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INVESTIGATION OF ENFORCEMENT TECHNIQUES AND TECHNOLOGIES TO SUPPORT HIGH-OCCUPANCY VEHICLE AND HIGH-OCCUPANCY TOLL OPERATIONS

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Abstract:

High-occupancy vehicle (HOV) facilities in Virginia have proven to be effective in enhancing mobility. This success, along with the availability of electronic toll collection technology, has led the Commonwealth to expand the HOV system and pursue the implementation of high-occupancy toll (HOT) facilities in the state. Although these facilities hold promise to help address the growing demand for travel in Virginia, a significant challenge in achieving their potential lies in the ability to enforce occupancy requirements in a manner that has minimal impact on the operation of the facilities. This has proven to be a challenge for HOV facilities and will be an even more complex undertaking on HOT facilities.

The purpose of this study was to examine occupancy enforcement on HOV and HOT facilities. This examination focused on three areas: assessing the impact of existing manual violation enforcement techniques on HOV violation rates; exploring the feasibility of using new technologies/techniques to improve the effectiveness of violation enforcement; and assessing the impact of violation enforcement techniques on the operations of HOV/HOT lanes.

The results of the research indicate that current saturation enforcement techniques are not effective in reducing violation rates. However, no proven technologies are currently available that offer the potential to automate enforcement of occupancy restrictions. Finally, a simulation methodology was developed that may be used to estimate the operations' impacts on current and future enforcement techniques and technologies.

The report offers a number of recommendations to address the challenges of HOV/HOT occupancy enforcement in Virginia: (1) the current practice of sporadic saturation enforcement should be discontinued in exchange for regular, continuous enforcement; (2) the HOV Enforcement Task Force should look critically at current HOV policies to identify and recommend specific changes to reduce the likelihood of citations being dismissed in adjudication; and (3) the methodology developed in this research should be used to evaluate new enforcement techniques and technologies before they are implemented.

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ABSTRACT

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INTRODUCTION

In a 2005 report, Dennis Morrison, the district administrator of the Virginia Department of Transportation's (VDOT) Northern Virginia District described Northern Virginia's high-occupancy vehicle (HOV) system as one of the most successful in the nation and added:

> The HOV lanes move more people in carpools, vanpools, buses, motorcycles, clean fuel vehicles and trucks from Virginia to the core areas of Arlington and D.C. than the regular highway lanes, Metrorail or Virginia Railway Express. Our transportation network could not properly function without HOV lanes.

Given the importance of these facilities, VDOT has looked for other opportunities to utilize managed lanes to address mobility challenges in the state. One such approach has been the pending introduction of high-occupancy toll (HOT) lanes. HOT lanes allow drivers of low-occupancy vehicles to pay a toll to use HOV lanes. HOT lanes are currently being constructed on I-495 in Northern Virginia in a public-private partnership.

One key challenge in effectively operating HOV/HOT facilities lies in ensuring that travelers comply with occupancy requirements. It has proven necessary to use law enforcement to ticket individuals who operate their vehicles in HOV facilities with fewer than the required number of occupants. In fact, a 2003 HOV Enforcement Task Force report cited effective enforcement of HOV restrictions to be the number one complaint that law enforcement receives in Northern Virginia. Further, with the introduction of tolling in HOT lanes, the enforcement task becomes significantly more complex. Traditional manual enforcement of HOV violations has often resulted in a significant increase in congestion. Extensive manual enforcement is also expensive, diverts resources from other important enforcement tasks, and is generally believed to have only a short-term impact on violation rates.

Because of the significant impact that violation enforcement has on HOV and HOT lanes, this research effort investigated the issue from three perspectives:

1. Given that the purpose of violation enforcement is to minimize the number of travelers who illegally use HOV/HOT lanes, it is important to have a solid understanding of the impact of enforcement on travelers' behavior. This study measured violation rates before and after enforcement operations to quantify the impact of violation enforcement.

2. Advanced technology may provide a means to enhance enforcement's effectiveness and mitigate its negative effects. Some state transportation agencies already have experience with designing, developing, and implementing HOV/HOT lanes and have experience with a variety of enforcement approaches. In this effort, the research team identified currently used or emerging technologies and then assessed their potential for use in enforcement of HOV/HOT restrictions in Virginia.

3. Violation enforcement has a significant impact on the operation of the facility. It is well known that blocking shoulder lanes, weaving to pull-over violators, and the presence of law enforcement itself reduces the effective capacity of travel lanes. This must be considered when one contemplates violation enforcement. Further, the use of new technologies and techniques will also result in operations' impacts. Thus, the team designed, developed, and demonstrated an evaluation framework to assess violation enforcement technologies and strategies. This framework includes a modeling and simulation component to determine the efficacy and suitability of the technologies and/or techniques.

PURPOSE AND SCOPE

The purpose of this project was to examine critically violation enforcement on HOV and HOT facilities in order to identify ways to decrease occupancy violations. This effort focused on three areas:

1. Assess the impact of existing manual violation enforcement techniques on violation rates of HOV lanes.

2. Explore the feasibility of using new technologies/techniques to improve the effectiveness of violation enforcement.

3. Assess the impact of violation enforcement techniques on the operations of HOV/HOT lanes.

METHODOLOGY

The research effort consisted of the following tasks:

1. *Review Literature.* The research team reviewed literature to synthesize information on HOV/HOT enforcement challenges, existing and potential technologies, strategies for enforcing high occupancy lane restrictions, and the impact of penalties on enforcement effectiveness. The team examined reports from transportation agencies who have implemented HOV and/or HOT lanes. For example, the Washington DOT, Minnesota DOT, and others have published reports detailing their HOT lane design and enforcement policies. In addition, the team explored a wide range of potential technologies that may be utilized for occupancy enforcement.

2. *Measure Impact of Violation Enforcement on Violation Rates.* In this task, the research team coordinated with VDOT and officials of the Virginia State Police to identify when and where manual violation enforcement operations would take place. Then, the team collected violation rate data prior to the enforcement, immediately after the enforcement, and a week after enforcement. The team then analyzed these data to determine the impact of enforcement and if the impact diminished as time moved beyond the enforcement date.

3. *Develop Operations Impact Evaluation Methodology.* In this task, the research team focused on the design and development of a detailed evaluation framework. A microscopic simulation package, VISSIM, was employed to model and simulate HOT enforcement strategies. The resulting framework could serve as a guide for use by VDOT and the Virginia State Police in enhancing or devising new enforcement strategies.

RESULTS

Literature Review

The research team gathered a large amount of information on current and proposed approaches to the enforcement of HOV/HOT occupancy restrictions. This information focuses on existing practices, experience in key national facilities, emerging enforcement technologies, and the impact of penalties on violation rates.

Manual Enforcement

Manual enforcement is the most widely used enforcement technique for occupancy violation on HOV/HOT facilities. The sequence for a typical manual enforcement operation consists of (1) visually check vehicle occupancy, (2) pursue an identified vehicle, and (3) issue citation. As implied by the name, none of the stages of manual enforcement is assisted by advanced technology.

Manual enforcement problems encountered by police officers were summarized in a study on HOV lane violations in California (Billheimer et al., 1990):

- *Difficulty of determining vehicle occupancy:* Police officers frequently found that they stopped vehicles with sleeping adults or small children sitting below window level.

- *Safety concerns and disrupting traffic:* On heavily traveled freeways during peak periods, officers found it extremely difficult to join the stream of traffic safely to pursue a potential violator. Further, when the officer escorted the vehicle to a shoulder, the traffic flow on the facility was disrupted.

- *Difficulty of citing suspected vehicles (nested violators):* When a potential violator is "nested" in a group of vehicles, especially consisting of large vehicles such as trucks or buses, the officer can rarely pursue the violator.

Although other studies have also addressed safety concerns regarding the practice of police vehicles weaving in and out of HOV lanes, they have concluded that there is no consistent correlation between accident rates and occupancy violation rates (Billheimer et al., 1990).

Enforcement with Assistance of Toll Transponders

Numerous facilities in the United States, including the I-15 Express Lanes in San Diego, I-394 MnPASS in Minneapolis, I-25 Express Lanes in Denver, I-10 West and US 290 in Houston, SR-91 Express Lanes in Orange County, California, SR 167 in Seattle, and I-95 in Miami-Dade County, are operating transponder-based HOV/HOT facilities. These HOV/HOT facilities require mandatory installment of transponders. Generally, installment of a transponder is mandated only for single-occupancy vehicles (SOVs).

When a transponder-based HOV/HOT lane is implemented, generally the enforcement task is divided into two parts: toll (or transponder) violation enforcement, and occupancy violation enforcement. Even though enforcement for transponder violation is assisted by automated technologies, two enforcement problems were identified in the literature review.

1. *Difficulty in identifying vehicle occupancy:* Although the validity of the transponder can be determined automatically, verification of the vehicle occupancy that would allow non-payment of the toll (i.e., HOV) remains a manual process.

2. *Difficulty in matching a signal of a violator to a real violator:* When a vehicle passes a roadside transponder reader, quickly matching the vehicle to the signal, which indicates the validity of a transponder within that vehicle, is a challenge for police officers.

Meanwhile, just as with traditional HOV facilities, enforcement of the occupancy violation does not use advanced technology. The occupancy violation of current HOT facilities depends on the traditional visual assessment of a police officer.

HOV/HOT Facilities and Enforcement in the United States

I-15 Express Lanes, San Diego, California

The I-15 Express Lanes in San Diego are 12.5 miles long from SR 163 to the Ted Williams Parkway, with only one entrance and exit point. The lanes require a minimum of two passengers for free use. An SOV may use the facility by paying a toll through the Electronic Toll Collection (ETC) system.

Enforcement is conducted at the toll zone where a specified area for violation enforcement is designated. A police officer observes the number of passengers in a vehicle that passes a transponder reader. If the reader signals that a vehicle does not have a transponder and the vehicle is identified as an SOV by the police officer, the vehicle can be pulled over for a citation. Enforcement is conducted by the California Highway Patrol (San Diego Association of Governments, 2006).

I-15 Express Lanes, Salt Lake City, Utah

The I-15 Express Lanes in Salt Lake City may be used by SOVs for a $50 monthly fee. Unlike other HOT facilities, I-15 operates 24 hours a day, 7 days a week. All vehicles with two or more occupants, motorcycles, emergency vehicles, buses, and clean-fuel vehicles can use the express lanes at no charge. If the driver of an SOV wants to use the facility, a monthly decal must be purchased and placed on the rear or front window.

The enforcement technique used on the I-15 Express Lanes in Salt Lake City is manual. State police visually monitor vehicles to identify SOVs; then, they look to see if the SOV is authorized to use the facility based on the decal affixed to the window. To support this higher level of enforcement, two additional state patrol vehicles were purchased for exclusive use on the facility (Utah DOT, 2009).

I-394 MnPASS, Minneapolis, Minnesota

HOT operation of I-394 began in 2005. The I-394 HOT lanes, known as MnPASS, are approximately 11 miles long and connect I-494 to the west of downtown Minneapolis. As with the I-15 facility in San Diego, SOV drivers must have valid transponders to use the lanes.

The enforcement system used in I-394 MnPASS is one of the most sophisticated systems in HOT operation, using a number of innovative technology applications (Halvorson and Buckeye, 2006). First, law enforcement officers use a transponder reader to detect automatically the presence of transponders in SOVs as they pass. This mobile enforcement reader gives more flexible options to the officers. An enforcement vehicle equipped with the mobile enforcement reader can detect a valid transponder while either parked on the shoulder or traveling adjacent to a vehicle. The reader provides the last time and date the transponder was read and the transponder's account status (valid or invalid). The information about the last time and date of the transponder's usage is shown to ensure that users are not disengaging their vehicle's transponders as they pass through the toll zone.

Since visual occupancy assessment by the police officer is still required to identify occupancy violations, the common problems associated with visual confirmation still exist in the MnPASS HOT facilities.

I-25 Express Lanes, Denver, Colorado

The I-25 Express Lanes in Denver consist of 7 miles between downtown Denver and US 36. The two-lane facility is barrier separated with shoulders on each side. All vehicles with more than one passenger, motorcycles, and buses can use the express lanes toll-free. As with other ETC facilities, a solo driver who wants to use the HOV lanes must install a transponder for automatic toll payment. The toll payment is based on self-declaration of vehicles by taking the designated access lanes according to their vehicle occupancy. When an SOV is approaching the toll collection zone, the vehicle must remain in the toll/express lane, otherwise, the vehicle will be ticketed. If the driver of a HOV with a transponder enters into the toll collection zone, the driver will be charged, regardless of the number of occupants. If the vehicle does not have a transponder, it will be issued a citation by mail.

Both electronic and manual enforcement techniques are used on the I-25 Express Lanes. At the toll collection zone, if any vehicle without a transponder passes through the toll/express lane, then the vehicle is declared as a "toll" violator. Since the toll is paid on a voluntary basis, the system inherently provides opportunities for HOV occupancy violation. In order to prevent the misuse of the HOV lanes, a police officer manually observes vehicle occupancy from the adjacent shoulder. If an SOV passes through the HOV lane, then the police officer stops the vehicle and issues a citation (Colorado DOT, 2009).

I-10 West and US 290 Houston

The lengths of the I-10 HOV lane and US 290 HOV lane are 13 and 14 miles, respectively. Both HOV lanes are one-lane, barrier-separated and located in the freeway median. When a 3+ occupancy requirement is in effect, two-person carpools equipped with a transponder can use the HOV lanes of the two corridors for $2. However, no solo driver is allowed to use the facilities.

Since the HOV lane has only one lane, limited enforcement strategies and locations are available. The transponder violation enforcement is also difficult. Because the location of the toll collection zone is far away from the enforcement area, police officers cannot check the validity of the transponder. Finally, the one-lane facility restricts the mobility of the police officers. Even if a police officer identifies a violator, it is difficult to issue a citation (Goodin, 2003).

SR-91 Express Lanes, Orange County, California

The SR-91 Express Lanes consist of two toll lanes in each direction located in the median of the highway, connecting the SR-55 interchange in Orange County and the Riverside/Orange County line. The lanes are separated from general purpose lanes by yellow pylons and a painted buffer, and they have no intermediate access or exit. Every vehicle using the facility pays a toll, except for vehicles with an occupancy of 3three or greater, which pay a half-price toll during congested hours only. Thus, all users must have valid transponders.

Toll violation enforcement is fully automated. When a vehicle without a valid transponder enters a toll plaza, a license plate recognition system photographs the license plate, allowing the California Highway Patrol to issue citations. The toll violation system recognizes a violator solely through the transponder signal, not by the number of occupants. Vehicle occupancy enforcement is performed by a police officer who assesses the number of occupants from an observation booth. Service patrol operators also assist in enforcement by recognizing violators at the tolling zone and then alerting downstream officers (Orange County Transportation Commission, 2009).

SR 167, Seattle, Washington

The HOT lanes on SR 167 in Seattle are composed of a single lane in each direction between Renton and Auburn. The enforcement scheme is similar to the one currently in operation on the I-15 Express Lanes in San Diego. The overhead transponder readers located near each access point flash a light when an SOV with a valid transponder appears. If the light does not flash, indicating an illegal entrance of an SOV, a state patrol officer will attempt to pull over the vehicle to the shoulder and issue a citation. Another enforcement scheme is the "HERO" program. The program encourages drivers to report HOV lane violators by e-mail or telephone. First-time violators receive an educational brochure. Second-time violators receive a letter from the Washington DOT. Third-time violators receive a letter from the Washington State Patrol (Washington DOT, 2009). Although these letters pose no legal consequences, they do raise the awareness of travelers.

I-95, Miami-Dade County, Florida

In July 2008, an 8-mile stretch of I-95 N in Miami-Dade County, connecting downtown Miami and the Golden Glades interchange, opened as an HOT facility. The southbound express lanes on that stretch of I-95 are scheduled to open in the fall of 2009. The HOT lane is separated from the general purpose lanes with lane candlestick markers. Currently, there is no access point in the middle of the lanes. Non-toll paying HOV users must register their vehicles at the South Florida Commuter Service to be exempt from the toll. Once they are registered, they receive a decal indicating a valid registration eligible for free use of the express lanes. SOV travelers must use a transponder.

As with the enforcement scheme of the I-15 Express Lanes in San Diego, enforcement beacons on a transponder reader gantry alert the Florida Highway Patrol when a vehicle without a valid transponder passes the gantry. The highway patrol then checks the vehicle occupancy and the validity of the registered decal. SOVs without a transponder or a vehicle with a decal that does not meet the minimum occupancy requirements will have their license plates photographed and the owners will receive an unpaid toll notice (Florida DOT, 2009).

In-Vehicle Occupancy Detection Technologies

In-vehicle occupancy detection systems have been developed primarily to support the safe deployment of airbags. Since the inappropriate position of occupants pose a risk of injury from airbag deployment, the controlled deployment of an airbag is necessary. As a consequence, the U.S. Federal Motor Vehicle Safety Occupant Crash Protection Standard now mandates the use of advanced or "smart" air bags in front seats of all new vehicles sold in the United States. To comply with the standards, manufacturers have developed in-vehicle technologies for occupancy detection, with many of these technologies already in production. A brief summary of in-vehicle systems is presented here.

Safety Belts

A safety belt is the most simple and basic device that has the potential for use in measuring vehicle occupancy. Its use is also monitored by a sensor integrated in the vehicle's electronics. A supplementary system that can monitor seatbelt movement over a period of time could be used as a measurement to confirm the occupancy of the seat.

However, the system does not guarantee precise measurement of vehicle occupancy. First, even though the seatbelt use is mandatory in most jurisdictions, seatbelt use still relies on individual action and 100% compliance has never been achieved. Second, it is highly likely that a pseudo-occupant can be placed in a seat with a seatbelt fastened (Schijns, 2004).

Weight Sensors

Weight sensors also hold potential for measuring vehicle occupancy. The occupancy is determined by measuring the force exerted on the seat with a weight sensor. The weight sensors are classified into two categories based on its location in the seat; cushion-based and frame-based sensors.

A cushion-based weight sensor system is usually implemented as an array of multiple sensor elements. By using the multiple sensor elements, the sensor can discern not only the total weight of the occupant but the pattern of the weight distribution. This information is helpful to differentiate adults, children or child seat and infer the occupant position (leaning forward or sitting back).

Frame-based systems incorporate strain sensors that are typically built into the seat mounting system to measure the weight of both the occupant and the seat. The strain sensors estimate the position of occupants by analyzing the weight distributions of loads.

Unfortunately, although weight sensors are incorporated in most vehicles, they are not well suited for occupancy monitoring given the ease of "tricking" the system by placing a large mass in a seat to mimic a human occupant.

Optical Systems

Video imaging optical systems use a vehicle compartment image for occupancy classification. A camera is located in the roof liner of the vehicle along the center line or on the rear-view mirror to capture the vehicle cabin image. An NIR (Near Infrared) illuminator is usually included to account for ambient lighting variations. To classify the cabin occupancy, the system takes two steps. First, a feature of human body is extracted from the raw image. Second, the vehicle occupancy is determined by applying an algorithm to the extracted image. Since the high accuracy of vehicle occupancy depends on the quality of the image of a vehicle cabin and the occupancy determination algorithm, the complexity of computational work and system design has been the major concern for a wide application of the system.

Capacitive Sensors

Capacitive sensors determine the vehicle occupancy by reading the change of the electromagnetic field when a dielectric (insulating) material is placed near or between the transmitter and the receiver sensor. Since the magnetic field is generated between a pair of sensors, the sensors are installed on the roof, on the dashboard, or under the surface of a seat. This technology exploits the fact that the human body, composed primarily of water, has a dielectric property approximately 80 times that of air. Therefore, a human body causes a significant change to the magnetic field and is easily discerned.

This technology can accurately discriminate many inanimate objects such as hats, newspapers, etc., since they have much lower dielectric constants than water. However, it is known that highly conductive materials such as metals can completely incapacitate the system making it “blind” (Schijns, 2004).

Ultrasonic/ Radar sensors

Ultrasonic sensors use the acoustic sound with frequencies above the range audible to human ears, to determine the presence of a human body. As the ultrasonic detection can be impaired by placing an extraneous reflecting object between the sensor and the occupant, at least four sensors should be used to insure the adequate coverage of the seating area and provide redundancy (Wikander, 2007).

Many challenges exist when applying the technology to vehicle occupancy detection. Bandwidth and intensity of the ultrasonic sound should be selected to avoid unwanted reflection, acoustical interference is frequent, and there is concern about exposure levels for people and animals (Wikander, 2007). However, accuracy levels of this technology appear to be acceptable for HOV monitoring purposes (Schijns, 2004).

Smart Cards and Readers

Items such as personal identity cards, driver’s licenses, transit passes, toll transponders or cellular phones could conceivably be used for the purpose of HOV occupancy monitoring. These devices may be read, in-vehicle, and then communicated with the roadside via dedicated short-range communication (DSRC) (Schijns, 2004). A count of unique "identities" (through licenses, passes, etc.) would then serve as a surrogate for vehicle occupancy.

Roadside Occupancy Detection Technologies

Video Systems

Some infrastructure-based video systems have been tested at HOV facilities. However, the performance of the video systems has proven to be inadequate for vehicle occupancy verification (Wikander, 2007).

Several different camera configurations were tested for monitoring vehicle occupancy on facilities in Southern California. Test results were not satisfactory. False alarm rates ranged from 21% to 51%. The study concluded that small children and sleeping adults largely contributed to the unacceptable false alarm rate (Wikander, 2007).

Another attempt to test the capability of video systems was implemented on I-30 in Dallas, Texas. The system called HOVER (High Occupancy Vehicle Enforcement and Review) successfully captured vehicle compartment images on 97% of all vehicles. However, on average, occupancy could be measured in only 85% of all vehicles (Turner, 1999).

Infrared Systems

The most distinctive advantage of offered by infrared systems is the ability to operate regardless of light conditions. However, the infrared system has the same disadvantages as video systems when the infrared rays are blocked by vehicle parts such as tinted glass, or when small children and sleeping adults are positioned in rear seats of vehicles. To overcome the disadvantage of the standard infrared systems, multi-band infrared systems which use NIR imagery were developed. The Minnesota DOT and U.K. Department of Environment, Transport, and the Regions developed their own automated vehicle occupancy camera systems that exploit the infrared reflection characteristics of human skin. The system developed by the Minnesota DOT uses two infrared bands to generate a different image, which could isolate the signature of human skin from that of inanimate objects. The Cyclops system developed in the U.K. employs the combination of visible and NIR images to contrast human skin with surrounding objects.

The field test for the system of the Minnesota DOT was successful. The vehicle occupancy was correctly measured in all cases. However, the field test was limited to the front seat occupants and the speed was constant at 50 mph at all times. Testing for the Cyclops system was conducted on the U.K's first HOV lane (on A467 in Leeds) in 2005. The system was reported to successfully detect the entire vehicle occupancy with a 95% accuracy rate (Wikander, 2007). However, to date, no independent testing of the system has been documented in the literature. An estimated cost of this technology is on the order of $170,000 per single lane.

Passive Microwave Systems

As with the infrared systems that exploit the signature of human skin, the passive microwave systems use natural radiation emitted and reflected by the environment. Passive microwave systems detect emissions through plastic and other thin, non-conductive material using longer wavelengths in microwave spectrum than infrared thermal imagers. The cost and its size are the most noticeable disadvantage of the system and the slow image processing speed for receiving sufficient amounts of microwave energy is another shortcoming (Wikander, 2007).

Impact of Penalties on Violation Rates

Although enforcement of occupancy restrictions is an important component of HOV/HOT operations, the penalty that violators face is also a factor in violation rates on HOV/HOT facilities. A recent national study found that the highest violation rates were primarily found on HOV facilities in San Diego and the Washington, D.C., metropolitan region (Chang et al., 2008). However, when consulting the national HOV facility inventory, it is also evident that these areas have some of the highest HOV violation penalties in the nation. Thus, there is no clear direct relationship between violation rate and penalty.

Another important factor lies in the adjudication process. If there is a reasonable likelihood that a violator will have the penalty negated by a judge, the deterrence is reduced (Wikander and Goodin, 2008). Anecdotal evidence in Northern Virginia suggests that the complexity of the HOV facilities in the region (Dulles Airport exemption, different occupancy restrictions by facility) has resulted in penalties frequently being reduced or eliminated in the adjudication process.

Impact of Violation Enforcement on Violation Rates

In order to assess the impact of enforcement on occupancy violation rates, the research team worked with the Virginia State Police to identify dates planned for saturation enforcement. The team collected violation rate data prior to the enforcement, immediately after the enforcement, and 1 week after enforcement.

In order to collect HOV violation information, a two-person data collection team manually observed vehicle occupancy from overpasses on I-66 and I-395. This viewpoint allowed the team to determine if a vehicle met occupancy restrictions for the facility. For 45-min periods, during both the morning and afternoon peaks, one person counted violators while the other person counted total vehicles.

Virginia allows hybrid vehicles to use HOV facilities with only one occupant. The team did not attempt to distinguish hybrid vehicles from others—thus resulting in a number of false-positive violator identifications. This was deemed acceptable since the objective of the research was to examine the difference in HOV violation rates before/after saturation enforcement. It was reasonable to assume that the overall HOV fleet would not change appreciably before/after enforcement, so the difference in violations would be representative. However, the reader should be cautioned not to directly use the "violation rates" reported for individual peak periods, since the measure is biased high.

Schedule and Locations of Enforcement Operation and Data Collection

I-66

The enforcement operation on I-66 was conducted for the exclusive HOV portion inside the Capital Beltway on March 24, 2008. The research team collected data on the Barbour Road Bridge as illustrated in Figure 1 on March 17, March 25, and April 2.

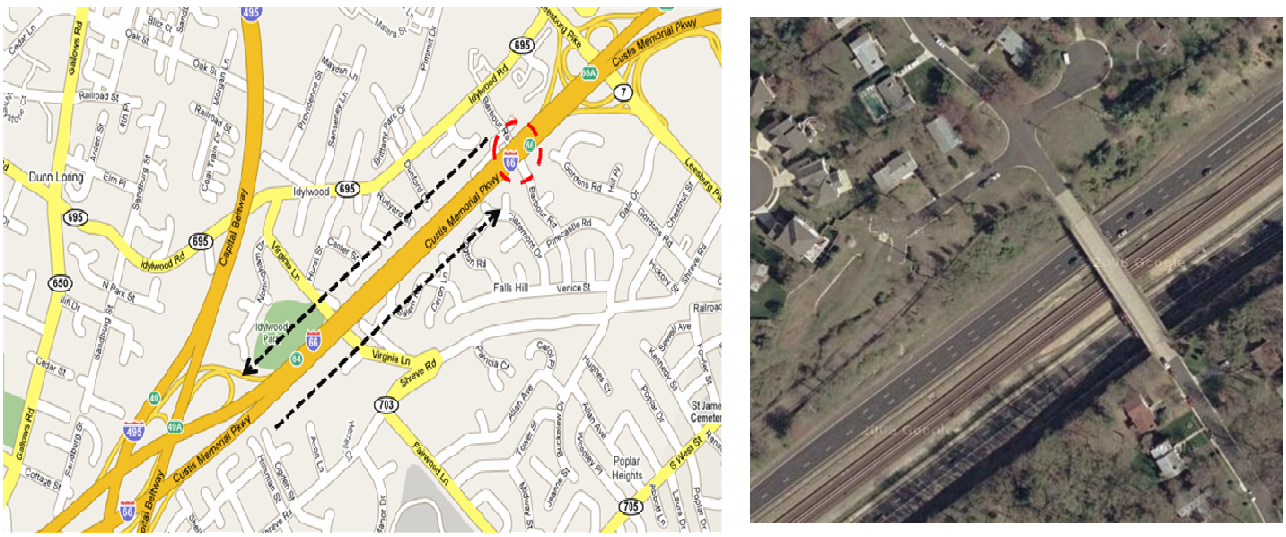

Figure 1. Data Collection Site – I-66 (dashed arrows indicate location of police enforcement)

I-395

The enforcement operation on I-395 was conducted on the reversible HOV portion inside the Capital Beltway on May 5, 2008. The research team collected data on the South Abingdon Street Bridge as illustrated in Figure 2 on May 2 and May 7. The third data collection effort was canceled because of the results obtained on the May 7 data collection.

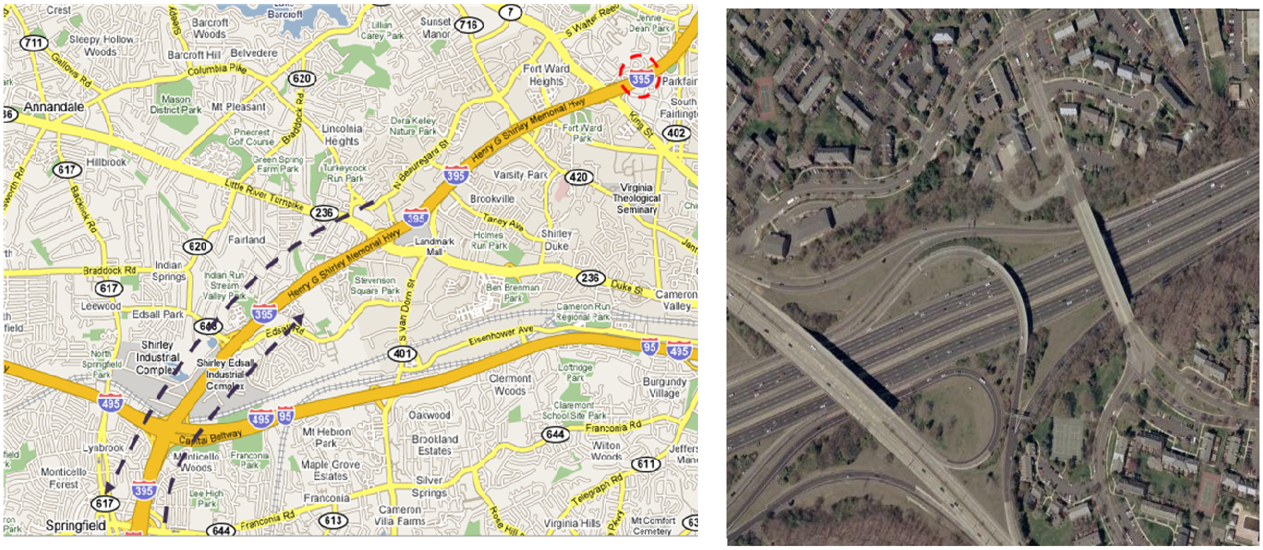

Figure 2. Data Collection Site – I-395 (dashed arrows indicate location of police enforcement)

Violation Rates

I-66 HOV

On March 24, 2008, the Virginia State Police issued 205 HOV violation citations, along with 45 other violations, during the saturation enforcement effort. Table 1 presents the violation data collected prior to the enforcement, on March 17, and after the enforcement on March 25 and April 2 for the AM and PM peak periods.

Table 1 shows that the saturation enforcement did not result in a reduction in the HOV violation rate. In fact, the rate rose slightly following the enforcement operation. Another important item to note is that the amount of time following enforcement does not have an impact on violation rates. Based on these empirical data, it is clear that the enforcement operation on March 24 did not significantly deter violators of HOV occupancy restrictions on I-66.

Table 1. HOV Violation Rates – I-66

	March 17 (Prior to Enforcement)	**March 25 (1 Day After Enforcement)**	**April 2 (9 Days After Enforcement)**
AM Peak	23%	26%	28%
PM Peak	28%	28%	28%
Daily Average	25.5%	27%	28%

I-395 HOV

On May 5, 2008, the Virginia State Police issued 93 HOV violation citations, along with 97 other violations, during the saturation enforcement effort during the AM and PM peak periods. Table 2 presents the violation data collected prior to the enforcement, on May 2, and after the enforcement on May 7 for the AM and PM peak periods.

Table 2. HOV Violation Rates – I-395

	May 2 (Prior to Enforcement)	May 7 (2 Days After Enforcement)
AM Peak	20%	19%
PM Peak	22%	19%
Daily Average	21%	19%

As was the case on I-66, Table 2 clearly shows that the saturation enforcement had very little impact on HOV violation rates on I-395. Although a 2% average decrease in the violation rate was observed, given the limitations of the data collection methodology (i.e., hybrid vehicles were not “extracted” from violators), such a small difference may or may not truly indicate an impact of enforcement. Given such a small impact, the research team decided not to invest the necessary resources into a second, post-enforcement data collection effort to investigate the longer term effect.

This large-scale field data collection effort demonstrated that saturation enforcement of HOV regulations had little to no impact on HOV occupancy violation rates on I-66 and I-395 in Northern Virginia.

Development of Method to Evaluate Impact of Violation Enforcement Techniques on the Operations of HOV/HOT Lanes

In this task, the research team focused on the development of a detailed evaluation methodology to use in assessing the impact of violation enforcement techniques on the operations of HOV/HOT lanes. The use of this methodology will allow VDOT to assess the likely impact of any enforcement technique/technology on the operation of the facility itself, prior to implementation.

The research team chose to use microscopic traffic simulation as the foundation for the evaluation methodology. This provides the ability to consider vehicle interactions that frequently result from enforcement (such as weaving)

Development of Evaluation Methodology

Two basic scenarios were considered in the evaluation methodology: traditional manual enforcement, and enforcement using automation technology. The following section explains how the enforcement techniques were modeled within the microscopic simulation.

Manual Enforcement

Since manual enforcement is conducted on either the mainline HOV/HOT facilities or entrance/exit ramps, these two enforcement areas were considered explicitly in this evaluation methodology. The conceptual locations of those two areas are depicted in Figure 3.

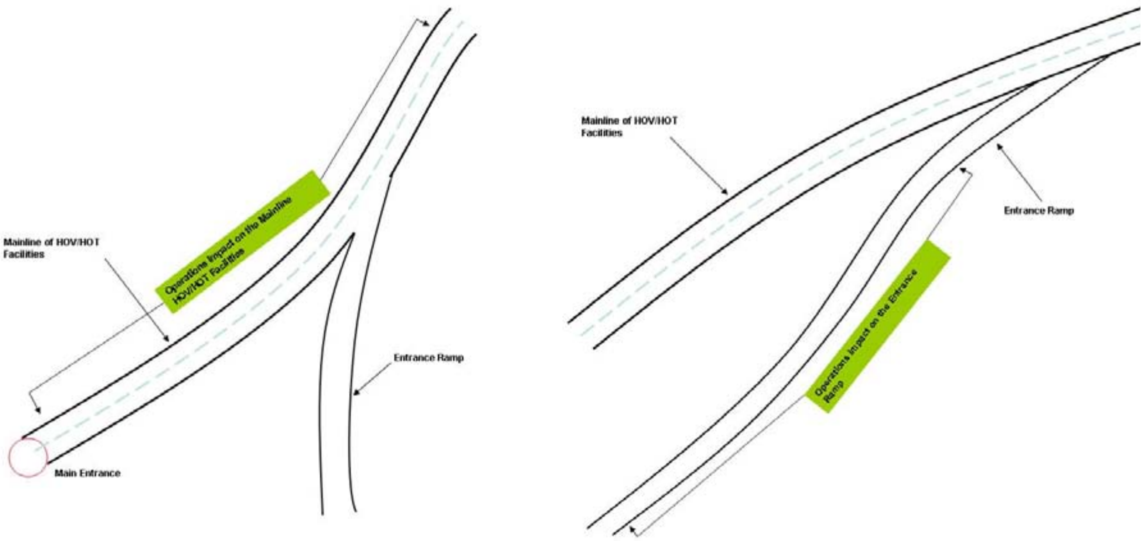

Figure 3. Enforcement Areas of Manual Enforcement

Interference caused by manual enforcement can be categorized into two parts: direct and indirect impact. This classification is based on the level of engagement of enforcement vehicles on the traffic flow of the HOV/HOT facilities. The patrol vehicle's movement to escort the violators to the shoulder directly impacts the traffic flow of the facilities. On the other hand, even though direct interaction does not exist, the traffic flow will be affected when a vehicle is stopped by a patrol vehicle on the shoulder. The incident that blocks the shoulder while a summons is issued can be regarded as an indirect impact. The following sections describe how these impacts of manual enforcement are simulated.

Direct Impact

The research team divided manual enforcement into four phases, based on the major activities of a patrol vehicle engaged in manual enforcement.

Phase 1: Monitoring the vehicle occupancy to identify suspect vehicles. At this stage, the enforcement officers monitor vehicle occupancy to find the suspected vehicles. The enforcement officers are usually stationed on a shoulder to visually "check" vehicles. Since the impact incurred by the activity of monitoring is negligible, the first stage of manual enforcement is not modeled in the simulation.

Phase 2: Identify and pursue the suspected vehicles. In the simulation model, if there is a violating vehicle within 100 feet of the patrol vehicle (to represent the visual range), the patrol vehicle begins to pursue the suspected vehicle by accelerating or decelerating to approach the target vehicle. The acceleration rate and deceleration rate of the patrol vehicle are based on the distance of the two vehicles, and each vehicle's speed. The acceleration rate and deceleration rate are determined by the following equations.

Acceleration rate $= \dfrac{(speed_{violator} \times time + dist - speed_{patrol} \times time) \times 2}{time^2}$

Deceleration rate $= \dfrac{(dist - speed_{patrol} \times time + speed_{violator} \times time) \times 2}{time^2}$

where

$dist$ = distance between the target vehicle and the patrol vehicle

$Speed_{violator}$ = speed of suspected vehicle

$Speed_{patrol}$ = speed of patrol vehicle

$time =$ time limit for pursuing the suspected vehicle.

Phase 3: Pull over violators. When the patrol vehicle closes to within a 20-foot radius of the suspected vehicle, the patrol vehicle begins to pull the suspected vehicle to the shoulder.

Phase 4: Issue the citations and release the apprehended vehicles. Once the violator is escorted onto the shoulder by the patrol vehicle, the enforcement officer issues a citation and releases the violator. In the simulation, the operations impact caused by issuing a citation is considered an incident, which influences the traffic flow. The duration of the incident is determined though a stochastic process which randomly produces the time based on a normal distribution with a mean of 5 min and a standard deviation of 1.5 min. At the completion of the citation, both vehicles then attempt to merge back into traffic.

Indirect Impact

According to previous research that estimated the capacity reduction incurred by blocking the shoulder, the capacity reduction of the mainline ranges from 19% to 33% (Smith and Qin, 2003). The average of those capacity reduction rates (26%) is applied to the HOV lanes while issuing a citation on the shoulder is simulated.

The simulation tool used in this research, VISSIM, does not reduce lane capacity when a shoulder is blocked. Thus, in order to achieve 26% capacity reduction, severe congestion on one HOV lane was created by forcing a randomly selected vehicle to decelerate significantly while a police officer issues a citation on the adjacent shoulder. Various speeds were examined to reach the appropriate speed of the randomly selected vehicle that could result in the required capacity reduction. Table 3 shows the capacity reduction rates corresponding to the speed of randomly selected vehicle.

HOV/HOT Facilities with Automation Technology

The most technically advanced enforcement techniques require occupancy "filtering" prior to entering an HOV/HOT facility. In other words, vehicles must weave to a specified lane.

Randomly Selected Vehicle Speed (mph)	Capacity per Lane	Reduced Capacity	Capacity Reduction
0	2,162	1,161	46%
6.8	2,162	1,239	43%
10.2	2,162	1,370	37%
13.6	2,162	1,643	24%

Table 3. Capacity Reduction Rates Corresponding to Speed of Randomly Selected Vehicle

Thus, it is highly likely that adverse impacts on traffic flow resulting from weaving will result. Figure 4 illustrates this concept.

The need for drivers to select appropriate lanes according to their vehicles' occupancy results in significant lane changing behaviors upstream of the entrance of HOT lanes. By designating a certain lane to a specific class of vehicles (HOV or LOV) near an entrance of a toll plaza, the lane changing behavior can be emulated within the microscopic simulation.

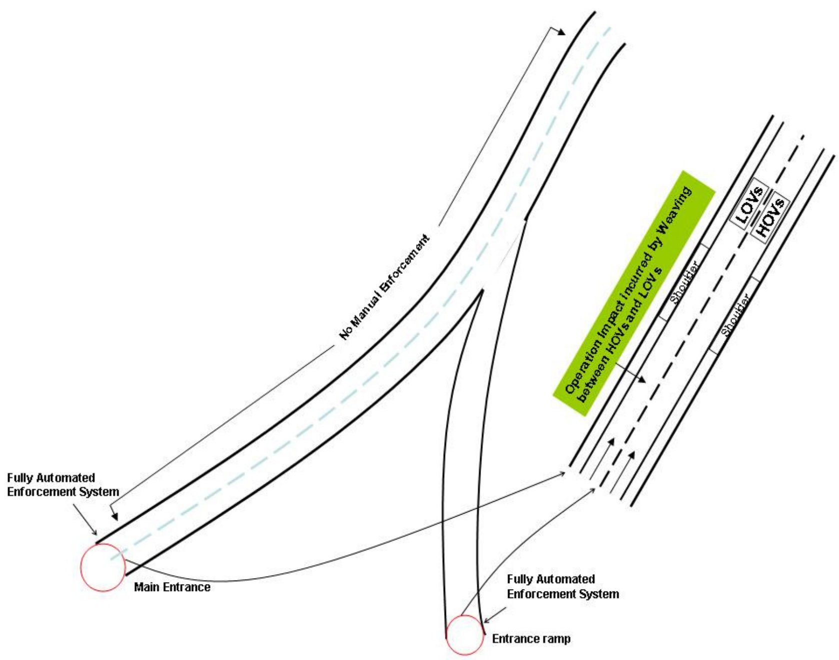

Figure 4. A Location of Enforcement with Automation

Example Application of Manual Enforcement

This section presents an example application of the methodology. The HOV facilities of I-95 and I-395 inside the Capital Beltway in Northern Virginia were selected as the study network.

In order to investigate the delay trajectory corresponding to the demand increase, the original demand (obtained from VDOT sensors) was increased in 10% increments. As shown in Table 4 and Figure 5, the delay caused by manual enforcement does not become noticeable until

Table 4. Delay Increase Corresponding to Demand Increase

Demand Increase (%)	Original Demand	10%	20%	30%	40%
Delay without enforcement (seconds/vehicle)	31.66	42.39	68.78	108.34	161.03
Delay with enforcement (seconds/vehicle)	42.61	55.27	84.71	128.69	209.86
Number of Passing HOV users	5,538	6,092	6,636	7,198	7,755

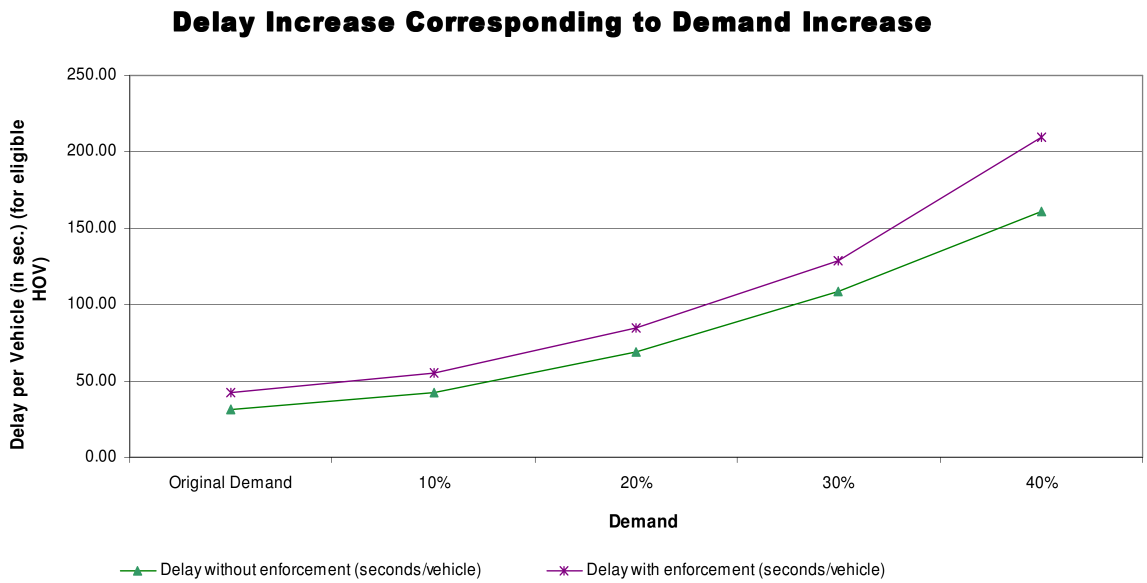

Figure 5. Delay Increase Corresponding to Demand Increase

the demand is increased beyond 20%. When the demand increases over 20%, the slope of the delay curve begins to increase. The amount of delay was doubled while demand was increased by only 30%.

One way the methodology may be of use is in planning enforcement efforts. For example, when considering the number of enforcement officers to devote to an enforcement operation, it is also important to understand the varying operations impacts. Using the proposed methodology with different numbers of enforcement officers, a delay curve is developed. The total number of attempts to issue citations is computed by multiplying the number of deployed officers by the number of maximum attempts attainable by one officer during a total of 3 hours of morning-peak HOV operation. The time for one attempt is assumed as 20 minutes. Table 5 and Figure 6 show the simulation results.

Table 5. No. Enforcement Officers and Delay

No. deployed officers	2	4	6	8	10
Total no. attempts for enforcement	18	36	54	72	90
No. citation issued	15	32	48	61	81
Delay (secs/veh)	7.81	18.54	30.71	33.13	42.98
Average speed (mph)	58.79	57.03	55.00	53.98	52.36

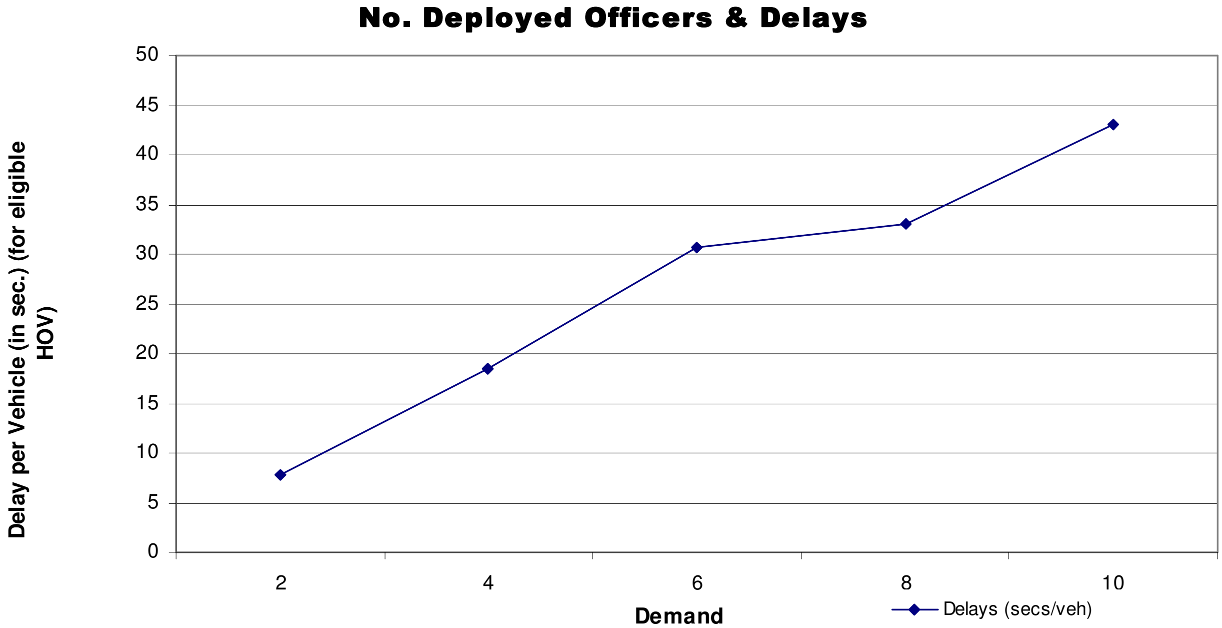

Figure 6. Number of Deployed Officers

Example Application of Enforcement with Automated Technologies

According to the proposal for the I-95/395 BRT/HOT system, the entrance to the existing HOV lanes Northbound at Quantico Creek will be used as a northbound access to the HOT lanes when the I-95 HOV lane is converted into HOT lanes in 2013. A 1.5-mile-long buffer area is provided upstream of the HOV entrance to ease the lane changing impact. Thus, this entrance is an appropriate site for examining the impact of weaving and diverging of approaching vehicles to HOT facilities. Figure 7 shows the configuration of the study network.

The delay experienced by each user group (HOV and SOV) is shown in Table 6 and Figure 8. In order to measure the negative impact of vehicles' lane changing behaviors under different total demand, the total demand is increased by 10% increments. As one might expect, the delay increases while the demand grows. SOVs undergo less delay than HOVs who have to pass through one designated lane with more demand.

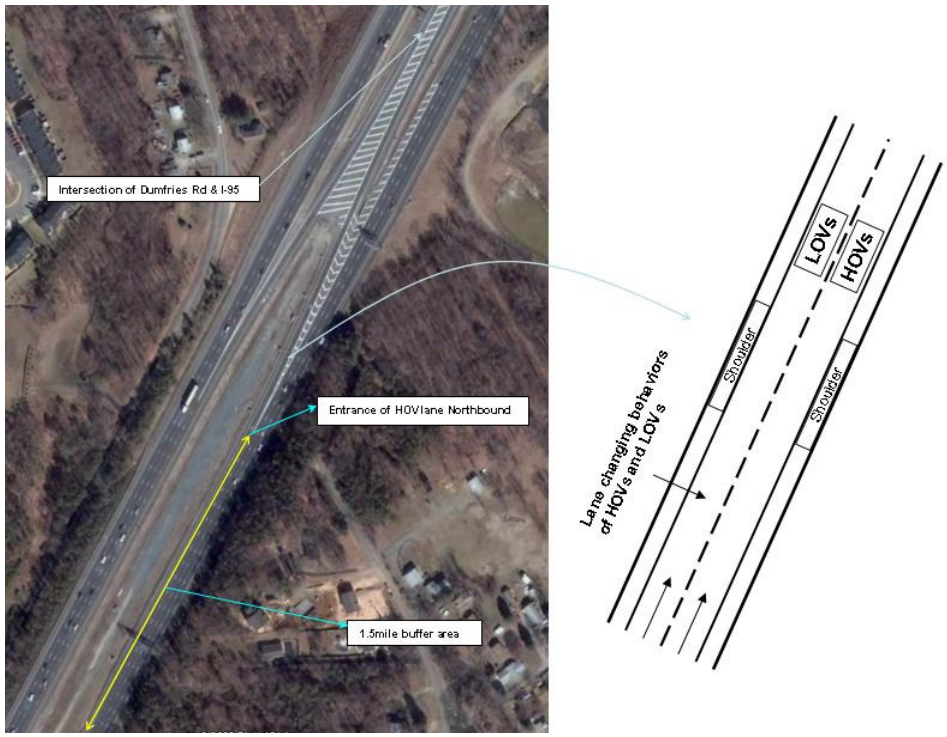

Figure 7. Study Network Configuration

Table 6. Delay Change Incurred by Lane-Changing Behavior

Demand increase (%)	**Original Demand**	**10%**	**20%**	**30%**
Delay caused by Lane Changing Behavior For HOV (seconds/vehicle)	3.88	4.50	5.28	6.11
Delay caused by Lane Changing Behavior For SOV (seconds/vehicle)	2.78	3.24	3.92	4.56

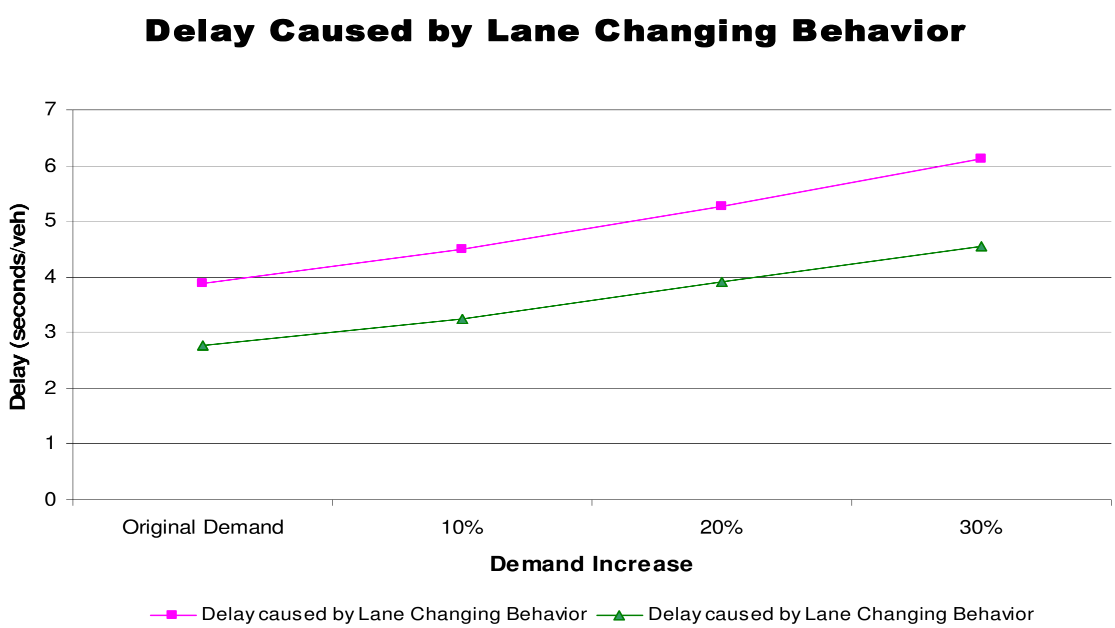

Figure 8. Delay Incurred by Lane-Changing Behavior

CONCLUSIONS

- *This research effort clearly documents the significant challenge of enforcing occupancy restrictions in HOV/HOT facilities. The literature review identified many alternative approaches to enforcement, both technical and non-technical. However, the review also revealed that all currently feasible approaches still require a manual enforcement component, and that although the use of toll tag technology may help enforcement, it alone will not provide sufficient enforcement effectiveness. Further, the violation penalty structure has not proven to be an effective deterrent.*

- *The results of the field evaluation of manual enforcement in Northern Virginia revealed that the current practice of infrequent saturation enforcement is not proving effective in reducing the proportion of HOV occupancy violators.* Despite the allocation of significant enforcement resources, the violation rate remained essentially constant after the enforcement operation.

- *The simulation-based enforcement evaluation methodology developed and demonstrated in this report will provide VDOT and the Virginia State Police with a tool that may be used in planning future enforcement techniques and technology.* The method allows the operational impact of enforcement to be estimated.

RECOMMENDATIONS

1. *For the foreseeable future, VDOT should plan to support the use of manual enforcement as there is no proven technology that completely supports automated occupancy enforcement.*

2. *The HOV Enforcement Task Force should propose specific changes to reduce the ambiguity and complexity of HOV operations in Northern Virginia.* This should include eliminating the Dulles Airport business exemption and setting a single occupancy rate for all HOV facilities. Adjudication of HOV occupancy violation cases plays an important role in violation rates.

3. *VDOT's Operation and Security Division (OSD) should work with the Virginia State Police to institute regular, consistent enforcement methods to provide a continual deterrent from violating occupancy restrictions. Changed procedures should be evaluated after implementation to quantify their effectiveness.* The current practice of infrequent saturation enforcement is not effective in preventing HOV occupancy violations.

4. *VDOT's OSD and the Virginia State Police should use the evaluation methodology developed in this report to plan future regular, consistent manual enforcement methods recommended in Recommendation 3.*

5. *VDOT's OSD should use the evaluation methodology developed in this report to evaluate new automated enforcement systems (as they become available) when considering their implementation.*

6. *VDOT should continually scan available technologies and systems to identify automated systems that hold the potential to enforce occupancy restrictions effectively.*

7. *The HOV Enforcement Task Force should explore the option of banning vehicles with two or more HOV violations through the use of toll tag transponders.* Given that the new HOT facilities in Northern Virginia will require all travelers on the facilities, both HOV and SOV, to be equipped with a transponder, this provides the opportunity to identify habitual offenders automatically. With enabling legislation to ban previous violators, this may serve as a much more powerful deterrent than is currently available.

BENEFITS AND IMPLEMENTATION PROSPECTS

The primary benefit of this research is that it provides VDOT with information to guide future occupancy enforcement methods on HOV and HOT facilities. Minimizing vehicle occupancy violation on HOV/HOT facilities is of significant importance to ensure that all available capacity is devoted to eligible travelers and to inspire confidence in system users. The information from the literature review, information on the effectiveness of current methods, and the evaluation methodology in this report are essential ingredients to help VDOT improve enforcement strategies.

The next steps to achieve the benefits of this work are for VDOT's OSD, in cooperation with the operations regions and the Virginia State Police, to revise current manual enforcement methods. The revision should utilize the evaluation methodology developed and demonstrated in this research.

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