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16. Abstract

This report documents a study conducted to assess and test promising technologies for HOV lane enforcement. After a qualitative assessment of video, automatic vehicle identification, and infrared machine vision technologies, the study was suspended because no preferred infrared technology was available for testing. The study was resumed when a vendor demonstrated promising video technology. The high-occupancy vehicle enforcement and review (HOVER) system was then developed for an operational test on the East R.L. Thornton (I-30) contraflow HOV lane in Dallas, Texas.

The results of the operational test indicated that the HOVER system, in its current state, could support a program that mails HOV information to suspected violators (similar to the HERO program). The study's limited budget prevented several improvements that could improve the capabilities of the HOVER system. With several enhancements to the system (e.g., improved license plate recognition and "whitelist" license plate database, etc.), the HOVER system could be used to perform enforcement screening. Significant enhancements to the system (e.g., high-quality video cameras and additional camera views, improved video signal transmission, improved license plate capture and recognition, etc.) could enable its use for HOV ticket-by-mail programs, although enabling legislation does not currently exist in Texas. The author recommends implementation of these enhancements and further testing to determine future system potential.

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VIDEO ENFORCEMENT FOR HOV LANES: FIELD TEST RESULTS FOR THE I-30 HOV LANE IN DALLAS

by

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Research Project Number 7-2901
Research Project Title: Use of Advanced Technology in HOV Lane Enforcement

Sponsored by the
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IMPLEMENTATION STATEMENT

This research study evaluated a semi-automated video enforcement system that could be used to assist police officers in HOV lane enforcement or enforcement screening. The results of the study will be used by the Dallas Area Rapid Transit (DART) and TxDOT for improving and potentially automating HOV lane enforcement procedures in the Dallas area and other urban areas in Texas.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation, the U.S. Department of Transportation, the Federal Highway Administration, the Federal Transit Administration, or the Dallas Area Rapid Transit. This report does not constitute a standard, specification, or regulation. It is not intended for construction, bidding, or permit purposes. This report was prepared by Shawn Turner (Texas certification number 82781).

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- Jerry Jones (previously Greg Jones), urban transportation engineer, Federal Highway Administration, Ft. Worth;
- Gail Lyssy (previously Kyle Mills), regional engineer, Federal Transit Administration, Arlington;
- Mark Olson, regional engineer, Federal Highway Administration, Austin;
- Koorosh Olyai, director of area mobility programs, Dallas Area Rapid Transit, Dallas; and
- John Blain, director of transportation planning and development, TxDOT, Dallas.

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- Sal D'Agostino, Computer Recognition Systems, system development and integration;
- Martin Merrick, Computer Recognition Systems, system development and integration;
- Prasad Golkonda, Dallas Area Rapid Transit, test coordination and system testing; and
- Tim Lomax, TTI, conceptual system design and general project support.

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LIST OF ACRONYMS

AVI	automatic vehicle identification
Caltrans	California Department of Transportation
CRS	Computer Recognition Systems, Inc.
DART	Dallas Area Rapid Transit
DOT	Department of Transportation
ERLT	East R.L. Thornton
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
FLIR	forward-looking infrared radar
HOT	high-occupancy vehicle and toll
HOV	high-occupancy vehicle
HOVER	High Occupancy Vehicle Enforcement and Review
SOV	single-occupant vehicle
STML	Symond Travers Morgan, Limited
Transfo	Transfomation System, Inc.
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation

SUMMARY

Introduction

The goal of this study was to improve the safety and cost-effectiveness of HOV lane enforcement through the use of advanced technologies. The study objectives were to investigate the use of advanced technology in HOV lane enforcement and perform an operational test of the most promising technology. Several agencies were involved in sponsoring or supporting the operational test and evaluation, including the Texas Department of Transportation (TxDOT), Dallas Area Rapid Transit (DART), Federal Highway Administration (FHWA), and Federal Transit Administration (FTA).

The study goal and objectives were quite challenging because of the inherent difficulty and technical challenges of using non-intrusive technology to count persons inside a vehicle for enforcement purposes. Very little developmental research had been conducted despite strong interest and the acknowledged challenges of traditional HOV lane enforcement methods by several transportation agencies. The study was initially suspended until TTI received a promising proposal from a video technology vendor. After an initial technology demonstration test, an operational test was initiated on a developmental, semi-automated video enforcement system. This report provides findings, conclusions, and recommendations based upon the operational test of this video enforcement system.

System Design

Based upon initial research and a promising technology demonstration test, the TTI research team, in cooperation with Transfomation Systems, Inc., developed performance specifications for a semi-automatic video enforcement system. These specifications required the video enforcement system to perform four basic tasks:

1. Collect and transmit video snapshot images of license plates and passenger compartments for all vehicles in the HOV lane to a remote computer workstation;
2. Perform automatic license plate character recognition on the license plate images;
3. Synchronize the captured images of vehicle occupants with license plate characters; and
4. Search a license plate database containing vehicle occupancy histories and, based upon failure to meet set criteria, display the vehicle license plate characters and vehicle compartment images on a computer monitor for review and enforcement purposes.

TTI contracted with Transfomation Systems, Inc. in October 1996 for the installation and a 12-month lease of a video enforcement system meeting these specifications. Transfo collaborated with Computer Recognition Systems, Inc. and others in developing, installing, and integrating the semi-automated high-occupancy vehicle enforcement and review (HOVER) system.

Findings

The study findings as they relate to the HOVER system and its basic functions are as follows:

- **HOVER system** - The existing HOVER system meets the original performance specifications in terms of its features and functions. Several changes and/or enhancements to the system could significantly improve its usability and its potential for use in HOV lane enforcement. Many of these changes and/or enhancements were not possible to include in this operational test because of the limited budget available for system development and refinement.

- **Vehicle compartment image capture** - The HOVER system performed adequately in capturing vehicle passenger compartment images, correctly capturing 97 percent of the front and side view images of vehicles in the HOV lane.

- **Vehicle compartment image quality** - The quality of vehicle compartment images from the HOVER system enabled human observers to positively determine required vehicle occupancy (i.e., 2 or more persons, DART buses, or motorcycles) for 89 percent of all vehicles reviewed. Another 0.5 percent were positively identified as single-occupant vehicles (i.e., violators or authorized police vehicles). Vehicle occupancy could not be determined in the remaining 10.5 percent of vehicles for several reasons, including glare, low light, vehicle obstructions, or incorrectly captured images. There were numerous other factors affecting visibility of vehicle passengers that are beyond the control of enforcement personnel, such as tinted side windows, obtrusive window molding or panels, or mobile children in the back seat.

- **License plate capture** - The HOVER system correctly captured 80 percent of the vehicle license plate images. The remaining 20 percent of the vehicles had plates incorrectly captured, either with partial or no license plate characters captured in the images. This 20 percent includes partial license plate captures, missed plate captures, and no license plates in the camera field-of-view. The 80 percent license plate capture rate is considered less than ideal for most enforcement applications.

- **License plate recognition** - The license plate recognition function of the HOVER system operated poorly, correctly recognizing only 20 percent of all vehicle license plates. Vendor-reported claims of license plate recognition range from 60 to 80 percent for the lighting conditions in which the system was tested (although different video camera systems are used).

- **"Whitelist screening database** - The "whitelist" screening database performed as designed in screening out frequent HOV lane users whose license plates were contained in the database. However, the "whitelist" database was not effective in significantly reducing the operator workload because very few vehicles were

screened from the review process. Reasons for the low number of screened vehicles could include a relatively small database (approximately 1,800 license plates) and a low license plate recognition rate.

Conclusions and Recommendation

Conclusions are provided below for three different HOV lane enforcement applications:

- **HOV information mailed to suspected violators** - In this application, HOV lane usage and educational information is mailed to suspected violators. Repeat violators could be sent warnings. With minor or no enhancements, the HOVER system could be used to identify suspected violators and mail HOV educational information. Desirable enhancements for this application include better quality video cameras, reduced video signal transmission loss, and one to two additional camera views.

- **Enforcement screening** - For this application, the HOVER system is used in real-time by a technician to identify suspected violators, who works in concert with a downstream police officer that verifies the vehicle occupancy of suspected violators. With several enhancements, the HOVER system could be used to perform enforcement screening. Required enhancements for this application include better quality video cameras, reduced video signal loss, one to two additional camera views, significantly better licence plate recognition, and a larger "whitelist" database.

- **Ticket-by-mail enforcement** - This application currently is not legal in the state of Texas, but consists of mailing a citation to the registered owner of the vehicle that was observed violating the HOV occupancy restriction. With many enhancements, the HOVER system potentially could be used for ticket-by-mail HOV lane enforcement if enabling legislation was passed. The required enhancements for this application include significantly better quality video cameras, reduced video signal transmission loss, one to two additional camera views, significantly better licence plate recognition, and a larger "whitelist" database.

The recommendation of this study is as follows:

- **Implement and test system enhancements** - The HOVER system in its current state could only be effectively used to mail HOV educational information to suspected violators. However, with some enhancements, the HOVER system could potentially be used for HOV enforcement screening. The enhancements that are needed to effectively perform enforcement screening include better quality video cameras, reduced video signal transmission loss, one to two additional camera views, significantly better licence plate recognition, and a larger "whitelist" database. Once these enhancements have been implemented, further testing is desirable to determine system accuracy and reliability.

1 INTRODUCTION

Adequate enforcement of vehicle occupancy restrictions plays a key role in the success of high-occupancy vehicle (HOV) facilities. A high number of unauthorized HOV lane users (e.g., single-occupant vehicles, or SOVs) can create congested traffic conditions on an HOV lane, thereby decreasing travel time savings and reliability incentives for commuters to carpool or use public transit. HOV lane violators also frustrate other motorists and weaken public and political support for HOV projects. This motorist frustration is often aimed at public agencies that operate or enforce the HOV lane. Lack of public support due to ineffective enforcement has closed several HOV projects in the U.S. (1).

The Texas Department of Transportation (TxDOT) and the Dallas Area Rapid Transit (DART) have plans to construct and operate an extensive regional network of HOV (or potentially high-occupancy and toll, or HOT) lanes. There are currently three HOV facilities totaling 31.0 km (19.3 mi) that operate in the Dallas area with an additional three HOV corridors planned to open by 2002, bringing the total to 63.1 km (39.2 mi) along six freeway corridors. The long-range transportation plan for the Dallas area, Mobility 2020, includes a total of 362 centerline-km (225 centerline-mi) of HOV facilities. Adequate and cost-effective HOV lane enforcement techniques are necessary to ensure the success of existing and planned HOV lanes in the Dallas area.

Current methods of HOV lane enforcement used in the Dallas area rely on DART transit police to position themselves near the HOV lane to observe vehicle occupancy compliance (Figures 1 and 2). To adequately view vehicle compartments to ensure occupancy compliance, most police officers must stand near the high-speed traffic lanes. The police officers patrolling the HOV lanes typically work in pairs, with a second officer downstream of the first officer to apprehend violators not stopping at the upstream officer. Alternatively, a single officer may pursue a violator along the HOV lane. These current enforcement methods have kept violation rates below 10 percent on the three existing HOV lanes, but safer, more cost-effective methods are being sought to improve the current state-of-the-practice in HOV lane enforcement.

In a January 1998 report, the Texas Transportation Institute (TTI) provided HOV enforcement program recommendations to DART (2). These recommendations focused on the type and level of enforcement, the amount of citations, the initiation of a HERO telephone hotline program, and other innovative enforcement techniques. The report did not recommend high-tech enforcement applications, such as ticket-by-mail via video enforcement, until such time as they are refined, proven to be reliable, and can be legally used in Texas. The findings described in this report discuss the reliability and accuracy of an HOV lane video enforcement system developed for this jointly sponsored study.

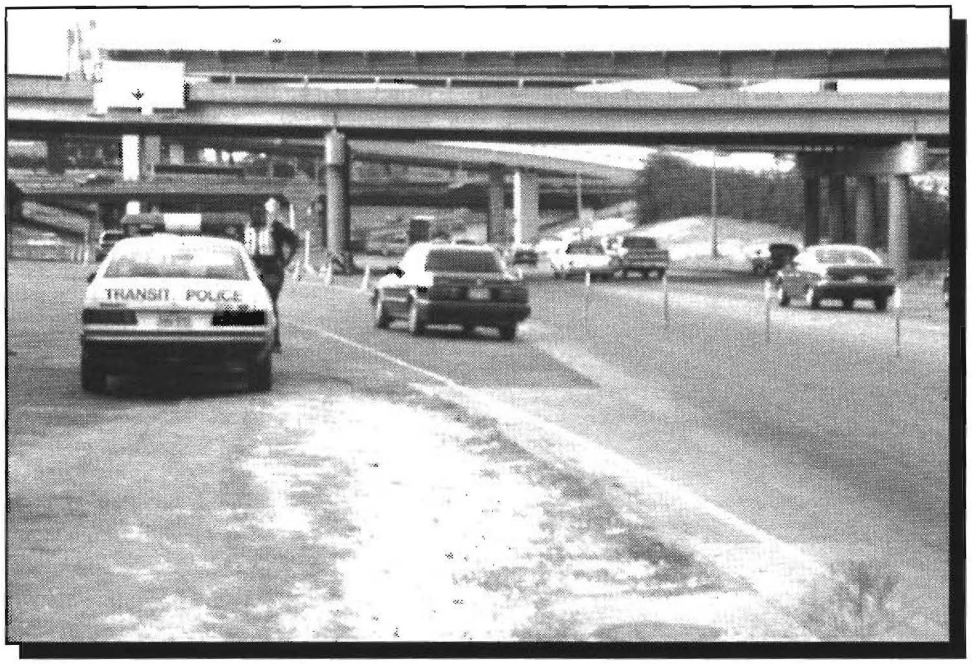

Figure 1. Manual Enforcement of East R.L. Thornton (I-30) HOV Lane (looking into lane entrance)

Figure 2. Manual Enforcement of East R.L. Thornton (I-30) HOV Lane (looking away from lane entrance)

1.1 Study Goal and Objectives

The goal of this study was to improve the safety and cost-effectiveness of HOV lane enforcement through the use of advanced technologies. The study objectives were to investigate the use of advanced technology in HOV lane enforcement and perform an operational test of the most promising technology. Several agencies were involved in sponsoring or supporting the operational test and evaluation, including TxDOT, DART, the Federal Highway Administration (FHWA), and the Federal Transit Administration (FTA).

The study goal and objectives were quite challenging because of the inherent difficulty and technical challenges of using non-intrusive technology to count persons inside a vehicle for enforcement purposes. Very little developmental research has been conducted despite strong interest and the acknowledged challenges of traditional HOV lane enforcement methods by several transportation agencies. A previous attempt in 1990 by the California Department of Transportation (Caltrans) at using video to enforce HOV lanes produced mediocre results, concluding that current video technology could not support automated HOV lane enforcement. Discussions with several national laboratories, defense contractors, and other potential leads produced no feasible solutions to the difficult task of vehicle occupancy determination for HOV lane enforcement. The study was initially suspended until TTI received a promising proposal from a video technology vendor. After an initial technology demonstration test, an operational test was initiated on a developmental, semi-automated video enforcement system. This report provides findings, conclusions, and recommendations based upon the operational test of this video enforcement system.

This report documents the efforts conducted in identifying and assessing potentially applicable automated enforcement technologies and presents the results of an operational test conducted on the East R.L. Thornton (I-30), or ERLT, HOV lane in Dallas to evaluate an HOV lane video enforcement system. The report also provides conclusions and recommendations regarding the implementation of the video enforcement system that was tested.

1.2 Organization of the Report

This report is organized into the following five chapters:

- **1 Introduction** - describes the challenges associated with HOV lane enforcement and presents the study goal and objectives;
- **2 Background** - provides background information on numerous topics, including the project history, a technology assessment performed in an initial study task, and the results of a technology demonstration test;
- **3 Study Design** - describes the conceptual design of the video enforcement system tested in this study, and includes the test criteria and methods used to evaluate the enforcement system;

- **4 Findings** - presents the findings of the study related to the effectiveness of the tested video enforcement system; and

- **5 Conclusions and Recommendations** - provides the study conclusions and recommendations regarding the application of video technology for HOV lane enforcement.

2 BACKGROUND

This chapter contains background information relevant to the study, including a project history, a technology assessment performed in an initial task, and the results of a technology demonstration test. The project history is provided here since the research efforts for this study have spanned six different calendar years. The technology assessment described in this chapter was performed at the beginning of the study to identify the most promising technology for operational testing. Also contained in this chapter, the technology demonstration test was performed to assess the potential capabilities of a video enforcement system before further operational testing proceeded.

2.1 Project History

TxDOT Research Study 7-2901, "Use of Advanced Technology in HOV Lane Enforcement," was originally conceived as a two-year study with seven work tasks (Table 1). The completion of the study, however, was delayed an additional three and one-half years for numerous reasons:

- **No promising technology available to test** - The technology assessment performed in Task One found that no promising automated enforcement technologies were available for testing, and, as a result, the project was suspended for seven months (December 1993 to July 1994).

- **Performance of a demonstration test** - The inclusion of a technology demonstration test (not in the original proposal) was necessary to assess video technology before a full operational test was conducted. The contracting for and performance of the demonstration test required an additional 12 months (July 1994 to July 1995).

- **Difficulty in equipment and services procurement** - Delays in getting the vendor listed in the Texas State Catalog and processing the purchase requisition required 18 months (July 1995 to October 1996), 14 more months than the original proposal.

- **System installation and integration** - The vendor experienced several delays in installing and integrating the HOV video enforcement system. Off-line testing of the system was able to begin in October 1997, 12 months after initial installation began.

Table 2 shows a summary of key decision points and other relevant actions relating to this study.

Table 1. Original Schedule of Activities for Study 7-2901

Work Task	Estimated Start Date	Estimated Completion Date
1 - Investigate Possible Automated Enforcement Measures and Implementation Issues	July 1993	October 1993
2 - Review by Sponsoring Agencies	November 1993	November 1993
3 - Procurement of Selected Technology	December 1993	March 1994
4 - Installation of Selected Technology	April 1994	May 1994
5 - Public Communication Plan	April 1994	May 1994
6 - Operational Testing and Evaluation "Before" Data "After" Data	 July 1993 June 1994	 May 1994 May 1995
7 - Final Project Report	February 1995	June 1995

Source: TxDOT Supplemental Agreement No. 25, Study 7-2901, FY 1993.

Table 2. Summary of Project History

Date	Action
August 9, 1993	Research study activated.
November 1993	TTI submits draft interim report recommending suspension of the study until suitable machine vision technology becomes available.
December 16, 1993	Project steering committee decides to suspend study pending development of suitable enforcement technology.
February 28, 1994	TTI submits final interim report.
May 31, 1994	TxDOT project director requests that study be suspended pending further technology development.
June 8, 1994	Huntington Engineering & Environmental submits proposal for a video technology demonstration test.
July 11, 1994	Project steering committee decides to conduct a technology demonstration test to assess the video enforcement technology.
August 8 and October 24, 1994	TxDOT project director requests contract modification that incorporates demonstration test.
April 10, 1995	TTI signs letter agreement with Huntington Engineering & Environmental to conduct demonstration test.
July 17, 1995	Transfomation Systems (formerly Huntington) delivers demonstration test results that recommend a semi-automatic video enforcement process.
July 24, 1995	Project steering committee decides to proceed with full operational test of the video enforcement system to be developed by Transfomation Systems.
May 8, 1996	Transfomation Systems gets listed in GSC's Texas State Catalog so that equipment and services can be requisitioned by TTI.
July 26, 1996	TTI issues purchase requisition for HOV enforcement and review (HOVER) workstation developed by Transfomation Systems.
November 1, 1996	TTI contracts with Transfomation Systems for the installation and a 12-month lease of their HOVER workstation and equipment.
October 23, 1997	Transfomation Systems demonstrates a partially operational enforcement system. TTI begins off-line testing of the HOVER system.

2.2 Technology Assessment

The first task of this study was to investigate technologies that potentially could be used to automate the enforcement of HOV lanes. The research team conducted a literature review and contacted technology vendors, national research laboratories, and defense technology contractors. TTI researchers identified three technologies potentially applicable to HOV lane enforcement:

- video cameras;
- automatic vehicle identification (AVI); and
- machine or infrared vision.

The researchers recommended machine vision as the preferred technology; however, no machine vision systems were available for testing at the time. Because the preferred technology was not available, the study was suspended until such technology became available. Shortly after suspension of the study, the TTI research team received a technology demonstration proposal for a video enforcement system. The project steering committee members agreed in July 1994 to assess the potential of the video technology in a small demonstration test before committing to a larger, more rigorous operational test.

TTI documented this technology assessment in an Interim Report in February 1994 (3). The following paragraphs provide a summary of this technology assessment as documented in a conference proceedings paper (4).

2.2.1 Literature Review

In 1978, Miller and Deuser (5) suggested the use of several techniques to improve HOV lane enforcement, including photographic instrumentation, mailing of citations, the use of para-professional officers (trained technicians), remote apprehension, and mass screening of license plates to identify habitual offenders. Several of the techniques, such as mailed citations or warnings and remote apprehension, are now commonly employed on HOV projects; however, the other techniques have not been widely used.

On several HOV lanes, state law permits the mailing of citations to the registered owner of vehicles violating an HOV occupancy restriction. The mailed citations are based upon the police officer's visual contact with a violating vehicle. This technique was used on the Southeast Expressway in Boston, Massachusetts, because police officers could not safely escort HOV lane violators across several lanes of congested freeway traffic (5). The Virginia Department of State Police also has the ability to mail citations to the registered owners of vehicles observed violating HOV occupancy restrictions (6).

Another technique that has been employed at several locations is mailed warnings or HOV lane information. This technique is geared more towards education and can be used where state law does not permit mailed citations. Repeat violators on the priority lanes of the San Francisco-Oakland

Bay Bridge were sent warnings and information on the possible consequences of their violation (5). The response to the letters was considered good, with only 10 percent of the repeat violators observed again in the priority lanes. The HERO telephone hotline program in Seattle, Washington, permits motorists to report HOV lane violators (7). HOV educational material and warnings are sent to the registered owners of violating vehicles. Before-and-after studies along I-5 in Seattle indicated the HERO program had reduced violation rates by approximately 33 percent. A similar telephone hotline program has been developed in Northern Virginia, where information and warnings are sent to the registered owner of violating vehicles (6).

In 1990, Caltrans tested the use of video in HOV lane surveillance and enforcement (8). The study examined the use of video cameras and recorders in determining vehicle occupancy, documenting violator identity, and assisting in the enforcement of HOV lanes. There were four typical camera positions used throughout the study: a long-distance (0.4 km or 0.25 mi.) oncoming view, a close-up view of the license plate, an oblique view downward into the passenger seat, and a side eye-level view into the vehicle. The study reported the following about the use of video in HOV lane enforcement:

- Video cameras operating alone cannot identify the number of vehicle occupants with enough certainty to support mailed citations for HOV lane restrictions. The video tests had a false alarm rate of 21 percent (21 percent of vehicles identified by video tape reviewers as violators actually had the required number of occupants). Small children or sleeping adults in the rear seat were not captured by the video camera, and poor light conditions, glare, and tinted windows compounded the problem of viewing passengers in the vehicle compartment.

- The use of video as a real-time enforcement aid appears to be limited to those locations lacking enforcement areas for officer observation. At these locations, a video camera could be safely positioned to assist a downstream officer in determination of vehicle occupancy. The study noted, however, that an officer stationed beside an HOV lane in an enforcement area was in a much better position to observe violations than an officer at a remote video monitor.

- Video provides a freeway and HOV lane monitoring tool that is potentially more consistent and accurate than existing techniques for documenting vehicle occupancy.

2.2.2 Technology Review

Many electronics vendors and research laboratories were contacted about technologies that could be used to automatically determine vehicle occupancy. The results of these discussions are summarized below by the three applicable technologies: video, AVI, and machine vision.

Video. Video already has numerous applications in transportation, including freeway surveillance and monitoring, various enforcement activities, and data collection. Coupled with

options like a zoom lens, automatic exposure control, high shutter speeds (up to 1/10,000 second), and light overload capability, current video cameras can capture high-quality images of a traveling vehicle (speeds up to about 100 km/h or 60 mph) from a distance in low-light conditions.

The most common application of video technology is freeway surveillance and monitoring. The cameras used for incident detection and verification need only to distinguish vehicle breakdowns or accidents, which typically do not require the use of high-resolution color cameras. Video cameras are also used by several agencies for enforcement of traffic signals and rail-highway grade crossings, although these applications typically employ a 35 mm camera that is triggered by an inductance loop or radar when a violation occurs.

A video enforcement system would consist of several video cameras on the HOV lane controlled and monitored from a remote location. A single officer located at a downstream enforcement station could have several minutes to respond to a possible violation, or an officer could be teamed with a trained technician that would alert the officer of any possible violations. The downstream officer would be responsible for verifying the HOV lane violation and issuing a citation in states that do not yet allow mailed citations.

The operating costs associated with a video enforcement system would be lower than manual enforcement, and the safety of police officers would be improved. However, video cameras may not be able to observe small children or sleeping adults in the rear seat. Poor light conditions, glare, and tinted windows compound the problem of viewing passengers in the vehicle compartment. Some of these problems can be addressed with supplemental lighting, high-end camera specifications, and image enhancing tools. Video surveillance of an HOV lane would be no more intrusive than officer observation. However, video surveillance of vehicle interiors could potentially have poor public acceptance because of perceived privacy issues.

Automatic Vehicle Identification. AVI systems are becoming increasingly common on toll facilities where a "toll tag" is used to debit a motorist's existing account. There are several basic elements typical of AVI systems, including a vehicle-mounted transponder (tag), a roadside reader and control unit, a central computer that processes and stores transponder-reader interactions, and an enforcement system.

There are numerous applications of AVI systems across the United States, and most of the systems are utilized for electronic toll collection purposes. An AVI system was considered in the initial stages of the Houston transitway system development, but was later dropped from consideration when it became apparent that carpools would be regular users of the transitway system (9). Consequently, the AVI concept has never been used or tested on HOV facilities. For carpool identification purposes, however, several AVI vendors indicated that multiple transponders could be read from a single vehicle (e.g., transponder for each carpool member).

An AVI enforcement system would require that all vehicles using an HOV lane be authorized users with an identification transponder(s) in their vehicle. Two basic options exist for registering

carpools and issuing AVI tags: requiring that only one transponder be registered for each carpool, or requiring that each carpool member register a transponder.

Enforcement of an HOV lane would be accomplished by monitoring the transponder-reader interactions. If the required number of transponders are not read from a single vehicle, a visual description of the vehicle can be obtained via video or still-frame pictures. A downstream officer would then be responsible for verifying the violation. If authorized vehicles are found in violation of the vehicle occupancy requirements, the HOV lane privileges of those persons registered to the transponder(s) could be revoked for a stipulated time period or indefinitely. Warnings or information packets could be given to first-time offenders or carpools without transponders.

The registration and authorization process associated with an AVI system may discourage current and potential users of the HOV lane. The Houston transitway system originally operated as authorized vehicle lanes, but the discontinuance of the authorization requirement prompted a substantial increase in carpool utilization of the transitway system. For example, peak period carpool volumes on the Katy Transitway increased by approximately 1,400 vehicles after one month and almost 2,000 vehicles one year after discontinuance of the authorization requirement (10). The privacy of authorized vehicle occupants can be protected through the use of confidential transponder-reader interactions commonly utilized at toll facilities.

Machine Vision. The concept of machine vision for HOV lane enforcement encompasses those technologies that utilize electro-optical infrared sensors and/or image processors with pattern recognition to remotely identify and distinguish individual vehicle occupants. Machine vision would theoretically be capable of distinguishing a live person from a mannequin by heat or heat differentials measured with an infrared sensor. Using pattern recognition, machine vision could theoretically distinguish a sleeping adult in the rear seat from a warm rear axle.

Forward-looking infrared radar (FLIR) and thermal imaging are established machine vision technologies that have been proven in military surveillance and reconnaissance applications but are just beginning to make the transition to non-military applications. Several research agencies and laboratories were contacted about machine vision technologies, and most could only propose or suggest some combination of infrared, radar, and electro-optical machine vision for HOV lane enforcement. Many researchers indicated that the presence of window glass severely limited the usefulness of commercially available infrared image sensors for HOV passenger identification and verification, since infrared energy emitted by a warm body is dissipated by the window glass.

A Georgia Tech researcher suggested the use of a radiometer and reported on a test that evaluated a radiometer and a FLIR device. According to the researcher, the test successfully demonstrated the potential usefulness of radiometer techniques in HOV identification and verification, whereas the FLIR device could not accurately distinguish vehicle occupants. The radiometer device requires extensive development before a test application could be considered.

This alternative would be considered favorably if machine vision equipment were commercially available for field testing. A machine vision alternative would not require the registration of carpools or carpool members and could potentially be more accurate than video techniques.

2.3 Technology Demonstration Test

Based upon the technology assessment, the research team recommended that the study be suspended until suitable machine vision technology became available for testing. Shortly after this decision, however, TTI was approached by a vendor with extensive video experience. After reviewing a video demonstration test proposal and obtaining concurrence from the project steering committee, TTI researchers contracted with Huntington Engineering and Environmental (later Transfomation Systems, Inc.) to perform a demonstration of their video system capabilities. The small-scale demonstration test was performed to assess the merits of video technology and determine if further operational testing was warranted.

Transfomation Systems, Inc. (Transfo) of Houston, Texas was contracted in April 1995 to perform a video demonstration test with the following objectives for HOV lane enforcement:

1. Identify optimal camera mounting arrangements, lens, and lighting configurations;
2. Identify the effects of low light and tinted windows on video effectiveness; and
3. Identify the potential for using pattern recognition to automate vehicle occupancy determination.

The demonstration test was performed on the North Freeway (I-45) HOV lane in Houston during the early morning and afternoon of normal weekday traffic. The video was later analyzed by Transfo, Computer Recognition Systems, Inc. (CRS), Symond Travers Morgan Limited (STML), and TTI. The results of the demonstration test are summarized below. Additional information on the demonstration test can be found in the final test report by Transfo (11).

The demonstration test identified optimal camera mounting arrangements, lens and lighting configurations that were evaluated and refined in the operational test. Several camera angles are required for determination of vehicle occupancy, with the most important angles including a close-range front windshield view and a passenger-side window view. Proper placement of the cameras was shown to reduce glare and other lighting problems previously encountered in other video surveillance projects.

Directional lighting was used to illuminate vehicle interiors in low light conditions and proved to be satisfactory for determining vehicle occupancy in early morning hours. When passing through the directional lighting, HOV lane users saw a brief flash of light. Some drivers were distracted by the light, but most drivers appeared oblivious to the directional lighting. The supplemental lighting did penetrate some lightly tinted widows during low-light conditions, but

tinted windows made it very difficult to capture clear images of occupants with the presence of abundant natural light.

TTI researchers reviewed several hours of the video to determine the ability to see inside vehicle passenger compartments. The results of this video review indicated that during ideal lighting conditions (early morning with minimal glare and directional lighting), the human reviewers could not positively determine vehicle occupancy on approximately 5 percent of the vehicles in the HOV lane. During less-than-ideal lighting conditions (strong sunlight and glare) later in the day, the ability to see vehicle compartments decreased; as a result, vehicle occupancy could not be positively determined on about 25 percent of all vehicles in the HOV lane.

Transfo, CRS, and STML analyzed the video to examine the potential of using pattern recognition to automatically detect vehicle occupancy. The results of their analysis indicated that automatic vehicle occupancy detection is very difficult using video-based machine vision technology. Several problems with using video-based machine vision technology for automatic vehicle occupancy detection were noted:

- Providing adequate lighting in the vehicle compartment can be accomplished, but is difficult without distracting the driver. Infrared or amber-colored light was suggested to lessen driver distraction.

- Locating the various vehicle passenger compartments automatically is difficult because of the wide variety of vehicle shapes, sizes, and windshield/window designs.

- Performing automatic image analysis is very challenging with "unconstrained scenes," or the wide variety of passenger positions and confusing features like head rests or hats that can exist within the vehicle compartment.

Transfo, CRS, and STML proposed two possible approaches to advance the use of video in HOV lane enforcement. A short-term solution could utilize vehicle image capture, an automatic license plate reader, and a semi-automatic review system. This technique would require enforcement personnel to manually review some vehicle compartment images before performing a traffic stop. A long-term approach would develop an automated approach that would address many of the pattern recognition problems noted earlier.

Because of the required development time and high uncertainty of results with developing a fully automated system, TTI researchers and project steering committee members selected a semi-automatic enforcement system for operational testing. The conceptual design for this semi-automatic video enforcement system is presented in the next chapter, as well as the test methods and criteria used to evaluate the video enforcement system.

3 STUDY DESIGN

This chapter presents the conceptual design of the HOV enforcement and review (HOVER) system that was tested on the ERLT (I-30) contraflow HOV lane in Dallas, Texas. The chapter also discusses the test criteria and methods used to evaluate the HOVER system.

3.1 HOVER System Design

TTI researchers, in cooperation with Transfo, developed performance specifications for a semi-automated video enforcement system as recommended in the Transfo demonstration test report. These specifications required the video enforcement system to perform four basic tasks:

1. Collect and transmit video snapshot images of license plates and passenger compartments for all vehicles in the HOV lane to a remote computer workstation;
2. Perform automatic license plate character recognition on the license plate images;
3. Synchronize the captured images of vehicle occupants with license plate characters; and
4. Search a license plate database containing vehicle occupancy histories and, based upon failure to meet set criteria, display the vehicle license plate characters and vehicle compartment images on a computer monitor for review and enforcement purposes.

In October 1996, TTI contracted with Transfomation Systems, Inc. (Transfo) for the installation and a 12-month lease of a video enforcement system meeting these specifications. The HOVER system was leased from Transfo because the TxDOT study budget included only $75,000 for capital equipment purchases, which was half of the estimated cost of the HOVER system. Transfo collaborated with Computer Recognition Systems, Inc. and others in developing, installing, and integrating the HOVER system.

The following sections discuss each of the enforcement system's functional capabilities in general terms. Because of the proprietary nature of the HOVER system, specific information about the system design can not be provided.

3.1.1 Collection and Transmission of Video Images

Two video cameras are used to capture front and side images of vehicle compartments (Figures 3 and 4). A third video camera collects synchronized images of the rear vehicle license plate (Figure 5). The cameras are capable of operating in low-light conditions with supplemental lighting (Figure 6) as required.

3.1.2 Automatic License Plate Recognition

Transfo installed an automatic license plate recognition system manufactured by CRS that works in conjunction with the license plate video camera. The license plate recognition system outputs license plate characters to a database, along with a time and date stamp and the corresponding license plate image for manual inspection. The software is also capable of linking a license plate record to several images of the respective vehicle's passenger compartment.

3.1.3 License Plate History Database Searching

TTI researchers built a license plate database of frequent HOV lane users from video collected by the system along the ERLT HOV lane. The license plate database is capable of being updated on a continuing basis by DART as they operate the enforcement system. Transfo and CRS developed a software interface that permits the license plate database to be searched to match a license plate record collected and recognized by the HOVER system in real-time. If a license plate is not in the "whitelist" license plate database, the license plate record and all vehicle interior compartment images are displayed on the HOVER workstation monitor for review by enforcement or other trained personnel (Figure 7).

The automatic license plate recognition, license plate database searching, and display of license plate records and vehicle interior video images are integrated into a single computer workstation interface (Figure 8). The computer workstation interface is Windows 95-compatible.

Because license plate information is maintained in the database, there are multiple layers of security to protect the privacy of this information. The license plate database and incoming license plate records are protected from insecure access through password protection.

3.1.4 Operational Testing of the Enforcement System

Real-time operational testing of the HOVER system requires two people: one person monitoring the HOVER workstation and one DART police officer located at an enforcement area about 5 km (3 mi) downstream of the video cameras (Figure 9). The person monitoring the HOVER workstation reviews the vehicle compartment images that are not contained in the "whitelist" database. If the person can confirm the vehicle being reviewed is a valid carpool, they can add the vehicle's license plate to the "whitelist" database.

If the vehicle is not in the "whitelist" database and the person can not confirm that it meets minimum occupancy requirements, the person can communicate the license plate and vehicle description to a DART police officer at the downstream enforcement area. The officer has approximately three minutes to move into an enforcement position for the suspected HOV lane violator.

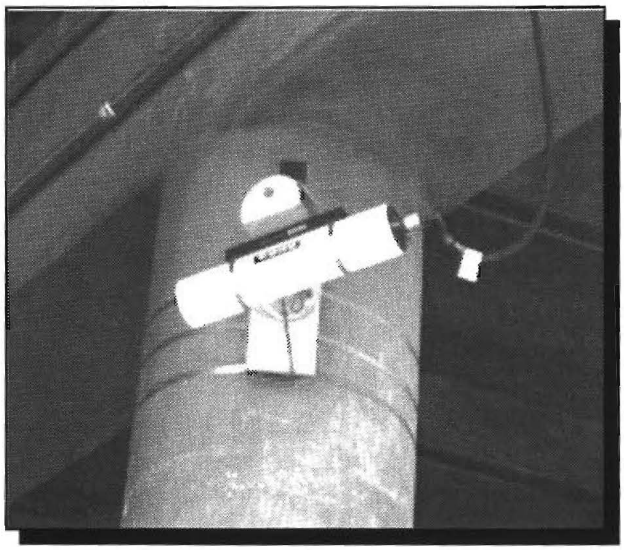

Figure 3. Front View Video Camera, HOVER System

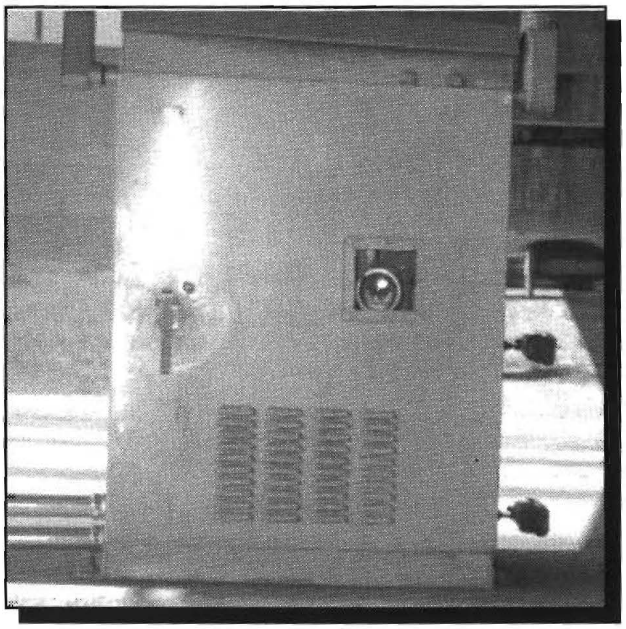

Figure 4. Side View Video Camera, HOVER System

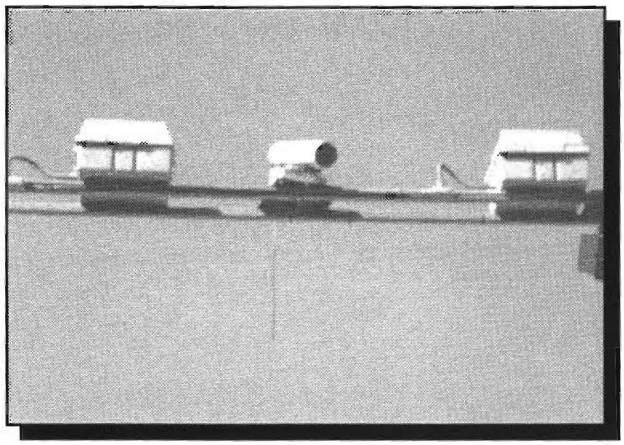

Figure 5. License Plate Video Camera, HOVER System

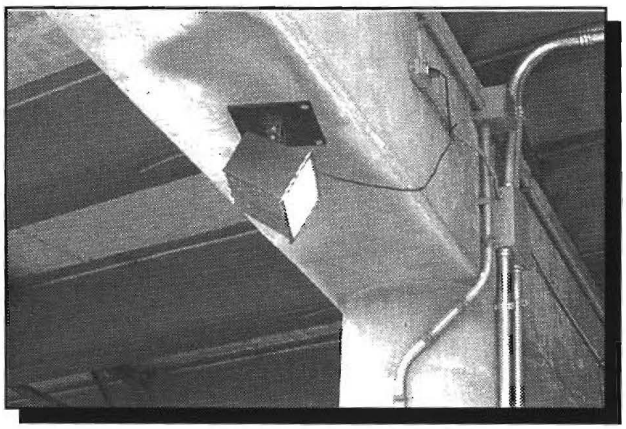

Figure 6. Supplemental Lighting, HOVER System

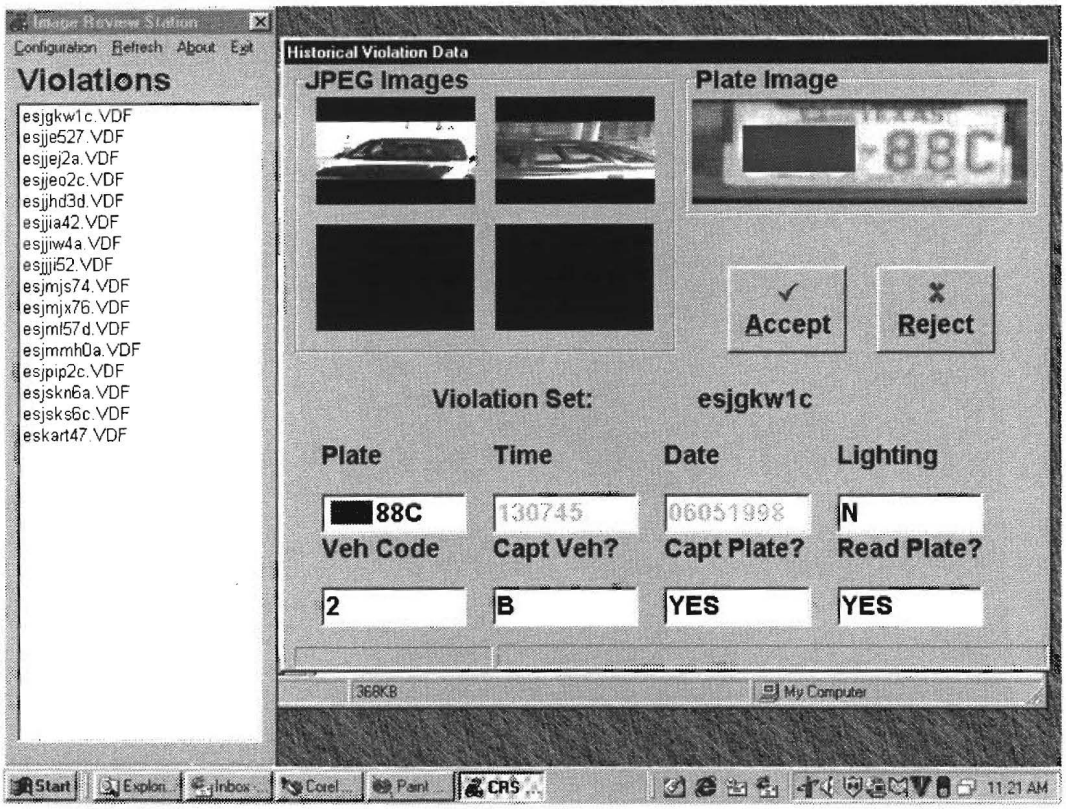

Figure 7. HOVER Enforcement Workstation Interface

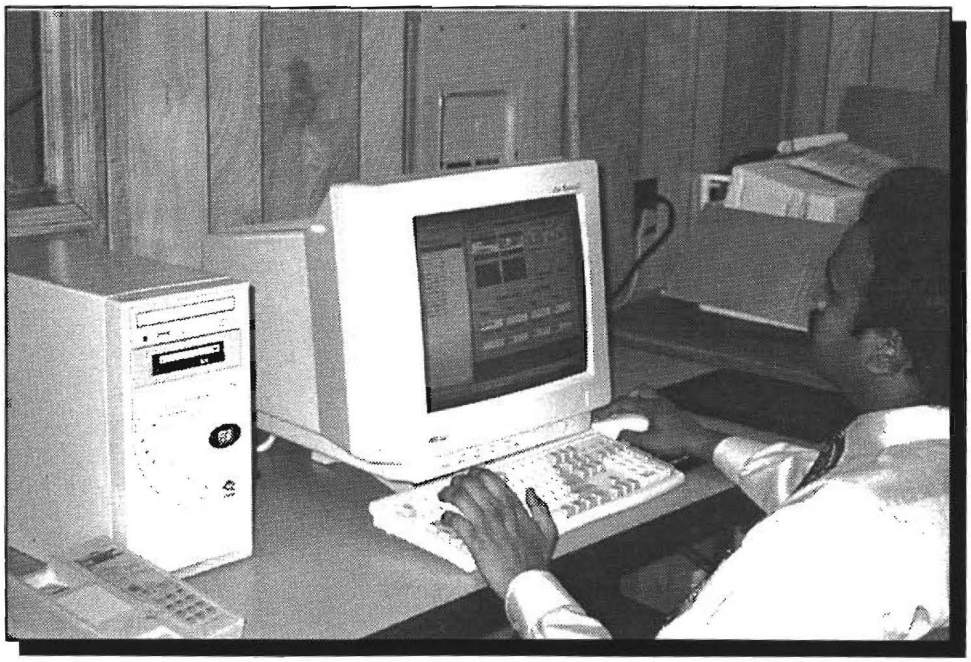

Figure 8. DART Personnel Operating HOVER Workstation

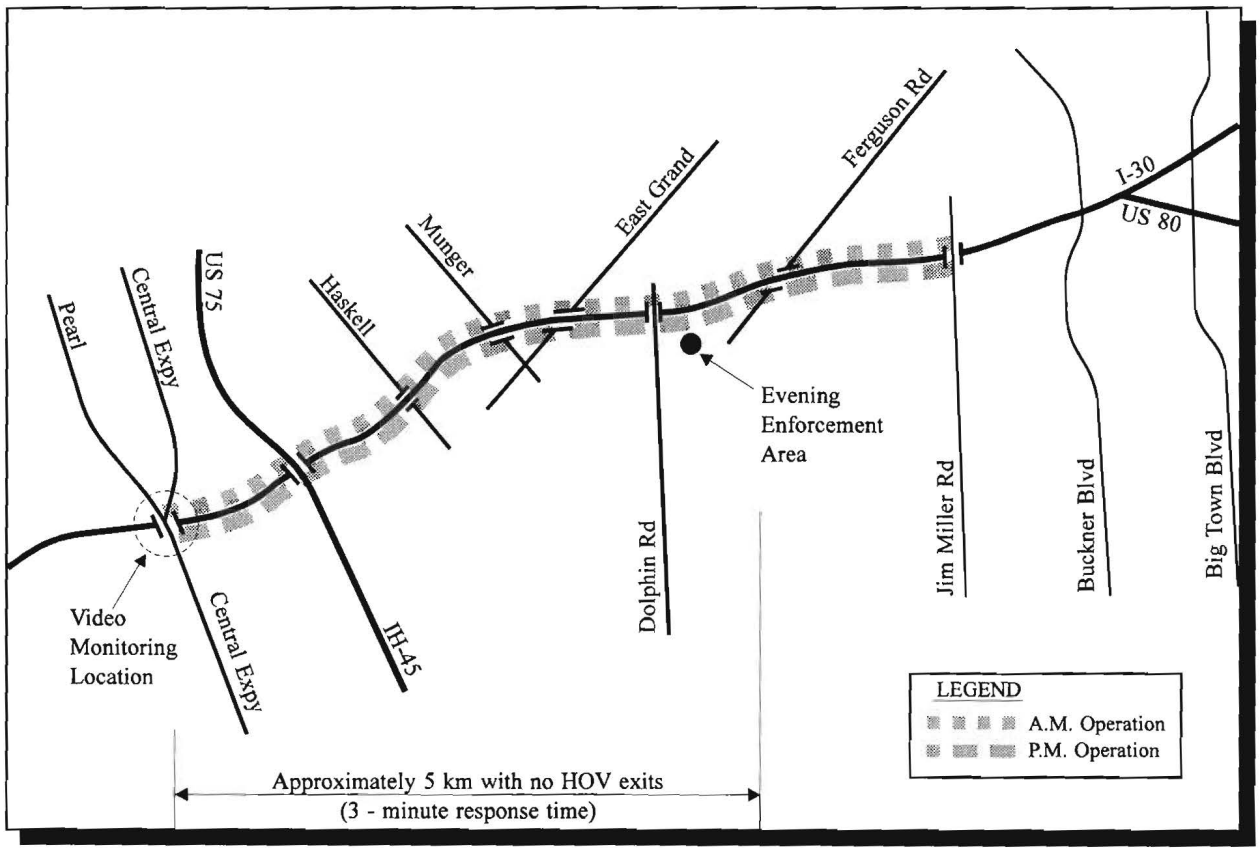

Figure 9. Operational Testing of the HOVER System

3.2 Evaluation Plan

TTI developed an evaluation plan that was to be used in assessing the effectiveness of the HOVER system in HOV lane enforcement. The evaluation plan was based on three basic goals for the HOV lane enforcement system:

- The enforcement system **should be capable of accurately detecting vehicle occupancy** using a combination of video image capture and license plate recognition;
- The enforcement system **should not adversely affect the HOV lane** in terms of reduced utilization or increased violation rates; and
- The enforcement system **should be cost-effective and easy to use**.

TTI researchers developed the evaluation criteria described below based upon these three evaluation goals.

3.2.1 Accurate Detection of Vehicle Occupancy

Under this goal, the HOVER system was evaluated for its ability to accurately detect vehicle occupancy using a combination of video image capture and license plate recognition. The HOVER system was to be evaluated under three different ambient light conditions: normal light (no glare, sufficient ambient and supplemental light); sunny/high glare conditions (direct, strong sunlight or low sun angles typical at sunset); and low light (rainy, foggy, after sunset, operating with supplemental light). TTI researchers planned to collect three to five hours of video images for each test condition (total of 9 to 15 hours), then classify each captured video image as follows:

- positive identification (ID) of 1 front seat passenger and 0 back seat passengers;
- positive ID of 1 front seat passenger and 1 or more back seat passengers;
- positive ID of 1 front seat passenger, uncertain about back seat passengers;
- positive ID of 0 front seat passengers and 1 or more back seat passengers;
- positive ID of 0 front seat passengers, uncertain about back seat passengers;
- positive ID of single-occupant vehicle (violator or authorized vehicle);
- suspected single-occupant vehicle but uncertain;
- unable to see inside vehicle because of glare or low light;
- unable to see inside vehicle because images captured incorrectly; and
- buses, motorcycles, and other special types of vehicles.

The measures of effectiveness for this goal include:

- percentage of correctly captured video images (number of correctly captured images/total lane volume);

- percentage of video images within each identification class; and
- false alarm rate (number of incorrect occupancy alarms/total alarms).

The accuracy of the HOVER system's license plate recognition component was also to be evaluated under the same three ambient light conditions. The results of the license plate recognition can be reported with a number of different measures of effectiveness:

- percentage of visible plates (total visible plates/total lane volume);
- percentage of correctly captured plate images (number of correct images/total visible plates);
- percentage of correctly read license plates (# correct plates/total plates read); and
- percentage of correct license plates after manual review (# correct plates after review/total plates read).

The effectiveness of the "whitelist" license plate database was also to be evaluated for the same ambient light and test conditions. The applicable measures of effectiveness include:

- number of vehicles reviewed per hour;
- percentage vehicles reviewed (number of vehicle images reviewed/total vehicle images collected); and
- mean time from image capture to workstation review.

3.2.2 Adverse Impacts on HOV Lane

For this goal, the HOVER system was evaluated for any adverse impacts or effects on the HOV lane in terms of reduced utilization or increased violation rates. TTI regularly collects operational data on the Dallas area HOV lanes, so the following criteria was to be used to gauge any adverse impacts on the ERLT (I-30) HOV lane:

- Compare HOV lane speeds at 1, 3, and 6 months;
- Compare HOV lane volumes/occupancies at 1, 3, and 6 months; and
- Compare HOV lane violation rates at 1, 3, and 6 months.

3.2.3 Cost-Effectiveness and Ease of Use

Under this goal, the HOVER system was to be evaluated for its cost-effectiveness and its relative ease of use. The following measures of effectiveness are used to quantify this goal:

- Cost-effectiveness: benefit-to-cost ratio; and
- Ease of use: qualitative assessment by enforcement personnel.

4 FINDINGS

This chapter presents and discusses the results of operational testing that evaluated the HOV lane enforcement and review (HOVER) system installed on the ERLT (I-30) contraflow HOV lane in Dallas. Specific test information includes the accuracy of the HOVER system in capturing vehicle compartment and license plate images, the ability to view the interior of vehicle compartments, and the effectiveness of the license plate recognition and screening database.

4.1 Evaluation Test Methods and Dates

Missing features in the HOVER system at the start of the operational test (October 1997) prevented the research team from performing certain tasks. The following list indicates features that were later implemented in March 1998:

- The lack of adequate supplemental lighting prevented the researchers from performing any evaluation tests in low light. Transfo supplemented the original low-powered lights with flood lights. Because the I-30 HOV lane operates only between 4 p.m. and 7 p.m. in the evening, low-light conditions are not able to be tested until later in the fall of 1998 when Central Standard Time returns.

- Missing file transfer features prevented the researchers from performing any real-time, on-line evaluation tests. The file transfer software is necessary to transfer license plate and vehicle image files from the license plate recognition computer to the HOVER workstation for review.

- The HOVER review software was not capable of automatically updating the records of vehicles arriving after the software had been opened. This further prevented the researchers from performing any real-time, on-line evaluation tests.

Because of these missing features during most of the operational testing, the research team tested several components of the HOVER system in an "off-line" manner. For off-line testing, the HOVER system was started but was not used in conjunction with a police officer on the HOV lane. The HOVER system was used to collect vehicle compartment and license plate images, automatically attempt to read the license plate, and compare the license plate recognition results to the "whitelist" license plate database. All image and data files were saved to computer disk for review and analysis at a later date. Researchers also attempted to record video to provide "ground truth" for the number of vehicles entering the I-30 HOV lane during the evaluation tests. Several difficulties were encountered with collecting "ground truth" video from the system itself (video recording apparently degrades system performance in the current configuration).

In the off-line testing described in this report, several important components of the HOVER system were evaluated:

- **Vehicle compartment image capture and review** - Ability to correctly capture front and side images of the vehicle's passenger compartment and the ability to see occupants from these front and side images. This component is essential for determining vehicle occupancy.

- **License plate capture** - Ability to correctly capture license plate images. This component is important for identifying individual vehicles (and potentially their registered owners in a mailed ticket program).

- **License plate recognition** - Ability to correctly read license plates. This component is essential in operating the HOVER system for real-time enforcement. The license plates are used to screen out frequent HOV lane users, which makes the workload of the HOVER system operator more manageable.

The off-line tests of the HOVER system were conducted on seven different days over several months (Table 3). Early tests of the system in late 1997 and early 1998 may not be representative of its current potential because of several improvements and/or changes effective March 1998. The tests conducted in April 1998 are most representative of current system potential. No significant differences were found between days with normal ambient light and strong, direct light, therefore all days are grouped together.

Table 3. Off-Line Evaluation Test Dates

Date	Time	Vehicles Recorded by HOVER System	Comments
December 9, 1997	4:05 p.m. to 4:38 p.m. (33 minutes)	430 vehicles	normal light, system most likely wired incorrectly
January 28, 1997	4:57 p.m. to 5:10 p.m., 5:26 p.m. to 5:51 p.m. (38 minutes)	645 vehicles	normal light, license plate data not available
January 29, 1997	3:59 p.m. to 4:59 p.m. (60 minutes)	800 vehicles	normal to low light, license plate data not available
February 12, 1998	4:00 p.m. to 5:01 p.m. (61 minutes)	838 vehicles	normal to low light
April 8, 1998	4:30 p.m. to 5:30 p.m. (60 minutes)	1,055 vehicles	high light, incorrect computer time stamps
April 21, 1998	4:35 p.m. to 6:03 p.m. (88 minutes)	1,591 vehicles	high light, incorrect computer time stamps
April 22, 1998	4:14 p.m. to 5:18 p.m. (64 minutes)	1,047 vehicles	high light, incorrect computer time stamps

4.2 Vehicle Compartment Image Capture and Review

The primary component of the HOVER system is a vehicle compartment image capture function. This component is essential for determining vehicle occupancy for all vehicles in the HOV lane. This component was designed to capture synchronized images of a vehicle compartment using video cameras focused on the front and rear seats. The quality of the captured images, as well as the ability to capture front and side view images from all vehicles, were evaluated in the off-line testing.

In the off-line testing, vehicle compartment images collected by the HOVER system were reviewed to determine the following:

1. Whether both front and side vehicle images were collected correctly (vehicle compartment in the field-of-view); and
2. The ability to recognize vehicle occupants from the front and side images.

The results of the vehicle compartment image capture are shown in Table 4 and illustrate the ability of the system to correctly capture vehicle compartment images. The results show that the HOVER system performed satisfactorily in correctly capturing vehicle compartment images, on the average correctly capturing more than 97 percent of all vehicle compartment images correctly. An external trigger (i.e., infrared light beam) is used to capture the images from video and is configured for the length of a typical passenger vehicle. The image capture system occasionally does not correctly capture images of larger vehicles (e.g., extended cab trucks, delivery vans) because of their greater length. Also, the system occasionally captured double images from the front or side camera. The cause of this "miscapture" is unknown but it typically occurred with less than 1 percent of all vehicle images.

The results of the vehicle compartment image review are shown in Table 5 and illustrate the ability of human observers to discern vehicle occupancy from captured images. The results show that, on average, human observers can discern vehicle occupancy (1 or more passengers) for nearly 85 percent of all vehicles. On this HOV lane, buses and motorcycles account for another 4 percent. The remaining 11 percent of vehicles in the HOV lane are either violators, suspected violators, or the vehicle occupancy could not be determined. The quality of the vehicle images were such that it was difficult to positively determine vehicle occupancy for this remaining 11 percent. For example, there were shadows inside many vehicle compartments that could potentially hide a passenger from view. It is important to note that less than 1 percent of the vehicles could be positively identified as violators or authorized police vehicles.

Table 4. Results of Vehicle Compartment Image Capture

Condition	Percentage of vehicles (number in parentheses)							
	Dec. 9	Jan. 28	Jan. 29	Feb. 12	April 8	April 21	April 22	Average % (Total)
Both front and side images correctly captured	**96.7 %** (416)	**96.0 %** (619)	**97.6 %** (781)	**98.9 %** (829)	**97.5 %** (1,029)	**96.7 %** (1,540)	**97.8 %** (1,025)	**97.4 %** (6,239)
Only front image correctly captured	**2.1 %** (9)	**1.9 %** (12)	**0.8 %** (6)	**0.4 %** (3)	**1.5 %** (16)	**1.3 %** (20)	**1.0 %** (10)	**1.2 %** (76)
Only side image correctly captured	**0.2 %** (1)	**0.9 %** (6)	**1.1 %** (9)	**0.4 %** (3)	**0.8 %** (8)	**0.7 %** (11)	**0.8 %** (8)	**0.7 %** (46)
Neither front nor side image correctly captured	**0.9 %** (4)	**1.2 %** (8)	**0.5 %** (4)	**0.4 %** (3)	**0.2 %** (2)	**1.3 %** (20)	**0.4 %** (4)	**0.7 %** (45)
Total	**100 %** (430)	**100 %** (645)	**100 %** (800)	**100 %** (838)	**100 %** (1,055)	**100 %** (1,591)	**100 %** (1,047)	**100 %** (6,406)

Table 5. Results of Vehicle Compartment Image Review

Condition	Percentage of vehicles (number in parentheses)							
	Dec. 9	Jan. 28	Jan. 29	Feb. 12	April 8	April 21	April 22	Average % (Total)
Positively identify 2 or more vehicle occupants	**83.5 %** (359)	**78.9 %** (509)	**82.4 %** (659)	**80.9 %** (678)	**85.0 %** (897)	**87.6 %** (1,394)	**88.0 %** (921)	**84.6 %** (5,417)
Positively identify 0 front seat passengers and uncertain about back seat passengers	**2.6 %** (11)	**1.5 %** (10)	**0.3 %** (2)	**1.0 %** (8)	**4.9 %** (52)	**2.4 %** (38)	**2.7 %** (29)	**2.3 %** (150)
Positively identify a single-occupant vehicle	**0.0 %** (0)	**0.2 %** (1)	**0.1 %** (1)	**0.1 %** (1)	**1.5 %** (16)	**0.6 %** (10)	**0.4 %** (4)	**0.5 %** (33)
Suspected single occupant-vehicle but uncertain	**3.5 %** (15)	**1.5 %** (10)	**3.4 %** (27)	**0.7 %** (6)	**3.1 %** (33)	**2.0 %** (32)	**2.1 %** (22)	**2.2 %** (145)
Unable to see inside vehicle because of glare or low light	**4.0 %** (17)	**12.2 %** (79)	**8.0 %** (64)	**11.6 %** (97)	**0.3 %** (3)	**1.4 %** (22)	**1.6 %** (17)	**4.7 %** (299)
Unable to see inside vehicle because images not captured correctly	**2.3 %** (10)	**1.9 %** (12)	**1.3 %** (10)	**1.3 %** (11)	**0.8 %** (8)	**1.6 %** (26)	**1.0 %** (10)	**1.3 %** (87)
Buses, motorcycles, and other special types of vehicles	**4.2 %** (18)	**3.7 %** (24)	**4.6 %** (37)	**4.4 %** (37)	**4.4 %** (46)	**4.3 %** (69)	**4.2 %** (44)	**4.3 %** (275)
Total	**100 %** (430)	**100 %** (645)	**100 %** (800)	**100 %** (838)	**100 %** (1,055)	**100 %** (1,591)	**100 %** (1,047)	**100 %** (6,406)

4.3 License Plate Capture

Another essential feature of the HOVER system is the license plate capture function. This component captures images of vehicle license plates that are synchronized with vehicle compartment images. When operating the HOVER system for real-time enforcement, the license plate images are necessary to uniquely identify individual vehicles at a downstream enforcement location. The license plate images are read by the license plate recognition component, then compared to the "whitelist" database. If the HOVER system is to be used for a mailed ticket program, the license plate information is necessary to identify the registered owner of the vehicle for ticket processing.

The images captured by the HOVER system were reviewed to determine the percentage of vehicles whose license plates were captured. Table 6 shows the results of the license plate capture component. The license plate capture results in Table 6 show that the system correctly captures license plate images from nearly 80 percent of all vehicles. The remaining 20 percent of vehicles either had all or several characters of the license plate not captured in the license plate image. The license plate capture function of the HOVER system is affected by the quality of license plate images captured. In cases where lighting was inadequate, license plate capture rates would be lower than expected. In other situations, a license plate may not have been visible in the camera field-of-view, such as missing rear license plates.

4.4 License Plate Recognition

The license plate recognition function of the HOVER system was designed to make it possible to review HOV lanes with high traffic volumes. This component attempts to read the license plate images using optical character recognition and, upon successful completion, provides license plate characters in an ASCII-text format to compare with the "whitelist" license plate database. License plate recognition is essential for real-time operation of the HOVER system, as it enables regular carpool vehicles to be screened from the image review process, enabling technicians or enforcement personnel to review a smaller set of suspected violators. The license plate recognition function would not be necessary in a mailed ticket program, but could automate ticket processing.

The captured license plate images were used to verify whether the vehicle license plates were correctly read. To be considered as a correct read, all license plate characters had to be read correctly. There were several license plates that were not readable because of various obstructions, and these license plates are labeled accordingly in the analysis. In other cases, the license plate was not read because the license plate was not captured correctly. Table 7 contains the results of the license plate recognition. The table illustrates that the automatic license plate reader performed poorly, even after some incremental improvements were made in early 1998. On average, the license plate reader read less than 21 percent of all vehicle license plates. The license plate reader misread 57 percent of the license plates and was unable to read another 20 percent because the license plates were not captured correctly. On average, about 2 percent of the license plates were unreadable by human observers because of various obstructions.

Table 6. Results of License Plate Capture

Condition	Percentage of vehicles (number in parentheses)							
	Dec. 9 [a]	Jan. 28 [b]	Jan. 29 [b]	Feb. 12	April 8	April 21	April 22	Average % (Total)
License plate correctly captured (all characters in field-of-view)	~~47.4 %~~ (204)	n.a.	n.a.	**83.3 %** (698)	**78.4 %** (827)	**78.9 %** (1,255)	**80.3 %** (840)	**79.9 %** (3,620)
License plate not correctly captured	~~52.6 %~~ (226)	n.a.	n.a.	**16.7 %** (140)	**21.6 %** (228)	**21.1 %** (336)	**19.7 %** (207)	**20.1 %** (911)
Total	~~100 %~~ (430)	n.a.	n.a.	**100 %** (838)	**100 %** (1,055)	**100 %** (1,591)	**100 %** (1,047)	**100 %** (4,531)

Notes: [a] License plate capture likely affected by incorrect system wiring.
[b] License plate data not available due to HOVER system malfunction.

Table 7. Results of License Plate Recognition

Condition	Percentage of vehicles (number in parentheses)							
	Dec. 9 [a]	Jan. 28 [b]	Jan. 29 [b]	Feb. 12	April 8	April 21	April 22	Average % (Total)
Correctly read plate	~~3.3 %~~ (14)	n.a.	n.a.	**24.3 %** (204)	**19.1 %** (202)	**18.0 %** (287)	**23.7 %** (248)	**20.7 %** (940)
Did not correctly read plate	~~40.9 %~~ (176)	n.a.	n.a.	**55.5 %** (465)	**57.5 %** (606)	**58.1 %** (925)	**56.0 %** (586)	**56.8 %** (2,576)
Plate not readable to human eye	~~3.3 %~~ (14)	n.a.	n.a.	**3.5 %** (29)	**2.2 %** (23)	**2.8 %** (45)	**0.6 %** (6)	**2.3 %** (103)
Plate not readable because plate not captured correctly (Table 6)	~~52.6 %~~ (226)	n.a.	n.a.	**16.7 %** (140)	**21.3 %** (224)	**21.0 %** (334)	**19.7 %** (206)	**20.1 %** (911)
Total	~~100 %~~ (430)	n.a.	n.a.	**100 %** (838)	**100 %** (1,055)	**100 %** (1,591)	**100 %** (1,047)	**100 %** (4,531)

Notes: [a] License plate capture likely affected by incorrect system wiring. Data was not used for evaluation purposes.
[b] License plate data not available due to HOVER system malfunction.

4.5 Adverse Impacts on HOV Lane

Operational problems prevented the research team from evaluating the HOVER system in real-time for enforcement purposes. Because the HOVER system merely collected data, there were no impacts on the operation of the HOV lane. For this reason, no information about HOV lane volumes, vehicle speeds, vehicle occupancy levels, or violation rates are provided here.

4.6 Ease of Use

The ease of use of the HOVER system was determined by obtaining feedback from the DART personnel that operated the system. The TTI researchers involved in testing the system also provided feedback about its ease of use. Recent improvements made to the system in March 1998 significantly improved the usability of the system for real-time enforcement screening. There are several remaining usability issues:

- **Manual adjustment of camera irises** - The quality of the captured vehicle and license plate images are highly dependent on lighting conditions. The iris for each of the three video cameras had to be manually opened or closed based upon the quality of images being captured by the HOVER system. During testing, system operation required two people: one person to review images on the HOVER system and another person to manually adjust camera irises. Situating the iris controls at the HOVER workstation may only marginally improve the difficulty of both viewing vehicle images for required occupancy and adjusting camera irises. Cameras with an auto-iris feature that are sensitive to small changes in lighting would be ideal but were not available for testing.

- **HOVER operator workload** - Operator workload of the HOVER system in its current state is overwhelming. The high workload is mostly due to the large number of vehicles being logged by the system. The "whitelist" license plate database is only able to screen a very small number of vehicles (because of the small database size and the inaccuracy of the license plate reader). As a result, the HOVER system logs approximately 1,000 vehicles per hour, or about one vehicle every 3.6 seconds. The review of a single vehicle typically requires between 5 and 15 seconds. Several improvements to the "whitelist" database and the license plate reader are necessary to make operator workload more manageable.

5 CONCLUSIONS AND RECOMMENDATION

This chapter contains study conclusions that are based upon operational testing of the HOVER video enforcement system. Recommendations for the use of the HOVER system in HOV lane enforcement are also provided.

5.1 Conclusions

This section provides study conclusions based upon an extensive off-line review of the HOVER system. The discussion is first centered on the capability of the various HOVER system components. Consideration is also given to the potential enforcement applications of the HOVER system.

- **HOVER system** - The existing HOVER system meets the original performance specifications in terms of its features and functions. Several changes and/or enhancements to the system could significantly improve its usability and its potential for use in HOV lane enforcement. Many of these changes and/or enhancements were not possible to include in this operational test because of the limited budget available for system development and refinement. The following points discuss specific features of the HOVER system.

- **Vehicle compartment image capture** - The HOVER system performed adequately in capturing vehicle passenger compartment images, correctly capturing 97 percent of the front and side view images of vehicles in the HOV lane. This component of the HOVER system requires little or no enhancement or modifications.

- **Vehicle compartment image quality** - The quality of vehicle compartment images from the HOVER system enabled human observers to positively determine required vehicle occupancy (i.e., 2 or more persons, DART buses, or motorcycles) for 89 percent of all vehicles reviewed. Another 0.5 percent were positively identified as single-occupant vehicles (i.e., violators or authorized police vehicles). Vehicle occupancy could not be determined in the remaining 10.5 percent of vehicles for several reasons, including glare, low light, vehicle obstructions, or incorrectly captured images. The quality of vehicle images was very dependent on lighting conditions, which can be controlled to some extent with adequate supplemental lighting. However, there are numerous other factors affecting visibility of vehicle passengers that are beyond the control of enforcement personnel, such as tinted side windows, obtrusive window molding or panels, or mobile children in the back seat. This component of the HOVER system potentially could be improved by using better quality video cameras, reducing the video signal transmission loss, and adding one or two additional camera views from the side or rear of the vehicle.

- **License plate capture** - The HOVER system correctly captured 80 percent of the vehicle license plate images. The remaining 20 percent of the vehicles had plates incorrectly captured, either with partial or no license plate characters captured in the images. This 20 percent includes partial license plate captures, missed plate captures, and no license plates in the camera field-of-view. The 80 percent license plate capture rate is considered less than ideal for most enforcement applications. The license plate capture rate potentially could be improved with several enhancements to the HOVER system, including better quality video cameras and reduced video signal transmission loss.

- **License plate recognition** - The license plate recognition function of the HOVER system operated poorly, correctly recognizing only 20 percent of all vehicle license plates. Vendor-reported claims of license plate recognition range from 60 to 80 percent for the ideal lighting conditions in which the system was tested (although different video camera systems are used). The license plate recognition component of the HOVER system potentially could be improved by using better quality video cameras and reducing the video signal transmission loss.

- **"Whitelist screening database** - The "whitelist" screening database performed as designed in screening out frequent HOV lane users whose license plates were contained in the database. However, the "whitelist" database was not effective in significantly reducing the operator workload because very few vehicles were screened from the review process. Reasons for the low number of screened vehicles could include a relatively small database (approximately 1,800 license plates) and a low license plate recognition rate. This component of the HOVER system could be substantially improved by updating and increasing the size of the "whitelist" database and improving the license plate recognition rate. The "whitelist" database could also be improved by tracking repeat HOV lane violators as well.

Conclusions are provided below that consider the use of the HOVER system for three different HOV lane enforcement applications:

- **HOV information mailed to suspected violators** - In this application, HOV lane usage and educational information is mailed to suspected violators. Repeat violators could be sent warnings. With minor enhancements, the HOVER system could be used to identify suspected violators and mail HOV educational information. Desirable enhancements for this application include better quality video cameras, reduced video signal transmission loss, and one to two additional camera views.

- **Enforcement screening** - For this application, the HOVER system is used in real-time by a technician or para-professional to identify suspected violators, who works in concert with a downstream police officer that verifies the vehicle occupancy of suspected violators. With several enhancements, the HOVER system potentially

could be used to perform enforcement screening. Required enhancements for this application include better quality video cameras, reduced video signal transmission loss, one to two additional camera views, significantly better licence plate recognition, and a larger "whitelist" database.

- **Ticket-by-mail enforcement** - This application currently is not legal in the state of Texas, but consists of mailing a citation to the registered owner of the vehicle that was observed violating the HOV occupancy restriction. With many enhancements, the HOVER system potentially could be used for ticket-by-mail HOV lane enforcement if enabling legislation was passed. The required enhancements for this application include significantly better quality video cameras, reduced video signal transmission loss, one to two additional camera views, significantly better licence plate recognition, and a larger "whitelist" database.

5.2 Recommendation

The recommendation of this study is as follows:

- **Implement and test system enhancements** - The HOVER system in its current state could only be effectively used to mail HOV educational information to suspected violators. However, with some enhancements, the HOVER system could potentially be used for HOV enforcement screening, where police officers along the HOV lane are given an advanced notice of suspected violators and are required to verify vehicle occupancy. The enhancements that are needed to effectively perform enforcement screening include better quality video cameras, reduced video signal transmission loss, one to two additional camera views, significantly better licence plate recognition, and a larger "whitelist" database. Once these enhancements have been implemented, further testing is desirable to determine system usability, accuracy, and reliability.

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