reflector target at least 6 inches (152.4 mm) on a side.

      (2) 10 to 24 VDC, 0.25-amp (min) power supply.

   b. Operational test.

      (1) Remove the enclosure cover.

      (2) Connect power supply.

      **(3)** Place square reflector 3 feet (0.9 m) from transmitter.

      Turn transmitter on after equipment warm-up time has elapsed.

      (5) Verify that appropriate LED indicator is on.

**2.** Minimum and maximum detectable radar cross section.

Calibrated corner reflectors (CRs) will be inserted into the FOV of the true presence detectors to determine the minimum detectable target size and the maximum target size that can be detected without saturating the detector. The latter result is not expected to affect detector operation for traffic management applications. An approximate range of CR sizes is from 5 $m^2$ to 100 $m^2$. Several reflectors in this range will be selected. Since the transmitted and received waveforms are linear and like polarized, trihedral (odd bounce) reflectors will be used.

3. Range test.

a. Objectives. This test applies to all microwave detectors. The objectives and testing techniques are the same as those discussed earlier for the ultrasonic detectors. The tests will verify boresight, detection range, sensitivity to inter-vehicle spacing, and beam patterns. If the detector measures speed, then its capability to measure speeds of individual and groups of vehicles will be verified.

b. Detection zone. The size of the detection zone will be measured by rolling a vehicle or inserting a corner reflector through the field of view and noting when the detector gives an output.

c. Minimum spacing between vehicles. The minimum spacing for differentiating between vehicles will be found by parking a vehicle at one end of the detection zone and rolling another towards it from the other end. The distance recorded when the detector no longer distinguishes between the two vehicles is the minimum spacing. For detectors that respond to vehicles traveling above a minimum speed, a vehicle simulator, such as a metal plate, will be towed behind the first vehicle. The spacing between the vehicle and the plate will gradually be decreased from run to run to determine the minimum spacing required for vehicle differentiation. Alternatively, a second vehicle may be towed behind the first at a preset distance.

d. Detection range. To characterize detection range versus vehicle type and speed, tests will be performed at the minimum and maximum operating ranges of the detectors, some of which extend out to 300 feet (91.4 m). Automobiles and pickup trucks will be driven through the field of view of the detectors at speeds between 5 and 55 mi/h (8.0 and 88.5 km/h), in 10-mi/h (16.1 -km/h) increments.

e. Sensitivity to vehicle density. As time permits, the performance of the detectors will be verified against low-density (<800 vehicles per hour per lane) and high-density (> 1800 vehicles per hour per lane) traffic volume. These data will aid in establishing optimal use of the detectors during field testing. The speed measurement accuracy of applicable detectors will be verified during these tests by using speed surveys performed by the host agency, e.g., the City of Los Angeles Department of Transportation. Techniques to be used include radar speed guns, infrared speed guns, and vehicles traveling at predetermined speeds through the detection zones.

### 6.2.3 Active Infrared Detectors

The following laboratory procedures are for testing Schwartz Electra-Optics active IR detectors that use a laser diode as the transmitting energy source.(15) This detector generates two beams to count and measure the speed of vehicles. Active IR detectors manufactured by other vendors may require modifications to the tests described below.

1. Setup.

The equipment for these tests consists of a sighting scope, IBM personal computer (PC), vendor-supplied test software, a black target having low reflectance, and a white target having high reflectance.

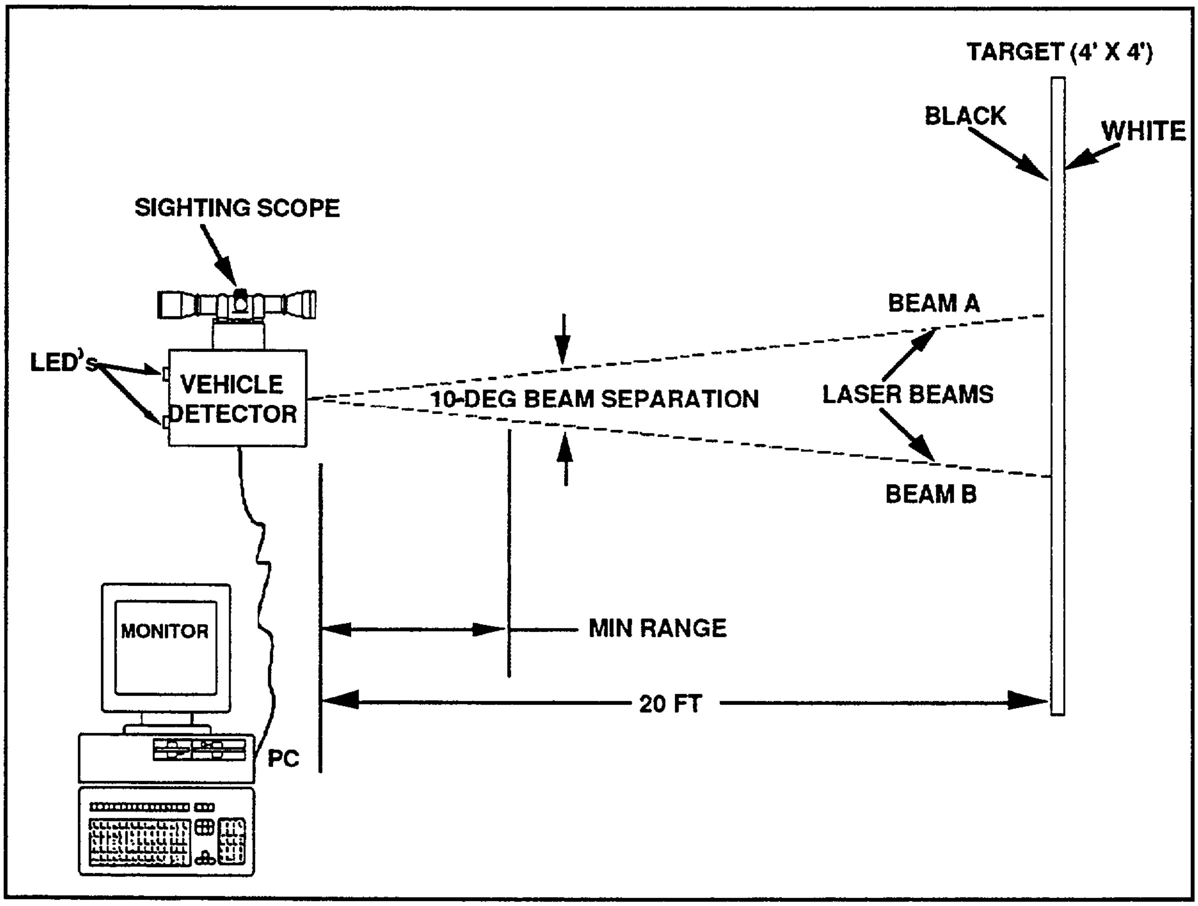
The layout for the laser radar IR detector functional tests is shown in Figure 6-l. The detector is oriented so that the cross hairs of the sighting scope are centered on the black target at a distance of 20 feet (6.1 m). A PC is connected to the vehicle detector's serial interface. Initially, an opaque screen is used to block the laser transmitter beam at a distance less than the detector's minimum range (as specified by the vendor).

2. Self-test.

After the detector is warmed up, the manufacturer-supplied test software will initiate a series of five self-tests.

In the first, the integrity of the operating software in read-only memory (ROM) will be verified by calculating an 8-bit checksum. Each byte in ROM will be accumulated, ignoring overflow, to form an 8-bit value that will be compared with the checksum that is stored in ROM. The second self-test verifies proper functioning of the RAM through a non-destructive read/write test that toggles each bit in memory from on to off. The third self-test uses the microprocessor to measure the laser's pulse repetition frequency (PRF). The last two tests measure the power supply voltages and the detector's temperature using the microprocessor's A/D (analog-to-digital) converter.

If the traffic detector passes all five self-tests, the green LED will flash for about 2 seconds and then remain on continuously. If the red LED flashes and then remains on continuously, the detector has failed one or more of the self-tests.



1 ft = 0.305 m

Figure 6-1. Setup Used to Verify Functioning of Active IR Detector with Laser Diode Transmitter

3. Initialization.

   With the laser beams blocked, the red LED indicator will glow continuously, indicating that the range is beyond the minimum/maximum limits. Upon removing the opaque screen, the red LED will turn off, indicating that the detector is measuring a range within its minimum/maximum limits.

   If the screen is inserted in the beam at a range greater than the minimum range, but less than the range to the target minus 1 foot (0.3 m), the green LED will turn off. This corresponds to a vehicle-presence indication. When these tests are complete, turn on the PC and load the test software.

4. Return-signal strength.

   With the vehicle detector viewing the black target at a distance of 20 feet (6.1 m), the return signal is displayed as a percent of full scale. If properly operating, the return signal will be within ±10 percent of the baseline value supplied with the detector (for a given ambient temperature).

5. Range measurement.

   If the laser power is within vendor specifications, the 20-foot (6.1 -m) range to the black target is displayed on the monitor to within the ± 0.25-foot (76.2-mm) accuracy of the detector. When the target is reversed so that range measurements are made to the white surface, the range value displayed is the same as that for the black target to within the detector's accuracy.

6. Speed measurement function.

   This test confirms that the detector's speed measurement circuit is functioning, but does not calibrate the speed measuring function. Pass the screen rapidly through the laser beams at a distance of 2 feet (0.6 m) from the target. The PC monitor should indicate vehicle count and speed. The vehicle count should be increased in increments of one each time the procedure is repeated.

7. Range test.

   a. Objectives. The objectives and test techniques for these range tests are the same as those for the ultrasonic detectors. The tests verify boresight, detection range, sensitivity to intervehicle spacing, and beam patterns. If the detector measures speed, then its capability to measure individual and group vehicle velocities is also verified.

   b. Viewing angle. The detectors are installed on the tower or overhead structure at viewing angles that are a function of the manufacturer-specified mounting height.

   c. Detection zone. The size of the detection zone is measured by rolling a vehicle or moving a reflector through the field of view and noting when the detector gives an output.

   d. Minimum spacing between vehicles. The minimum spacing for differentiating between vehicles is found by parking a vehicle at one end of the detection zone and rolling another towards it from the other end. The distance recorded when the detector no longer distinguishes between the two vehicles is the minimum spacing.

   e. Detection range. Detection range versus vehicle type and speed are measured to determine the minimum and maximum operating ranges of the detectors. Automobiles and pickup trucks are driven through the field of view of the detectors at speeds between 5 and 55 mi/h (8.0 and 88.5 km/h) in 10-mi/h (16.1-km/h) increments.

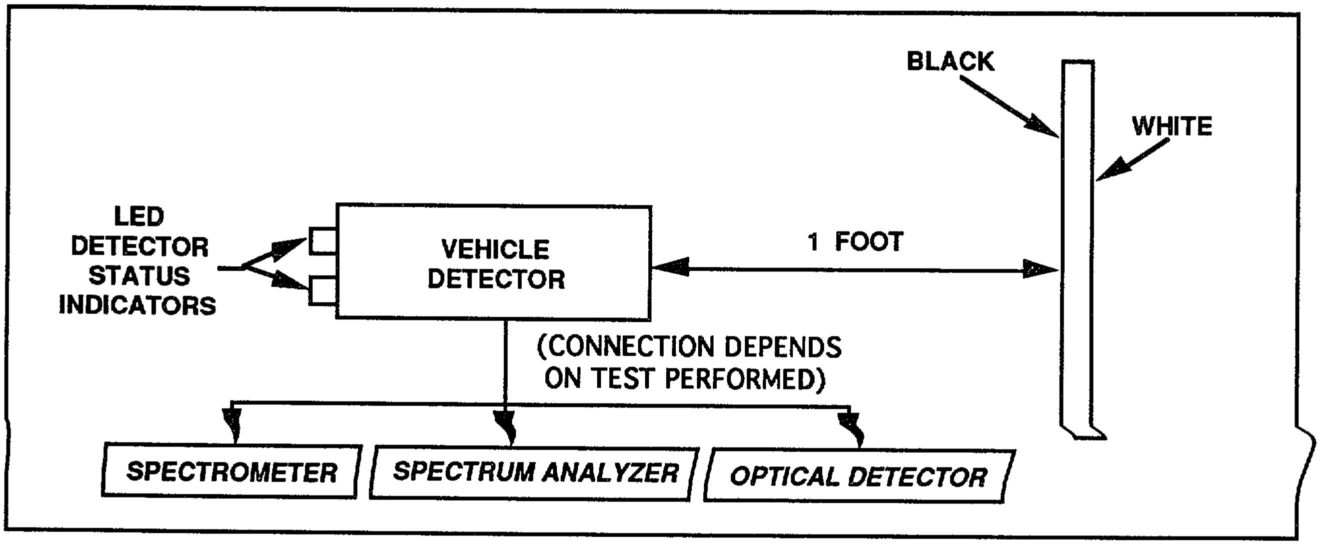
f. Sensitivity to vehicle density. The performance of the detectors are verified in low-density (<800 vehicles per hour per lane) and high-density (>1800 vehicles per hour per lane) traffic flows. These data aid in establishing optimal use of the detectors during field testing. The speed measurement accuracy of the laser radar is verified by using speed surveys performed by the host agency. Truth data are obtained from radar speed guns, infrared speed guns, and vehicles traveling at predeter-mined speeds in the detection zones.

### 6.2.4 Passive Infrared Detectors

The indoor tests of the passive IR detectors are designed to measure frequency response, sensitivity, boresight, and effects of temperature changes on performance. The plans and equipment for testing passive infrared detectors are described below.(16)

1. Indoor test setup.

   The passive infrared detector is mounted such that its field of view is focused on a calibrated "blackbody radiator" target as shown in Figure 6-2. After power is applied and the detector has stabilized, the blackbody emission source, whose temperature corresponds to that of an operating vehicle, is used to characterize the detector. The blackbody is located at a relatively short distance (e.g., 1 foot [0.3 m]) from the detector to obtain an accurate reading that is not degraded by background objects.



1 ft = 0.305 m

Figure 6-2. Indoor Test Setup for Passive IR Detector Frequency Response, Sensitivity, and Detection Pattern Tests

2. Indoor test.

   a. Frequency response. A frequency spectrometer is used to measure the response of the detector to different wavelengths of radiation.

   b. Detector sensitivity. Distance between detector and calibration source, size of the calibration source,. its temperature, and its emissivity are variables that are parametrically varied for this measurement. The gain of the detector is adjusted to prevent saturation at maximum signal strength. The distance between the blackbody and the detector is increased until the radiance signal-to-noise ratio (S/N) drops below the level sufficient for detection. A spectrum analyzer is used to check the specific detector detectivity D* value (which is proportional to S/N).

c. Detection pattern. The detection pattern is measured by plotting the output of the detector as a function of the range and azimuth position of a blackbody. An optical transducer is used to convert the output of the passive IR detector under test into units of volts that are then plotted against azimuth angle. The test is repeated at several ranges within the operational limits.

3. Range test.

a. Objectives. The objectives and test techniques for the range test are the same as those discussed earlier for the ultrasonic detectors. The tests provide vehicle tracking data as a function of vehicle speed (although the actual speed cannot be measured by the passive IR detectors), number of vehicles in the FOV, vehicle separation distance, and vehicle color. The tests verify boresight, detection range, and beam pattern.

b. Viewing angle. The detectors are installed at a viewing angle commensurate with the mounting height as specified by the vendor. Overhead and side-mounting operation are characterized.

c. Detection zone. The size of the detection zone is measured by rolling a vehicle or moving an emissive object through the field of view and noting when the detector gives an output.

d. Minimum spacing between vehicles. The minimum spacing for differentiating between vehicles is established by parking a vehicle at one end of the detection zone and rolling another towards it from the other end. The distance recorded when the detector no longer distinguishes between the two vehicles is the minimum spacing. These tests are performed for light- and dark-colored vehicles.

e. Detection range. To characterize detection range versus vehicle type and speed, tests are performed at the minimum and maximum operating ranges of the detectors. Automobiles and pickup trucks are driven through the field of view of the detectors at speeds between 5 and 55 mi/h (8.0 and 88.5 km/h), in 10-mi/h ( 16.1 -km/h) increments.

f. Sensitivity to vehicle density. The performance of the detectors is verified against low-density (<800 vehicles per hour per lane) and high-density (> 1800 vehicles per hour per lane) traffic flows. These data aid in establishing optimal use of the detectors during field testing.

### 6.2.5 Video Image Processors

The VIP described below is typical of those that function as ILD replacements in that they provide vehicle count, presence, occupancy, and speed. Additional data that can be provided by more advanced VIP systems in development include vehicle classification and tracking from lane to lane. The VIP illustrated in Figure 6-3 contains four representative subsystems.

The camera subsystem consists of an infrared or a visible-spectrum camera with an externally controllable and automatic iris mode, luminance/chrominance (Y/C) (when a color camera is configured) and National Television Standards Committee (NTSC) video outputs, and a fixed focal length lens. Additional items may include a filter, lens shade, zoom lens, and a remotely controlled rotatable pan/tilt camera mount.

The camera enclosure subsystem consists of a reinforced, environmentally controlled enclosure; transparent window; camera mount; and mounting brackets.

The processor subsystem contains the circuit boards and software that detect vehicles in the camera's field of view and calculate vehicle count, velocity, and length. This subsystem may be rack-mountable in a 19-inch (482.6-mm) chassis, but may be substantially smaller as well. In fact, some systems in development will perform the processing within the camera enclosure. The output data are transmitted through a communications interface (I/F) to a traffic management center. NTSC video can be made available on demand for surveillance or can be continuously transmitted over suitable bandwidth channels. Locally, data can be accessed on an RS-232 serial interface and video accessed from a standard BNC connector.

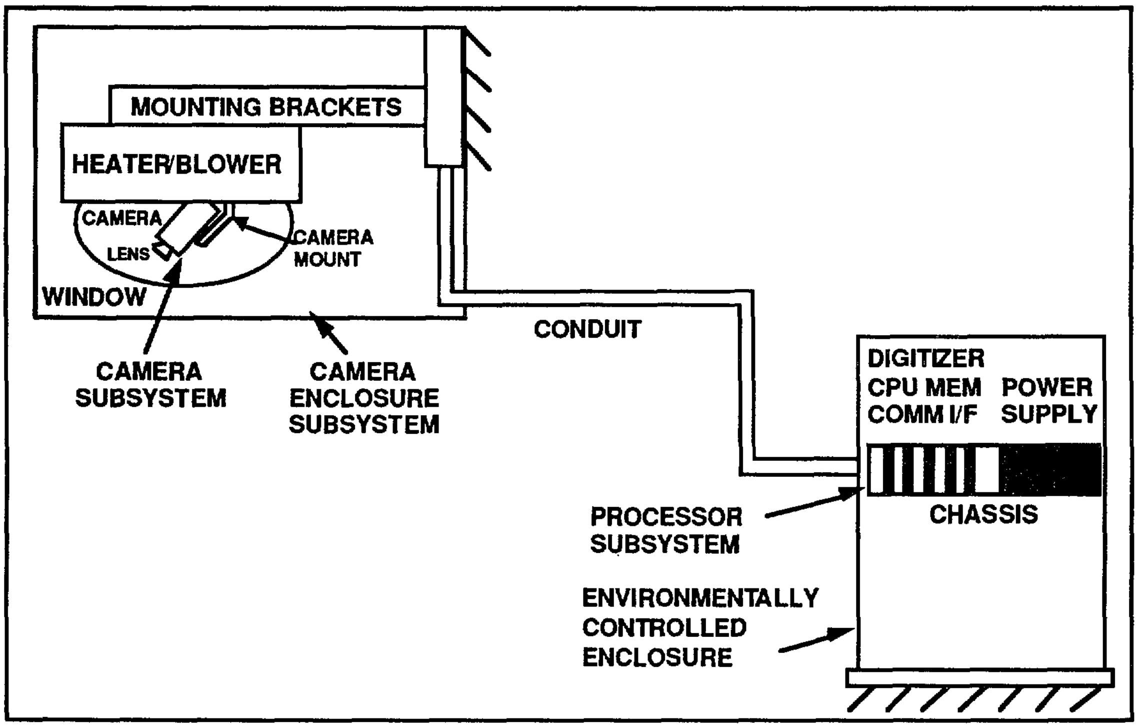


Figure 6-3. Representative Video Image Processor System

The cable subsystem consists of the video cable that transmits video from the camera to the processor subsystem, and the power and control cables that transmit all power, environmental, and operational control signals for the camera and enclosure from the processor subsystem to the camera.

The installation and test procedures for the VIPs consist of:

1. Installation.

   The camera enclosure and subsystems are mounted over the traffic lanes to be monitored. The viewing angle is adjusted to give the camera an unobstructed view of the traffic lanes, while excluding the sky from the field of view of the camera.

The processor subsystem is housed in an environmentally controlled enclosure to maintain the required temperature range, with relative humidity 0 to 90 percent, non-condensing. The enclosure supplies standard 120 VAC, 60 Hz, 200 watts power with surge protection to the processor chassis. The processor is typically installed within 150 feet (45.7 m) of the mounted camera subsystem (the maximum length of the standard cables). However, video supplied over longer dedicated lines is also accept-able. If cable installation requires weatherproof or underground conduit, appropriate arrangements are to be made with local traffic engineers.

2. Test station.

Portable setup/test equipment is required for some VIP systems. The setup equipment can typically include a keyboard, two monitors, and a joystick. In this example, the user follows the procedures for the indoor tests and for detector placement in the video scene and initiation of the VIP functions specified in the range test.

3. Indoor test.

This test verifies basic operation of the detector algorithms using pre-recorded imagery data.

Required equipment includes an optical disc player and the portable setup/test station described above. The preferred input for the recorded video is through the Red-Green-Blue (RGB) or Y/C connectors to the processor, although standard NTSC video can be used if necessary. The user performs the following setup procedure as though the data were from a live source:

a. Connect the recorded video to the vehicle detector.

b. View the video on the set up station monitor.

c. Use the keyboard and joystick to place the detectors in the traffic lanes as seen on the monitor.

d Start vehicle detector operation using the keyboard.

The number of vehicles detected by the VIP and their speeds are compared to the truth data set for the environmental and traffic conditions on the recorded video. Typical conditions that are evaluated include variations in the number of lanes, shadows, rain, and day/night transitions.

4. Range test.

a. Objectives. The objectives of these tests are to verify the detection range and zone boundaries, verify the ability of the detector to measure vehicle speed and vehicle count, and verify the resistance of the detector to artifacts such as shadows.

b. Mounting. The VIP camera is installed in an overhead-mounted configuration above the test track. If the detector is mounted between 18 and 24 feet (5.5 and 7.3 m) above the track, it is generally placed over the center of the traffic lanes to be monitored. With mounting heights of 40 to 50 feet (12.2 to 15.2 m), the camera may be located off to the side of the traffic flow. Higher mounting generally produces more accurate speed measurement.

c. Detection range and speed. The test vehicle is driven from a range of 300 feet (91.4 m) towards the camera to verify the detection-range boundaries and speed outputs of the VIP. The speed accuracy is checked at one or more specific speeds.

d. Multiple-vehicle detection. Single-lane traffic consisting of two or more vehicles separated by 10 feet (3.0 m) verifies the ability of the VIP to detect multiple vehicles.

e. Resistance to artifacts. Opposing traffic is used to verify the ability of the VIP to detect a vehicle and measure its velocity in the presence of an opposite-moving shadow in its lane.

f. Truth data. Parameters (such as vehicle counts per lane, average vehicle speed, and vehicle lengths) obtained from the imagery using human analysts are used as “truth” data. Such data are gathered for various camera positions, traffic conditions, weather variations, and over a 24-hour period representative of various lighting conditions.

The speed measurement accuracy of the detectors is verified during these tests by using speed surveys performed by the host agency. Techniques used include radar speed guns, infrared speed guns, and vehicles traveling at predetermined speeds through the detection zones.

Effects of stationary and moving shadows from both man-made and natural objects, such as buildings, bridges, trees moving in the wind, and other vehicles are studied as they are available. Vehicle-length data probably cannot be generated in darkness when the vehicles themselves are not visible. Under these conditions, most present-day algorithms use vehicle lights to provide an indication of vehicle presence.

### 6.2.6 Summary

Detector specifications and a test plan have been developed to perform the required laboratory tests. These tests help ensure adequate testing at a minimum cost before subjecting the detectors to the more rigorous field trials. The detector manufacturers have provided detector specifications and selected laboratory test procedures. These procedures can be used to further understand the strengths and weaknesses of each type of detector.

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# 7. TASK E SUMMARY

# CONDUCT LABORATORY DETECTOR TESTS

The Task E reports update the laboratory test plans and describe the results obtained from evaluation of above-the-road vehicle detectors conducted at Hughes Aircraft Company in Fullerton, CA and in the City of Los Angeles. Part I of the report describes the results obtained at the Munson test track at Hughes-Fullerton where vehicles were driven through the field of view of the detectors at low speed. Parameters such as power consumption, detection range, delay time, ground illumination pattern, and detection sensitivity with respect to vehicle type were characterized. Passive infrared detectors, originally scheduled for evaluation on the test track and in the laboratory, were not available for these tests. Part II describes indoor bench tests and results for the microwave detectors. Here, output power and frequency, input power consumption, minimum detectable signal, response time, and antenna patterns were measured. Part Ill describes the results from tests performed by the City of Los Angeles Department of Transportation at their Exposition Boulevard test site under real traffic flow conditions. Here the performance of the above-the-road detectors were compared with those of inductive loops and magnetometers. Video image processors were not evaluated during any of the laboratory tests because they were not available at the time.

## **7.1** SCOPE

Tests conducted at Hughes Aircraft Company in Fullerton, CA evaluated:

- Detector outputs in response to motor vehicles traveling on a test track.
- Power consumption, detection range, and delay time.
- Detector beam patterns and sensitivity to different types of vehicles.

## 7.2 DETECTORS EVALUATED

The following detectors were evaluated during the laboratory tests:

Microwave Detectors

- Microwave Sensors Model TC-20
- Microwave Sensors Model TC-26
- Whelen Engineering Model TDN-30

Ultrasonic Detectors

- Microwave Sensors Model TC-30C
- Sumitomo Electric Industries Model SDU-200
- Sumitomo Electric Industries Model SDU-300

Laser Radar Detectors

- Schwartz Electra-Optics Model 780D1000

Passive Infrared Detectors

- Eltec Model 842 (Los Angeles only)

Inductive Loop Detectors

(Los Angeles only)

Magnetometers

(Los Angeles only)

Two of each detector were furnished by the manufacturers, with the exception of the Sumitomo SDU-200, where one was supplied. We later learned that the correct model number for the SDU-200 is the RDU-101. However, since the SDU-200 nomenclature was already in use for this detector, we kept it as the designation for the Sumitomo Doppler ultrasound detector.

## 7.3 MUNSON TRACK FACILITIES

A scissors lift, shown in Figure 7-1, was used at the Munson track to support the overhead detectors and adjust their heights.

Figure 7-1. Munson Test Track
Shown are the scissors life upon which the detectors are mounted, power supplies are meters, and a passing target vehicle

### 7.3.1 Test Track

The portion of the track composed of a 350-foot (106.7-m) straight section of conventional single-lane road was used during the test. The paved road had a 2-degree incline approaching the detector mounting location that was accounted for when adjusting the incidence angle of the detectors.

Marking the location of the scissors lift (i.e., the detector mounting location) as 0 feet, 150 feet (45.7 m) of the track was striped at IO-foot (3.0-m) intervals and the distance was marked along the edge. Additional markings were placed at 50-foot (15.2-m) intervals through 250 feet (76.2 m). These markers were used for estimating distances between the detector being evaluated and the vehicle when an event occurred. Additional markers were added at 5-foot (1.5-m) intervals in critical detection areas to more accurately measure detection ranges.

### 7.3.2 Detector Mounting

A scissors maintenance lift was used as the detector mounting platform. Attached to and protruding from the lift was a length of 1-inch (25.4-mm) galvanized pipe upon which the detectors were mounted as shown in Figure 7-2. The lift was elevated to the appropriate height for the detector performance measurements.

### 7.3.3 Target Vehicle Descriptions

Three vehicle types were used as targets.

**Vehicle 1:** 1985 Ford Mustang two-door sedan, representing a medium-sized automobile. Its external dimensions were:

Length = 180 inches (4.6 m);
Width = 68 inches (1.7 m);
Height = 45 inches (1.1 m).

**Vehicle** 2: 1986 Honda Goldwing 1200 motorcycle, representing the class of large motorcycles. Its external dimensions were:

Length = 98 inches (2.5 m);
Width = 38 inches (0.97 m);
Height = 59 inches (1.5 m).

**Vehicle** 3: 1986 Honda Rebel 450 motorcycle, representing the class of small motorcycles. Its external dimensions were:

Length = 89 inches (2.3 m);
Width = 34 inches (0.86 m);
Height = 49 inches (1.2 m).

### 7.3.4 Detector Evaluation Procedure

Different procedures were established for detectors that relied on vehicle motion to produce an output and for those that were true presence detectors, capable of detecting stopped vehicles.

#### 7.3.4.1 Speed/Motion-Sensing Detectors

Performance data for motion detectors were collected in one of two ways: (1) an observer located on the elevated scissors lift recorded the approaching vehicle with a camcorder, producing a record to be evaluated at a later time, or (2) a roadside observer, located at the range where vehicle detection was anticipated, recorded the vehicle position at the time an alarm sounded, signifying detection by the detector under test.

#### 7.3.4.2 Presence-Sensing Detectors

The presence-sensing detectors available for these tests gave an output when a vehicle entered its field of view, but did not provide speed information. These detectors were evaluated for their presence-sensing consistency and beam-pattern size.

#### 7.3.4.3 Detector Output Monitor

A detector output monitor was attached to the camcorder. Housed in a small plastic enclosure, it consisted of a battery, piezoelectric alarm, and a light-emitting diode (LED). The LED was mounted at the end of the enclosure on an arm that positioned the LED in the lower part of the field of view of the camcorder. When connected to an appropriate detector output, the LED was turned on and the piezoelectric alarm sounded when a vehicle was detected. The camcorder captured both the LED and audible signals during the recording process and helped identify the correct detection range.

Figure 7-2. TC-30C, SDU-200, SDU-300, and 780D1000 Detectors (From Left to Right)
Mounted On the Scissors Lift

#### *7.3.4.4 Measurements*

The sequence shown in Figure 7-3 illustrates the test event sequence.

*Power:*

The applied voltage was adjusted to the manufacturer's low and high limits and the current draw was measured at each voltage.

*Delay Time:*

Several detectors have adjustable delay times that maintain the detection signal after the vehicle passes through the detector's field of view. The minimum and maximum values were measured.

*Detection Range:*

The detection range was variable on several of the speed/motion and presence detectors through a sensitivity adjustment. The detection ranges for minimum and maximum sensitivity settings were recorded when this adjustment was available.

*Incidence Angle:*

The incidence angle of most of the speed/motion and presence detectors can be varied to change the engagement range. The exception is the presence-type ultrasonic detectors that operate at a nadir (0 degree or straight down) incidence angle. As detector design and operation permitted, incidence angles of 45 and 70 degrees were used to measure detection range.

*Inbound/Outbound Vehicle Detection:*

This feature was evaluated if the detector had the capability of detecting both inbound and outbound vehicles.

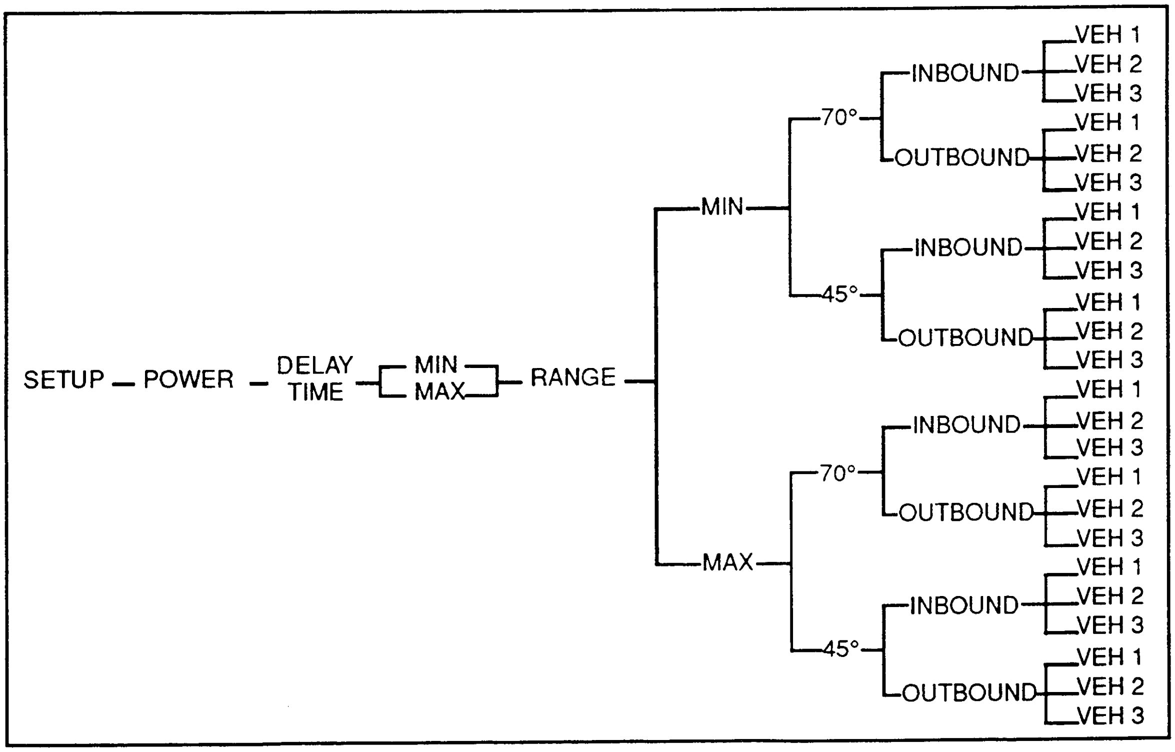


**Figure 7-3. Munson Test Track Event Sequence**

## 7.4 LESSONS LEARNED FROM TEST TRACK DETECTOR EVALUATION

Hughes tested seven vehicle detectors during June through July 1992 on the Munson test track. The detectors included three ultrasonic (SDU-200, SDU-300, TC-30C), three microwave (TC-20, TC-26, TDN-30) **and** an infrared laser radar (780D1000).

### 7.4.1 Microwave Detectors

The three microwave detectors, Microwave Sensors TC-20 and TC-26 and Whelen Engineering TDN-30, operated at an X-band frequency of 10.54 GHz.

#### *7.4.1.1 TC-20*

The TC-20 detector was raised to 17 feet (5.2 m) above the road surface with incidence angles of 70° and 45° with respect to nadir. Although only one traffic lane was used in the test, the wide-beam (16°) antenna should detect multiple lanes of traffic in a real traffic flow environment, since it has a 14-foot (4.3-m) diameter 3-dB footprint approximately 60 feet (18.3 m) downstream when mounted at a 70° incidence angle. The potential to detect traffic outside the lane of interest is reduced by decreasing the detection range by turning the range adjust screw counterclockwise (CCW). The minimum hold time (hold time screw fully CCW) was 0.5 second.

#### *7.4.1.2 TC-26*

The TC-26 was operated at a height of 17 feet (5.2 m) with both inbound and outbound vehicles, at incidence angles of 70° and 45° with respect to nadir, and at high and low sensitivity settings. The detector can be operated with the low-range setting to minimize detection of adjacent-lane vehicles. In the low-range mode the footprint on the road surface is narrowed. However, even in this mode, the 15-foot-long (4.6-m-long) Ford Mustang was detected at a range of 200 feet (61.0 m).

#### *7.4.1.3 TDN-30*

The TDN-30 detector was configured for the freeway traffic management mode to demonstrate its detection-range envelope. The TDN-30 has a narrow-beam antenna, requiring jumper JP8 to be installed on the electronics board in the housing. Jumper JP2 was installed to detect approaching vehicles or removed to detect departing vehicles. Other jumpers specify the serial communications data transmission rate and mode, dwell time, and application. When the detector is mounted parallel to the roadway surface, the antenna boresight is 45 degrees with respect to nadir.

The ability of the narrow-beam antenna to discriminate between two vehicles traveling at the same speed, one behind the other, was evaluated. In the first run, the Ford Mustang and a small Toyota pickup truck were driven at 10 mi/h (16.1 km/h) with 15 feet (4.6 m) separation. The detector indicated constant presence when the vehicles were driven into the detection zone. In the following run, the same two vehicles were driven at 15 mi/h (24.1 km/h) with an estimated separation distance of 20 feet (6.1 m). This time a momentary break in the tone from the detector output monitor was heard, indicating separate detection of both vehicles as they were driven through the detection zone.

### 7.4.2 Ultrasonic Detectors

Microwave Sensors' TC-30C and Sumitomo's SDU-200 and SDU-300 were the ultrasonic detectors evaluated. The TC-30C and the SDU-300 are presence detectors that mount directly over a lane and look straight down at the road surface at an incidence angle of 0 degrees. The SDU-200 (RDU-101) is a Doppler device that operates at an incidence angle of 45 degrees.

#### *7.4.2.1 TC-30C*

Operator adjustments on the TC-30C were the detection-range control and the relay hold time. The range control was set so that the receiver didn't trigger on the road surface, but instead detected the tops of vehicles 2 to 3 feet (0.6 to 0.9 m) above the road surface. The detection range was established by first turning the range-control screw clockwise until the detector detected the road surface and then turning the screw counterclockwise until the detection was dropped. The relay hold time was adjusted for minimum hold (0.25

seconds) by turning the appropriate screw fully counterclockwise. If vehicle detection did not occur, the receiver gain was adjusted.

#### *7.4.2.2 SDU-200 (RDU-101)*

The SDU-200 was evaluated for vehicle detection and speed-measuring capability.

Accurate speed measurements are dependent on the speed correction switch, DSW1, that controls the reading on the digital speed display. When the spring-loaded three-position Display/Operate/Test switch is momentarily placed in the Test (down) position, the display should read between 92 and 96 km/h.

The digital display read 98 km/h when the three-position switch was placed in Test during the first run. Since this value was too high, DSW1 was adjusted from 9 (normal) to 8, corresponding to a 3 percent reduction in the displayed value. When the digital display was interrogated again, it showed 96 km/h, a reading within specifications.

The small vehicle/large vehicle discrimination value was adjusted next. It enables vehicle counts to be made in each of two vehicle size classes. A value is normally chosen to differentiate between vehicles below and above 6.0 m in length. Since the largest vehicle in these tests was 15 feet (4.6 m) long, SW1 was set to the minimum value of 4.4 m.

The VR2 sensitivity adjustment is used to specify whether vehicles in one or more lanes are detected. Since the test was designed to detect vehicles in one lane only, VR2 was set near the full clockwise or minimum sensitivity position.

#### *7.4.2.3 SDU-300*

The three switches located in the right corner behind the front panel of the SDU-300 control unit are set at the factory for normal operation. The detector functioned properly during the tests using these settings.

### 7.4.3 Infrared Laser Radar Detector

The Schwartz Electra-Optics 780D1000 active infrared laser radar was operated at incidence angles of 0° (nadir), 45°, and 60°. It was designed to function with approaching traffic only at the time of these tests.

Detector data were evaluated by connecting the RS-232 connector to a personal computer that runs a setup and data acquisition program supplied by Schwartz. The detector functioned properly at 45° and 60° incidence angles. If the backscattered laser signal is too weak to be detected at 60°, as may happen with some reflecting surface shapes, the incidence angle must be reduced to increase the magnitude of the returned signal. Generally, in a normal installation, the incidence angle is 45° or less. Zero-degree incidence is beyond the normal operational design limit of the detector.

## *7.5* DETECTOR PERFORMANCE RESULTS FROM TEST TRACK MEASUREMENTS

The detectors were evaluated with respect to:

- Test vehicle,
- Operating current,
- Delay time,
- Engagement range,
- Disengagement range,
- Beam pattern, and
- Operational and functional anomalies.

### *7.5.1* TC-20 Microwave Detector

The TC-20 was evaluated at incidence angles of 45° and 70°.

#### *7.5.1.1 Operating Current*

The operating voltages for the TC-20 are 10 to 24 VAC or 12 VDC at 250 mA. During the Munson tests, the voltages ranged from 18 to 24 VAC. Additional power consumption measurements for the microwave detectors are given in Section 6 of this chapter.

**Table 7-1. Input Power for TC-20**

| VOLTAGE | CURRENT |
|---|---|
| 18 VAC | 223 mA |
| 24 VAC | 225 mA |

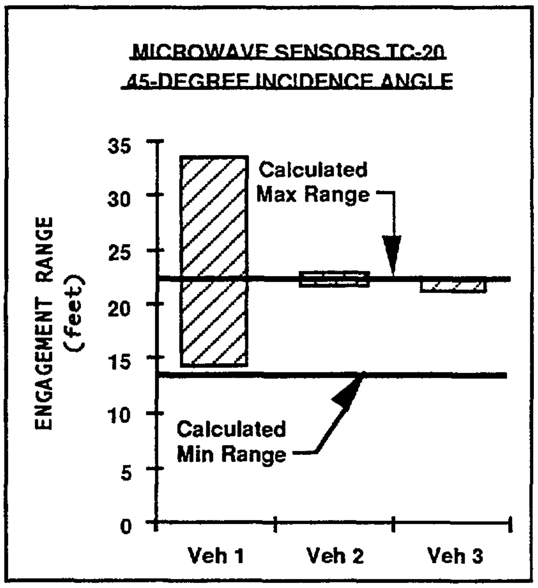
### 7.5.1.2 Delay Time Measurement

**Table 7-2. Delay Time For TC-20**

| DELAY TIME |
|---|
| 270 ms minimum |
| 9.6 s maximum |

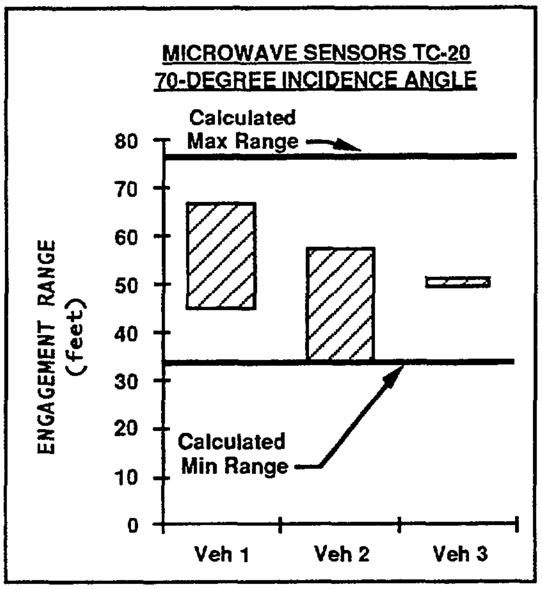
### 7.5.1.3 Detection Range

Figures 7-4 and 7-5 show the TC-20 engagement range using the detector's maximum range setting and 45° and 70° incidence angles, respectively, compared to the calculated engagement range. The calculated engagement range is based on geometrical factors that include mounting height, beamwidths, and incidence angle as tabulated in Appendix C of Part I of the Task E Report and Appendix F of this Final Report. It assumes that receiver output power, sensitivity, and target radar cross section are adequate to receive the signal at the detector. Vehicle 1 is the Ford Mustang, vehicle 2 is the large motorcycle, and vehicle 3 is the small motorcycle.



1 ft = 0.305 m

**Figure 7-4. Detection Range of TC-20 at 45-Degree Incidence Angle**



1 ft = 0.305 m

**Figure 7-5. Detection Range of TC-20 at 70-Degree Incidence Angle**

### 7.5.2 TC-26 Microwave Detector

The TC-26 was evaluated at incidence angles of 45° and 70°.

### 7.5.2.1 Operating Current

The operating voltages for the TC-26 are specified at 12 to 24 VAC or VDC with a current of 350 mA.

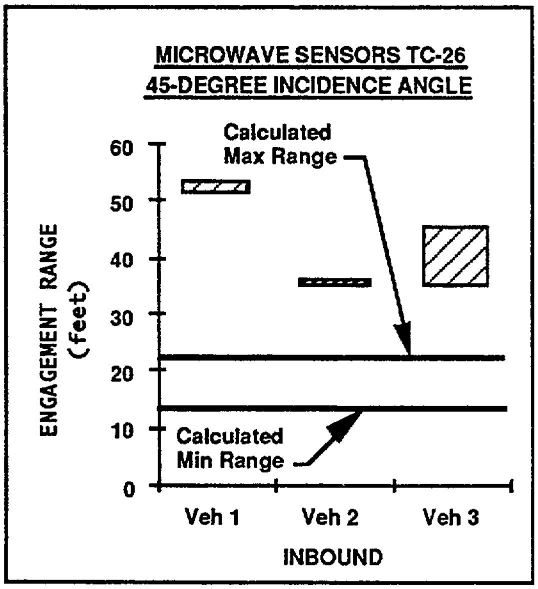
**Table 7-3. Input Power for TC-26**

| VOLTAGE | CURRENT |
|---|---|
| 18 VAC | 505 mA |
| 24 VAC | 518 mA |

### *7.5.2.2 Detection Range*

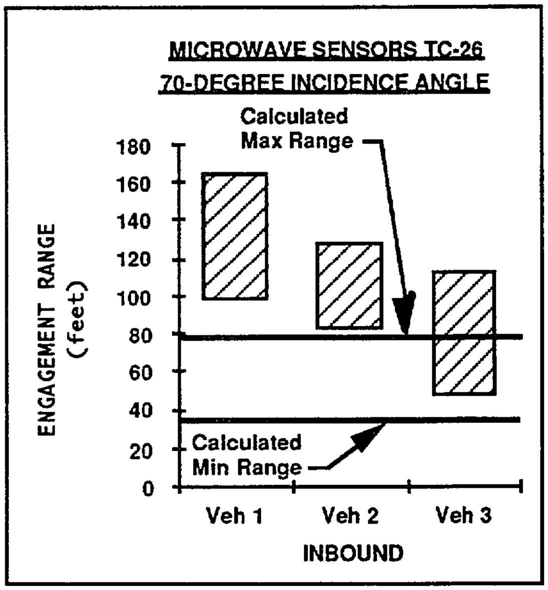
Figures 7-6 and 7-7 show the engagement range of the TC-26 at the maximum range setting and 45° and 70° incidence angles, respectively, for inbound vehicles as compared to the calculated engagement range.

Figures 7-8 and 7-9 show the engagement range at the maximum range setting and 45° and 70° incidence angles, respectively, for outbound vehicles as compared to the calculated engagement range. Vehicle 1 is the Ford Mustang, vehicle 2 is the large motorcycle, and vehicle 3 is the small motorcycle.



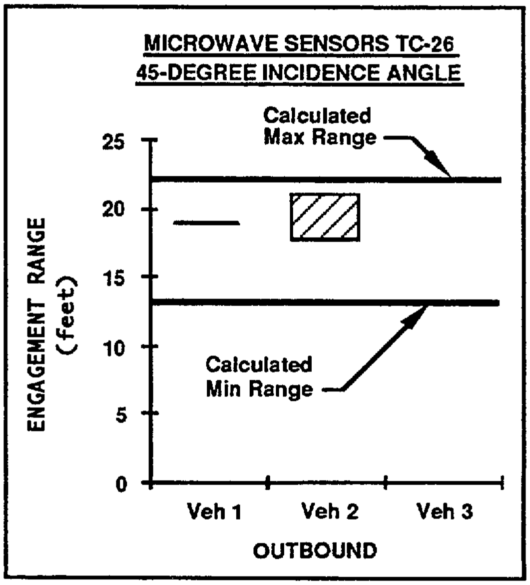
1 ft = 0.305 m

**Figure 7-6. Detection Range of TC-26 at 45-Degree Incidence Angle, Vehicles Inbound**



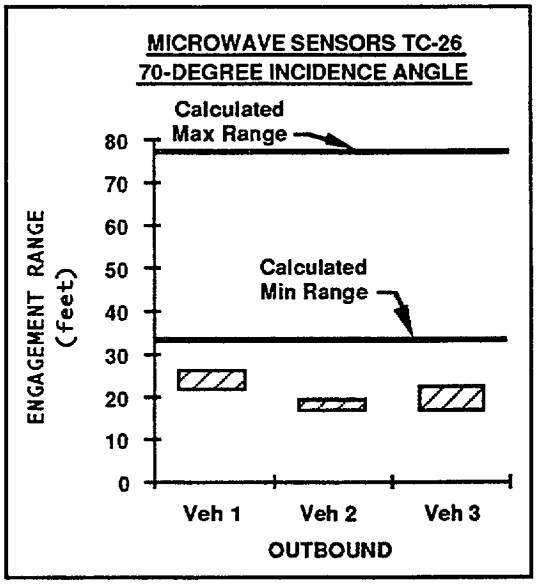
1 ft = 0.305 m

**Figure 7-7. Detection Range of TC-26 at 70-Degree Incidence Angle, Vehicles Inbound**



1 ft = 0.305 m

**Figure 7-8. Detection Range of TC-26 at 45-Degree Incidence Angle, Vehicles Outbound**



1 ft = 0.305 m

**Figure 7-9. Detection Range of TC-26 at 70-Degree Incidence Angle, Vehicles Outbound**

### 7.5.3 TDN-30 Microwave Detector

The TDN-30 operates at an incidence angle of 45° when the bottom of the detector housing is parallel to the road surface.

#### *7.5.3.1 Operating Current*

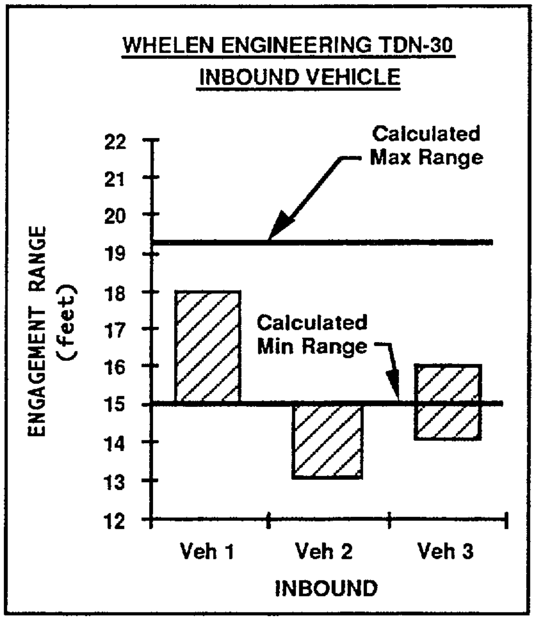
The specified operating voltages for the TDN-30 are 11 to 15 VDC at 200 mA.

**Table 7-4. Input Power for TDN-30**

| VOLTAGE | CURRENT |
|---|---|
| 11 VDC | 150 mA |
| 15 VDC | 155 mA |

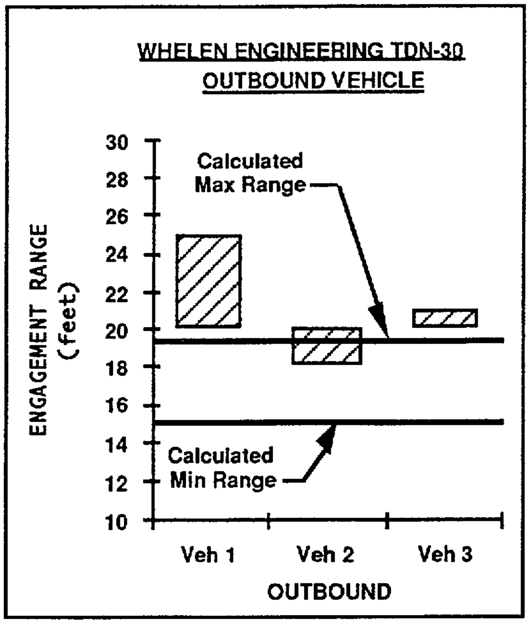
#### *7.5.3.2 Detection Range*

Figures 7-10 and 7-11 show the measured engagement range of the TDN-30 compared to the calculated range for inbound and outbound vehicles, respectively. The calculated range is based on geometrical factors that include mounting height, beamwidths, and incidence angle. Vehicle 1 is the Ford Mustang, vehicle 2 the large motorcycle, and vehicle 3 the small motorcycle.



1 ft = 0.305 m

**Figure 7-10. Inbound Vehicle Detection Range of TDN-30 at 45-Degree Incidence Angle**



1 ft = 0.305 m

**Figure 7-11. Outbound Vehicle Detection Range of TDN-30 at 45-Degree Incidence Angle**

### 7.5.4 TC-30C Ultrasonic Detector

The TC-30C operates at 0° incidence angle.

#### *7.5.4.1 Operating Current*

The specified operating voltages for the TC-30C are 6 to 12 VDC or 12 to 24 VAC at 150 mA.

**Table 7-5. Input Power for TC-30C**

| VOLTAGE | CURRENT |
|---|---|
| 12 VAC | 332 mA* |
| 24 VAC | 268 mA* |

*With no vehicle in detection zone.

### *7.5.4.2 Delay Time Measurement*

The delay time measurements compare favorably with the manufacturer's specification of 0.25-s minimum to 10-s maximum.

**Table 7-6. Delay Time for TC-30C**

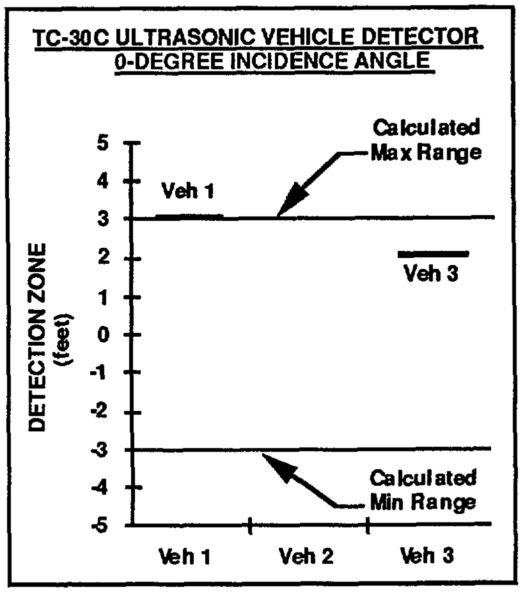
| DELAY TIME |
|---|
| 270-ms minimum |
| 9.6-s maximum |

### *7.5.4.3 Detection Zone*

Since the TC-30C operates at nadir, the range measurement nomenclature was changed to "detection zone" from "detection range."

Figure 7-12 shows the measured detection zone of the TC-30C at a 0° incidence angle as compared to the calculated zone. The calculated zone is based on geometrical factors that include mounting height, beamwidths, and incidence angle. It assumes that receiver output, sensitivity, and target reflective properties are adequate to receive the signal at the detector. Vehicle 1 is the Ford Mustang and vehicle 3 the small motorcycle.

The detection zone starts at the engagement range where the vehicles enter the beam. The nonzero nature of the minimum delay time affects the disengagement range measurement (i.e., the range at which the vehicle presence signal is dropped by the detector). Because of this, distances at which the vehicle presence was dropped were not measured. Vehicle 2 was not available when the TC-30C engagement range was measured.

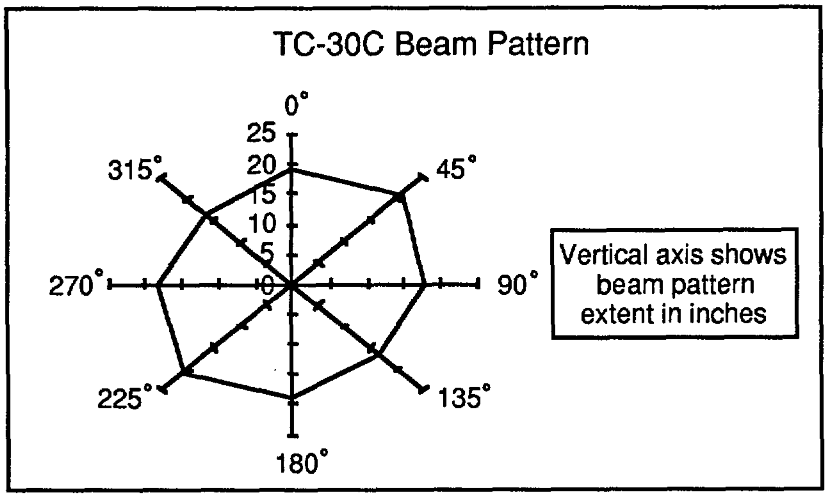


1 ft = 0.305 m

**Figure 7-12. Detection Zone of TC-30C at 0-Degree Incidence Angle**

### *7.5.4.4 Beam Pattern*

The TC-30C beam pattern is shown in Figure 7-13. The measurements were taken at approximately 15 feet (4.6 m) below the detector.



1 in = 25.4 mm

**Figure 7-13. Beam Illumination Pattern of TC-30C Ultrasonic Detector**

### 7.5.5 SDU-200 Ultrasonic Detector

The SDU-200 Doppler detector has a transmitting horn transducer and a receiving horn transducer that are mounted at 45° with respect to nadir. The horn furthest from a wall or other barrier is used as the transmitter.

#### *7.5.5.1 Operating Current*

The detector operates at a nominal voltage of 100 VAC. Its power consumption was measured at the minimum and maximum specified operating voltages.

**Table 7-7. Input Power for SDU-200**

| VOLTAGE | CURRENT |
|---|---|
| 80 VAC | 102 mA |
| 110 VAC | 102 mA |

#### *7.5.5.2 Detection Range*

Since the incidence angle of the detector must be at 45°, detection range measurements as a function of angle were not made, other than to confirm that the detector did sense the vehicles as they passed through its field of view.

### 7.5.6 SDU-300 Ultrasonic Detector

The SDU-300 is mounted at a nadir incidence angle.

#### *7.5.6.1 Operating Current*

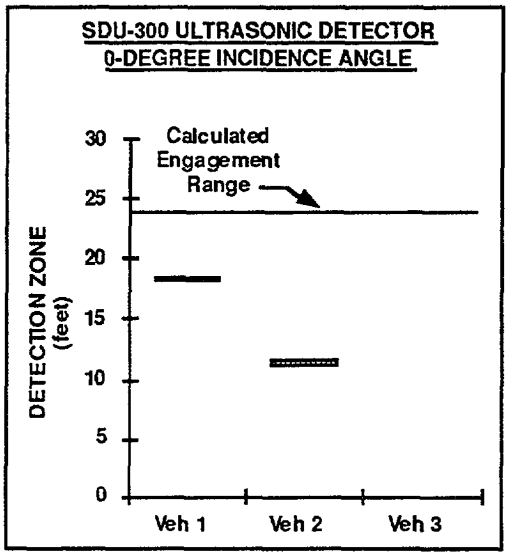
This presence detector operates at a nominal voltage of 100 VAC. Once again, its power consumption was measured at the minimum and maximum specified operating voltages.

**Table 7-8. Input Power for SDU-300**

| VOLTAGE | CURRENT |
|---|---|
| 80 VAC | 54 mA |
| 110 VAC | 69 mA |

#### *7.5.6.2 Detection Zone*

Figure 7-14 shows the measured detection zone of the SDU-300 at a 0° incidence angle as compared to the calculated zone.



1 ft = 0.305 m

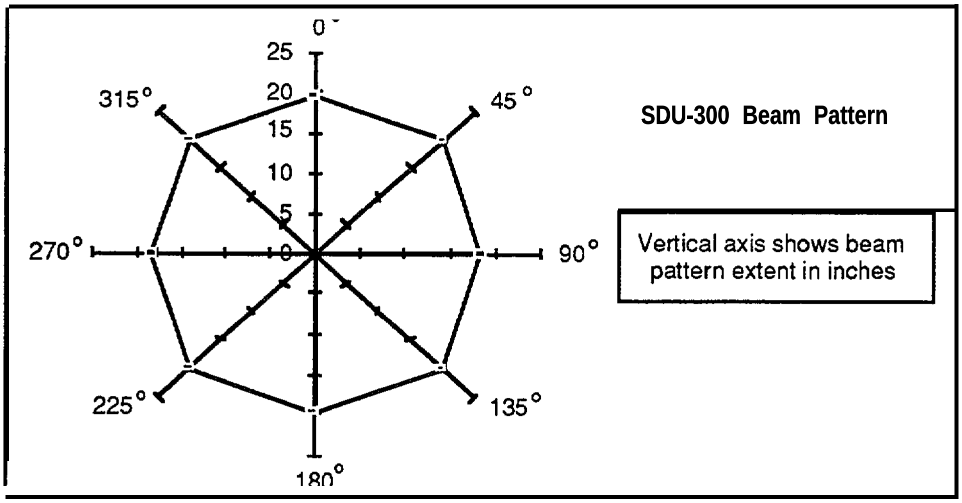
**Figure 7-14. Detection Zone of SDU-300 at 0-Degree Incidence Angle**

The calculated zone is based on the beamwidth, mounting height, and incidence angle of the detector. It assumes adequate receiver sensitivity and target reflective properties to detect a vehicle at the range calculated from the geometrical factors. Vehicle 1 is the Ford Mustang and vehicle 2 the large motorcycle. Vehicle 3, the small motorcycle, was not available for this test.

The detection point used in the measurements for vehicles 1 and 2 was the distance at which they entered the beam. The nonzero hold time affects the measurement of the distance at which the presence call is dropped when vehicles leave the beam. Because of this, the distance at which presence was dropped was not measured.

#### *7.5.6.3 Beam Pattern*

The beam pattern, shown in Figure 7-15, was measured at nadir from a height of approximately 13 feet (4.0 m) above the road surface.



**1 in = 25.4 mm**

Figure 7-15. Beam Pattern of SDU-300 Ultrasonic Detector

### 7.5.7 780D1000 Laser Radar Detector

The 780D1000 laser radar detector is normally mounted at incidence angles of less than 45°. However, in these tests, the incidence angle envelope was stretched to measure the performance limits of the detector.

#### *7.5.7.1 Operating Current*

The nominal operating voltage for the laser radar detector is 115 VAC.

Table 7-9. Input Power for 780D1000

| VOLTAGE | CURRENT |
|---|---|
| 90 VAC | 44 mA |
| 130 VAC | 34 mA |

#### *7.5.7.2 Vehicle Speed*

Table 7-10 compares the speed measured by the 780D1000 to the speed recorded from the speedometer on vehicle 1. The vehicle speedometer was not calibrated by an independent source for this evaluation.

Table 7-10. Measurement of Vehicle 1 (1985 Ford Mustang) Speed With Laser Radar Detector

| incidence Angle (degrees) | Speedometer (mi/h) | **780D1000 Measured Speed (mi/h)** |
|---|---|---|
| 45 | 8 | 7 |
| 45 | 15 | 15 |
| 45 | 20 | 21 |
| 45 | 20 | 19 |
| 60 | 11 | 12 |
| 60 | 8 | 7 |
| 60 | 8 | 8 |

**1 mi/h = 1.61** km/h

## 7.6. DETECTOR PERFORMANCE RESULTS FROM BENCH TEST MEASUREMENTS

Bench tests were performed to measure radio frequency (RF) output power, output frequency, minimum detectable signal, input power consumption, and response time of the microwave traffic detectors (Microwave Sensors TC-20 and TC-26 and Whelen TDN-30). A photograph of the measurement equipment is shown in Figure 7-16 with the Whelen TDN-30 as the detector under test.

The instrumentation horn was used to capture the radiated energy from the detector under test and transmit it to other equipment. The connections made to the instrumentation horn for various measurements are shown in Table 7-l 1. Volt meters and current meters were used to measure the input power to the detector. The response time was found by measuring the time difference between the injected RF signal and the closure of a relay.

Table 7-11. Device Connected to Instrumentation Horn for Measuring Various Detector Characteristics

| Measurement | Device Used |
|---|---|
| Output power | Power meter |
| Frequency | Spectrum analyzer |
| Minimum detectable signal | Sweep oscillator |

A summary of the bench test measurements and the manufacturers specifications is shown in Table 7-12. A comparison of the input power consumption of the detectors as measured during the Munson track tests and the bench tests is given in Table 7-13.

Table 7-l 2. Microwave Detector Bench Test Results

| Parameter | Whelen TDN-30 SN 00109 *Specified* | Whelen TDN-30 SN 00109 Measured | Microwave Sensors TC-20 SN 234242 *Specified* | Microwave Sensors TC-20 SN 234242 *Measured* | Microwave Sensors TC-26 SN 234326 *Specified* | Microwave Sensors TC-26 SN 234326 *Measured* |
|---|---|---|---|---|---|---|
| output power | Not specified | 4.6 dBm or 2.9 milli-watts | 10 dBm or 10 milli-watts | 10.2 dBm or 10.5 milli-watts | 10 dBm or 10 milli-watts | 11.9 dBm or 15.5 milli-watts |
| output frequency | 10.525 GHz | 10.520 GHz | 10.525 GHz | 10.520 GHz | 10.525 GHz | 10.519 GHz |
| Minimum detectable signal | Not specified | Not able to perform test | Not specified | -54 dBm or 4 microwatts | Not specified | -60.7 dBm or 0.9 microwatts |
| Input power consumption | 1.8 watts typical | 2.2 watts | 3.0 watts | 2.8 watts | 8.5 watts maximum | 3.9 watts |
| Response time | Not specified | Not able to perform test | 165 ms | 8.4 ms average | 250 ms | 11.5 ms average |

Figure 7-16.  Bench Test Setup

**Table 7-13. Munson Track and Bench Measurements of Input Power Consumption With Different Voltage Sources**

| Data Source | Whelen TDN30 | Microwave Sensors TC-20 | Microwave Sensors TC-26 |
|---|---|---|---|
| Manufacturer's Specification | 1.8 (nominal) to 2.8 Watts (maximum) using 12 VDC and 14 VDC, respectively | 6.0 Watts (maximum) using 10 to 24 VAC or 12 VDC | 8.5 Watts (maximum) using 12 to 24 VAC/DC |
| Munson Test | 1.65 to 2.3 Watts using 11 VDC and 15 VDC inputs, respectively | 4.0 to 5.4 Watts using 18 VAC and 24 VAC inputs, respectively | 9.1 to 12.4 Watts using 18 VAC and 24 VAC inputs, respectively |
| Bench Test | 2.2 Watts using 13.5 VDC input | 2.8 Watts using 13.5 VDC input | 3.9 Watts using 13.5 VDC input |

## 7.7 DETECTOR PERFORMANCE RESULTS FROM TESTS IN THE CITY OF LOS ANGELES

Beginning in August 1992, the City of Los Angeles Department of Transportation, in conjunction with Hughes Aircraft Company, evaluated the effectiveness and operating characteristics of various overhead vehicle detection systems. Eleven detectors comprising six different technologies were used: passive infrared, ultrasound, microwave, laser radar, inductive loop, and magnetometer. The inductive loops and magnetometers were already installed in the Exposition Boulevard test area. Their performance was compared with those of the overhead technologies. The first set of data was collected from August 25 to October 19, 1992. Computer data files were analyzed beginning with September 29 and continuing through October 19, 1992.

### 7.7.1 Test Site Description

The detector test site was located on Exposition Boulevard, near University Avenue, in the City of Los Angeles. Three eastbound lanes, shown in Figure 7-17, were already instrumented with inductive loops, magnetometers, passive IR, and ultrasonic detectors. The TCSOC, TC-26, 780D1000, and TDN-30 were mounted on the pole closest to the foreground. The middle pole contained the 842s. The pole farthest in the background supported the TC-20 and SDU-300. The traffic lanes monitored by each detector are shown in Table 7-14. Lane 1 is the leftmost lane.

### 7.7.2 Data Analysis Methods and Results

The count accuracy of the inductive loop detectors was 99.4 percent ±0.6 percent as computed from the recorded imagery that provided visual verification of the count. Inductive loop volume data collected in the lanes monitored by the in-ground and above-ground detectors under test were used to determine the relative accuracy of the other detectors. Fifteen-minute data increments were used in the analysis.

#### *7.7.2.1 Accuracy*

The base accuracy for each detector in each 15min period is expressed as a ratio of the count from the detector under test to the count from the calibrated loop detector. This detector accuracy ratio (DAR) is given by

$$\text{DAR} = \frac{\textit{Test Detector Count}}{\textit{Calibrated loop Detector Count}} \qquad \textbf{(7-1)}$$

Table 7-15 gives the accuracy ratios of the detectors. A ratio of unity indicates a 100-percent correlation between the detector under test and the calibrated loop detector. An accuracy ratio greater than unity indicates a tendency for the detector under test to overcount, while an accuracy ratio less than

Figure 7-17. Eastbound Lanes on Exposition Boulevard Test Site

## Table 7-14. Detector Mounting Locations

| Detector | Lane Location |
|---|---|
| Inductive Loops | 1, 2, and 3 |
| Magnetometers | 1, 2, and 3 |
| Sumitomo SDU-300 (Ultrasound) | 3 |
| Eltec 842 (Passive Infrared) | 3 |
| Microwave Sensors TC-20 (Microwave Detector) | 2 |
| Microwave Sensors TC-30C (Ultrasound) | 1 |
| Microwave Sensors TC-26 (Microwave Detector) | 2 |
| Schwartz Electra-Optics 780D1000 (Laser Radar) | 3 |
| Whelen TDN-30 (Microwave Detector) | 3 |

## Table 7-15. Accuracy of Detectors Under Test

| Detectors Listed in Descending Order of Overall Accuracy | Accuracy Ratio |
|---|---|
| SEO 780D1000 Laser Radar Detector | 0.996 |
| Whelen TDN-30 Microwave Detector | 1.020 |
| Eltec 842 Infrared Detector (#430) | 0.955 |
| Microwave Sensors TC-20 Microwave Detector | 0.954 |
| Eltec 842 Infrared Detector (#429) | 0.952 |
| Magnetometer Lane #3 | 1.055 |
| Sumitomo SDU-300 Ultrasonic Detector | 0.944 |
| Magnetometer Lane #1 | 1.102 |
| Microwave Sensors TC-30C Ultrasonic Detector | 1.113 |
| Magnetometer Lane #2 | 0.774 |
| Microwave Sensors TC-26 Microwave Detector | 2.711 |

unity indicates a tendency for the detector under test to undercount.

Some of the tested detectors show a low accuracy ratio because of the long hold time built into the detector by the manufacturer. When there is a high frequency of occurrence of closely spaced, high-speed vehicle traffic, a short detector hold time is needed to obtain accurate volume measurements. Other applications may require a high resistance to multiple counts provided by the long hold time, as when detecting long wheelbase vehicles.

### 7.7.2.2 Reliability

The periods in which vehicle counts did not meet Chauvenet's criterion (i.e., those periods where readings were greater than 2.81 times the standard deviation of the mean daily counts) were treated as a failure of the detector under test to provide accurate data. This was in addition to any detector data dropout times recorded by the Los Angeles Department of Transportation's Automated Traffic Surveillance and Control (ATSAC) computers. The ATSAC analysis computation returns a zero accuracy value if the detector under test returns a zero volume when the inductive loop detector returns a non-zero volume. Thus, any 15-min period in which the test detector accuracy was zero was considered to be an undercount failure. An analysis algorithm also tested for ghost signals generated by the detector under test in the absence of vehicles detected by the calibrated loops.

As a measure of the reliability of detector data output, the detector data dropout ratio ($D^3R$) shown in Table 7-16 was computed as

$$D^3R = 96/(\text{Number of Zero Accuracy Results} + \text{Number of Ghost Signals}) \quad (7\text{-}2)$$

where 96 is the number of 15-min periods per day.

Table 7-16. Detector Data Dropout Ratio for Detectors Under Test

| **Detectors Listed in Descending Order of Detector Data Dropout Ratio** | **$D^3R$ in Hours*** |
|---|---|
| Whelen TDN-30 Microwave Detector | 74.67 |
| Microwave Sensors TC-20 Microwave Detector | 69.52 |
| Sumitomo SDU-300 Ultrasonic Detector | 59.29 |
| Eltec Infrared Detector (#430) | 51.69 |
| Microwave Sensors TC-30C Ultrasonic Detector | 42.89 |
| Eltec Infrared Detector (#429) | 42.00 |
| Microwave Sensors TC-26 Microwave Detector | 41.14 |
| Magnetometer Lane #3 | 38.77 |
| SEO 780D1000 Laser Radar Detector | 36.08 |
| Magnetometer Lane #1 | 27.24 |
| Magnetometer Lane #2 | 19.02 |

*Detector data dropout ratio accounts for the number of 15-minute intervals in which: (1) the test detector returns a zero volume and the inductive loop detector returns a non-zero and (2) the test detector returns a non-zero volume and the inductive loop detector returns a zero.

The laser radar dropout ratio calculated from the April to June 1993 data (shown in the table) was degraded by a 2.25-h interval on June 23 (survey day 16) during which no data were output by the laser radar. The problem was at the detector site and did not apparently involve the local signal controller or existing communication network. Whether the data dropout was due to the detector itself or to the detector's power supply could not be determined from the available information. However, even with this outage, the performance of the laser radar was comparable to that of the other detectors.

Sumitomo raised other issues that may have affected the accuracies reported in Table 7-15 with respect to undercounting of vehicles. They pointed out that vehicle lane changing may have occurred in the region between the overhead detectors and the calibrated loops, although this did not appear to be a significant problem.

The measures of data output reliability used in the Los Angeles evaluation (namely, daily percent downtime and detector data dropout ratio) are not meant to be absolute measures of the detector's hardware reliability. The data dropout ratios simply provide a comparison between the various detectors as they operate with the current California Type 170 Traffic Signal Controllers, and their ability to cope with the traffic conditions encountered during the tests. Therefore, some of the dropouts or gross inaccuracies in the detectors under test may be caused by either compatibility problems with local equipment or unusual traffic conditions. Hard reliability figures for the inductive loop detectors are not available. Hence, the numbers shown in Table 7-16 should be used only as relative values for comparing the data dropouts from the detectors during this test.

# 8. TASK F SUMMARY

## DEVELOP VEHICLE DETECTOR FIELD TEST SPECIFICATIONS AND FIELD TEST PLAN

### 8.1 TEST OBJECTIVES

The primary objective of the field tests was to quantify the performance of traffic detector technologies with respect to the types and accuracy of the data they provide for the IVHS applications identified in the Task A report.(1) The detectors were evaluated in freeway and arterial street traffic. The video recording of the traffic flow in the detectors' field of view provided truth data for vehicle count and presence against which to compare detector output data from the technologies under test. Speed guns and probe vehicles were also used to supply truth data.

A second objective was to expose the detector technologies to a variety of weather conditions. This required the selection of geographically diverse test sites and seasons in which to conduct the tests and the capability to not only measure the accuracy of the traffic data supplied by the detectors, but also to monitor and record the environmental conditions prevailing throughout the tests.

The third objective was to compare the performance of the new detector technologies with that of current inductive loop detectors (ILDs) and magnetometers.

The fourth objective was to engage diverse vehicle and driver populations in different regions of the United States in the detector technology performance evaluation and, thus, enhance the national applicability of the test results.

### 8.2 DETECTOR TECHNOLOGIES EVALUATED

Table 8-1 lists the detectors and the technologies they represent that were evaluated in the field test program. Inductive loop detectors were also included in the test matrix, although they are not listed in the table. A list of detector manufacturers is provided in Appendix B.

### 8.3 TRAFFIC PARAMETERS MEASURED

Flow rate, speed, and density, or its surrogate occupancy, are an interrelated set of traffic parameters used to describe the quality of traffic flow on a highway. To measure flow rate accurately, detectors need to discriminate between vehicles where there are gaps on the order of 25 feet (7.6 m) and time headways of 1 to 2 seconds. Speeds can be measured using ILDs in speed traps composed of two closely spaced (15 to 20 feet [4.6 to 6.1 m] apart) loops excited by oscillators that are continuously dedicated to each loop in the pair, or less accurately with a single loop and an assumed vehicle length. Some microwave detectors, such as the device that transmitted a frequency modulated continuous wave (FMCW) and the laser radar evaluated in this project, measure speed by noting the time it takes for the vehicle to arrive at two points a known distance apart. Microwave Doppler and ultrasound detectors measure speed using the Doppler effect.

Density (vehicles per mile per lane) is difficult to measure directly, except with some type of picture format, such as video imaging or aerial photography. Consequently, lane occupancy (the percent of time the detection zone of a detector is occupied by a vehicle) has been used as a surrogate measure for density. In this case, the requirement to discern the boundaries of vehicles is much more stringent than for counting. Accurate occupancy measures require discriminating between vehicles and gaps to within 1 to 5 percent of their true values, as discussed in the Task A report.(l)

Other traffic parameters important for traffic management are presence, queue length, travel time, intersection turning movements, and vehicle classification. Presence needs to be measured, even if the vehicle is stationary, for applications that include intersection control and ramp metering. Therefore, detectors which require motion in order to be

Table 8-1. Detectors and Technologies Evaluated During Field Tests

| Symbol | Technology | Manufacturer | **Model** | **Quantity** |
|---|---|---|---|---|
| U-l | Ultrasonic Doppler | Sumitomo | SDU-200 (RDU-101) | 1 |
| U-Z | Ultrasonic Presence | Sumitomo | SDU-300 | 2 heads,<br>1 controller |
| U-3 | Ultrasonic Presence | Microwave Sensors | TC-30C | 2 |
| M-1 | Microwave Detector<br>Motion<br>Medium Beamwidth | Microwave Sensors | TC-20 | 2 |
| M-2 | Microwave Detector<br>Doppler<br>Medium Beamwidth | Microwave Sensors | TC-26 | 2 |
| M-4[a] | Microwave Detector<br>Doppler<br>Narrow Beamwidth | Whelen | TDN-30 | 2 |
| M-5 | Microwave Detector<br>Doppler<br>Wide Beamwidth | Whelen | TDW- 10 | 2 |
| M-6 | Microwave Radar<br>Presence<br>Narrow Beamwidth | Electronic Integrated Systems | RTMS-X1 | 2 |
| IR-1 | Active IR<br>Laser Radar | Schwartz Electro-Optics | 780D1000 (Autosense I) | 1 |
| IR-2 | Passive IR<br>Presence | Eltec | 842 | 1 |
| IR-3 | Passive IR<br>Pulse Output | Eltec | 833 | 1 |
| IR-4[b] | Imaging IR | Grumman | Traffic Sensor | 1 |
| VIP-1 | Video Image Processor | Econolite | Autoscope 2003 | 1 |
| VIP-2 | Video Image Processor | Computer Recognition Systems | Traffic Analysis System | 1 |
| VIP-3[c] | Video Image Processor | Traficon | CCATS-VIP 2 | 1 |
| VIP-4[b] | Video Image Processor | Sumitomo | IDET- 100 | 1 |
| VIP-5[d] | Video Image Processor | EVA | 2000 | 1 |
| A-1[e] | Passive Acoustic Array | AT&T | SmartSonic TSS-1 | 1 |
| MA-1 | Magnetometer | Midian Electronics | Self-Powered Vehicle Detector | 2 |
| L-lb | Microloop | 3M | 701 | 4 |
| T-1[b] | Tube-Type Counter | Timemark | Delta 1 | 1 |

a. M-3 was designated for a microwave radar detector that was not received.

b. Used at Tucson, Arizona test site only.

c. Used at all Arizona test sites.

d Used in Phoenix, Arizona 7/94 test only.

e. Used in Phoenix 11/93 and Tucson tests.

activated, such as passive magnetic detectors and others that transmit continuous wave energy, cannot perform this task. Queue length, as density, requires wide-area detection to be measured directly.

Travel time is inversely proportional to average speed. For travel time to be measured directly, the same vehicle has to be identified at several points along a highway using either ( 1) a roadside-mounted detector or (2) a vehicle identification device mounted on the vehicle that is interrogated by readers deployed along the highway system. Thus, travel time could be a side benefit of instituting an automatic vehicle identification (AVI) system in which the vehicles act as "probes." Vehicle classification could also be an offshoot of AVI if it was widely deployed. However, AVI systems are considered beyond the scope of the field testing portion of this project. Imaging systems, high-resolution ranging systems such as active infrared and some ultrasonic systems, and ILDs coupled with special vehicle transmitters and receiver amplifiers also have vehicle classification ability.

## 8.4 ENVIRONMENTAL FACTORS

The environmental factors considered during the field tests were precipitation, wind, temperature, barometric pressure, acoustic noise, electromagnetic interference, shadows, and vibration.

### 8.4.1 Precipitation

Precipitation in the form of rain and snow affects the operation of visible, infrared, and ultrasonic detectors. In addition, fog and mist have a detrimental effect on those detectors using the visible and infrared spectrum.

### 8.4.2 Wind

Wind is a factor in ultrasonic detector operation as it causes turbulence that can distort the ultrasonic waveform. The Sumitomo SDU-200 ultrasonic speed detector is designed to operate at wind speeds up to 56 mi/h (25 m/s). Wind is also a cause of detector movement, discussed further in the section on vibration.

### 8.4.3 Barometric Pressure

Barometric pressure changes may affect the speed of propagation of ultrasonic waves and thus the accuracy of range measurements. An automatic calibration feature on some ultrasonic detectors, such as those from Sumitomo, eliminates most weather-related effects.

### 8.4.4 Acoustic Noise

Acoustic noise in the audible or ultrasonic ranges could conceivably interfere with the operation of passive acoustic arrays and ultrasonic detectors. However, the relatively small and focused field of view used by the overhead detectors makes this event unlikely.

### 8.4.5 Electromagnetic Interference

Electromagnetic interference has the potential to affect the operation of all types of traffic detectors, as it can enter through the aperture of the detector or through the enclosure that protects the electronics that process the data. Broad-spectrum electromagnetic interference can thus insert noise into the signal and data processing hardware. For the special case of microwave detectors, interference may occur when the detector is operated in the vicinity of high-power radars transmitting at nearby frequencies. The use of radars for speed enforcement by local police did not interfere with the operation of the microwave detectors during the field tests. Computers and video monitors produced interference that degraded the operation of the SPVD magnetometer receiver when the receiver was not isolated on its own AC circuit.

### 8.4.6 Shadows

Shadows can affect the operation of video image processors. During cloudless midday operation, the contrast between shadow and sunlit areas can be great, perhaps leading to false declarations of shadows as vehicles. In addition, low-angle direct sunlight and glint from the reflection of sunlight off other surfaces can produce glare in the scene or on the detector lenses. These effects can be eliminated or reduced through advanced signal processing and proper mounting of the VIP camera.

### 8.4.7 Vibration

Vibration can pose a problem both for the image processing detectors and possibly for some of the other detectors mounted above ground. This is most likely to occur when the detectors are mounted on high poles, or when video images are obtained with a long focal-length lens. Wind is likely to be a common cause of vibration; but for detectors located on structures, vibration could also develop from heavy trucks moving across or below the structure.

## 8.5 GROUND TRUTH

Accurate data against which to evaluate state-of-the-art detector technologies were obtained from the recorded video of the traffic flow. A video home system (VHS) format video camera and computer-controlled video cassette recorder (VCR) with stop-motion capability were used to manually sample the recorded video to obtain count, volume, and presence truth data. A data logger system that automatically records, time tags, and displays the vehicle detections from all the detectors under test was developed to simplify the data analysis process. The data logger is described later in this section and in Appendix C.

In addition to serving as a database from which traffic parameter truth data are obtained, the video provides a visual record of environmental conditions encountered during testing and a visual record to aid in resolving anomalies that may arise during data analysis.

By analyzing the video record off-line, manual counts were made to verify the real-time data collected by the detectors. The following comments illustrate how the video imagery was used to obtain ground truth data for selected traffic parameters.

### 8.5.1 Volume

Volume data were obtained manually by replaying the video to count the required vehicle types and movements, such as lane crossings. The time stamp of detector output events provided by the data logger, along with the recorded video tape index number, allowed correlation of video imagery with detector data.

### 8.52 Speed

Speed ground truth data were obtained by driving a marked probe vehicle through the detection zone during data collection periods. The driver recorded vehicle speed, lane, and approximate time for each run. The exact time was obtained from the corresponding time stamps supplied by the data logger. The probe vehicle was identified by hanging a flag from the radio antenna or the truck lid, by inserting a traffic cone through the window of the probe, by driving with the trunk open, or by waving a hat or other object from the window of the vehicle while driving through the field of view of the camera. Beginning with the Tucson runs, a Detector Systems vehicle-mounted transducer was used to emit a vehicle identification code that was picked up by the inductive loops and recorded by the data logger. Speed truth data were also manually recorded from a police radar during the evaluations at the Orlando freeway site.

### 8.5.3 Occupancy and Presence

Occupancy and presence data were verified by superimposing the detector relay closure event on the video whenever the detector sensed a vehicle within its capture zone. This procedure is controlled by the application-specific Phase II software written for the data analysis process.

### 8.5.4 Queue Length, Turning Movements, and Vehicle Classification

When available as outputs from detectors, these parameters can be manually verified from the video.

## 8.6 TRAFFIC DATA COLLECTION REQUIREMENTS

The data collection requirements differ slightly for the freeway and surface arterial test locations.

### 8.6.1 Freeway Test Locations

For the freeway test sites, count, flow rate, speed, and occupancy were measured by the detectors under test and compared with simultaneous data obtained from inductive loop detectors and video during peak and off-peak hours.

### 8.6.2 Surface Arterial Test Locations

Data to calculate presence, flow rate, speed, and occupancy were recorded for the signalized intersection environment on a signal cycle-by-cycle basis and categorized signal cycle-by-cycle basis and categorized for peak and off-peak periods. Queue length and turning movements were not output by any of the detectors evaluated.

## 8.7 TEST SITE LOCATIONS

The detector technology evaluation sites were located in Minneapolis, MN; Orlando, FL; Phoenix, AZ, and Tucson. AZ as shown in Table 8-2. The expected weather conditions are listed. Detailed descriptions are provided in the Task B report.(2)

Table 8-2. Test Sites

| City | Freeway | Surface Arterial | Weather | Test Period |
|---|---|---|---|---|
| Minneapolis | I-394 at Penn Avenue | Olson Highway at Lyndale Avenue | Cold, snow, sleet, fog | Winter 1992-1993 |
| Orlando | I-4 at SR 436 | SR 436 at I-4 | Hot, heavy rain, lightning | Summer 1993 |
| Phoenix | I-10 at 13th Street | Not applicable | Warm, heavy rain, lightning | Autumn 1993 |
| Tucson | Not applicable | Oracle Road at Auto Mall Drive | Cool to warm, heavy rain, lightning | Winter-Spring 1994 |
| Phoenix | I-10 at 13th Street | Not applicable | Hot, heat waves, heavy rain, lightning | Summer 1994 |

## 8.8 DETECTOR INSTALLATION

### 8.8.1 Site Preparation

Site preparation included arranging for the housing and installation of data recording equipment in a portable trailer, installing sufficient data and power cables to connect the detectors with the data recording apparatus and power supplies, painting of calibration marker distances on the roadway surface, and obtaining descriptions of each of the ILDs that were installed for the tests.

Calibration distance markers were painted across each lane or on the shoulder of the test section of roadway, where possible, to aid in measuring the distance of vehicles from the above-the-road detector mounting location and for VIP calibration. The stripes were painted at 5- to 25-foot (1.5- to 7.6-m) intervals (depending on the requirements for VIP setup and calibration) out to approximately 300 feet (91.4 m), with the zero-foot mark located at the detector mounting location.

### 8.8.2 Overhead Detector Mounting

In order to have space to mount and operate all the overhead detectors at the same time, they were attached to two or more grids constructed of 1. S-inch (38.1 -mm) galvanized pipe and secured with various types of pipe clamps or manufacturer-supplied mounting hardware. When the mounting of the detectors on the pipe grids was not practical, they were attached directly to the overhead structure.

The pipe grid was connected to a central ground in the trailer at the equipment rack to minimize ground currents that affect some detectors. An uninterruptable power supply and lightning protection devices on all input data lines were used to help protect data recording equipment.

### 8.8.3 Overhead Detector Layouts

The overhead detectors were configured into arrays at each evaluation site. Specific conditions, such as the number of active traffic lanes and the existing structures available on which to mount detectors, influenced the specific configuration and array mounting technique.

### 8.8.4 In-Ground Detectors

The detector evaluation site layout accommodated the requirement to compare ILD and magnetometer technology performance with that of the above-ground detectors. The location of the buried detectors were indicated by temporary pavement markings, sealants used in the installation process, or traffic cones on the shoulders when snow was present. These markings appear in the video record of the tests.

### 8.8.5 Cable Requirements

Detailed information about detector operation, mounting, power requirements, and output data are found in the detector manufacturers operations manuals and the Task D report that were supplied to the state agencies hosting the field tests.(3) Summaries of the installation requirements to accommodate detector size, weight, data transmission, and power are given in Table 8-3. Input power sources included 115 VAC, 100 VAC, 12 VAC, 12 VDC, and 24 VDC. Wind-shear loads on the bolts that attach poles to the subground support structure were taken into account. About 200 lines were required for input power and data output. Detector output data and 115-VAC input power were not transmitted in the same cable to lessen the likelihood of data corruption by the power lines.

## 8.9 TEST PROCEDURES

### 8.9.1 Run Times

The detectors were operated for several multi-hour time intervals during a 24-h period to obtain data for various levels of traffic flow and different light levels and lighting transition periods throughout the day and night. Shadows and daylight-to-darkness transitions were encountered with this test regime. Typical runs started at predawn and continued through the end of the morning rush hours. A second run was made each day beginning at about 3:30 in the afternoon and continuing well into nighttime darkness. As these two runs spanned light and heavy traffic and various lighting conditions, a midday run was unnecessary most of the time. They were made, however, when traffic or weather conditions dictated.

### 8.9.2 Weather Data

Temperature and wind speed and direction were recorded on the data logger. Temperature sensors were generally placed in two locations, one on the detector mounting structure and another near the ground surface. The wind sensors were placed on an 8- to 15-foot (2.4- to 4.6-m) high pole near the trailer or the side of the road. When available, daily hour-by-hour weather records were obtained from local newspapers. A record of any visible precipitation was made on the video tapes recorded for each run. The official weather observations at each field test site were obtained from the National Climatic Data Center (NCDC) in Asheville, NC after the tests were completed as contained in Appendix J.

### 8.9.3 Equipment Checkout Runs

Once the detectors were installed, checkout tests were performed to ensure that the equipment was functioning in a manner consistent with the laboratory tests described in the Task C and E reports and the specifications of the detector manufacturers.(4,5) In the checkout tests, marked vehicles traveling at known speeds traveled through the detector test area. Normal traffic was also used to verify that the detectors are responding to vehicles passing through their fields of view.

Table 8-3. Detector Installation Requirements

| Detector Symbol | Manufacturer and Model Number | Input Power | Detection Range (feet) | Discrete Detector Outputs | Serial Detector Outputs |
|---|---|---|---|---|---|
| U-1 | Sumitomo SDU-200 | 80-110 VAC<br>6 Watts | 26 max | Relay Contacts:<br>2 amp max<br>500 V max<br>100 VA max | Detection by vehicle length: 1 bit;<br>Speed (binary): 8 bits;<br>Speed (in terms of pulse width): 1 bit |
| U-2 | Sumitomo SDU-300 | 80-110 VAC<br>6 Watts | 5 to 26 | Relay Contacts:<br>2 amp max<br>500 V max<br>100 VA max | |
| U-3 | Microwave Sensors TC-30C | 6-12 VDC<br>12-24 VAC<br>150 mA | 3 to 22 | Relay Contacts:<br>Form C, 5 A @ 24 VDC | |
| M-1 | Microwave Sensors TC-20 | 10-24 VAC<br>12 VDC<br>250 mA | 3 to 100 | Relay Contacts:<br>Form C, 2 A | |
| M-2 | Microwave Sensors TC-26 | 12-24 V AC or DC<br>350 mA | 200 max (autos) | Relay Contacts:<br>Form C, 5 A @ 24 VDC & 5-5V logic level outputs | |
| M-4 | Whelen TDN-30 | 11-15 VDC<br>200 mA | 100 max | Two opto-isolator outputs: 40 V holdoff, ON <1 V @ 50 mA | RS-232 @ 1200 or 2400 baud |
| M-5 | Whelen TDW-10 | 11-15 VDC<br>200 mA | 100 max | Two opto-isolator outputs: 40 V holdoff, ON <1 V @ 50 mA | RS-232 @ 1200 or 2400 baud |
| M-6 | Electronic Integrated Systems RTMS-X1 | 95-135 VAC<br>150 mA | 200 max | 12 isolated o.c. contact pairs (1 pr/ln) rated for 50 mA @ 30 V | RS-232 data bus @ 9600 baud |
| IR-1 | Schwartz Electro-Optics 780D1000 | 115 VAC<br>20 Watts | 5 to 50 | Presence Relay | RS-232 for speed, count, and range |
| IR-2 | Eltec 842 | 95-135 VAC<br>10 watts max | 21 to 54 | Relay Output:<br>3.5 A, 250 VAC<br>300 W | |
| IR-3 | Eltec 833 M2 | 100-130 VAC<br>22 mA | 16 to 98 | Relay Output:<br>3.5 A, 120 VAC<br>200 VA | |
| IR-4 | Grumman IIR Traffic Sensor | 115 VAC | up to 1000 | | RS-232 data @ 9600 baud |
| VIP-1 | Econolite/ Autoscope 2003 | 115 VAC<br>100 Watts | up to 300 | RS-170 Video | RS-232 data @ 2400 or 9600 baud |
| VIP-2 | Computer Recognition Systems Traffic Analysis System | 95-132 VAC<br>400 VA | up to 300 | CCIR standard or RS-170 Video.<br>Also VME bus | RS-422, RS-232<br>Opto 22 Relays<br>16-bit parallel |
| VIP-3 | Traficon CCATS-VIP 2 | 115 VAC | up to 300 | RS-170 Video | RS-232C data @ 9600 baud |
| VIP-4 | Sumitomo IDET-100 | 100 VAC<br>≤ 200 VA | | RS-170 Video | RS-232 data @ 9600 baud |
| VIP-5 | EVA 2000 | 41 VAC ± 15%<br>48 VDC ± 15%<br>25 to 35 Watts | up to 300 | RS-170 Video or CCIR PAL | RS-232 data up to 19200 baud;<br>RS-422 to 64k baud |
| A-l | AT&T TSS-1 | 24 VDC<br>250 mA | | Two opto-isolator outputs | 170/NEMA interface |

**1 ft = 0.305 m**

Table 8-3. Detector Installation Requirements (continued)

| etector Symbol | Depth (inches) | Width (inches) | Height (inches) | Weight (pounds) | Height Above Roadway (feet) | Angle From Vertical (degrees) | Beam-width (degrees) | Look Up-Stream? | Look Down-Stream' |
|---|---|---|---|---|---|---|---|---|---|
| U-1 | 6.6 | 11.8 | 7.2 | Not available | 16.4 to 18.0 | 34 to 55 | 15 | Yes | No |
| U-2 | 6.3 | 6.3 | 5.1 | Not available |  | 0 | 13 | Nadir | Nadir |
| U-3 | 7.0 | 4.5 | 4.0 | 3.0 | 12 to 18 | 0 | 20 | Nadir | Nadir |
| M-1 | 7.5 | 4.5 | 4.5 | 4.0 | 12 to 18 | 20 to 70 | 16 Az<br>15 El | Yes | Yes |
| M-2 | 7.0 | 4.0 | 4.0 | 3.0 | 14 to 18 | 20 to 70 | 16 Az<br>15 El | Yes | Yes |
| M-4 | 10.0 | 12.0 | 10.0 | 10.5 | 16 to 32 | Incidence angle is 45 deg when properly mounted | 7 | Yes | Yes |
| M-5 | 10.0 | 12.0 | 10.0 | 10.5 | 12 to 40 | Incidence angle is ≈70 deg when properly mounted | 25 | Yes | Yes |
| M-6 | 6.0 | 11.0 | 9.0 | 10.0 | 16 to 32 |  | 15 Az<br>≈50 El | Yes | Yes |
| IR-1 | 6.3 | 6.3 | 3.5 | 6.0 | 15 to 20 | 0 to 45 | 1 mrad (El) x 9.4° (Az) | Yes | No |
| IR-2 | 8.7 | 4.7 | 3.1 | 6.0 | 15 to 20 | 45 to 68 | 4 | Yes | Yes |
| IR-3 | 8.3 | 4.7 | 3.2 | 3.0 | 13 to 20 | 14 to 43 |  | Yes | Yes |
| IR-4 | 30 | 9.0 | 7.9 | 25.0 |  |  | HFOV = 27°<br>320 (H) x 240 (V) pixels | Yes | Yes |
| VIP-1 | 10 | 17.5 | 5.75 |  |  |  |  | Yes | Yes |
| VIP-2 |  |  |  |  |  |  |  | Yes | Yes |
| VIP-3 | 9.0 | 3.0 | 7.0 |  |  |  |  | Yes | Yes |
| VIP-4 |  |  |  | 14.0 |  |  |  | Yes | Yes |
| VIP-5 | 9.3 | 12.4 | 10.7 | 6.6 | 33 to >59 |  |  | Yes | Yes |
| A-I | 3.5 | 22.0 | 22.0 | 25.0 | 20 to 35 |  | 6 (3 dB)<br>20 (10 dB) | Yes | Yes |

1 in = 25.4 mm
1 ft = 0.305 m
1 lb = 0.454 kg

### 8.9.4. Video Peed to Image Processors

At most sites, black-and-white video imagery was supplied by a common camera and a video distribution amplifier to the VIPs, monitors, and VCR. The Autoscope system, however, used a separate camera designed specifically for its processor, except in Minnesota where a Burle camera supplied by MnDOT was used.

## 8.10 DATA RECORDING AND ANALYSIS

A PC-based data logger, shown in Figure 8-1, automatically recorded and time-tagged data and assisted in their analysis. Application-specific software run by the 386 PC formatted the VCR video tapes and issued stop and start commands to the VCR. Video tape index numbers were recorded by the data logger to correlate with the time tags and detectoroutput events.

The data logger is capable of recording 8 analog signals, such as Doppler frequency, air temperature, and wind speed and direction; 16 relay-based detector output transitions; 40 optically isolated detector output transitions; and 16 RS-232 serial inputs. Since the protocols for reading the serial data are unique to each detector, the detector's serial output was connected to a specific RS-232 input port on the data logger as identified in Figure 8-l. Further description of the data logger is given in Appendix C.

The Phase II software developed for the data logger converts the raw input data into comma-delimited format, and Paradox software converts that into a database from which a direct comparison of speeds, counts, occupancies, etc. can be made across the detectors. The database values can be plotted as a function of time or green-phase cycle length using a program such as Mathcad to simultaneously display parameters from the selected detectors. Statistics such as means and standard deviations can also be computed to assess the accuracies of the detectors.

In Tucson, data produced by high-frequency sampling of the change in inductance produced by the passage of a vehicle over inductive loops were recorded on a dedicated personal computer and hard drive along with time stamps supplied by the data logger computer. The high sampling rate needed to reproduce the frequencies of interest required a separate computer and hard drive to prevent overloading of the drive on which the other detector output data are recorded. Waveforms associated with the passage of vehicles through the magnetic field produced by an array of magnetometers were recorded on a Metrum recorder located in the field trailer. These were transcribed onto suitable magnetic media that are compatible with the data analysis system.

## 8.11 SECURITY FOR THE EVALUATION SITE

Provisions were made to secure the trailer and equipment from burglary. These measures included the installation of extra locks and a cellular-phone-based security system that automatically notified appropriate authorities in the event of unauthorized access to the trailer or a fire. Land-line telephone service was installed in the trailer as well when it was available. When a possibility existed for the public to interfere with the operation of the overhead detectors, measures such as fencing off the detectors from public access were employed.

Figure 8-1.  Data Logger

## REFERENCES

1. Detection Technology for IVHS: Task A Report - Development of Traffic Parameter Specifications. Federal Highway Administration Contract DTFH61-91-C-00076, U.S. Department of Transportation, Washington, DC. (1994).

2. Detection Technology for IVHS: Task B Report - Selection of Field Sites. Federal Highway Administration Contract DTFH61-91 -C-00076, U.S. Department of Transportation, Washington, D.C. (1994).

3. Detection Technology for IVHS: Task D Report - Select and Obtain Vehicle Detectors, Highway Administration Contract DTFH61-9 1 C-00076, U.S. Department of Transportation, Washington, D.C. (1994).

4. Detection Technology for IVHS: Task C Report - Laboratory Test Specifications and Test Plan, Federal Highway Administration Contract DTFH61-91 -C-00076, U.S. Department of Transportation, Washington, D.C. (1994).

5. Detection Technology for IVHS: Task E Report - Laboratory Test Results, Parts I, II, and III, Federal Highway Administration Contract DTFH61-91-C-00076, U.S. Department of Transportation, Washington, D.C. (1993).

# 9. TASK G

# INSTALL VEHICLE DETECTORS AT FIELD SITES AND COLLECT FIELD TEST DATA

Six field sites were selected in which to evaluate modern detector technologies suitable for traffic management on freeways and surface streets. Table 9-l summarizes the location, evaluation period, weather, and traffic flow direction at each site. The Phoenix freeway site was visited twice in order to obtain hot weather data that were not gathered during the first visit. The detectors installed at the sites and the technologies they represent are listed in Table 9-2.

**Table 9-1. Descriptions of Detector Technology Evaluation Sites**

| Location | Evaluation Period | Weather | Traffic Direction |
|---|---|---|---|
| Minneapolis freeway:<br>I-394 at Penn Avenue | Winter 1993 | Cold, snow, sleet, fog | Departing (AM);<br>Departing and approaching (PM) |
| Minneapolis surface street:<br>Olson Highway at East Lyndale Avenue North | Winter 1993 | Cold, snow, sleet, fog | Departing |
| Orlando freeway:<br>I-4 at SR 436 | Summer 1993 | Hot, humid, heavy rain, lightning | Approaching |
| Orlando surface street:<br>SR 436 at I-4 | Summer 1993 | Hot, humid, heavy rain, lightning | Departing |
| Phoenix freeway:<br>I-10 at 13th Street | Autumn 1993 | Warm, rain | Approaching |
| Tucson surface street:<br>Oracle Road at Auto Mall Drive | Winter 1994 | Warm | Departing |
| Phoenix freeway:<br>I-1 0 at 13th Street | Summer 1994 | Hot, low humidity, thunder storms, lightning | Approaching |

## 9.1 MINNEAPOLIS EVALUATION SITES

The Minneapolis freeway site at I-394 and Penn Avenue is shown in Figure 9-l as the overhead detectors were installed. The boom truck was used to attach the pipe trees to the concrete overpass structure and adjust the alignment of the detectors so that they observed traffic in their designated lanes and at manufacturer-specified incidence angles. Details of the pipe tree attachment to the overpass are contained in Appendix E. This site was unique in that a reversible traffic flow lane was instrumented with several detectors along with the permanent eastbound freeway lanes. The reversible lane was located between the nonreversible westbound and eastbound lanes as shown in Figure 9-2. Data from approaching traffic using the reversible lane was recorded during afternoon rush hours. The approximate locations of the areas viewed by the detectors are indicated in the figure. The size of the ground footprints of the detectors is a function of the mounting height, aperture beamwidth, and incidence angle as tabulated in Appendix F.

Overhead detector mounting locations on the pipe tree are shown in Figures 9-3 and 9-4. Lane 1 refers to the reversible lane, lane 2 to the leftmost eastbound lane, and lane 3 to the rightmost eastbound lane. The lowest pipe on

## Table 9-2. Detectors Used During Field Tests

| Symbol | Technology | Manufacturer | Model | Output Data |
|---|---|---|---|---|
| **U-1** | Ultrasonic Doppler | Sumitomo | SDU-200 (RDU-101) | Count, speed |
| U-2 | Ultrasonic Presence | Sumitomo | SDU-300 | Count, presence |
| U-3 | Ultrasonic Presence | Microwave Sensors | TC-30C | Count, presence |
| M-1 | Microwave Detector<br>Motion<br>Medium Beamwidth | Microwave Sensors | TC-20 | Count |
| M-2 | Microwave Detector<br>Doppler<br>Medium Beamwidth | Microwave Sensors | TC-26 | Count, speed binning |
| M-4[a] | Microwave Detector<br>Doppler<br>Narrow Beamwidth | Whelen | TDN-30 | Count, speed |
| M-5 | Microwave Detector<br>Doppler<br>Wide Beamwidth | Whelen | TDW-10 | Count, speed |
| M-6 | Microwave Radar<br>Presence<br>Narrow Beamwidth | Electronic Integrated Systems | RTMS-XI | Count, presence, speed, occupancy |
| IR-1 | Active IR<br>Laser Radar | Schwartz Electra-Optics | 780D1000 (Autosense I) | Count, presence, speed |
| IR-2 | Passive IR<br>Presence | Eltec | 842 | Count, presence |
| IR-3 | Passive IR<br>Pulse Output | Eltec | 833 | Count |
| IR-4[b] | Imaging IR | Grumman | Traffic Sensor | Presence, speed |
| VIP-1 | Video Image Processor | Econolite | Autoscope 2003 | f |
| **VIP-2** | Video Image Processor | Computer Recognition Systems | Traffic Analysis System | f |
| VIP-3[c] | Video Image Processor | Traficon | CCATS-VIP 2 | f |
| VIP-4[b] | Video Image Processor | Sumitomo | IDET-100 | f |
| VIP-5[d] | Video Image Processor | EVA | 2000 | **f** |
| **A-1[e]** | Passive Acoustic Array | AT&T | SmartSonic TSS-1 | Count |
| MA-1 | Magnetometer | Midian Electronics | Self-Powered Vehicle Detector | Count, presence |
| L-Ib | Microloop | 3M | 701 | Count, presence |
| T-1[e] | Tube-Type Vehicle Counter | Timemark | Delta 1 | Count |

**a.** M-3 was designated for a microwave radar detector that was not received.

b. Used at Tucson, Arizona test site only.

c. Used at all Arizona test sites.

d. Used in Phoenix, Arizona 7/94 test only.

e. Used in Phoenix 1 I/93 and Tucson tests.

f. Count, presence, occupancy, speed, classification based on length. Some provide headway, density, and alarm functions.

Figure 9-1. Installation of Overhead Detectors at I-394 Freeway Site

Figure 9-2. Location of Detectors on I-394

Figure 9-3. Detectors Over Eastbound and Reversible Lanes on I-394

Figure 9-4. I-394 Overhead Detector Layout the pipe tree was 18 feet (5.5 m) above the road surface and the separation between pipes was 2 feet (0.6 m). The black-and-white video camera was located 24 feet (7.3 m) above lane 2. A pair of 6-foot (1.8-m) square inductive loop detectors was installed in each of the three lanes with a 15-foot (4.6-m) leading-edge-to-leading-edge spacing. Inductive loop specifications used by each of the states are furnished in Appendix G. The self-powered magnetometers were not available at this site. Traffic cones were placed on the freeway shoulder at 50-foot (15.2-m) intervals to aid in video image processor field-of-view calibration.

The trailer that housed the detector data and video recording equipment, power supplies, and detector electronics is shown in Figure 9-5. It was located at the southeast corner of the intersection of Penn Avenue with the I-394 freeway, behind a barrier rail. About 200 wires were run from the trailer to the detectors to supply power and record the output data as shown in Figure 9-6.

After data acquisition at the freeway site was completed, the trailer and overhead detectors were removed and transported to the surface-street evaluation site at Olson Highway and East Lyndale Avenue North. Here, westbound departing traffic was monitored as shown in Figure 9-7. The trailer is shown in Figure 9-8. The pipe trees were fastened to a sign bridge, as illustrated in Appendix E, that spanned the westbound lanes. Two of the overhead detectors, the TC-20 microwave detector and the 780D1000 laser radar, monitored approaching traffic. The laser radar could only respond to approaching traffic at this stage in its design (it was later modified to monitor both approaching and departing traffic), while the TC-20 was used to provide vehicle-count data to compare with the laser radar since the video camera did not record traffic flow in this region. Cables were run from the trailer on the south side of Olson Highway to the overhead sign structure on the north side of the street as shown in Figure 9-9. A high-gain antenna was mounted on one corner of the trailer to receive signals from the self-powered magnetometers. The overhead detector layout for the Olson High-way site is shown in Figures 9-10 and 9-11. White stripes, spaced at intervals of 50 feet (15.2 m) as measured from the sign bridge, were painted on the edges of the westbound lanes to aid in calibration of the field of view seen by the video image processors.

Figure 9-12 shows Olson Highway being cored in the center of the loops in lane 2 (middle through lane) for the self-powered magnetometer detectors. The hole was approximately 22 inches (559 mm) deep by 6 inches (152 mm) in diameter. Two to three inches (51 to 76 mm) of cold patch were placed on top of the magnetometer to seal the hole as in Figure 9-13. The extra magnetometer in the upper part of the photograph shows the relative size of the detector that was buried. A side-mounted TC-30C ultrasonic detector and a Remote Traffic Microwave Sensor (RTMS) microwave radar were attached to a streetlight pole as shown in Figure 9-14. The TC-30C monitored traffic in lane 3 (the rightmost lane) of Olson Highway and the RTMS-monitored traffic in the three westbound lanes. Both detectors were lowered from the positions shown in the photograph before they were made operational. Since the video camera did not record traffic in this area, there is no video ground truth for these two devices. The time of occurrence of the green-phase signal at the Olson Highway-Lyndale Avenue intersection was recorded on a relay data logger input. The green phase was used to correlate the occurrence of vehicle queues with detector output.

The electronics racks that housed the power supplies, terminals for the outgoing power and input data, video recorder, video monitor, video image processor equipment, and inductive loop electronics cards at the Minneapolis sites are shown in Figure 9-15. In the lower left of the photograph is the data logger with the front panel removed. On the top of the leftmost rack is the video monitor used to observe traffic flow. Mounted in the rack, from top to bottom, are the Autoscope 2003 electronics, a personal computer (PC)-controlled video recorder, sliding shelf on which the computer keyboard is shown, a Type 170 chassis in which inductive loop electronics cards were inserted, and power-supply modules. The power output to the detectors came from a panel on the right side of this rack. The rack on the right of the photograph shows the panel to which the

Figure 9-5. Data Acquisition Trailer at I-394

Figure 9-6. Cable Run From Trailer to Detectors at I-394

Figure 9-7. Olson Highway Surface-Street Site in Minneapolis

Figure 9-8. Data Acquisition Trailer at Olson Highway

Figure 9-9. Installation of Detector Output Data Cables and Input Power Cables at Olson Highway Surface-Street Site

Figure 9-10. Detectors Over Westbound Lanes on Olson Highway Surface-Street Site

Figure 9-11. Olson Highway Overhead Detector Layout

Figure 9-12. Coring of Olson Highway for Self-Powered Magnetometers

Figure 9-13. Hole With Magnetometers in Place

Figure 9-14. Olson Highway Overhead Site Showing Detectors Mounted on Sign Bridge and Light Pole

Figure 9-15. Data Recording Equipment as Configured at I-394 and Olson Highway detector outputs were connected before being routed to the data logger. The connections from the detectors to the data logger and power supplies are shown in Appendix H for all the sites.

## 9.2 ORLANDO EVALUATION SITES

The Florida freeway detector evaluation site was located on I-4 at SR 436 just north of Orlando in Altamonte Springs. The overhead detector configuration of Figures 9-16 and 9-17 viewed approaching traffic in the leftmost and middle lanes (lanes 1 and 2, respectively) of the westbound freeway into Orlando. The pipe trees were attached to the north face of the SR 436 overpass. The bottom pipe was 16.56 feet (5.05 m) above the road surface in lane 1 and 16.26 feet (4.96 m) above the road. surface in lane 2. Horizontal pipe sections were 2 feet (0.6 m) apart. The modified Burle camera supplied with the Autoscope VIP had an 8-mm, f/1.4 lens and was mounted 24.26 feet (7.39 m) above lane 2. Pairs of 6-foot (1.8-m) square inductive loop detectors were installed in lanes 1, 2, and 3 (the rightmost lane) as shown in Figure 9-18. The self-powered magnetometer detectors with 15-foot (4.6-m) center-to-center spacing were located in the center of the loops in lane 1. The Autoscope detection zones, inductive loop detectors, and camera field of view are shown in Figure 9-19. The south loop in each lane was not in the viewing area of the camera.

A TC-20 microwave detector was side-mounted on an overpass support in the median to view traffic in the left westbound lane of I-4 as shown in Figure 9-20. The traffic flow was at an angle of between 20 and 30 degrees with respect to the antenna boresight. A side-mounted RTMS microwave radar was bolted to a round wooden utility-type pole on the shoulder of the eastbound lanes. The antenna boresight of the detector was perpendicular to the traffic flow as in Figure 9-21. The pole was set in a grassy area 16 feet (4.9 m) from the right edge of the right-most eastbound freeway lane and 27 feet (8.2 m) from the north face of the SR 436 overpass. It monitored traffic in the three westbound lanes within the viewing area of the video camera. In this way, the video imagery could be used to obtain vehicle count ground truth to calibrate the RTMS detector. The side-mounted RTMS detector was also configured to monitor traffic in the three eastbound lanes. However, the video imagery did not cover this area. The trailer, video camera, overhead detectors, and chain-link fence are also shown in the photograph. Traffic cones and paint stripes numbered 1, 2, 3, . . . (also shown in Figure 3-8) were placed on the right shoulder of the westbound freeway in 25-foot (7.6 m) intervals for video image processor calibration.

The trailer was located on the shoulder of the eastbound lanes under the SR 436 overpass. This location was chosen so that the overhead detectors could later be moved to the surface street above the freeway without moving the trailer. A high-gain antenna was mounted on one corner of the trailer to receive signals from the self-powered magnetometers. The cables were run from the trailer along the overpass to the detectors. A chain-link fence was installed on the overpass to prevent tampering with the overhead detectors and the cables.

The data recording configuration used in Orlando is shown in Figure 9-22. The edge of the PC keyboard is at the extreme lower left corner of the photo. To its right is the Puma 88 drive that contains the removable 88MB cartridges used to record the digital and analog outputs of the detectors during each run. The 386 PC containing the application-specific software that controls the data logger is to the right of the Puma drive. The interface for the 16 detector RS-232 serial inputs is on top of the computer. The main data logger is located to the right of the computer. It contains hardware and software that support the 8 analog detector outputs, 16 relay outputs, and 16 optically isolated detector outputs. To its right is a panel on which the outputs from the traffic detectors and environmental sensors are connected as they enter the trailer on cables. The Sumitomo electronics for the SDU-200 (RDU-101) and SDU-300 ultrasonic detectors were placed on the floor under the table. An uninterruptable power supply and surge protectors on each data line entering the trailer from the outside protected the recording equipment from lightning strikes.

Figure 9-16. Detectors Over Westbound Lanes at Orlando I-4 Freeway Site

Figure 9-17. I-4 Overhead Detector Layout

Figure 9-18. I-4 Freeway Lanes Showing Installed Inductive Loops and Self-Powered Magnetometers

Figure 9-19. Location of Inductive Loop Detectors, Autoscope Detection Zones, and Camera Field of View on I-4

Figure 9-20. Side-Mounted TC-20 Microwave Detector on Overpass Support Structure on I-4 Freeway Median

Figure 9-21. View Toward Eastbound I-4 Showing Side-Mounted RTMS Microwave Detector, Trailer, Video Camera, and Overhead Detector

Figure 9-22. Data Recording Equipment as Configured at Orlando

Sitting on top of the 19-inch (483-mm) rack are a monitor that displays video of the traffic flow, the receiver for the self-powered magnetometer detectors, and a speaker that emits a tone when a vehicle passes over the magnetometers. Mounted in the rack, from top to bottom, are the auxiliary data logger that records an additional 24 optically isolated detector outputs, a computer-controlled VHS video recorder upon which the traffic flow is recorded, a Type 170 electronics chassis in which inductive loop electronics cards were inserted, and the Autoscope 2003 video image processor electronics, Output power to the detectors is available on the right side of the rack (not shown).

When the evaluation on the I-4 freeway was completed, the overhead detectors were moved to the SR 436 overpass and mounted behind the signs on a sign-bridge structure. Here they monitored westbound departing traffic on the SR 436 surface arterial as shown in Figures 9-23 and 9-24. The construction details for the overpass are given in Appendix I. The software in the 780D1000 laser radar required it to monitor approaching traffic in lane 1. A monochrome, 1/2-inch (12.7-mm) (6.4- x 4.8-mm) Charge Coupled Device (CCD) Cohu series 4910 camera with an 8- to 48-mm zoom lens was mounted 32 feet (9.8 m) above lane 2. RS-170 resolution was 580 horizontal TV lines by > 350 vertical TV lines. Figure 9-25 shows the road surface as marked for video image processor calibration. Since SR 436 went over a bridge at the evaluation site, the self-powered magneto-meters were mounted under the road at the approximate center of the loops in lane 2 as indicated in Figure 9-26. The magnetometers were put into wooden boxes that were placed on bridge vertical support structures that were already located under the overpass.

An RTMS microwave radar was mounted on a specially erected pole on the south edge of the overpass across the road from the westbound lanes as in Figure 9-27. It was aimed at traffic (side viewing) in the stopbar region of the roadway. During its calibration, the video camera was repositioned to view traffic in the area observed by the RTMS. After calibration of the side-viewing unit, an interruption in the serial communication between the RTMS and the data logger occurred. As a result, no valid data were recorded for the side-looking unit at the Florida surface-street site. The locations of the loops, self-powered magnetometers, and Traffic Analysis System calibration zones are shown in Figure 9-28. The time of occurrence of the green phase signal at the SR 436 and I-4 off-ramp intersection was recorded using a relay data logger input.

## 9.3 PHOENIX EVALUATION SITE

The westbound I-10 freeway near Thirteenth Street in Phoenix was used as the detector evaluation site for regions representative of warm and hot dry climates. This site was used twice, once in Autumn 1993 and again during the Summer of 1994. Approaching traffic was observed by the overhead detector configuration shown in Figures 9-29 and 9-30 during the Autumn 1993 evaluation and by Figures 9-31 and 9-32 during the Summer 1994 evaluation. The AT&T acoustic array was designed to look downstream and view departing traffic as shown in Figure 9-33. The AT&T array and Sumitomo IDET-100 video image processor were evaluated in the Autumn 1993 period. The EVA 2000 video image processor was evaluated during the Summer 1994 period. A side-mounted RTMS microwave radar, shown in Figure 9-34, was installed in the shoulder area on a wooden pole aligned with the first inductive loop.

The stub antenna that received the signals from the self-powered magnetometers installed in the center of the inductive loops in lane 2 was also mounted on this pole. We found that the larger, higher gain antenna was not needed since the trailer containing the magnetometer signal receiver was relatively close to the magnetometers. The higher gain antenna also appeared to pick up more of the noise generated by the PCs in the trailer, even though it was attached to the outside of the trailer. The noise prevented the receiver from generating tones corresponding to the signals transmitted by the magnetometers. Another remedy that eliminated most of the external noise from the magnetometer receiver was to connect the receiver to its own AC voltage circuit in the trailer.

Figure 9-23. Detectors Over Westbound Lanes on SR 436 Surface-Street Site North of Orlando

Figure 9-24. SR 436 Overhead Detector Layout

Figure 9-25. SR 436 marked With Calibration Distances for Video Image of Progressors

Figure 9-26. SR 436 Road Surface Showing Inductive Loop and Self-Powered Magnetometer Locations

Figure 9-27. Side-Mounted RTMS Microwave Detector on SR 436

Figure 9-28. Location of Inductive Loop Detectors, Self-Powered Magnetometers, Traffic Analysis System Calibration Regions, and camera Field of View on SR 436

Figure 9-29. Detectors Over Westbound Lanes of Phoenix I-10 Freeway Site (Autumn 1993)

Figure 9-30. I-10 Overhead Detector Layout. (Autumn 1993)

Figure 9-31. Detectors Over Westbound Lane of Phoenix I-10 Freeway Site (Summer 1994)

Figure 9-32. I-10 Overhead Detector Layout (Summer 1994)

Figure 9-33. Overhead Detectors at I-10 Freeway Showing AT&T Acoustics Array Monitoring Departing Traffic (Autumn 1993)

Figure 9-34. I-10 Freeway Site Showing Side-Mounted RTMS Microwave Detector

Locations of in-ground detectors and video image processor calibration zones were measured from the poles that support the sign structure, as shown in Figures 9-35 and 9-36 for the Autumn 1993 evaluation and in Figure 9-37 for the Summer 1994 evaluation. The downward-looking detectors observed traffic directly below the sign structure. The others, with the exception of the acoustic array and the Eltec 833, observed approaching traffic in the vicinity of the inductive loops. The acoustic array was designed to detect departing traffic and was, therefore, aimed toward the other side of the sign structure, observing traffic in lane 2 (middle through-traffic lane).

The trailer was located at the far edge of the shoulder for the westbound lanes at the top of an incline as shown in Figure 9-38. The cables were run out of the trailer through an opening in the bottom, along the ground and to the top of the wooden pole on which the side-looking RTMS detector was mounted, and then over to the sign-bridge structure.

The sign structure was accessed with a ladder that led to a hatch in the walkway. The detectors were attached to the walkway, located 19 feet 8 inches (6.0 m) above the freeway, or to vertical and horizontal elements on the structure with an assortment of clamps. The walkway provided a relatively easy way to aim the overhead detectors at the desired traffic lanes. The heights of the detectors above the top surface of the walkway are shown in Table 9-3.

Table 9-3. Heights of Detectors Above Walkway* at Phoenix 1993 Evaluation

| Detector | Symbol | Height Above Walkway |
|---|---|---|
| **SDU-200 (RDU-101)** | **U-1** | **36 inches** |
| **SDU-300** | **U-2A, U-2B** | **8 inches to center of horn aperture** |
| **TC-20** | **M-1A** | **37-3/4 inches to bottom of detector** |
| **TDN-30** | **M-4A, M-4B** | **0 inch** |
| **TDW-10** | **M-5A** | **0 inch** |
| **RTMS-X 1** | **M-6A** | **50 inches** |
| **780D1000 (Autosense I)** | **IR-1** | **0 inch** |
| **842** | **IR-2** | **6 inches** |
| **833** | **IR-3** | **39 inches to bottom of detector<br>36 inches to center of lens** |
| **SmartSonic TSS-1** | **A-1** | **37 inches to bottom of array<br>43 inches to center of array** |

• Walkway is 19 feet 8 inches above freeway surface

1 in = 25.4 mm
1 ft = 0.305 m

Two video cameras were used in both the Phoenix and Tucson locations, one for the Autoscope video image processor and one for the other image processors. The Autoscope employed a specially modified camera to provide imagery features that maximized its performance. It was mounted 26-1/4 feet (8.0 m) above the freeway road surface. Since the Autoscope manufacturer believed that his camera would enhance the performance of the other image processors, we obtained a second camera from the Arizona Department of Transportation for the Autumn 1993 runs that provided imagery to the rest of the image processors. This camera was a Burle Model TC301 with a 12.5mm, f/1.4 lens. It was also mounted 26-1/4 feet (8.0 m) above the road surface and covered the same viewing area as the Autoscope camera. In Summer 1994, the camera was supplied by Sumitomo and was the model recommended for use with the IDET-100 video image processor. Its characteristics were: 1/2-inch (12.7-mm) CCD format (6.2 mm x 4.6 mm), auto iris on, Automatic Gain Control (AGC) off, and 525 useful Electronic

Figure 9-35. Location of Inductive Loop Detectors, Self-Powered Magnetometers, Traffic Analysis System and CCATS Calibration Regions, and Burle Camera Field of View on I-10 (Autumn 1993)

Figure 9-36. Location of Autoscope Detection Zones on I-10 (Autumn 1993 and Summer)

Figure 9-37. Location of In-Ground Detectors, CCATS Detection Zones, and IDET-100 Camera Field of View on I-10 (Summer 1994)

Figure 9-38. Data Acquisition Trailer on I-10

Industry Association (EIA) lines. During the Summer 1994 evaluation, an infrared camera was obtained from Amber and was used to record concurrent imagery of the traffic flow in the 8- to 12-um region of the infrared spectrum on a third video recorder. However, this infrared video was not frame or time synchronized with the other detector data recorded by the data logger. (The data logger was designed to operate with two VCRs only.) Because of lens focal length restrictions, the area monitored by the Amber camera was several hundred feet upstream of the sign bridge and did not coincide with the viewing area of the other detectors.

The equipment rack as configured for Phoenix in Autumn 1993 is shown in Figure 9-39. On the top is one of the monitors, the distribution amplifier for the video image processors except Autoscope, and the CCATS-VIP 2 video image processor. Mounted in the top of the rack is the Autoscope 2003. Below it are the two PC-controlled VCRs, the Type 170 interface that holds the inductive loop detector amplifier electronics cards and the AT&T SmartSonics card, and the power supply modules. Near the bottom of the rack is the auxiliary data logger that supports up to 24 optically isolated detector inputs. Mounted on the left side of the rack is the panel that accepts the outputs from the detectors. A connection panel on the right side of the rack, shown in Figure 9-40, supplies input power to the detectors.

Figure 9-41 shows the table on which were placed the data logger, keyboard, 386 PC and computer monitor, the video monitor for the Autoscope camera, and the Puma 88 disk drive. The DigiChannel interface for the RS-232 detector serial outputs is on top of the PC. The electronics for the Sumitomo SDU-200 (RDU-101) and SDU-300 ultrasonic detectors and IDET-100 video image processor were located under the table. The Traffic Analysis System (TAS) video image processor is next to the table with the laptop PC.

The equipment rack as configured for Phoenix in Summer 1994 is shown in Figure 9-42. The layout of the equipment is similar to that used before. On the left, above a monitor, is the EVA 2000 video image processor. The TAS video image processor is to the right of the rack on its shipping case. Unfortunately, it was not operational during the Summer 1994 Phoenix evaluation because it was not shipped with the configuration needed for freeway traffic data collection. The table with the rest of the electronics is shown in Figure 9-43. The self-powered magnetometer signal receivers and Detector Systems 613-SS inductive loop detector amplifiers are on the right side of the table. The data logger, computer, and monitor are to their left. The electronics for the Sumitomo ultrasonic detectors and the uninterruptable power supply are on the floor of the trailer as shown in Figure 9-44.

In the Phoenix 1994 evaluation, the Detector Systems Model 613-SS inductive loop detectors were used to aid in ground truth vehicle speed measurement. Used in pulse mode, they provided a solid-state optically isolated transistor closure each time a vehicle passed over the loops. In addition, a probe vehicle equipped with the Loop Comm Model 600A vehicle transmitter generated a pulse output on another wire each time it passed over one of the loops connected to a 613-SS detector. By mounting the transducer on the bumper of our probe vehicle, as shown in Figure 9-45, vehicle speed ground truth data were obtained by noting the time, lane number, and speed from the vehicle’s speed indicator when the probe vehicle passed over a loop in a particular lane. This procedure was repeated several times during a run for each monitored traffic lane.

## 9.4 TUCSON EVALUATION SITE

The Tucson surface-street evaluation site was located at the southwest corner of Oracle Road and Auto Mall Drive, across the street from the Tucson Mall. All three southbound lanes were instrumented with loops and the right and center lanes (lane 3 and lane 2, respectively) had the overhead detectors installed above them as shown in Figures 9-46 and 9-47. The Autoscope and Sumitomo IDET-100 VIP video cameras were used in Tucson. The field of view for the IDET-100 camera (also used for CCATS) is shown in Figure 9-48, along with the locations of the other detectors. The Autoscopn, CCATS, and Grumman imaging infrared calibration areas

Figure 9-39. Data Recording Equipment Configured for I-10 (Autumn 1993)

Figure 9-40. Data Recording Equipment Showing Detector Power Panel

Figure 9-41. Data Logger, Computer and Traffic Analysis System Video Image Processor As Used on I-10 (Autumn 1993)

Figure 9-42. Data Recording Equipment Configured for I-10 (Summer 1994)

Figure 9-43. Data Logger, Computer, and Detectors as Configured for I-10 (Summer 1994)

Figure 9-44. Sumitomo Ultrasonic Detector Electronics and Uninterruptable Power Supply in I-10 Trailer (Summer 1994)

Figure 9-45. Detector Systems LoopComm Transducer Installed on Front Bumper of Probe Vehicle

Figure 9-46. Detectors Over Southbound Lanes of Tuscon Oracle Road Surface-Street Site

Figure 9-47. Oracle Road Overhead Detector Layout

Figure 9-48. Location of Detectors on Oracle Road are illustrated in Figure 9-49. A rubber tube for a Timemark Delta 1 traffic counter was installed across lane 3 at the leading edge of each square loop. The counter was modified with an RS-232 interface that transmitted the count information to the data logger. The AT&T sonic array was installed to monitor traffic in lane 3. In addition to the usual 6-foot (1.8-m) square loop pairs, 6-foot (1.8-m) diameter round loops installed by Max Kutter and 3M microloops were placed in lane 3 as shown in Figure 9-50. The microloops in lane 3 are in between the pair of round loops (near the 60-foot (18.2-m) mark) and in lane 2 are at the same relative location. The numbers on the pavement show the distance in feet from the mast arm on which the overhead detectors are mounted.

The wind speed and direction sensors and side-looking RTMS microwave radar, shown in Figure 9-51, were mounted on a 4-inch by 4-inch (101.6-mm by 101.6-mm) pole approximately 30 feet (9.1 m) south of the mast arm. The trailer and barricades around the trenches for the cables can be seen in the photo. The stub antenna for the magnetometer was mounted and hidden in a tree north of the pole. The time of occurrence of the green-phase signal at the southbound Oracle Road and Auto Mall Drive intersection was recorded using a relay data logger input.

The Tucson evaluation had other unique features. An array of five three-axis fluxgate magnetometers was installed across lanes 2 and 3 as sketched in Figure 9-48 and shown in the photograph of Figure 9-50 parallel with the 30-foot (9.1-m) paint mark. A sixth magnetometer was buried off the road near the 4-inch by 4-inch (101.6-mm by 101.6-mm) pole. Cables from the magnetometers ran to electronic signal amplifiers mounted on the 4-inch by 4-inch pole shown in the lower part of Figure 9-51. From here, cables brought the signals into the trailer where they were input to a Metrum recorder and recorded on VCR magnetic media as shown on the left side of Figure 9-52. The magnetometer array data was stripped from the VCR tapes in later processing at Hughes and placed into files that were archived on 1/4-inch (6.4-mm) magnetic tape used for 250MB PC backup systems.

A high sampling frequency Model 2020 detector built by 3M was connected to the second 6-foot by 6-foot (1.8-m by 1.8-m) square loop in lane 3. This allowed signals produced by the undercarriage of vehicles to be sampled and recorded by the data logger. Because of the high data rate output of the 2020 detector, a separate PC incorporating a fast serial input/output board with the 16550 Universal Asynchronous Receiver-Transmitter (UART) was used to record these data. The second PC also recorded the time code furnished by the data logger to aid in the correlation of the 2020 data with data from the other detectors.

As part of the data collection effort associated with the three-axis magnetometer array and high sample rate inductive loop detector, lane 3 was closed to normal traffic and several types of test vehicles were driven through the lane at slow speeds and were also stopped at several stations in the lane. In this way, signature data were obtained for known vehicles corresponding to known areas under the vehicle. The vehicles used in these tests are listed in Table 9-4. The large-boom lift truck is shown in Figures 9-53 and 9-54 and the Dodge Caravan in Figure 9-55. The stations are shown in Figure 9-56. In the tests where the vehicle was stopped in lane 3, the front bumper of each vehicle was stopped parallel to each station. At station 5, the vehicles were also stopped so that the middle of the vehicle and the rear bumper were parallel to the station.

An imaging infrared detector developed by Grumman Aircraft Company was evaluated at Tucson. The infrared camera was mounted on the mast arm between lanes 2 and 3, as shown in Figure 9-48, and viewed the area downstream from the second round loop between approximately 68 and 120 feet (20.7 and 36.6 m) from the mast arm. The infrared imagery processing electronics were located in the trailer as shown in the background of Figure 9-52. An infrared image of vehicles is shown in Figure 9-57. In the infrared spectrum, the hotter areas appear lighter in color and the colder areas appear darker. Since the character of the infrared image does not change appreciably from day to night (even when a vehicle's lights are on), it may be possible to use the same signal processing

Figure 9-49. Fields of View and Calibration Areas forAutoscope, CCATS, andGrumann Video Image Processors on Oracle Road

Figure 9-50. Oracle Road Marked with Calibration Distances for Video Image Processors and Subsurface Detectors

Figure 9-51. Pole-Mounted Wind Speed and Direction Sensors and Side-Viewing RTMS Microwave Detector at Oracle Road Site

Figure 9-52. Metrum Recorder and Power Supplies Used to Record Three-Axis Magnetometer Signals at Oracle Road Site

Figure 9-53. International S1600 Large Boom-Lift Truck (Side)

Figure 9-54. International S1600 Large-Lift truck (Front)

Figure 9-55. Dodge Caravan

Figure 9-56. Stations Used to Record Signatures of Stopped Vehicles in Lane 3 on Oracle Road

Figure 9-57. Infrared Image of Vehicles Taken With Grumman Imaging Infrared Detector algorithms for day and night operation. The infrared image processing technology may thus avoid possible performance degradation that can occur when transitioning from day to night algorithms in visible-spectrum video image processors.

The trailer was located in a shopping center parking lot on the southwest corner of the intersection. The cables were laid in a trench dug from the trailer to the sidewalk and then under the sidewalk to the pole that supported the mast arm upon which the detector pipe trees were hung. Additional trenches were dug for cables to the side-viewing RTMS microwave radar and the telephone service connection. Trenching had two drawbacks: flooding of the trench by a rain storm and having to erect barriers to prevent people from walking into the trench. Overhead cable installation is, therefore, preferable.

The equipment rack for Tucson is shown in Figure 9-58. On the top is one of the monitors used to view the traffic flow. To its right is the CCATS-VIP 2 image processor. The Autoscope 2003 is mounted in the top of the rack. Under it are the two PC-controlled VCRs that were used to record the traffic flow. Under these is the Type 170 electronics rack that held the Detector Systems inductive loop detectors, 3M 2020 high-frequency loop detector, and the AT&T SmartSonics detector. The power supply panel appears next. At the bottom of the rack is the auxiliary data logger for the additional 24 optically isolated detector inputs. The Detector Systems LoopComm inductive loop detector amplifiers are shown on the table to the left of the rack. They were connected to the downstream (second) square loop in lanes 2 and 3 to provide vehicle speed ground truth data. Behind them is the receiver for the self-powered magnetometers.

Figures 9-59 and 9-60 show the inductive loop detector electronics, self-powered magnetometer receiver, main data logger, 386 PC and monitor, keyboards, a 486 PC and monitor on which the 3M 2020 high-frequency loop data were recorded, and a monitor for the second video camera, all located on a table in the trailer. The electronics for the Sumitomo SDU-300 ultrasonic detector, uninterruptable power supply, Sumitomo IDET-100 video image processor, and Sumitomo SDU-200 (RDU-101) ultrasonic detector were placed on the floor of the trailer under the table as shown in Figure 9-60.

In addition to the conventional traffic monitoring, we also mounted 4-foot by 8-foot (1.2-m by 2.4-m) sheets of Styrofoam on the top of a Chevrolet Corsica and drove it through the field of view of the overhead detectors as shown in Figures 9-61 and 9-62. The purpose of these tests was to simulate the effects of snow on the performance of the ultrasonic, infrared, and microwave detectors. The Styrofoam layers were 1, 2, and 3 inches (25.4, 50.8, and 76.2 mm) thick. This evaluation was performed at the same time lane 3 was closed to gather data for the three-axis magnetometers and high sample frequency inductive loop amplifier.

## 9.5 AMOUNT OF DATA COLLECTED AT EACH SITE

Table 9-5 shows the amount of data collected at each field test and evaluation site. Since the Tucson site included the three-axis magnetometer detector array, high sampling rate inductive loop detector amplifier, imaging infrared detector, circular inductive loops, and microloops not installed at the other sites, the data quantity at Tucson was greater than at the other sites.

Figure 9-58. Data recording Equipment as Configured for Oracle Road

Figure 9-59. Data Logger, Computer, and Subsurface Detector Electronics at Oracle Road

Figure 9-60. Sumitomo Detector Electronics and Uninterruptable Power Supply on Floor of Trailer

Figure 9-61. Chevrolet Corsica With Styrofoam Sheet Tied to Vehicle Top

Figure 9-62. Corsica With Styrofoam Sheet Parked Under Detector Array

# Table 9-5. Quantity of Data Acquired

| Location | Date | Runs | Data Collected (MB) |
|---|---|---|---|
| Minneapolis Freeway | Winter 1993 | 15 | 200 |
| Minneapolis Surface Street | Winter 1993 | 7 | 32 |
| Orlando Freeway | Summer 1993 | 28 | 670 |
| Orlando Surface Street | Summer 1993 | 21 | 200 |
| Phoenix F | Autumn 1993 | 32 | 868 |
| Tucson Surface Street | Winter 1994 | 34 | 815 |
| Tucson Surface Street | Winter 1994 | 31 | 577 (with 3M 2020 high sampling rate amplifier) |
| Tucson Surface Street | Winter 1994 | 16 | 1500 (from three-axis magnetometer array) |
| Phoenix Freeway | Summer 1994 | 31 | 1060 |

# 10. TASK H

# GENERATE FIELD TEST RESULTS

(Click here)

# 11. TASK I

# DETERMINE WHICH OF THE CURRENTLY AVAILABLE DETECTORS MEET THE IVHS SPECIFICATIONS OF TASK A

Accuracies for traffic parameters that support future applications of signalized intersection control, freeway incident detection and management, and freeway metering control were presented in Section 2. Not all of the parameters can be addressed based on the results of the Detection *Technology for IVHS* field tests. Among the information that can be evaluated at this time are data relating to vehicle counts, speed, and, to some extent, presence.

Several flow requirements are listed in the Traffic Parameter Specifications tables in Section 2. In the signalized intersection control, freeway incident detection and management, and freeway metering control applications, the allowable error for measuring traffic flow is ±2.5 percent at 500 vehicles per hour per lane. The data collection intervals vary by the period over which control of the traffic is exercised, namely, tactical, strategic, or historic.

For the postulated 20-second data collection interval for tactical control, an error of 0.07 in vehicle count for every 2.8 vehicles is implied at a flow of 500 vehicles per hour. Practically, this means that all vehicles must be detected during each 20-second interval. While no detector guaranteed 1 00-percent detection accuracy, some did perform with less than 1 -percent error. Video image processors that use the detection zone approach to loop emulation can increase their detection accuracy by placing multiple zones in critical areas of the roadway.

For a S-minute data collection interval typical of strategic control, the acceptable error is one vehicle count for every 41.7 vehicles at the specified flow rate. This requirement seems to be within the capability of currently available commercial technologies. As the data collection interval increases, as in the gathering of historic data, larger errors in count are acceptable (e.g., error of 3.1 in count for every 125 vehicles for a 1 S-minute interval and an error of 12.5 in count for every 500 vehicles during a 1 -hour interval).

While inductive loops are probably the most consistently accurate detectors for vehicle counting applications currently available, several other candidates show a great deal of promise. Among them are video image processors, magnetometers, and microwave detectors. These technologies, as well as the ultrasonic, infrared, and acoustic devices, will continue to mature as they are deployed in support of new applications. Many of these technologies have only been applied to traffic management applications for a short time and will continue to improve as they gain acceptance and are used within the industry.

Unfortunately, many manufacturers cannot afford to develop their technology further without assurances, in the form of buy orders, from the traffic management community that a tangible market for their product exists.

The speed measurement requirement varies by application. Freeway metering control has the most relaxed accuracy of the applications that were studied, namely a mainline speed measurement accuracy of ±5 mi/h (±8.0 km/h) over a speed range of 0 to 80 mi/h (0 to 129 km/h). The data collection intervals for tactical, strategic, and historic collection periods are 20 seconds, 5 minutes, and 15 minutes or 1 hour, respectively. Signalized intersection control is postulated to have a future speed measurement requirement of ±2 mi/h (3.2 km/h) and a freeway incident detection requirement of ± 1 mi/h (1.6 km/h).

Currently available Doppler microwave detectors are able to support the 5-mi/h (8.0-km/h) speed accuracy requirement on a per vehicle basis. The data collection interval can be under the control of the microprocessor that accumulates the data in the traffic controller or traffic management center. Doppler detectors, however, cannot detect stopped or slow (nominally below 3 to 5 mi/h [4.8 to 8.0 km/h]) traffic. The future and as yet in-development algorithms for signalized intersection control and freeway incident detection raise the speed measurement . accuracy requirement further. The ±1-mi/h (1.6-km/h) accuracy is beyond the current state of the art of most detectors. If the importance of zero speed measurement during bumper-to-bumper traffic conditions is not critical to the execution of the traffic control algorithm, as when a lower speed threshold greater than 3 to 5 mi/h (4.8 to 8.0 km/h) is set, then the Doppler detectors will suffice. If speeds less than 3 to 5 mi/h are needed, improved video image processors and true-presence microwave radars or laser radars may have to be used.

Vehicle presence is an important parameter in signalized intersection control. Although it is difficult to compare the actual presence times from detector to detector because of differences in hold time and sensing area, it is intuitively possible to correlate vehicle presence with vehicle count. That is, as a vehicle is counted, it can be assumed that the presence of the vehicle is also detected, although no inference about the length of the presence time can be made. If the assumption about vehicle presence and vehicle count correlation is valid, then those detectors having the most accurate counts will also provide the most accurate presence in terms of identifying that a vehicle is within the sensing area of the detector.

# 12. CONCLUSIONS

One of the goals of the field tests and subsequent data reduction was to ascertain the relative performance of various detector technologies in different traffic and climatic conditions. These results are useful for assessing the applicability or suitability of particular types of technology to specific traffic management applications. The assessments were made with respect to only detector performance and not cost. Cost considerations must be traded off by the procuring organization. The cost-effectiveness of a particular detector or type of technology can only be judged when applied to a specific application and should include total life-cycle costs (i.e., take into account purchase price, installation, data interface preparation, and maintenance over an extended time period of 10 to 20 years) and the equivalent number of lower cost detectors (e.g., inductive loops) that it replaces.

Candidate overhead detector technologies have been identified for several traffic management applications and operational requirements as listed in Table 12-l. The technologies were selected based on the capabilities and types of outputs currently available from a particular technology and their suitability to the application. This list does not take into account the performance of these technologies during the field tests. The quality of the technology performance is discussed in Section 12.1.

Table 12-2 lists advantages and disadvantages associated with each technology. A more detailed matrix was presented in Appendix A of the Task A Report. For example, infrared detectors have an advantage over visible wavelength sensors in foggy conditions, but their effectiveness may still be limited by heavy rain or snow. Each technology has strengths and weaknesses imposed by the physics that governs its operation and the resolution of the detector. These may cause a specific technology to be wholly unsuitable or ideally suited for a particular application.
The diversity of operating conditions and applications demonstrates the detector-specific selection that must be made for each installation. There is no generic “best detector.” Selection of the appropriate traffic management system components is dependent upon not only the traffic management application, but on the operating conditions (including weather) and mounting requirements (e.g., in-road versus overhead, mast arm versus pole, upstream or downstream viewing of traffic).

## 12.1 ASSESSMENT OF BEST PERFORMING TECHNOLOGIES BY APPLICATION

Both quantitative and qualitative observations were made regarding how well a particular technology performed relative to others at the evaluation sites employed during the field tests. Judgments were made regarding which technologies exhibited the best performance with respect to supplying different traffic parameters. Table 12-3 provides a summary of the conclusions based on the results from the limited number of runs reduced so far and the general qualitative opinions gained from using these devices over an 1 8-month evaluation period.

### 12.1 . 1 Most Accurate Vehicle Count for Low Traffic Volume

Most of the detectors gave good results when used under light traffic conditions. It should be stressed that some detectors had an inherent advantage in the results displayed in Section 10 by virtue of their multiple outputs or detection zones. The most favorable of the outputs, when more than one zone was available, was shown in the graphs. For example, if loop #1 showed better agreement with the ground truth value than loop #2 (for the same lane), then the loop #1 results were presented. Likewise, if a single traffic detector had multiple detection zones, the most favorable of the outputs was used in the plotted results. This affords a greater opportunity for these devices to appear in a favorable light; whereas, a simple detector having a single relay output was represented solely on the basis of that single output.

Table 12-l. Overhead Detector Technology Applications to Traffic Management

| Application | Assumptions | Overhead Technology |
|---|---|---|
| • Signalized intersection control | • Detect stopped vehicles<br>• Weather not a major factor | • True-presence microwave radar<br>• Passive infrared<br>• Laser radar<br>• Ultrasound<br>• Video image processor |
| . Signalized intersection control | • Detect stopped vehicles<br>• Inclement weather | • True-presence microwave radar<br>• Ultrasound<br>• Long-wavelength imaging infrared video processor |
| • Signalized intersection control | • Detection of stopped vehicles not required<br>• Inclement weather | • True-presence microwave radar<br>• Doppler microwave detector<br>• Ultrasound<br>• Long-wavelength imaging infrared video processor |
| • Real-time adaptive signal control (e.g., SCOOT) | • Desirable for detector footprint to emulate a 6-ft x 6-ft inductive loop<br>• Side-mounting capability | • Video image processor<br>• True-presence microwave radar<br>• Passive infrared (with suitable aperture beamwidth) |
| • Vehicle counting (surface street or freeway) | • Detect and count vehicles traveling at speeds > 2-3 mi/h | • True-presence microwave radar<br>• Doppler microwave detector<br>• Passive infrared<br>• Laser radar<br>• Ultrasound<br>• Video image processor |
| • Vehicle speed measurement | • Detect and count vehicles traveling at speeds > 2-3 mi/h | • True-presence microwave radar<br>• Doppler microwave detector<br>• Laser radar<br>• Video image processor |
| . Vehicle classification | • By length | • Video image processor<br>• Laser radar |
| . Vehicle classification | • By profile | • Laser radar |

1 ft = 0.305 m
1 mi/h = 1.61 km/h

Table 12-2. Advantages and Disadvantages of Various Detection Technologies

| Technology | Advantages | Disadvantages |
|---|---|---|
| Ultrasonic | • Compact size, ease of installation | • Performance may be degraded by variations in temperature and air turbulence |
| Microwave Doppler | • Good performance in inclement weather<br>• Direct measurement of speed | • Cannot detect stopped or very slow-moving vehicles<br>• Requires narrow-beam antenna to confine footprint to single lane in forward-looking mode |
| Microwave True Presence | • Good performance in inclement weather<br>• Detects stopped vehicles<br>• Can operate in side-looking mode to service multiple lanes | • Requires narrow-beam antenna to confine footprint to single lane in forward-looking mode |
| Passive Infrared | • Greater viewing distance in fog than with visible-wavelength sensors | • Performance potentially degraded by heavy rain or snow |
| Active Infrared | • Greater viewing distance in fog than with visible-wavelength sensors<br>• Direct measurement of speed | • Performance degraded by obscurants in the atmosphere and weather |
| Visible VIP | • Provides visible imagery with potential for incident management<br>• Single camera and processor can service multiple lanes<br>• Rich array of traffic data available | • Large vehicles can mask trailing smaller vehicles<br>• Shadows, reflections from wet pavement, and day/night transitions can result in missed or false detections |
| Infrared VIP | • Possibility of using same algorithms for day and night operation and avoiding day/night algorithm transition problems<br>• Rich array of traffic data available | • May require cooled IR detector focal plane for high sensitivity; implies somewhat more power and less reliability |
| Acoustic | • Potential for identifying specific vehicle types by their acoustic signature | . Signal processing of energy received by the array is required to remove extraneous background sounds and to identify vehicles |
| Magnetometer | • Can detect small vehicles, including bicycles<br>• Useful where loops cannot be installed | • Difficulty in discriminating longitudinal separation between closely spaced vehicles |
| Inductive Loop Detectors | • Standardization of loop amplifier electronics<br>• Excellent counting accuracy<br>• Mature, well understood technology | • Reliability and useful life are a strong function of installation procedures<br>• Traffic interrupted for repair and installation<br>• Decreases life of pavement<br>• Susceptible to damage by heavy vehicles, road repair, and utilities |

Table 12-3. Qualitative Assessment of Best Performing Technologies for Gathering Specific **Data**

| **Technology** | Low-Volume Count | **High-Volume** Count | **Low-Volume** Speed | **High-Volume** Speed | **Best In** Inclement **Weather** |
|---|---|---|---|---|---|
| Ultrasonic | | | | | |
| Microwave Doppler* | - | - | - | - | - |
| Microwave True Presence | - | - | | | - |
| Passive Infrared | - | | | | |
| Active Infrared | | | | | |
| Visible VIP | - | - | | | |
| Infrared VIP | | | | | |
| Acoustic Array | | | | | |
| SPVD Magnetometer | - | | | | - |
| Inductive Loop | - | - | | | - |

- Indicates the best performing technologies.
/ Indicates performance not among the best, but may still be adequate for the application.
No entry indicates not enough data reduced to make a judgment.
* Does not detect stopped vehicles.

The ultrasonic and infrared detectors exhibit count accuracies that make them suitable for a variety of applications, but they were typically not among the most accurate. The SPVD magnetometer performed well in low-volume applications, as demonstrated by the zero-percent error over a 2-hour run during snowfall conditions for the Minnesota surface-street Run 0309 10 19 (reference Figure 10-22).

Microwave radars were also well suited to low-volume conditions. The presence-type microwave radar consistently provided better vehicle count results in forward-looking operation than in side-looking orientation. Forward-looking count accuracies to within 1 percent were not uncommon; however, these accuracies were typically provided by only a single detection zone, due to the difficulty in confining the detector's elliptical beam footprint to **a-single** lane of traffic. Because of this footprint geometry, only one detection zone tends to be optimally matched to the dimensions of the traffic lane, while the remainder of the zones tend to undercount (in the narrow parts of the beam where the detection zones are not as wide as the lane) or overcount (where the wide part of the beam tends to spill over into adjacent lanes of traffic).

Doppler-type microwave detectors fare well in low-to-moderate traffic volume conditions, where free-flowing **traffic** consistently provides a component of motion in the detector's viewing direction that is necessary for the operation of these units.

However, there can conceivably be traffic management applications where a knowledge of decreasing speeds can be used to infer that stopped vehicles are present even though the Doppler detector does not give an output indication. Again, care must be taken to ensure that the detector's beam footprint on the roadway is confined to the desired monitoring area.

Some video image processors exhibit counting characteristics similar to microwave detectors. The Autoscope 2003, for example, can be configured to have three separate detection zones per lane (two emulating a pair of inductive loops and a third configured as a speed trap). Data show that count results tend to be optimized for a given zone.

Inductive loops are among the most consistent performers, with count-accuracies typically in the 99-percent range. Even so, problems with crosstalk and double- or triple-counting large trucks and tractor-trailer rigs have been seen when reviewing videotapes of the field tests.

### 12.1.2 Most Accurate Vehicle Count for High Traffic Volume

Many of the same observations made in the previous section apply here as well. However, counting vehicles at freeway speeds or during periods of heavy congestion presents additional difficulties. The electronic hold time of a detector begins to become an important factor when inter-vehicle gap times decrease. The hold time is the period over which a detector remains in the active state after the initial detection of a vehicle. Hold time is often adjustable by means of a potentiometer setting in the detector electronics or by software via a remote serial interface to the hardware.

For the field tests, the hold time of each device was always set to its minimum value. Increasing the hold time in heavy traffic conditions has a negative impact on count accuracy due to the detector's inability to determine when one vehicle departs' the detection zone and another enters, With long hold times, a second vehicle enters the detection zone prior to the falling edge of the pulse created by the first vehicle. This can result in several closely spaced vehicles registering only a single count on a given detector. Such events are characterized by abnormally long presence times in the Paradox database file.

Although several detectors evaluated were designed with long hold times because of an initial traffic management requirement, devices of similar types can certainly be redesigned with shorter hold times as new applications arise.

### 12.1.3 Most Accurate Speed for Low Traffic Volume

Speed accuracy is a difficult parameter to assess due to the challenge of obtaining the true speeds against which to compare the detector speed outputs. Some detectors compute speeds based on average vehicle lengths. Such devices may yield acceptable accuracies over the long term, but not for applications that require periodic updates or vehicle-by-vehicle speeds. This requirement favors the implementation of detectors that make direct speed measurements, or pairs of detectors that can be used in a speed-trap configuration.

Speed traps are difficult to implement accurately due to the precision required in time-tagging the two pulse outputs that provide the time difference between passage of a vehicle over the two zones in the speed-trap. Further hindering the process is the probability that the two detectors have dissimilar sensing areas or detection zones. For instance, the fields associated with two inductive loops may not subtend the same sensing area due to differences in gain or sensitivity. They may have different response times or varying pulse widths. Although the two loops are similar, they do not necessarily share identical characteristics. These small differences are magnified greatly when monitoring the high speeds that occur in low-volume applications. In addition, the controller must have the programming capability to compute speeds from speed-trap timing pulses.

The simplest and most accurate way to measure speed is to use a detector that provides it directly, such as a Doppler microwave detector. Doppler devices require a component of motion in the direction of operation. Since free-flowing traffic is readily available in low-volume conditions, a Doppler device would seem a logical choice for such an application. Speed as measured by Doppler microwave detectors usually agreed within 1 to 2 mi/h (1.6 to 3.2 km/h) with readings from the speedometers of the probe vehicles. However, the imprecision associated with a human observer recording these values from an analog speedometer of unknown accuracy yields, at best, a reference value, not absolute truth.

Some detectors capable of providing speed outputs could not be evaluated with the single probe vehicle. These units output average speed data collected over some integration interval and, as such, do not give information on a per vehicle basis. Among these devices were several video image processors and the RTMS-Xl microwave true-presence radar. Thus, the selection of a preferred technology is application-dependent. If the requirement is for a unit that will supply average speed, occupancy, or some other statistically derived parameter, the choice should be one of the sophisticated detection systems employing enough processing capability to accurately compute the desired parameter(s). Conversely, if the data are required on a per vehicle basis, the choice narrows to devices that output the desired parameters in real time as they are acquired. Certainly the more sophisticated units, such as video image processors, multi-zone radars, and laser radars, have the ability to output data on a per vehicle basis as they must measure the characteristics of individual vehicles in order to produce their normal statistical outputs. However, the cost of these units will likely dictate that they be utilized only for applications that require statistical data or where their cost can be justified on an equivalent per detector basis or through life-cycle cost considerations.

### 12.1.4 Most Accurate Speed for High Traffic Volume

Many of the same points made in Section 12.1.3 apply here as well. The main difference in requirements between low- and high-volume applications stems from the change in vehicle speeds. Vehicles in low-volume conditions are likely to be free-flowing and unconstrained in their movements, while vehicles in high-volume conditions, where the roadway is at or near its designed capacity, will be restricted in their speed. When the traffic demand exceeds the capacity of the roadway, speeds will obviously decrease. If the speeds slow significantly and bumper-to-bumper traffic conditions ensue, then Doppler detectors will significantly degrade in their ability to accurately measure vehicle speeds. Perhaps this will not matter as the necessity for zero speed measurement may decrease once the traffic flow falls below some fixed threshold.

### 12.1.5 Best Performance in Inclement Weather

The detectors that seemed the most impervious to inclement weather conditions were the microwave detectors. No appreciable change in performance was noted during conditions such as rain, snow, wind, and extreme cold or heat. As mentioned earlier, one of the Doppler microwave units demonstrated degraded performance when an appreciable amount of rain leaked into the unit, but this was not a limitation of the technology. Likewise, the SPVD magnetometers suffered some rain-related damage, but the failure stemmed from a crack in the cylindrical case housing the electronics. The magnetometers performed well in the snow during the Minneapolis surface-street tests. The inductive loops, when properly installed, performed reliably through a broad spectrum of weather conditions.

The technologies with the greatest extreme weather limitations include the ultrasonic, infrared, acoustic, and video image processors. This is not due to any flaw in the design of these units, but rather to physical limitations caused by weather-related phenomena, such as gusty winds {greater than 56 mi/h [>25 m/s] in the case of the Doppler ultrasound detector) or the presence of atmospheric obscurants. However, even these devices are relatively unaffected by inclement weather conditions when operating at the short ranges typically associated with their normal usage.

### 1 2.1.6 Microscopic Single-Lane vs. Macroscopic Multiple-Lane Data

Several of the detectors were better suited for collecting data that characterized individual vehicles in multiple lanes, while others were better for gathering data from groups of vehicles in multiple lanes. The detectors best suited for acquiring microscopic (individual vehicle) data over multiple lanes were the true-presence microwave radar and the video image processors. Those useful for collecting macroscopic (groups of vehicles) data were the wide-beam Doppler microwave detectors, true-presence microwave radar, and the video image processors. Sufficient data have not been reduced to rank these detectors for these applications.

## 12.2 LESSONS LEARNED

Many of the qualitative results were gained from the familiarity that came with utilizing these detectors day in and day out in a number of different weather and traffic environments. The dynamic nature of the field tests and the interest displayed by the detector manufacturers to participate in them caused the number of devices under evaluation to grow steadily. This necessitated changes to both the data logger hardware and the software (both to record and post-process the data) so that the expanding number of detector outputs could be accommodated. Each new serial interface required that device-specific code be written to provide the'proper RS-232 communication interface. In order to minimize this problem in future applications, a standardization of serial communication protocols would be most helpful.

The considerable amount of time necessary to examine the processed data and video imagery in detail dictated that only a portion of the runs were analyzed in depth for this report. Analyzed runs were selected to be representative of the broadest possible spectrum of weather and traffic conditions encountered. While this approach provided the analyst with a diverse.set of data to evaluate, it did not allow for any detailed statistical analyses to be performed. Such analyses and conclusions should be a part of future efforts that explore more of the available database.

## 12.3 CONCLUDING REMARKS

The Detection Technology for IVHS field tests provided a substantial database of traffic detector performance information for a broad spectrum of weather and traffic conditions. Future data reduction will include analyses of additional runs to produce a larger set of results from which statistical conclusions may be drawn. Additional runs will be subject to ground truth. Vehicle-count ground truth will be analyzed over short intervals (such as a signal cycle period) in addition to the 1- to 2-hour intervals prevalent in previous analyses. This will better determine whether existing technologies are able to meet the traffic parameter update accuracy requirements specified for applications such as real-time signalized intersection control.

Additional ground truthing also is required for the Tucson surface-street site in order to minimize the effect of anomalies that occur when vehicles sweep out into multiple lanes as they complete their turning movements. This entails overlaying the signal green phase status on the video imagery and counting only those vehicles exiting the intersection during the green or yellow phase. This will eliminate most of the false counts associated with left or right turns and allow the count to properly reflect the vehicles that travel straight through the intersection with minimal lane changes.

The project wishes to express its gratitude to the many people who provided support in the acquisition and evaluation of the detectors. Engineers and technicians from the various detector manufacturers were consulted frequently and responded with timely and helpful technical advice. Some personally assisted with the installation of their systems. Their willingness to provide evaluation units and the spirit of cooperation with which they participated are greatly appreciated.

The assistance of the state, county, and municipal DOTs was invaluable. They supplied personnel, equipment, and use of their facilities, and patiently accommodated numerous requests for lane closures and adjustment of the detector viewing angles. The professionalism demonstrated by these agencies was a critical ingredient in the success of the field tests.

# LINKS TO APPENDICES