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Final Report

USE OF AUTOMATIC VEHICLE IDENTIFICATION TECHNIQUES FOR MEASURING TRAFFIC PERFORMANCE AND PERFORMING INCIDENT DETECTION

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16. ABSTRACT

Traffic performance information is an integral part of traffic control and motorist information systems. Good traffic performance information is also needed to optimize system control functions, detect congestion and incidents, and inform travelers to help them plan their trips. Yet, good traffic performance information is rarely available for these functions. One of several new technologies being investigated to improve the collection of traffic performance information is automatic vehicle identification (AVI).

The primary objectives of this project were to determine the possible benefits of using AVI systems for monitoring the performance of traffic and detecting incidents. A secondary objective was to determine whether the truck fleet tagged as part of the Heavy Vehicle Electronic License Plate (HELP) project, or even the entire truck population, would provide an unbiased measure of traffic performance.

The findings presented in this report show that AVI based systems can produce superior traffic performance data for use in both real-time control systems and more general transportation planning and engineering analyses. Furthermore, the mathematical algorithms needed to operate the AVI system are straightforward and easily programmed.

Continuing improvements in transponder, computing, and communications technologies provide the opportunity to reliably collect the information necessary to operate the planned intelligent vehicle-highway systems of the future. Given the current state of the technology and expected improvements, the impediments to using AVI technology in this manner are not technical, but fiscal and political.

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FOREWORD

Much of the information in this report was developed as part of Master's thesis projects by Mr. Tim Boyle and Ms. Jennene Ring. Additional background on automatic vehicle identification (AVI) technologies and techniques can be found in their theses, as well as the general NTIS database. An excellent primer on AVI is NCHRP report 340, "Assessment of Advanced Technologies For Relieving Urban Traffic Congestion."

EXECUTIVE SUMMARY

INTRODUCTION

Traffic performance information is an integral part of traffic control and motorist information systems. Good traffic performance information is also needed to optimize system control functions, detect congestion and incidents, and inform travelers to help them plan their trips. Yet, good traffic performance information is rarely available for these functions. Consequently. many urban traffic control centers are looking for more accurate measures of travel times for use in emerging traffic control and motorist information systems.

One of several new technologies being investigated to improve the collection of traffic performance information is automatic vehicle identification (AVI). For AVI, electronic transponders (tags) are placed on vehicles and electronic devices for reading those tags are placed along the roadway to determine when each vehicle passes those locations. These AVI systems provide data that indicate that a specific tag has passed a specific point at a specific time. When this information is available at several locations, it becomes useful for traffic performance monitoring.

AVI technology can potentially be applied to a number of transportation functions, for example, automated toll collection, automated route guidance, expediting the passage of trucks through state port-of-entry facilities, and as a component of advanced control systems. The installation and testing of AVI equipment for these purposes is already occurring across the United States. Because AVI is being investigated for a variety of uses, it may become available to traffic operations personnel as a "free" means of collecting traffic data. That is, because other systems (such as automated toll collection) are using AVI data collection, those data may become available for other uses for the marginal cost associated with transferring the data from one application's database to another.

Because AVI information can be used for several purposes, an AVI based system may allow the WSDOT to fund expanded incident detection systems by sharing the cost of system installation and operation with other potential users of the data. This cost sharing among multiple users would allow the Department to construct, operate, and maintain systems that it could not otherwise afford.

PROJECT OBJECTIVES

The primary objectives of this project were to determine the possible benefits of using AVI systems for monitoring the performance of traffic and detecting incidents. A secondary objective was to determine whether the truck fleet tagged as part of the Heavy Vehicle Electronic License Plate (HELP) project, or even the entire truck population, would provide an unbiased measure of traffic performance.

RESEARCH APPROACH

The research approach for this project involved a combination of literature review, theoretical modeling, and field testing. The testing was undertaken after consultation with the Washington State Department of Transportation and the HELP Executive Committee, which reviewed and permitted the use of the HELP vehicle tag information for this project.

FIELD INSTALLATIONS

To perform these tests, three AVI readers were purchased and installed on Interstate 5, south of the Tacoma CBD (see Figure 2) and incorporated into the Crescent Demonstration Database. The three AVI stations were located on the northbound lanes of Interstate 5, south of the Tacoma Hill. The stations were spaced at roughly 1-mile intervals. Reader antennae were placed in the two right most through lanes of traffic at each location. The data collected at the three Tacoma AVI sites were transmitted to the HELP database in Santa Clara, California, and then provided to the research team by the HELP system integration contractor, Lockheed Integrated Solutions Corporation.

FINDINGS

Simple AVI systems, such as that used in the primary HELP system tests, provide limited types of data; vehicle tag IDs, location information, and the time each tag passes a reader. However, these data can yield a surprisingly rigorous picture of traffic performance.

There are two basic methods for using the data AVI systems produce for measuring traffic performance. The most simple method is to simply count the volume of tagged vehicles that pass a point while measuring the headways between tagged vehicles. The second method is to combine the tag and time-of-passage information from two or more locations to calculate the travel time between those two points. Incorporating the known distance between the two reader points also allows the average (section) speed to be calculated for each tagged vehicle. Both of these techniques can be used simultaneously to provide an even more effective monitoring system.

In practice, the technique that monitors vehicle headways detects incidents more quickly than the travel time technique when incidents occur immediately downstream from an AVI reader or when a road is completely blocked by an incident. The travel time detection technique is more effective in almost all other situations. Specific congestion detection algorithms for both of these techniques are presented in the main body of this report.

For both monitoring techniques, AVI system response is controlled by four basic variables; the headway of tagged vehicles, the distance between AVI readers, the speed of the vehicles on the roadway, and the number of vehicles that must be monitored to detect a change in traffic conditions. For example, if five vehicles with an average speed 5 mph lower than the "normal" speed are needed to detect a "statistically significant" change in traffic performance (given an arbitrary value for the variation in those speeds), the system can not detect that change in speeds until five vehicles have passed the downstream station. If the headway between tagged vehicles is 1 minute, this process will take an average of 5 minutes to allow the measurement of these five vehicles. Obviously, the larger the speed differential between current traffic and the "alarm" value, the smaller the number of vehicles needed to detect this change with a given statistical probability. Similarly, the shorter the distance between readers and the faster the cars are traveling, the more quickly incidents between those readers can be detected.

These four factors (the headway between vehicles, the distance between stations, the speed of the vehicles, and the number of vehicles needed to measure changes with a given level of confidence) interact to determine the detection times possible with the AVI travel time technique. Furthermore, some trade-offs can be made between these parameters to maintain detection times within a desired range. The more tagged vehicles there are, the greater the station distance can be without badly affecting the responsiveness of the detection system. The smaller the number of tagged vehicles traveling in the section (and thus the larger their headway), the smaller the distance between stations needs to be to achieve short detection times.

Because of the complex interaction of these variables, it is not possible to provide a single table or figure that summarizes the time required for detecting changes in travel time (or vehicle speed) using the travel time technique. The complexity of estimating detection times is further increased if statistical levels of confidence are associated with these variables. (That is, vehicles do not always arrive at the rate indicated by the headway. Their arrival rate is really a distribution, which will affect the actual response time of the AVI monitoring system. This is examined more fully in the main body of this report.)

Tables 3 and 6 present a representative set of expected (average) detection times using the travel time monitoring technique for various types of conditions. As can be determined from these tables, any one of these four factors can be a limiting factor in determining response time of the system. For example, no matter how many tagged vehicles there are, detection time can not be faster than the time required for a vehicle to travel the distance from the incident to the downstream reader. Similarly, no matter how closely spaced the detectors are, an incident can not be detected until a tagged vehicle passes a detector.

For a heavily instrumented, urban freeway (1 mile spacings, 60 mph speeds, and 2 second headways), detecting a 10 mile per hour change in vehicle speeds for 5 vehicles will take an average of 46 seconds. The controlling factor in this case is the 30 seconds it takes for vehicles to travel from the midpoint of the section to the downstream reader. If detector spacing is cut in half, detection time drops to 28 seconds.

For a less heavily traveled roadway (60 second headways or 60 vehicles per hour), the 1 mile spacing requires 336 seconds (5 1/2 minutes) to detect that same change in travel times. In this case, the vehicle headways control the detection time much more than the distance between AVI readers.

TAGGED VEHICLE VOLUMES IN THE FIELD TESTS

Project researchers used the instrumented HELP vehicles as the major source of tagged vehicles for the field tests performed for this project. Unfortunately, because of the large geographic area covered by the HELP test, the number of vehicles passing through the Tacoma test section was too small to perform real-time congestion detection. Tagged vehicle volumes rose from approximately 15 to 20 vehicles per weekday at the beginning of the tests to the current level of 40 to 45 vehicles per day. This number corresponds to a headway of slightly greater than 30-minutes between vehicles.

Manual traffic counts determined that if all trucks were AVI tag equipped, a vehicle headway of just over 20 seconds per vehicle (175 vehicles per hour) would be achieved during peak periods. Larger headways were prevalent during late night and early morning periods. The result of these low volumes of tagged vehicles is that congestion detection with the AVI system would be moderately fast during peak periods (on the order of 2 minutes, assuming 1 mile detector spacings and depending on the speed change to be detected), and very poor in late night and early morning periods.

However, even at the low level of data available in this test, the data that can be collected from an AVI system can be very useful. While the data are scarce, if they are collected daily, they can be used to determine the frequency of the occurrence of congestion, as well as the approximate length and severity of those occurrences. While the accuracy and timeliness of this information is not acceptable for use in real-time freeway control systems, they are sufficient for conducting facility performance monitoring, air quality planning, and air quality monitoring, as well as for monitoring the impacts of various freeway management actions adopted by the Department of Transportation.

One other use for the data collected with AVI systems is to calibrate information for the four-step planning models used in urban areas. The AVI data available from freeway sections could provide a basic idea of the origin/destination patterns of the freeway users. This information could also be very useful in determining the spatial and temporal demand for travel. Over time, these data could also be used to determine the impacts of new development on changes in origin/destination travel patterns. Data of this type are currently available only through extensive surveys, and even then, these surveys often do a poor job of determining travel patterns for non-work purposes.

INTERPRETATION AND APPLICATION

The findings presented above show that AVI based systems can produce traffic performance data for use in both real-time control systems and more general transportation planning and engineering analyses. Furthermore, the mathematical algorithms needed to operate the AVI system are straightforward and easily programmed.

Continuing improvements in transponder, computing, and communications technologies provide the opportunity to reliably collect the information necessary to operate the planned intelligent vehicle-highway systems of the future. Given the current state of the technology and expected improvements, the impediments to using AVI technology in this manner are not technical, but fiscal and political.

While the cost of AVI technology was not thoroughly explored in this project, a quick review of vendor quotes for AVI and loop equipment show that the infrastructure costs for a fully implemented AVI based detection system are roughly equivalent to those for a conventional loop system covering a similar geographic area. The costs included in this comparison include equipment costs, installation costs, communications costs, and software costs, but do not include the cost of vehicle tags or tag distribution. If purchased in bulk quantities, these tags can be as inexpensive as $10 to $20 each. However, in smaller numbers or with more complex tags, the cost per tag can run as high as $50 or $100 per tag. The operating agency will have to pay for these tags unless consumers perceive use of the tag as providing a benefit worth the cost of purchasing one.

An even more significant constraint to AVI system implementation is the political decision of which vehicles should be tagged. This decision may create problems associated with vehicle bias (are trucks a good indicator of traffic stream performance?), privacy (does the highway agency have a right to know where my vehicle is as I drive down the road?), data access (who has access to the fact that this vehicle was at this location at a particular time?), legality of enforcement (can speeding tickets be written using the AVI data?) and mandatory/voluntary tag use (do vehicle operators choose to have tags on their vehicles, or are tags required for some reason?).

Of these issues, the privacy and enforcement issues are the most likely to prevent the implementation of an AVI system. Without widespread use of AVI tags, only a limited number of tagged vehicles will pass through AVI sections during any given period, and system response times will be poor. As a result, it is important for any AVI system implementation strategy to directly address the privacy and enforcement issues, both by providing safeguards on the collection and use of the AVI tag information and by creating incentives that encourage motorists to place AVI tags on their vehicles.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Both the theoretical and field tests have shown that the use of AVI based vehicle detection could significantly improve the data available for both real-time traffic control decision making and transportation planning and analysis. The AVI based system provides several basic advantages over loop detector based systems. These advantages include the following:

- provision of section speed data, rather than point speed data,
- faster congestion detection than possible with conventional loop systems if AVI tags were widely used,
- provision of ramp origin and destination information,
- greater flexibility in control algorithm design,
- direct computation of travel time and delay information needed for a variety of operational and planning functions, and
- improved system performance and accuracy.

As with all new technologies and with all traffic performance monitoring systems, the proposed AVI system has several major drawbacks, including the following:

- the system requires a significant infrastructure that must be retrofitted to the existing roadway system;
- the system will be expensive to develop, install, and maintain;
- lack of standardization in the AVI field may result in some vehicles having to carry more than one vehicle tag to operate on all of the facilities that want to use AVI technologies; and
- public resistance to instrumenting vehicles may be strong, particularly if vehicle owners must pay for the vehicle tags and/or do not receive "benefits" equal to or greater than the cost of those tags.

Recommendations

This investigation has shown that AVI technology holds considerable promise for significantly improving traffic performance information. However, it is not clear that the provision of performance information alone would justify the cost of the infrastructure needed to operate an AVI based system. Instead, an AVI based system should be added only in areas where a significant number of tagged vehicles already exist, or where other uses of the AVI tag information can spread the cost of the system among several budgets.

An ideal location for an initial AVI based performance monitoring system would be an urban toll facility that was adopting AVI tags as part of its revenue collection system. In this instance, the tag readers located at the toll collection points would already exist, as would the vehicle tags. Thus, the marginal cost of the obtaining the performance monitoring data would be simply the cost of the software necessary for performing the required calculations.

In return, the toll facility would obtain accurate facility performance information between the toll collection points. This information could be used to meet the needs for

- facility operation
- motorist information
- planning analysis, and
- overall facility performance monitoring,

and all of this information could be obtained at a relatively modest price.

INTRODUCTION AND BACKGROUND

Traffic performance information is an integral part of traffic control and motorist information systems. Good traffic performance information is needed to optimize system control functions, detect congestion and incidents, and inform travelers to help them plan their trips. As traffic control systems attempt to obtain the maximum possible performance from facilities of finite size, accurate and comprehensive traffic performance information becomes more important.

EXISTING WSDOT FACILITIES

For WSDOT, like many of the nation's highway system operators, most of the traffic performance data from its urban freeway system are gathered with electro-magnetic inductance loop detectors and their associated electronic components. (1) The vast majority of the WSDOT urban loop detector locations contain one loop per lane of traffic. These single loop detectors provide the WSDOT with two basic types of information:

- volume estimates, and
- lane occupancy estimates, in terms of the percentage of time each loop detection zone is occupied by a vehicle.

By assuming an average vehicle length, WSDOT also estimates the average speed of the vehicles crossing each loop detector. While this technique yields a reasonable estimate of mean traffic speed, it is subject to considerable error, both because vehicle length is not a constant value and because loop sensitivities vary as a result of different roadway geometries and electronic operating conditions. Neither of these effects can be completely eliminated by calibration of the loop electronics.

By placing a second loop immediately down-stream from the first loop (i.e., dual loops) vehicle speed can be directly calculated using loop detectors. The two loops act as a speed trap, since speed can be calculated by dividing the distance between the leading edges of the two loops by the time difference between vehicle detection at the loops. The use of a second loop considerably improves the accuracy of speed estimates from loop detectors. In addition, a second loop verifies the volume and occupancy data collected by the first loop.

LIMITATIONS IN LOOP TECHNOLOGY

Loop detectors monitor traffic performance reasonably well but have distinct limitations for some data collection tasks. In addition, because they are installed in the road surface, their repair and replacement are costly and inconvenient.

While dual loop detectors provide more reliable speed estimates than single loop systems, both types of detectors provide "point" estimates of traffic speed. That is, they measure traffic performance at a specific site rather than over a section of roadway. While these estimates are helpful in many respects, they often provide a skewed view of traffic performance simply because traffic performance elsewhere in the section may be different than that at the loop location. This is particularly evident at interchanges, where traffic speeds often slow as a result of merging and diverging traffic.

Loop detectors are better able to estimate traffic conditions in road sections that are immediately adjacent to the detectors than in sections farther upstream or downstream. Thus, the more detectors that are placed in the roadway and the more closely they are spaced, the better the loops are able to monitor traffic conditions. (2) When loops are spaced closely enough, they are capable of providing excellent performance information on any road section. Unfortunately, placing and maintaining loops at these high densities is impractical (except for critical sections of roadways, such as tunnels, where traffic detection is crucial to motorist safety) because of the costs involved. Where loop detectors can not be spaced close together, their ability to accurately detect changes in roadway performance decreases.

Because spot speed estimates are not necessarily reliable for describing conditions upstream or downstream of the loop itself, one function for which loop detector estimates are less accurate is congestion detection. Loops can detect changes in vehicle speed at the loop location, but when the spacing between loop detectors is over 1/2 mile, significant congestion can exist within a road section without significantly changing the speeds directly over the loop detectors. This is particularly true where congestion begins immediately upstream from a loop detector.

This situation is illustrated in Figure 1. The loop detectors at location A monitor near free-flow traffic speeds. The detector at location C will not detect congestion beginning to form at location B until the vehicle queue caused by the congestion reaches a point where vehicles crossing detector C start to slow in preparation for reaching the back of the queue that begins just upstream of A. The longer the distance from B to C, the greater the queue length must be before vehicle speeds over detector C are reduced by incidents occurring at Point B.

In addition to being slow to detect reduced speeds in the road section, the detectors in the previous example can not determine how the delay between points A and C relate to total travel time within the section. That is, the detectors are not capable of determining the scope of the congestion, just the fact that slow speeds (or reduced volumes) either do or do not exist on top of each loop detector. For example, if an incident occurs immediately downstream of a detector, the detector will observe slow travel speeds. If the incident is minor, speeds will pick back up to free-flow speeds immediately after the detector. Thus, the detector's estimate of speed will underestimate the actual speed for the section as a whole.

Consequently, users of loop data consider the data valuable, but not necessarily an accurate measure of total traffic performance. Many urban traffic control centers are looking for more accurate measures of sectional travel times for use in emerging traffic control strategies. The most important of these are motorist information systems, new control system algorithms, and high technology vehicle guidance and routing systems. To meet the data needs of these systems, technologies that provide more representative traffic information must be developed.

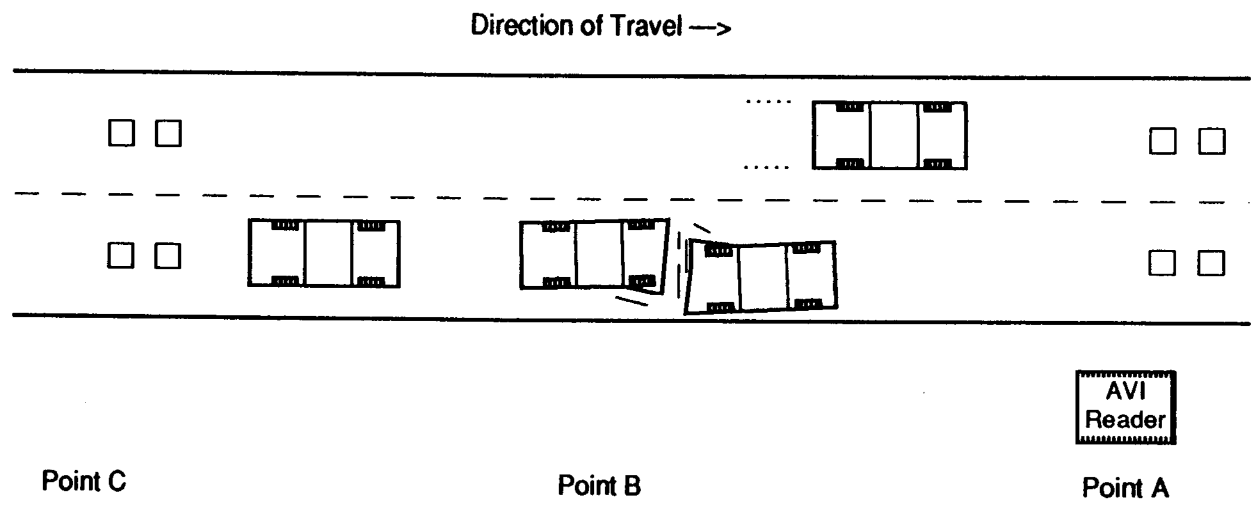

Figure 1. Detecting Congestion with Loops

AVI

One of several new technologies being investigated to improve the collection of traffic performance information is automatic vehicle identification (AVI). For AVI, electronic transponders (tags) are placed on vehicles and electronic devices for reading the tags are placed along the roadway to determine when each vehicle passes each location. One common way to read tags is with roadside interrogation devices ("readers") that monitor the movement of transponders past a specific point. The information available from the simplest of these AVI devices is that a specific tag has passed a specific point at a specific time. When this information is available at several locations, it becomes useful for traffic performance monitoring.

When an AVI equipped vehicle passes a "reader," the reader energizes the AVI tag, and a data transfer takes place. Data stored on the AVI tag are transferred first to the reader and then to a computer at the reader site or in a nearby central location. In some AVI systems, information stored at the reader site is also transferred to the passing vehicle. The data available from an AVI tag depend on the technology used for the AVI system, but they always include a unique tag identifier (for each passing AVI tag). The time of passage for that tag is available from the reader device. The use of tag numbers and passage times from multiple roadside reader locations allows vehicle travel times between reader locations to be computed, and thus traffic performance can be estimated between those reader locations.

Among other uses, AVI technology has potential for application in automated toll collection, as a component in automated route guidance equipment, as a means of expediting the passage of trucks through state port-of-entry facilities, and as a component of other transportation control systems. The installation and testing of AVI equipment for these purposes are already occurring across the United States. (3, 4, 5, 6) Because AVI is being investigated for a variety of purposes, traffic operations personnel may be able to use it as a "free" means of collecting traffic data by treating tagged vehicles as "probes" operating on the highway system. That is, because other systems (such as automated toll collection) are using AVI data collection, those data may become available for other uses for the marginal cost associated with transferring the data from one application's database to another. This is true because the installation and operation costs of the basic AVI system will be borne by the original system implementer. Similarly, two users of AVI data could jointly fund the infrastructure development required to create an AVI system, providing both users with data at a lower cost.

HELP SYSTEM TESTS

WSDOT is currently contributing funding for tests of one set of AVI technology as part of the Heavy Vehicle Electronic License Plate (HELP) program's Crescent Demonstration Project. WSDOT purchased two AVI systems for installation at the Bowhill and Kelso weigh stations. In addition, WSDOT purchased three more AVI readers to test the use of AVI for incident detection and traffic performance monitoring in urban settings. Many of the data analyzed for this report were collected with this equipment.

The HELP program has many goals and objectives. Among these goals is to provide improved commercial vehicle monitoring for both trucking firms and the state agencies charged with enforcing commercial vehicle regulations. (7) To meet this particular goal, the HELP program envisions a network of AVI reader locations that will monitor the passage of tagged commercial vehicles. This information will be made available to the owners of those vehicles to give them precise time and location information for monitoring and improving truck productivity. The network will also yield information needed by states to audit the trucking industry's taxation reports that list vehicle mileage by state.

INCIDENT DETECTION

Detection of incidents (non-recurring disruptions of traffic flow, such as accidents) is one use of traffic performance information. The faster an incident can be detected, the more quickly a response can be implemented. And the more quickly a response is implemented, the more quickly traffic conditions can be returned to normal.

Incident detection can be performed either through visual observation of roadways or through use of automated traffic performance monitoring. For automated systems, deviations from expected traffic flow and sudden disruptions in traffic stream parameters, such as vehicle volume and speed, signal the possible occurrence of an incident. Automated incident detection systems most often use loop detectors and commonly suffer from the limitations in loop technology discussed previously.

As noted above, WSDOT's loop detector system monitors traffic performance effectively at the loop locations, but its accuracy suffers as distances increase between the loop sites. As a result, loops are a useful part of the incident detection system but must be supplemented by other detection techniques. As noted above, WSDOT views loop detectors as expensive to install and maintain. Consequently, it is pursuing the expansion of the existing system, reductions in the spacing between loops, or the addition of loops to single loop locations only as funding permits and in conjunction with other projects that require roadway closures.

JOINT USE OF AVI DATA

Because AVI information can be used for several purposes, an AVI based system may allow the WSDOT to fund expanded incident detection systems by sharing the cost of system installation and operation with other potential users of the data. As indicated earlier, this cost sharing among multiple users would allow the Department to construct, operate, and maintain systems that it could not otherwise afford. For example, use of the HELP AVI system for this purpose would be beneficial both to the WSDOT, which would get extra traffic detection from the system, and to HELP, which would gain support for additional reader devices and expanded geographic coverage.

PROJECT OBJECTIVES

The primary objectives of this project were to determine the possible benefits of using AVI vehicle location information for monitoring the performance of traffic and detecting incidents. A secondary objective was to determine (if AVI proved likely to provide benefits for performance monitoring) whether the truck fleet tagged as part of the HELP project, or even the entire truck population, would provide an unbiased measure of traffic performance.

RESEARCH APPROACH

The research approach for this project involved a combination of literature review, theoretical modeling, and field testing. The testing was undertaken after consultation with the Washington State Department of Transportation and the HELP Executive Committee, which reviewed and permitted the use of the HELP vehicle tag information for this project.

The initial phase of this project included a thorough review of the AVI and traffic performance monitoring literature. Particular attention was paid to the HELP system testing reports, as well as reports describing AVI systems that were being installed and tested elsewhere in the country.

The second phase of the project included a theoretical analysis of the operational ability of AVI systems to monitor traffic. This analysis involved determining the types of algorithms and procedures that would be needed in an operational AVI traffic monitoring system, a simulation of those procedures, and a simulation of the results of using those procedures within the expected ranges of available traffic data. The ranges of data used in these tests were selected to simulate both different levels of public participation in the AVI program and different AVI system designs and configurations.

While the theoretical work was being accomplished, data on vehicle movements through the Tacoma test site were obtained from the Crescent Demonstration project contractor and a number of field tests. These data were used to perform the following analyses.

- The researchers determined how often the 5,000 trucks instrumented in the Crescent Demonstration Project passed through the Tacoma test area. This information helped determine the number of vehicles that would have to be instrumented for a specified number of vehicles to pass through the system at different hours of the day and whether sufficient AVI data were available from the preliminary Crescent Demonstration project vehicle fleet to test actual incident detection capabilities.

- The distribution of trucks in the traffic stream was compared with theoretical distributions to determine whether the theoretical computations on expected vehicle arrivals were accurate.
- The performance (i.e., travel speeds) of trucks was compared to the performance of passenger cars operating in the test area.
- The performance of test vehicles, as calculated with the AVI system, was compared with the actual travel times and speeds measured from those test vehicles.
- The effects of entrance and exit ramps on the ability to monitor tagged trucks was measured to determine the importance of ramps on an AVI monitoring system's design (that is, did too many trucks enter or exit the freeway in the middle of the test section?).

The results of these tests are described in the Findings section of this report.

FIELD INSTALLATIONS

To perform these tests, three AVI readers were purchased and installed on Interstate 5, south of the Tacoma CBD (see Figure 2) and incorporated into the Crescent Demonstration Database. The three AVI stations were located on the northbound lanes of Interstate 5, south of the Tacoma Hill. The stations were spaced at roughly 1-mile intervals. Reader antennae were placed in the two right most through lanes of traffic (see Figures 3, 4 and 5) at each location. As Figures 4 and 5 show, in two locations heavy merge and diverge movements would cause through trucks to move out of the shoulder lane and into the adjacent lanes. Therefore, the second and third lanes in these locations were instrumented, rather than the first (shoulder) and second lanes of the facility.

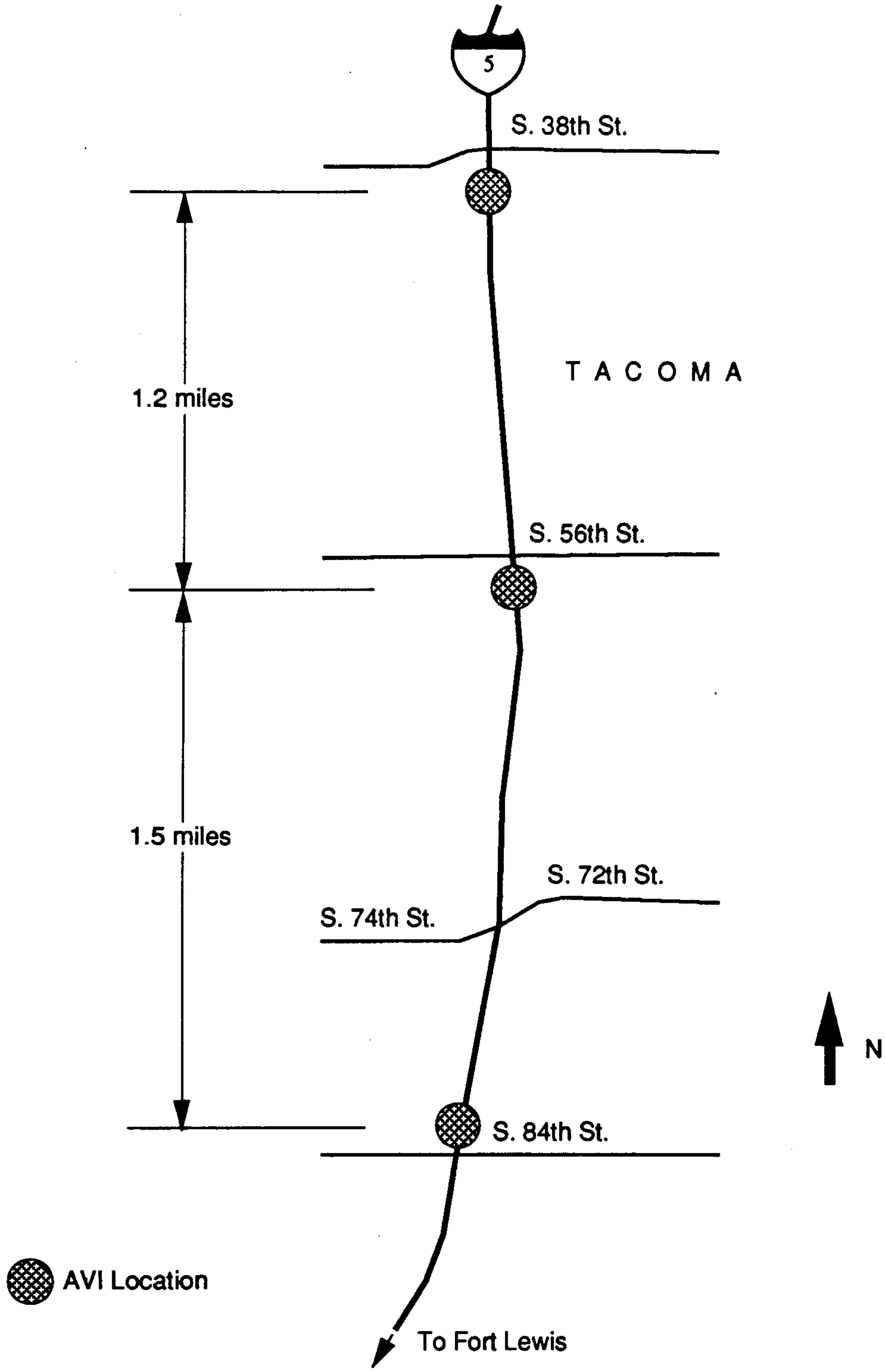

Figure 2. Location of Tacoma AVI Sites

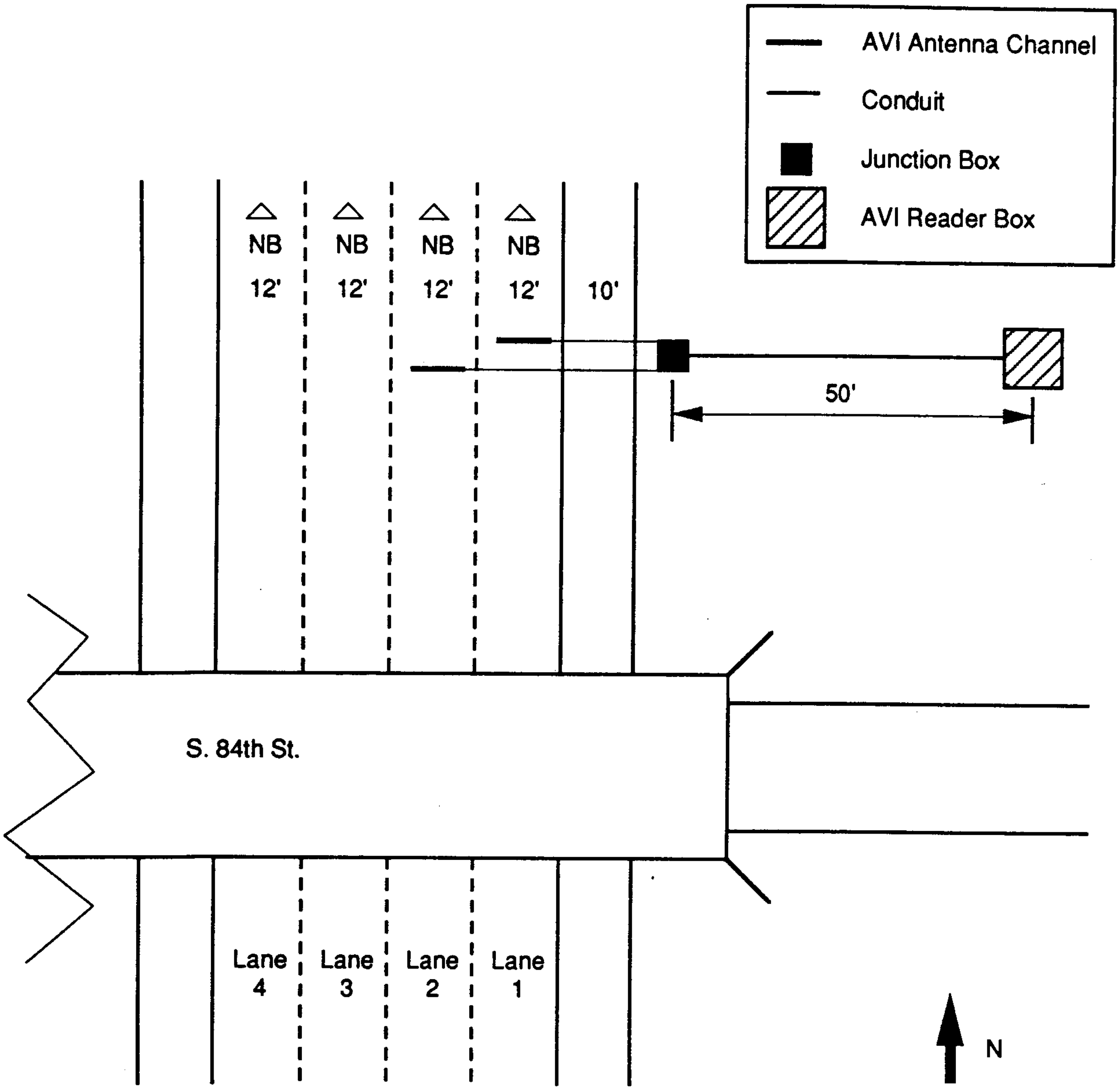

Figure 3. Southern AVI Site – S. 84th St. (I-5, mp 128.9)

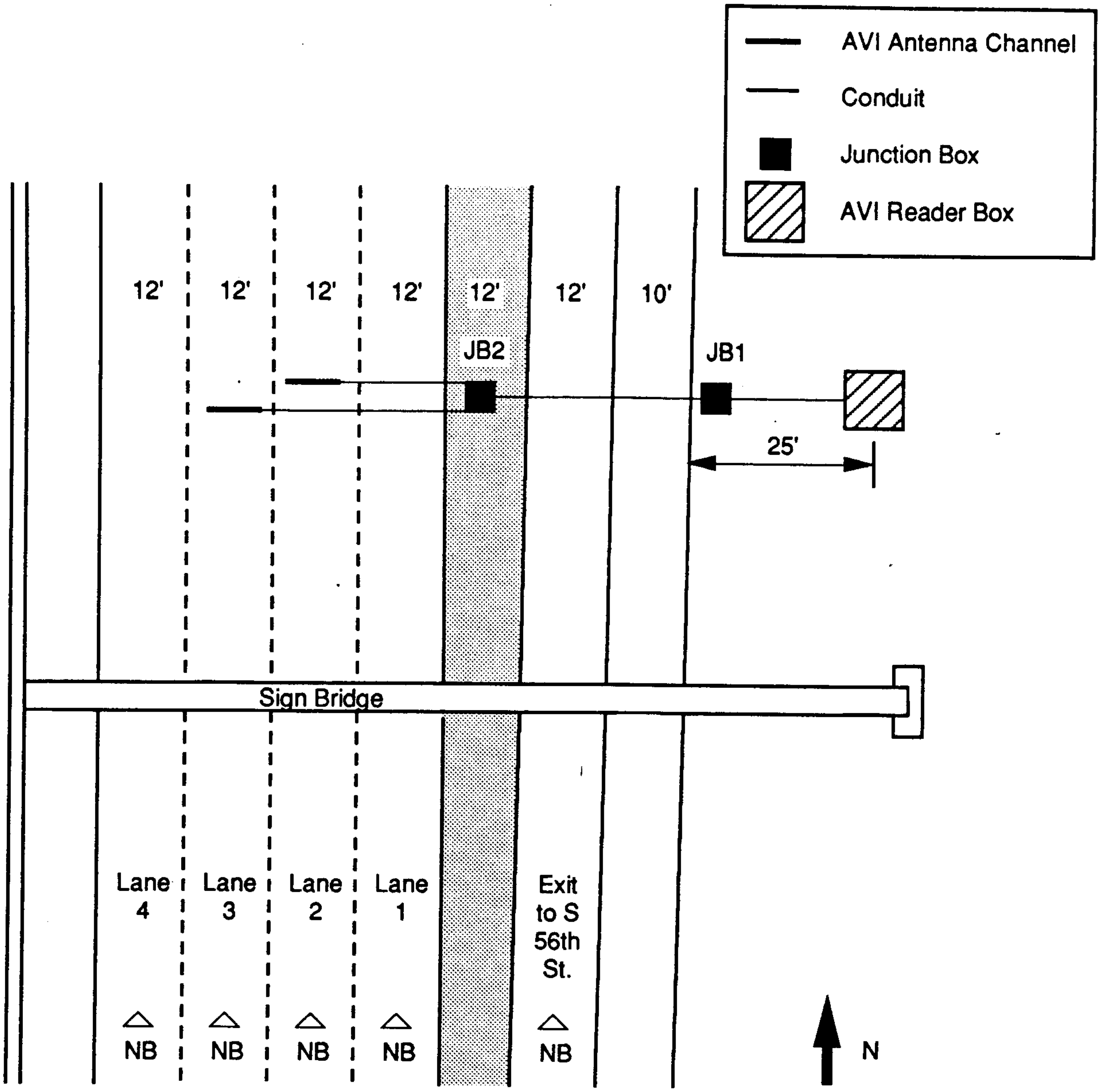

Figure 4. Middle AVI Site – S. 56th St. (I-5, NB, mp 130.4)

potential advantages and disadvantages of such a system. These findings are presented throughout the remainder of this report.

FINDINGS

This section presents the results of both the theoretical analysis and the field tests of AVI technology as it was used for monitoring traffic performance. The initial section of this chapter explores the systems that must be developed to make use of the AVI data, the procedures that must be adopted, and the theoretical response times of such a system. The second half of the chapter presents the results of field tests of AVI tags and readers placed as part of the HELP/Crescent Demonstration project.

THEORETICAL USE OF AVI

AVI technology is not omni-present. In likely scenarios, AVI technology will be employed on a certain group of vehicles and then its use will slowly expand as its benefits become clear. Thus, at least in the beginning, only a limited number of vehicles will be equipped with AVI tags. This situation will create some limitations in the responsiveness of AVI based data collection systems. In addition, like most data collection efforts, AVI readers are too expensive to install on all roads at close spacings. Consequently, the spacing between new AVI readers will be larger than desired in a mature system.

Because of these two basic constraints, the theoretical analyses presented below describe the effects of both varying the percentage of the vehicle fleet that is equipped with AVI devices and varying the distance between AVI readers.

Simple AVI systems, such as that used in the primary Crescent Demonstration system tests, provide limited types of data; vehicle tag IDs, location information, and the time each tag passes a reader. However, these data can yield a surprisingly rigorous picture of traffic performance. If a fairly large number of tagged vehicles pass the AVI readers, these data can be used as a real-time measure of traffic performance, but even a fairly low number of vehicle tags can provide important planning and engineering information to the transportation professional.

Measurement Techniques

There are two basic methods for using the data AVI systems produce for measuring traffic performance. The most simple method is to count the volume of tagged vehicles that pass a point while measuring the headways between tagged vehicles. The second method is to combine the tag and time-of-passage information from two or more locations. With these data, the travel time between those two points can be calculated for each tagged vehicle observed at both points. Incorporating the known distance between the two reader points also allows the average (section) speed to be calculated for tagged vehicles. Both of these uses are described below.

Monitoring the Volume of Tagged Vehicles

If all vehicles in the traffic stream are tagged, monitoring the passage of vehicles with AVI technologies is essentially equivalent to collecting volume information with loop detectors or other conventional vehicle monitoring systems. That is, the AVI system yields measures of total traffic volume and the average headway of traffic. One advantage of AVI systems is that most are designed for a higher level of accuracy and reliability than loop detector systems (because of their use in toll road revenue collection), and thus the volume estimate from a properly installed and calibrated AVI system will be more accurate than that from a loop system.

When all vehicles are not tagged, the AVI data no longer represent total traffic volumes on the facility, only the volume of tagged vehicles. This information is not as useful for operational purposes as total volume, but it can be useful for many special applications. For example, if specific types of vehicles are tagged, say taxis, it is possible to determine the number of those vehicles using the facility. Equipping buses would allow an operator to monitor the use of HOV facilities by buses, while also describing the operating speeds of those vehicles on that facility.

A partial volume count can also be used in several ways to monitor traffic performance. For example, given the number of tagged vehicles using the facility, it is possible to use statistics to predict when the next tagged vehicle should be observed. If a tagged vehicle does not appear within the expected time frame, an alarm can be sounded to indicate a possible problem on the facility.

The expected time between vehicles can be selected

- by using historical patterns (e.g., there should be 100 tagged vehicles in the peak hour, or roughly one every 36 seconds; if one is not observed every x minutes traffic is performing below expectations);
- by monitoring changes in the current pattern (e.g., there has been one tagged vehicle every 30 seconds for the last 10 minutes; if the AVI system observes no tagged vehicles in the next 90 seconds, there has been a change in traffic performance); or
- by comparing patterns at consecutive stations on the same roadway (e.g., Station A has been seeing five vehicles per minute during the last 15-minute period; Station B downstream of Station A should see roughly that many vehicles per minute during the next 15 minute time span).

The larger the number of tagged vehicles, the more accurate and useful all of these monitoring techniques become, but all vehicles operating on the facility do not have to be tagged for the system to yield useful information. The impact of the number of tagged vehicles on the responsiveness of the monitoring system is described later in this section.

Monitoring Vehicle Travel Times

Combination of tag and time-of-passage information from two or more locations is potentially a better source of traffic performance information than simply monitoring the number of passing tags. However, to make the required calculations, the clocks of all AVI readers used in the data collection process must be synchronized.

By combining the travel time estimates for all vehicles passing between two points within a specified time window, the travel time (or speed) distribution for all tagged vehicles can be determined for that period. If the tagged vehicles are representative of all vehicles in the traffic stream, this distribution provides an excellent measure of facility performance for the road section defined by the AVI reader locations. Unlike the volume measurement discussed above, all vehicles do not have to be tagged to obtain an accurate travel time estimate. Even a small percentage of vehicles in the traffic stream will yield an accurate measure of the average condition, provided that the tagged vehicles are representative of the system as a whole.

Combining Monitoring Techniques

Combining these two types of traffic monitoring algorithms can create a comprehensive system that is more capable than either of the two systems operating independently. A combination of the two types of systems reduces the limitations inherent in each system when it is used independently. The operational capabilities and limitations of each of these two techniques is described below.

To explain the capabilities and limitations of using AVI data collection, Figure 6 will be referred to throughout the remainder of this section. In Figure 6, the upstream AVI reader is designated as Point A. Points B, C and D represent tagged vehicles inside the section. (The tagged vehicle at Point C is involved in an accident.) Their tags have been read by the reader at Point A. The downstream AVI reader is at Point E. The vehicles at points B, C and D have not yet reached Point E.

Computation and Use of Travel Time Data

Travel time information is obtained by subtracting the time a vehicle passes Point A from the time it passes Point E. This is expressed mathematically as shown in equation 1.

$$TT_i = TP_{ei} - TP_{ai} \tag{1}$$

where: TT = travel time of any vehicle i

TP_{ei} = the time vehicle i passes point E

TP_{ai} = the time vehicle i passes point A

Because travel times (and speeds) vary from vehicle to vehicle, the travel time of interest to the highway facility operator is really the mean travel time of vehicles in the section (the standard deviation of these travel times is also useful), which can be represented as the mean of travel times for some given length of time, as shown in Equation 2.

$$\overline{TT_y} = \sum_{0}^{N} TT_i \tag{2}$$

where N equals the number of vehicles passing through the section during the time span y

Note that the travel time computed from the above formula represents the time period that has just ended. This is not <u>necessarily</u> an accurate predictor of the travel time required to traverse the section by a vehicle entering the section immediately after the computation has been made, because conditions within the section may have changed while that vehicle was in the section. However, under continuous flow conditions, the travel times obtained in this manner will accurately represent the section's actual driving conditions.

Computing the standard deviation of the measured travel times yields a measure of the variation in vehicle speeds within the traffic stream. Calculation of this measure of the distribution of speeds is important for determining when conditions have actually changed and when measured changes are simply a function of the sampling process. By maintaining both a rolling average of vehicle travel times and a historical record of the previous 5-minute period (or any other time period), the system can determine both current conditions and when those conditions begin to deteriorate as a result of congestion.

The occurrence of congestion must be determined by a statistical comparison of the current average travel conditions with some preset value (e.g., mean speed is below 50 mph on a freeway), some previous value in the day (e.g., mean speeds have slowed 5 mph in the last 5 minutes), or some historically expected value (e.g., traffic at this bottleneck is usually 45 mph, and abnormal congestion is not present until speeds drop below 40 mph).

<u>Congestion Detection</u>

The above discussion suggests that as long as the tagged vehicles are representative of the vehicle fleet's performance as a whole, and if these vehicles occur "reasonably" often in the traffic stream, the AVI system should provide a good measure of traffic performance.

Similarly, if conditions change gradually, a rolling average of travel time estimates should successfully track those changes in travel times and speeds. Furthermore, such a system should detect changes in traffic performance that result from incidents, but like other traffic monitoring systems, an AVI based system will be unlikely to detect "incidents" separately from more routine congestion, particularly where congestion occurs routinely because of geometric constraints or extremely high vehicle volumes. Thus the AVI based system is really more of a congestion detection system than an incident detection system, although some logic should allow it to determine the presence of severe incidents.

It may be possible to use site specific geometric information and historical traffic information to differentiate between recurrent traffic congestion caused by capacity limitations and incident caused congestion. Unfortunately, the limitations in the data available from the field tests prevented the rigorous examination required to test this theory. So, initially AVI can only be used as a supplement to an incident detection system.

The ability to quickly discern the onset of congestion is a good determinant of the capability of the detection system. The following discussion reviews the theoretical limitations of using an AVI system to detect sudden changes in performance. Figure 6 is referenced to assist in the explanations.

Incidents can produce several levels of congestion. These levels of congestion relate to the volume (or demand) to capacity ratio experienced on a facility as a result of an incident or other limitation in capacity. These cases include

- complete facility blockage,
- significant blockage, and
- minor blockage.

Each of these situations results in a different type of traffic flow pattern. In addition, each of these cases has a different effect on traffic performance because of the relationship between volume and facility capacity both before and after the incident. The ability of the AVI system to detect these changes in traffic patterns is discussed below.

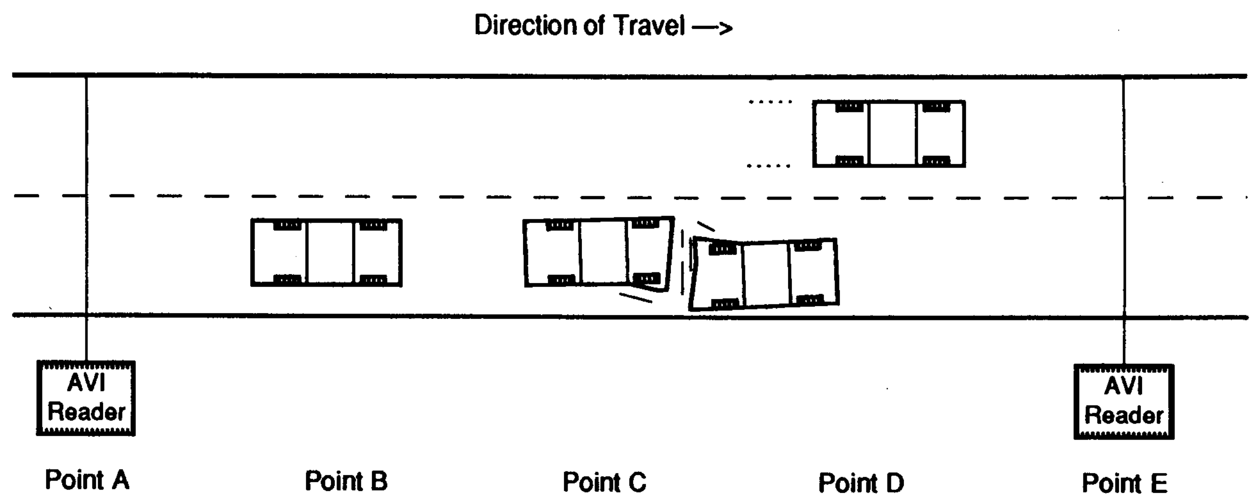

Figure 6. AVI Traffic Monitoring Section

Complete Lane Blockage

To illustrate the case of a complete lane blockage, an accident has occurred at point C in Figure 6. The tagged vehicle at point D in Figure 6 is unaware of the accident and continues through the road section at an unchanged speed. A tagged vehicle at point B, immediately behind the accident, is not able to bypass the accident and is thus stuck in traffic.

The AVI system can detect this incident at either AVI reader points A or E. If congestion backs up quickly (for example if the incident point is located near the upstream reader, Point A), the congestion will be indicated by the fact that no new tagged vehicles have passed the reader at Point A. They will be prevented from reaching the reader by the congestion. If a tagged vehicle is stopped within the reader's detection zone, the system will also be possible to detect stopped traffic from the multiple readings of that vehicle's tag.

Unless a tagged vehicle has stopped within the reader's detection zone, the time required to detect stopped traffic at Point A can be determined by the formula shown in Equation 3:

$$DT = \left[(T)\ (-\ln\ (LevCon))\right] + \left[\frac{(L)\ (DB)}{(Vol)(VehLen)}\right] \qquad (3)$$

where DT = detection time,

T = mean headway of tagged vehicles,

ln() = the natural log of the value in (),

LevCon = the level of confidence desired by the user that this detection time will not be exceeded,

L = the number of lanes (one direction),

DB = the distance from the reader to the lane blockage,

Vol = the total directional volume (all vehicles) at that time, and

VehLen = the average length per vehicle in a queue when all vehicles are stopped due to a lane blockage.

This formula contains two basic terms. The first term gives the maximum expected time required for the "next" tagged vehicle to pass the reader location for a given headway of vehicles and a selected level of error (i.e., the probability that the calculated time will not be exceeded under "normal" conditions). The second term represents the time needed for the queue to grow to such a length that no more vehicles can pass the upstream reader.

The first term in Equation 3 is dependent on the expected headway between tagged vehicles and the statistical level of confidence required by the operator before the system alarm indicates that traffic is not performing as expected. The greater the number of tagged vehicles that use the facility, the smaller are the expected headways, and the faster the system's ability to detect stopped traffic. The theoretical effect of the number of tagged vehicles on the speed with which traffic blockages can be detected is shown in Table 1.

Table 1 shows that at high volumes of tagged vehicles, detection times approach 1 second. (The highest volumes in Table 1 represent volumes present if 50 percent or more of all vehicles using urban interstates during the peak periods were AVI tagged equipped.) At lower volumes of tagged vehicles (e.g., 2 vehicles per hour), the detection times are so long with this technique that they are essentially useless.

Table 1 also illustrates that the speed with which the alarm is sounded is also a function of the statistical limits selected. These same limits also control the frequency with which the system gives false alarms. Essentially, the greater the certainty that is built into the alarm function, the more slowly the alarm will be sounded. The more sensitive the alarm function, the more false alarms the system will give.

As noted previously in this paper, the estimate of expected tagged vehicle headways used in this equation can be obtained from either historical values, the headway of tagged vehicles observed at upstream stations, or the headways experienced by the station in question during some previous period of operation.

While the headway detection term is important, with the AVI system it will most likely not be the controlling factor in determining whether a lane has been blocked . This is

Table 1. Effect of Vehicle Volume on Detection Time*

Number of Tagged Vehicles Per Hour (veh/hr)	Headway Between Vehicles (sec/veh)	Detection Time at 99.9% Confidence Interval (min)	Detection Time at 99% Confidence Interval (min)	Detection Time at 95% Confidence Interval (min)	Detection Time at 90% Confidence Interval (min)
2	1800	207	138	90	69
4	900	104	69	45	34.5
6	600	69	46	30	23
12	300	46	23	15	11.5
20	180	21	14	9	7
30	120	14	9	6	4.6
60	60	7	4.5	3	2.3
120	30	3.5	2.3	1.5	1.2
240	15	1.7	1.2	0.75	0.5 (34 sec)
720	5	0.5 (34 sec)	0.4 (23 sec)	0.25 (15 sec)	12 sec
1800	2	0.2 (14 sec)	9 sec	6 sec	5 sec
2000	1.8	0.2 (12 sec)	8 sec	5 sec	4 sec
3600	1	0.1 (7 sec)	5 sec	3 sec	2 sec

* This table assumes that the incident occurs at the reader location and that no vehicles pass the reader location after the incident.

because the second term in Equation 3 will usually be much larger than the first term. As noted above, the second term provides a measure of how long the congestion caused by the accident at Point C will take to reach Point A and thus prevent other tagged vehicles from passing the AVI reader. This time is dependent on the current volume of traffic, the number of lanes of the facility, and the distance between the incident and the reader. In most cases, this time period will be much greater than is acceptable for congestion detection. Loop detector systems also have this same limitation, which is a primary reason why loop systems are slow to detect many incidents. In cases where the queue builds quickly, or the incident is very close to the upstream reader (Point A), this time will be small and the traffic blockage will be detected in the approximate time span indicated by Table 1.

A second method of detection using vehicle headways is also possible. This method can also be used with loop detectors, and is likely to detect roadway blockages more quickly than the technique that uses Equation 3. This second technique relies on the reader at point E to detect the lack of tagged vehicles passing the downstream end of the section. This will occur because no additional tagged vehicles are able to pass Point C.

The reader at Point E will not detect a change in traffic performance until after the vehicle at Point D has reached the reader. After this vehicle has passed point E, the reader will not see another tagged vehicle until the blockage has been cleared. Thus the detection time required for the reader at Point E to determine that a total blockage has occurred is given by Equation 4:

$$DT = \left[(T)\,(-\ln\,(LevCon))\right] + \left[\frac{(DR)}{(Vehspd)}\right] \tag{4}$$

where DR = the distance from the blockage to the downstream reader, and

vehspd = the speed of the last tagged vehicle traveling between the blockage and the downstream reader (i.e., Vehicle D).

Equation 4 is similar to Equation 3, except that the second term simply represents the travel time necessary for the last tagged vehicle to reach the end of the section from the accident location. This second term is a maximum value. If the tagged vehicle at Point D is downstream of Point C (but is still the last tagged vehicle on the downstream side of the accident), then the travel time portion of this equation will overstate the required detection time.

Once this vehicle has passed Point E, then the first term of the equation indicates the remaining time required to detect the change in traffic performance. Obviously, the smaller the spacing between the AVI reader stations (Points A and E), the more quickly the "last" vehicle passes the downstream end of the section, and the more quickly traffic interruptions can be detected. The impacts of vehicle speed and the distance between detectors on this portion of the detection time equation are shown by Table 2.

Note that the times shown in Table 2 must be added to the times found in Table 1 to estimate total detection time using this technique. Where the volume of tagged vehicles is high, the first term in Equation 4 tends towards zero, and the total detection time is roughly equal to that shown in Table 2. Where there are very few tagged vehicles, the detection time is controlled by the times given in Table 1.

Also note that the travel time that is important for incident detection is not actually based on the distance between the readers, but the distance between the incident location and the downstream reader. On average, this will be one-half the distance between readers, and thus the <u>average</u> time required for the last unaffected vehicle to reach the downstream reader site will be roughly one half the travel time between the readers. The times given in Table 2 indicate the maximum time required for an incident to be detected (assuming high vehicle volumes) as a result of an incident's location within the section defined by the reader locations.

As with Equation 3, the expected headway for tagged vehicles for the first term in Equation 4 can be determined from either historical operating conditions, upstream station experience, or headways experienced by Station E earlier in the day.

Table 2. Effect of Vehicle Speed and the Distance Between Readers on Vehicle Detection Times*

Vehicle Speed	Travel Time Between Readers (in minutes)			
	1/2 Mile Between Readers	1 Mile Between Readers	2 Miles Between Readers	5 Miles Between Readers
10	3	6	12	30
15	2	4	8	20
20	1.5	3	6	15
25	1.2	2.4	4.8	12
30	1	2	4	10
35	0.9	1.7	3.4	8.6
40	0.75	1.5	3	7.5
45	0.7	1.3	2.7	6.7
50	0.6	1.2	2.4	6.0
55	0.55	1.1	2.2	5.5
58	0.52	1.0	2.1	5.2
59	0.51	1.0	2.0	5.1
60	0.50	1.0	2.0	5.0
65	0.46	0.92	1.8	4.6
70	0.43	0.85	1.7	4.3
75	0.40	0.80	1.6	4.0
80	0.38	0.75	1.5	3.8
85	0.35	0.71	1.4	3.5
90	0.33	0.67	1.3	3.3
100	0.30	0.60	1.2	3.0

* The detection times shown on this table assume that detection occurs at the time the subject vehicle crosses the downstream AVI reader location. (i.e., only one vehicle is needed for detection, and the number of tagged vehicles exceeds 3,600 per hour.)

Significant Lane Blockage

Both of the detection algorithms described above can be used with existing loop detection systems. However, unlike loop detection systems, AVI based techniques can use a variety of other detection algorithms that are not based strictly on point volumes and speeds. One of the most powerful AVI based detection algorithms uses vehicle travel times to measure changes in traffic performance.

In the previous examples, because the roadway is blocked, the AVI system can not detect changes in travel times and speeds between the two readers. The last vehicle measured at both AVI readers operated through the road section under "normal" conditions. Congestion occurs only behind the last tagged vehicle (Point D), and since no other vehicles reach Point E, no new travel times can be computed. Thus a complete roadway blockage cannot be detected from a measured change in travel times along the section.

If the accident at Point C does not completely block traffic, some vehicles will continue to pass both Points A and E. This means that some tagged vehicles may pass these points (although they will travel more slowly because of the congestion at Point C), and the detection algorithms described above may not detect the change in traffic performance. If none of the vehicles passing the blockage are tagged, the previous point still applies. If the number of vehicles passing the blockage is small, the change in vehicle headways may also be large enough that the change in performance can be statistically detected. But even for large incidents, the change in headways is insufficient to quickly detect the incident. However, if tagged vehicles are still moving through the road section, the change in travel time (section speed) caused by the congestion at the incident site can be monitored, and that measure can be used to determine the onset of congestion.

Essentially, when significant lane blockage occurs, the travel time for vehicle B from Point A to Point E will be considerably longer than that for vehicle D (the last vehicle ahead of the incident) as a result of the congestion caused by the incident. As congestion increases upstream of the incident, the travel time between Points A and E will continue to increase because of the delays in moving from Point A to Point C, and this continuing increase will be apparent in the travel times of subsequent tagged vehicles passing both Points A and E. This increase in congestion will be continuously detected each time a new tagged vehicle passes Point E.

Whether congestion is detected using vehicle speeds and travel times is then dependent on the differences in travel times between the last vehicle (or set of vehicles) and some standard set by the system operator. Reduced speeds can also be detected by comparing the travel times of a set of vehicles with the travel times of a previous set of vehicles operating over the same section of road.

Because the vehicle travel times and speeds vary on any facility, one abnormally slow vehicle may or may not trigger a congestion alarm. The sensitivity of the congestion alarm to single vehicles or groups of vehicles must be calibrated to the conditions normally found on each section of roadway. The alarm should be based on statistical levels of confidence, the measured differences in vehicle speeds, and the measured or expected distribution of those speeds under "normal" operation. As with the statistical tests of headway distributions, the test parameters of the alarm can be set for different levels of sensitivity. The more sensitive the alarm, the more quickly incidents will be detected, but the more often the false alarms will be sounded. The more restrictive the alarm, the fewer the number of false alarms, and the slower the response time of the system.

If few vehicles on the facility are tagged, the detection system may have to rely on the travel times of individual vehicles. Equation 5 illustrates one method for determining a significant change in travel time on the basis of a single vehicle tag reading. It assumes that the single vehicle's travel time exceeds the bounds of the expected distribution of travel times to such an extreme that the system can say with statistical confidence that a change in travel times has occurred.

$$\text{Alarm} = TT_e - TT_i - (z * \sigma_{TT}) \tag{5}$$

where Alarm = the alarm variable. If this value is positive, the tested travel time is great enough to warrant the incident or congestion alarm.

TT_i = the travel time obtained from the AVI reader,

TT_e = the mean of the distribution of expected travel time,

σ_{TT} = the standard deviation of the expected travel times, and

z = the statistical level of confidence associated with the alarm.

This equation is very simplistic and assumes a normal distribution of travel times. Many other alternative equations and tests exist.

Where more tagged vehicles operate through the monitored section, the average travel time of some specified number of tagged vehicles can be used to detect changes in travel time on the facility. This method is less sensitive to false alarms than the test given in Equation 5, and like the single vehicle alarm, this sensitivity can be partially controlled by the selection of the statistical parameters used in the test. Equation 6 illustrates how to test for a significant change in travel time on the basis of multiple vehicle tag readings. This test uses the Student's t-statistic for small samples.

$$t = (\overline{TT}_i - TT_e) \,/\, (s/\sqrt{n}) \tag{6}$$

where t = the student's t-statistic,

$\overline{TT}_i$ = the average section travel time for the tested time period,

TT_e = the expected travel time,

s = the standard deviation of TT_i, and

n = the number of samples used to compute $\overline{TT}_i$

The value of t is compared against the defined values of t at different levels of statistical confidence, to determine whether an alarm should be sounded.

The advantage of multiple tag readings is that false alarms are less likely to be triggered by a vehicle traveling abnormally slowly for some reason other than congestion. This allows the AVI system to detect smaller changes in travel time with a higher statistical reliability. The disadvantage is that more than one vehicle must pass both AVI readers before detection can take place, and this can slow the response time of the system, especially if few tagged vehicles are operating on the facility.

Equation 6 assumes that the average travel time for vehicles in the monitored section is compared with some fixed value. This is good for some uses but not others. For example, this assumption can be used to determine when freeway traffic is no longer operating with a mean speed above 55 mph. However, after traffic has already become congested and speeds are below 55 mph, it is not capable of detecting the continuing change in traffic performance unless the terms in the equation have been updated.

Use of a slightly different formula allows tests of changes in traffic performance over time, as opposed to a comparison of performance with an arbitrary value. Under this formulation, the average travel times for some period or set number of vehicles can be compared with the conditions from some group of vehicles passing through the section in a prior time period.

Mathematically, this comparison of sample means can be expressed as shown below in Equation 7.

$$t = \frac{\left|(\overline{TT}_1 - \overline{TT}_2)\right| - DT_0}{s\sqrt{\frac{1}{n_1} - \frac{1}{n_2}}} \tag{7}$$

where:

s = the pooled estimate of the standard deviation for the two samples,

t = the student's t-statistic

$\overline{TT}_1$ = the mean for travel times in the current period,

$\overline{TT}_2$ = the mean for travel times in the previous period,

DT_0 = the difference necessary to indicate a change large enough to require an alteration in control strategies, and

$n1, n_2$ = the number of travel times in the two samples.

Here again, the value of t is then used to determine whether the measured travel time differences are statistically significant at a predetermined level of confidence.

As can be seen in both equations 6 and 7, the sensitivity of the detection algorithm can be set by both the difference in travel time that is to be detected and the statistical level of confidence required in that detection.

Equations 5 through 7 provide only the statistical tests that can be used to detect differences in travel times or speeds using the AVI information. As was shown in equations 2, 3, and 4, the time required to detect changes in conditions on the facility must also include the time necessary for tagged vehicles to reach the downstream AVI detectors. Thus, even with the travel time based detection technique, AVI system response is controlled by the headway of tagged vehicles on the system, the distance between AVI readers, and the speed of the vehicles on the roadway.

For example, if five vehicles with an average speed 5 mph lower than the "normal" speed are needed to detect a "statistically significant" change in traffic performance (given an arbitrary value for the variation in those speeds), the system can not detect that change in speeds until five vehicles have passed the downstream station. If the headway between tagged vehicles is 1 minute, this process will take an average of 5 minutes to allow the measurement of these five vehicles. Obviously, the larger the speed differential between current traffic and the "alarm" value, the smaller the number of vehicles needed to detect this change with a given statistical probability. Similarly, the shorter the distance between readers and the faster the cars are traveling, the more quickly incidents between those readers can be detected using the travel time detection technique.

These four factors (the headway between vehicles, the distance between stations, the speed of the vehicles, and the number of vehicles needed to measure changes with a given level of confidence) interact to determine the detection times possible with the AVI travel time technique. Furthermore, some trade-offs can be made between these parameters to maintain detection times within a desired range. The more tagged vehicles there are, the greater the station distance can be without badly affecting the responsiveness of the detection system. The smaller the number of tagged vehicles traveling in the section (and thus the larger their headway), the smaller the distance between stations needs to be to achieve short detection times.

Because of the complex interaction of these variables, it is not possible to provide a single table or figure that summarizes the time required for detecting changes in travel time (or vehicle speed) using the travel time technique. The complexity of estimating detection times is further increased if statistical levels of confidence are associated with these theoretical times. However, a simplified form of the response time equation can be computed as follows:

$$DT = (\text{\# vehicles required} * \text{tagged headway}) + \text{travel time} + \text{time lost to delay} \tag{8}$$

where: DT = the average detection time for a given section of roadway.

The first term in this equation represents the time needed until the required number of tagged vehicle reaches the incident congestion. This may be one or two vehicles for large changes in travel time, or it may be five or ten vehicles, if the change in travel times is fairly small. This is the same probability function used in earlier equations to reflect the headway distribution of the tagged vehicles (the average response time is simply the expected headway between tagged vehicles). The second term represents the time necessary for the tagged vehicle that first encounters the congestion to reach the downstream reader. On average, incidents will take place halfway between the readers, so the middle term in the above equation is equal to one half the distance between readers, divided by the average speed of the vehicles under "normal" conditions. The third term is equal to the time difference between the "normal" travel time and the slower "congested" time caused by the incident.

Tables 3, 4, 5 and 6 present a representative set of expected detection times for various types of conditions. As can be seen in these tables, any one of these four factors can be a limiting factor in determining response time of the system. For example, no matter how many tagged vehicles there are, detection time can not be faster than the time required for a vehicle to travel the distance from the incident to the downstream reader. Similarly, no matter how closely spaced the detectors are, an incident can not be detected until a tagged vehicle passes a detector.

For a heavily instrumented, urban freeway (1 mile spacings, 60 mph speeds, and 2 second headways), detecting a 10 mile per hour change in vehicle speeds for 5 vehicles will take an average of 46 seconds. The controlling factor in this case is the 30 seconds it takes for vehicles to travel from the midpoint of the section to the downstream reader. If detector spacing is cut in half, detection time drops to 28 seconds.

For a less heavily traveled roadway (60 second headways or 60 vehicles per hour), the 1 mile spacing requires 336 seconds (5 1/2 minutes) to detect that same change in travel times. In this case, the vehicle headways control the detection time much more than the distance between AVI readers.

Tables 3 through 6 illustrate the interaction of the four principal factors affecting average detection time. Actual detection times will vary somewhat, because of the variable nature of vehicle speeds and headways.

Minor Lane Blockage

When the incident at Point C (from Figure 6) is minor, some congestion will occur within the section, but the change in traffic performance will be reasonably small. From the perspective of the AVI based congestion detection procedures, this case is identical to the major lane blockage situation described above. However, in this case, the AVI system will detect the congestion increase only through the change in travel times, as the blockage is too small to cause a statistically significant change in the headway between vehicles.

The time required for the system to detect changes caused by small incidents is computed exactly as shown above for major lane blockages, and detection times are similar. The only difference is that the travel time differences measured will be smaller, and thus more vehicles will have to be monitored at that speed in order to be statistically confident that a change has actually taken place.

Table 3. Example Detection Times (Seconds)*

Headway (secs)	Number of Vehicles Needed			
	1	**5**	**10**	**30**
1	37	41	46	66
2	38	46	56	96
5	41	61	86	186
15	51	111	186	486
60	96	336	636	1836

* Assumes a 1 mile spacing between detectors with incidents occurring at the midpoint, speeds of 60 mph, and detection of a 10 mph change in speed.

Table 4. Example Detection Times†

Headway (secs)	Number of Vehicles Needed			
	1	**5**	**10**	**30**
1	19	23	28	48
2	20	28	38	78
5	23	43	68	168
15	33	93	168	468
60	78	318	618	1818

† Assumes a 0.5 mile spacing between detectors with incidents occurring at the midpoint, speeds of 60 mph, and detection of a 10 mph change in speed.

Table 5. Example Detection Times*

	Number of Vehicles Needed			
Headway (secs)	**1**	**5**	**10**	**30**
1	91	95	100	120
2	92	100	110	150
5	95	115	140	240
15	105	165	240	540
60	150	390	690	1890

* Assumes a 1 mile spacing between detectors with incidents occurring at the midpoint, speeds of 30 mph, and detection of a 10 mph change in speed.

Table 6. Example Detection Times†

	Number of Vehicles Needed			
Headway (secs)	**1**	**5**	**10**	**30**
1	181	185	190	210
2	182	190	200	240
5	185	205	230	330
15	195	255	330	630
60	240	480	780	1980

† Assumes a 2 mile spacing between detectors with incidents occurring at the midpoint, speeds of 30 mph, and detection of a 10 mph change in speed.

For minor incidents, as with all traffic performance based incident detection systems, the AVI system will have difficulty determining whether the change in traffic performance is caused by an incident or simply oversaturation of the roadway. (This is particularly true for small incidents.) Furthermore, the AVI system will have difficulty detecting the presence of very small incidents because of the relatively small changes in vehicle performance that small incidents cause. This can be partially offset by using very short detector spacings and high numbers of tagged vehicles, although, the distance needed between AVI stations to detect small changes in sectional traffic speeds is often considerably shorter than is economically practical.

Still, the ability of the travel time technique to monitor small changes in vehicle speed (given a large number of tagged vehicles) at any distance is greater than that of conventional loop detector systems at that same detector distance. In addition, the rolling average speed that can be kept by the AVI system yields an excellent measure of the true performance of the roadway over whatever distance exists between the AVI readers. This measure also provides an important input to motorist information systems, traffic operations decisions and traffic control algorithms.

ACTUAL EXPERIENCE WITH THE HELP OF AVI SYSTEM

The project team performed field tests as described in the Research Approach section of this document. The field test results were not as decisive as had been anticipated because of equipment reliability problems early in the project and a lack of instrumented vehicles routinely passing through the test section. These issues are explored below, along with the findings of the field tests.

Installation and Operation of the Equipment

The testing of the HELP system hardware and software did not proceed as smoothly as intended. The initial system installation for HELP was scheduled for September 1990, but the system was not installed until March 1991. Furthermore, because of equipment problems, the AVI system did not function correctly until July 1991. Then after the system began operation in July, a number of hardware failures occurred.

Two of the three AVI readers (stations 128 and 130) operated 76 percent of the time from July 20, 1991, to September 20, 1991. The third station (number 132) operated for only 36 percent of that time. After September 20, Station 128 failed and did not come back on-line until January 22, 1992. Stations 130 and 132 operated continuously from September 20, 1992.

Data Access

Access to the data was provided free of charge by Lockheed Information Management Services Corporation (Lockheed). However, the Lockheed database system was not able to transfer data to TRAC electronically. Instead, the data were dumped to paper and mailed to TRAC. While the cost of transferring all the data from the Tacoma site was low, TRAC had more difficulty using the data because they had to be reentered by hand for use in this project's analyses.

Reader and System Accuracy

The researchers tested AVI tag reading accuracy by driving an instrumented test vehicle repeatedly through the test section. One of the AVI readers failed just before this test, so that the procedure tested only two readers. In the six passes over the tag readers, no reader misses occurred.

More extensive tests were performed by Castle Rock Consultants, the HELP technical consultants, in May of 1991. (8) These HELP tests found that the AVI readers could successfully read tags at up to 110 mph, as well as detect tagged vehicles passing the system simultaneously in adjacent lanes. The HELP tests also showed that the AVI equipment worked well in various degraded environmental conditions, including heavy rain and simulated snow and ice. Finally, the system was shown to be immune from potential electrical interference from cellular phones, CB radios, and electric generators.

To calculate the accuracy of the AVI travel time computations, floating car runs through the Tacoma test section were also timed with a stop watch. Travel times based on the AVI system averaged 1.8 seconds slower (2 percent) than the travel times taken from the floating car runs. While this level of accuracy is sufficient for almost any traffic monitoring requirement, the project team believes that the AVI system can even more closely replicate travel times if the clocks in the AVI readers are synchronized more effectively.

The initial check of the AVI reader clocks indicated that they were completely unsynchronized. As a result, preliminary computations with HELP data yielded negative travel times through the system. Apparently the clocks had never been synchronized. The clock for each device had simply been set from the watch of the person installing the equipment. The project's tests pointed out that while this level of clock accuracy may be sufficient for an interstate system such as HELP, where consecutive readers are often 100 miles or more apart, much closer tolerances are necessary if the data will to be used for urban congestion monitoring.

After this finding, the AVI clocks were changed so that the devices were synchronized within the tolerances of the experiments in this project. Because of the nature of clock drift, a fully operational system may require periodic clock reviews to maintain system accuracy.

Truck Performance and Facility Performance

The purpose of one of the major analyses for this project was to determine whether the trucks outfitted with AVI tags could be used for traffic performance monitoring if both the number of trucks participating in the HELP system test and the number of Tacoma AVI readers were expanded. The analysis consisted of two parts: the first examined whether trucks are representative of traffic as a whole; the second investigated whether there were enough trucks in the traffic stream.

While performing the system accuracy tests described above, the test car followed trucks operating within the test section. The test car would join the traffic stream immediately behind a conventional 5-axle semi-trailer unit and follow that vehicle through the test section. During the period in which these tests took place, traffic conditions ranged from level of service (LOS) B to D. The performance of trucks in relation to automobiles in LOS E and F was also observed during other phases of the project.

The results of these tests showed that on the flat stretch of roadway used in the system tests, trucks performed similarly to traffic as a whole. During poorer LOS conditions, the trucks tended to operate slightly more slowly than the "average" automobile, but this was due more to lane position than vehicle performance. Traffic performance on the test highway section was significantly affected by on- and off-ramps in the section. During LOS D conditions, vehicles in the right two lanes of the facility operated more slowly than traffic in the leftmost lane(s), regardless of vehicle type. (The test section varied in width from three to five lanes, depending on the presence of add and drop lanes.)

A comparison of these travel times estimates with automobile travel time measurements made using a license plate matching technique during the same period showed that the truck travel times were actually slightly faster (by 4.3 seconds or 5 percent) than the automobile travel times. However, the automobile travel times came primarily from the rightmost lane of traffic and were not considered representative of the total traffic stream because of merge/diverge effects.

Casual observation of trucks on significant hills near the test section showed that travel time estimates based exclusively on trucks in these areas would not be accurate estimators of general traffic flow. However, outside of those specific geographic locations, the data indicated that trucks were an acceptable estimator of general traffic performance.

Tagged Vehicle Volumes

660 of the roughly 5,000 trucks that have been instrumented for the HELP project are based in Washington. The researchers hoped that a significant number of these vehicles, supplemented by trucks based in other states but operating in Washington, would routinely travel through the test section, providing a strong traffic database for this project. Unfortunately, they did not.

When the AVI readers began operation in July 1991, approximately 15 to 20 tagged vehicles per day operated through the test section. This number increased slowly as the project matured to the current level of 40 to 45 vehicles per day for weekdays, with somewhat fewer vehicles per day on weekends. This number corresponds to a slightly greater than 30-minute headway between vehicles. Figures 7 and 8 show, for two representative days, how these vehicles were distributed over the day and illustrate how the travel times experienced by these vehicles changed over the course of those specific days.

Figure 7 suggests the presence of minor congestion in the morning rush hour (from 5:00 to 8:00) and then reoccurring congestion in the afternoon from 2:00 to 7:00. Travel times in the off-peak hours represented a vehicle speed of roughly 56 mph. Travel times in the peak hour were closer to 51 mph. In Figure 8, not only is this minor peak-hour congestion present, but significant congestion was detected in the early afternoon as a result of an accident.

While the travel times determined by the HELP AVI system accurately detected the presence of both recurring congestion and incident caused congestion, the very high headway between vehicles caused by the low level of AVI tag use, prevented the system from detecting the onset of these occurrences in a timely fashion. An increase in the number of vehicles by roughly a factor of ten, spread evenly throughout the day, would have been necessary to provide congestion detection within several minutes of its onset.

In reality, even if the number of tagged trucks were expanded significantly, the number of tagged vehicles passing through the test section during the late night/early

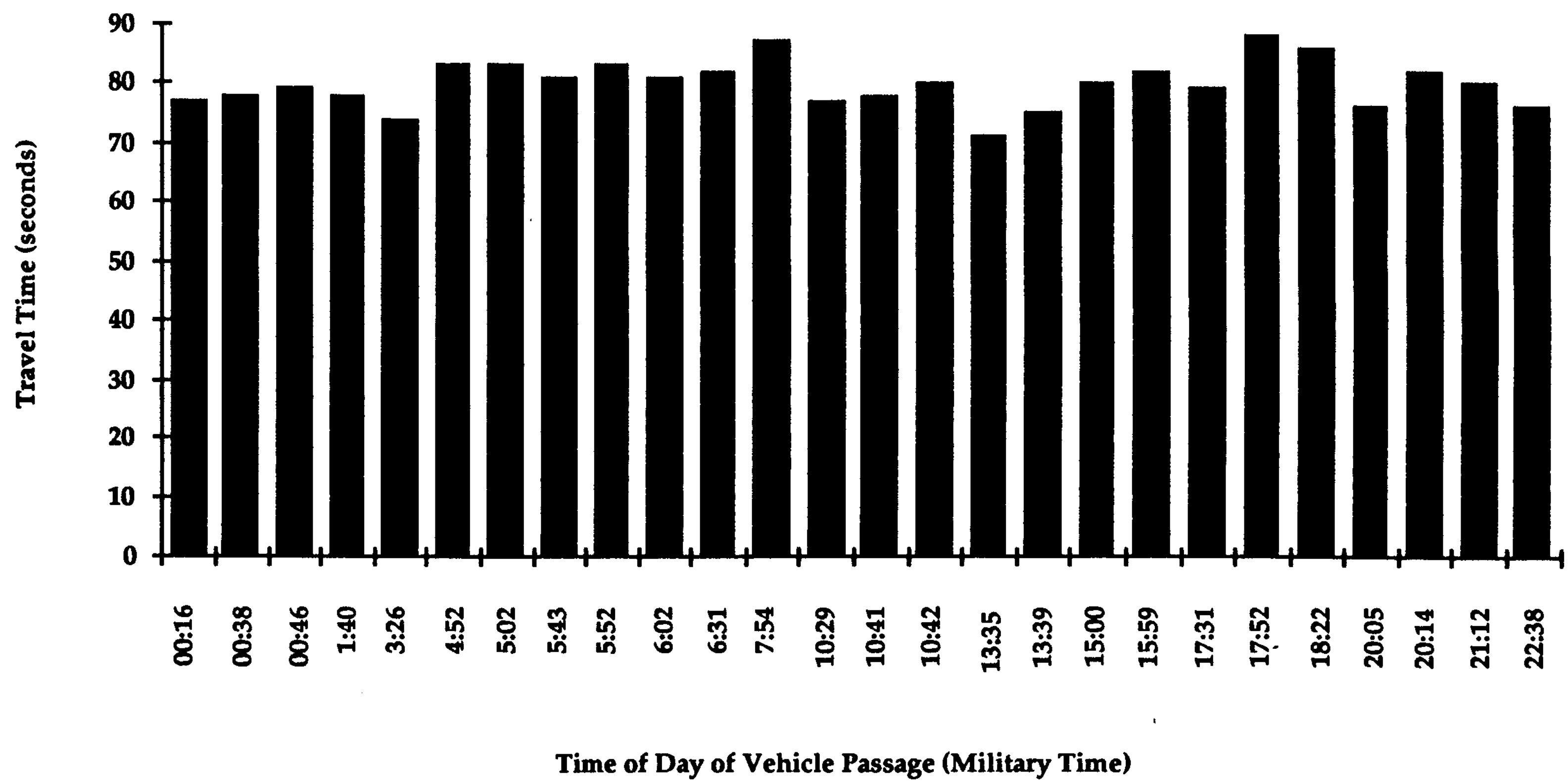

Figure 7. Typical Travel Times

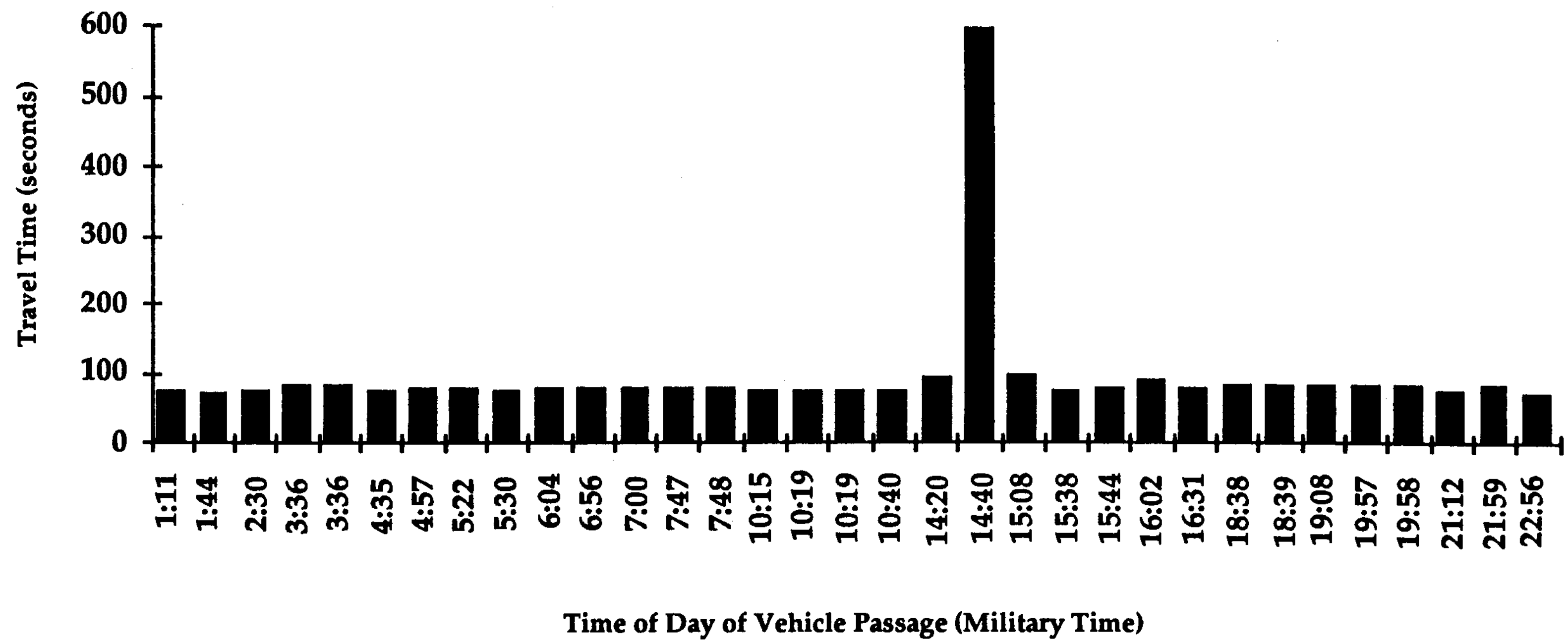

Figure 8. Impact of Incident Caused Congestion on Travel Times

morning hours would still be small because trucks are not equally distributed throughout the day. Even during peak hours, there are relatively few trucks in the traffic stream, as most drivers of trucks traveling through a metropolitan area attempt to avoid the delays caused by peak traffic conditions. In Tacoma, only 3 percent of the vehicles present during the peak hour are trucks. This provides a headway of 20 seconds between trucks, or about 175 trucks per hour. If all trucks were tagged, a reasonable system response time would result (see Table 3 (page 37)).

However, even at the low level of data available in this test, the data that can be collected from an AVI system can be very useful. While the data are scarce, if they are collected daily, they can be used to determine the frequency of the occurrence of congestion, as well as the approximate length and severity of those occurrences. While the accuracy and timeliness of this information is not acceptable for use in real-time freeway control systems, they are sufficient for conducting facility performance monitoring, air quality planning, and air quality monitoring, as well as for monitoring the impacts of various freeway management actions adopted by the Department of Transportation.

OTHER AVI DATA USES

One other use for the data collected with AVI systems is to calibrate information for four-step planning models used in urban areas. The AVI data available from freeway sections could provide a basic idea of the origin/destination patterns of the freeway users. This information could also be very useful in determining the spatial demand for travel throughout the day. Over time, it could also be used to determine the impacts of new development on changes in origin/destination travel patterns. Data of this type are currently available only through extensive survey techniques, and even then, these surveys often do a poor job of determining travel patterns.

This origin/destination data would relate directly to the vehicles that were tagged. If trucks were tagged, freight movements on the highway system would be better understood.

If passenger cars were tagged, information on both commute and non-work travel patterns would be available.

INTERPRETATION AND APPLICATION

The findings presented above show that AVI based systems can produce traffic performance data for use in both real-time control systems and more general transportation planning and engineering analyses. Furthermore, the mathematical algorithms needed to operate the AVI system are straightforward and easily programmed.

Continuing improvements in transponder, computing, and communications technologies provide the opportunity to reliably collect the information necessary to operate the planned intelligent vehicle-highway systems of the future. Given the current state of the technology and expected improvements, the impediments to using AVI technology in this manner are not technical, but fiscal and political.

FISCAL CONSTRAINTS

While the cost of AVI technology has not been explored in this report, a quick review of vendor quotes for AVI and loop equipment show that the infrastructure costs for a fully implemented AVI based detection system are roughly equivalent to those for a conventional loop system covering a similar geographic area. The costs included in this comparison include equipment costs, installation costs, communications costs, and software costs, but do not include the cost of vehicle tags.

The cost of retrofitting an existing facility with either type of detection system is heavily influenced by the need for traffic control while the equipment is installed. Furthermore, because little new freeway construction will occur in the U.S., the addition of AVI (or new loop) systems must be completed as a retrofit of existing, heavily used facilities. This situation adds considerably to the cost of system implementation because of the need for traffic control and for installers to work at night in most urban areas.

The relatively high cost of loop based detection systems and the reluctance of many highway agencies to perform "non-critical" work in heavily traveled urban areas because of safety or congestion concerns have tended to limit the implementation of these systems to the areas with the most significant traffic congestion problems and areas where traffic information is needed for new control systems. In many cases, equipment installation is limited to facilities where major freeway construction or reconstruction is already planned or underway because the detection system installation can take place at the same time as the other maintenance work.

AVI systems like that selected for the HELP project suffer from both of these deterrents to implementation. While several existing AVI systems include tag readers mounted above the roadway, the restrictions on installing this type of infrastructure are still significant because of the need to bring adequate power and communications support to the AVI reader locations, as well as the safety concerns associated with working above a heavily traveled roadway.

While increasing the spacing between AVI readers (on facilities that have high volumes of tagged vehicles) may reduce total installation cost, the cost of installing a full AVI system will still be high. This cost is unlikely to be favorably viewed within many highway agencies unless more uses for the AVI system data exist than simply providing traffic performance information.

Finally, the system implementation costs for an AVI system must include the cost of the individual vehicle tags. If purchased in bulk quantities, these tags can be as inexpensive as $10 to $20 each. However, in smaller numbers, or with more complex tags, the cost per tag can run as high as $50 or $100 per tag. (9)

In some cases, the cost of the tags can be passed on to the vehicle owner. (For example, in toll facilities, the advantage of not having to wait in line to pay a toll may be worth a one-time $10 fee to obtain an AVI tag that lets the owner by-pass the toll booth queue.) In other cases, particularly where little direct benefit to the vehicle owner is apparent, the highway agency will have to provide the funds to purchase the tags.

Finally, a cost is associated with distribution of the tags. This cost exists unless the tags are provided as part of the standard equipment for new cars. In addition, if the tag information is needed for some purpose other than simple traffic performance monitoring, a procedure must be developed to accept returned tags and to repair tags that fail.

POLITICAL CONSTRAINTS

Of all the constraints on implementing AVI systems that could be used for traffic performance monitoring, the fiscal constraint described above is the most obvious, but political constraints may be the most difficult to overcome.

The initial step in implementing AVI will be to determine which vehicles will be tagged. This decision may create the problems associated with

- vehicle bias (are trucks a good indicator of traffic stream performance?),
- privacy (does the highway agency have a right to know where my vehicle is as I drive down the road?),
- data access (who has access to the fact that this vehicle was at this location at a particular time?),
- legality of enforcement (can speeding tickets be written using the AVI data?) and
- mandatory/voluntary tag use (do vehicle operators choose to have tags on their vehicles, or are tags required for some reason?).

Of these issues, the privacy and enforcement issues are the most likely to prevent the implementation of an AVI system. The HELP project serves as a good case study on how these issues can cause significant friction in the development and implementation of an AVI system.

The HELP project selected a specific group of vehicles (trucks) to instrument. As a result of that decision (which was not made with a traffic performance system in mind) researchers had to examine the bias inherent in truck performance in comparison with automobile performance. In the case of the Tacoma tests, the bias produced by exclusively using trucks in the AVI system was fairly small, except when traveling up steep grades.

Privacy was a major concern of the trucking industry participating in the HELP project. A great deal of time was spent in HELP meetings discussing who would have access to the HELP data, as the trucking firms participating were concerned that their competitive positions might be harmed if the other trucking firms had access to the types of data that would be collected by the AVI devices.

The trucking industry was similarly concerned that state police would use the AVI data to enforce speed limits using AVI measurements. Essentially, the AVI system allows a police office to prove that a vehicle must have averaged a speed greater than the speed limit to travel from one AVI reader to another in the time period measured. This concern was finally addressed by having the participating states explicitly agree to not use the HELP AVI data for speed enforcement.

The decision to use vehicle tags was voluntary on the part of the trucking firms participating in the study. This voluntary decision helped reduce some of the bigger concerns about privacy, in that trucking firms that believed the AVI tags would infringe on their privacy did not choose to tag their vehicles.

However, trucking firms were given incentives to have their vehicles tagged. They were allowed to proceed through some ports of entry more quickly than non-tagged vehicles, and thus gained a competitive advantage over non-tagged vehicles. Participating firms also received information from the HELP database that helped them manage their vehicle fleets more effectively.

Despite these incentives, many trucking firms and trucking industry representatives voiced considerable resistance to the study. These concerns and fears would have been expressed more strongly if the program had not been voluntary.

The primary resistance to using AVI tags comes from a possible loss of privacy. An AVI based urban traffic monitoring system would allow specific vehicles to be tracked as they progressed through the street network. Essentially, the AVI system would know where specific vehicles were (and by inference specific people) within close tolerances.

This information could conceivably be used to write speeding tickets, prove the whereabouts of persons for court cases, or simply "track" individuals in which some person or agency had an interest.

Not surprisingly, public resistance to the government's ability to obtain and use this information is very strong. While no plans to use AVI data in this manner exist, the threat of "big brother" can create significant public reaction, and this reaction must be addressed as part of any implementation plan. Furthermore, the resistance that can be expected to an AVI based system will increase if carrying an AVI tag on a vehicle is mandatory, primarily as a result of the reaction to the privacy issue.

However, as was shown in the previous chapter, without widespread use of AVI tags only a limited number of tagged vehicles will pass through AVI sections during any given period, and system response times will be poor. As a result, it is important for any AVI system implementation strategy to directly address the privacy issue, both by providing safeguards on the collection and use of the AVI tag information and by creating incentives that encourage motorists to place AVI tags on their vehicles.

OBTAINING HIGH RATES OF AVI TAG USE

For any AVI based monitoring system to be successful, a large number of AVI tags must be operating on the monitored facilities. A variety of incentives can be used to encourage motorists to place tags on their vehicles. In addition, penalties can be developed to help force motorists to place tags on their vehicles. As indicated above, voluntary compliance reduces public resistance to the AVI system, so incentives are preferable to penalties. Potential incentives for encouraging AVI tag use include, but are not limited to:

- priority passage through toll facilities,
- priority passage through weigh stations and other truck inspection facilities (for trucks only),
- ability to receive traffic information,

- theft deterrence, and
- some form of payment.

The first of these techniques is already being used around the country. Several toll authorities are actively promoting AVI tag use to reduce vehicle queues and improve revenue controls. Motorists are given two major incentives for using the AVI tags, a reduction in the time they spend at toll booths and the elimination of the need to keep large quantities of change in their vehicle.

The HELP project is only one example of several trucking industry tests involving AVI tags and the various advantages these technologies can provide for both the trucking industry and regulatory agencies. In each case, the incentive to trucking firms and owner/operators to equip their vehicles with AVI tags is the ability to reduce the non-productive time required to check vehicle permits and certificates as trucks cross state borders or pass through weight enforcement stations.

AVI devices that act as theft deterrents are currently on the market in several large cities. Current theft deterrent systems use satellite based AVI systems to determine the location of a tagged vehicle whenever the owner wants to know that tagged vehicle's location. In this manner, when a vehicle is reported stolen, its location can be immediately identified, the police can be directed to that location, and the vehicle can be recovered. While the beacon based AVI system described in this report is not as flexible as these satellite based systems (a vehicle is only located when it passes a beacon, not whenever the owner wants to know its location), the AVI system could be easily programmed to identify vehicles carrying tags that had been reported stolen. If the AVI readers were located throughout an urban area (on all major roads) the effectiveness of the satellite AVI system could be approached.

Paying vehicle owners to equip their vehicles would probably also result in a reasonable number of tagged vehicles. Unfortunately, this would also create an additional cost for implementing the system. Simply giving the AVI tags to the motorists could be considered one form of "payment," in that the motorist would not be required to pay to have the device. However, simply giving the devices away might be insufficient incentive to entice vehicle owners to use the devices.

Mandatory AVI Tags

Making vehicle tags mandatory is one way of ensuring that enough tags are in use, but such a requirement would likely create significant public resistance to the project. Several agencies are considering requiring AVI devices for specific vehicles as part of performing a particular function, but the vehicles to be instrumented are limited in number and "unusual" in some manner. Further, in all of the mandatory use scenarios, the vehicles to be tagged are either identified with some type of safety concern or the AVI system is being used as a revenue collection device. (That is, if the vehicle wants to operate in a specific business, for example as an airport limousine service, then a vehicle tag must be carried to ensure that the vehicle operator pays the appropriate access fees to the facility (airport) operator.)

These mandatory systems are not being developed with the intent to provide traffic performance information. Instead they are being designed to meet a specific information need of the sponsoring agency. However, as has been demonstrated with the HELP AVI data, these tags could be used as part of a traffic performance monitoring system if additional infrastructure (e.g., more AVI readers) were installed.

Some western states are investigating a requirement that all trucks that need special permits or transport hazardous materials carry an AVI tag. AVI readers would then be placed at strategic locations to track the movement of these loads through the state.

While the mandatory nature of the tag in these applications might elicit resistance from the trucking industry, the states pressing for these uses are taking the position that the nature of the material being carried, or the concerns about vehicle safety for oversize/overweight vehicles, override the trucker's right to privacy. So far, the only mandatory systems in operation at this time are airport based, revenue collection systems.

Another approach to requiring AVI vehicle tags would be to use those tags in place of the current license plates used in all 50 states. It could be argued that tags would be no more intrusive than the license plates, however, the public is unlikely to accept such a change easily. It is also unlikely that police forces would readily accept the change, as such a change would eliminate their ability to easily identify vehicles with out-of-date registrations, a task currently done by visual observation of the month and date tags on the license plates.

Using Other AVI Tags

Another option for obtaining the necessary number of tags required for traffic monitoring is to use AVI tags that are being brought into the transportation industry for other reasons. For example, AVI tags are being attached to intermodal containers as a method of tracking the movement of goods around the world. Containers are "logged in" and "logged out" of ports, trans-shipment points, and terminals as a means of reducing theft, providing up-to-the-minute cargo location information, and providing shippers with an audit trail of goods movement.

One advantage of these systems is that the tags placed on containers are similar to those used for cars in some toll facilities and can be read by roadside AVI devices.

A second advantage to this approach is that a large measure of the privacy debate would be diffused because no tag information that identified a specific vehicle would be available to the highway agency. That is, unless the owner of the container told the highway agency that a specific tag belonged to a specific container, the highway agency would have no means of determining which vehicle was carrying the tagged container. This lack of information would not hinder the highway agency's use of the tag information, because tag ownership is not important to performance monitoring, only the location of the tag at specific points in time and space.

A third advantage to using tags distributed for other purposes is that the highway agency collecting performance information would not be responsible for the purchase, distribution, or maintenance of the tags themselves. While the tag readers and communications hardware and software would still be the responsibility of the highway agency, the reduction in the cost of the total system would be significant.

The primary disadvantage of the option of using tags distributed for non-monitoring purposes is that there might not be enough tagged vehicles using the highway system to provide the accuracy desired by the highway agency. Further, since the tags would not be within the control of the highway agency, no method for increasing the number of tagged vehicles would be within its control.

An Alternative Solution

One alternative solution is for vehicle manufacturers to include a simple AVI tag as part of all new vehicles. Each AVI tag would uniquely identify that vehicle, just as the vehicle identification number stamped on the engine block and attached to the vehicle frame does now.

With the exception of including the AVI tag number in the vehicle's title information, the tag numbers would not be reported by the owners to state or federal regulatory agencies, including the police. (A law might have to be passed to ensure the confidentiality of this information.) If the motorist desired to use the AVI tag for other purposes (e.g., to use the tag in a toll system operation), the vehicle owner could voluntarily provide the tag information to that agency in return for the desired services. These services could also include providing the tag number to police if the vehicle was stolen.

There are several advantages to this system proposal.

- If all new vehicles sold in the U.S. had tags, roughly 10 percent of the vehicle fleet would be tagged within a year, providing the necessary number of vehicles for accurate, timely system monitoring, and this percentage would expand rapidly over time.

- The cost per tag would be very small, given the large quantity of tags installed each year.
- The price of the tags could be incorporated into the new car price. (Regulatory incentives might be given to the automobile manufacturers to reduce any negative impacts on car prices, although the price should be small, as noted above.)
- A relatively high level of privacy could be ensured because vehicle owners would have a relatively high level of control over their tag information.
- If owners decided to use the tags as part of a toll collection or theft deterrent system, their vehicles would already be equipped for that task, so that retrofitting the vehicles would not be necessary.

The disadvantages to this proposal are that it would require a great deal of cooperation from vehicle manufacturers, and it would essentially create a "mandatory" system that might not be well received by the public, despite the controls suggested.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Both the theoretical and field tests have shown that the use of AVI based vehicle detection could significantly improve the data available for both real-time traffic control decision making and transportation planning and analysis. However, several major barriers would have to be overcome before such a system could be implemented.

Advantages of the System

The AVI based system provides several basic advantages over loop detector based systems. These advantages include the following:

- provision of section speed data, rather than point speed data,
- faster congestion detection than possible with conventional loop systems if the AVI tags were widely used,
- provision of ramp origin and destination information,
- greater flexibility in control algorithm design,
- direct computation of travel time and delay information needed for a variety of operational and planning functions, and
- improved system performance and accuracy.

Disadvantages of the System

As with all new technologies and with all traffic performance monitoring systems, the proposed AVI system has several major drawbacks. These drawbacks include the following:

- the system requires a significant infrastructure that must be retrofitted to the existing roadway system;
- the system will be expensive to develop, install, and maintain;

- lack of standardization in the AVI field may result in some vehicles having to carry more than one vehicle tag to operate on all of the facilities that want to use AVI technologies; and
- public resistance to instrumenting vehicles may be strong, particularly if vehicle owners must pay for the vehicle tags and/or do not receive "benefits" equal to or greater than the cost of those tags.

RECOMMENDATIONS

This investigation has shown that AVI technology holds considerable promise for significantly improving traffic performance information. However, it is not clear that the provision of performance information alone would justify the cost of the infrastructure needed to operate an AVI based system. Instead, an AVI based system should be added only in areas where a significant number of tagged vehicles already exist, or where other uses of the AVI tag information can spread the cost of the system among several budgets.

An ideal location for an AVI based performance monitoring system would be an urban toll facility that was adopting AVI tags as part of its revenue collection system. In this instance, the tag readers located at the toll collection points would already exist, as would the vehicle tags. Thus, the marginal cost of the obtaining the performance monitoring data would be simply the cost of the software necessary for performing the required calculations.

In return, the toll facility would obtain accurate facility performance information between the toll collection points. This information could be used to meet the needs for

- facility operation
- motorist information
- planning analysis, and
- overall facility performance monitoring,

and all of this information could be obtained at a relatively modest price.

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