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16. Abstract

Limited capital investment for major transportation improvements and growth in metropolitan areas require the most efficient use of the existing transportation system. Provisions of the Clean Air Act Amendments and TEA21 further intensify these concerns. One means to improve mobility is high-occupancy vehicle (HOV) lanes. Although HOV lanes have been shown to be very successful in Texas, they have been met with skepticism in several areas across the country. Public criticism of HOV lanes in two corridors in New Jersey (IH-287 and IH-80) led to their closure. In the wake of the actions of New Jersey, legislation has been introduced in California to limit the implementation of new HOV lanes and to potentially remove existing HOV lanes. Inappropriate data, such as vehicle volumes, are used as a basis for removing the facilities. The states of Colorado, Virginia, and Georgia have also proposed legislation to either eliminate HOV lanes or convert them to high-occupancy toll (HOT) lanes. While some of the claims against HOV lanes may be justified, a need exists to evaluate new HOV lanes implemented in the Dallas area as well as to continue an evaluation of existing HOV lanes.

While developers plan an extensive system of permanent HOV lanes for the Dallas-Fort Worth urbanized area, the Texas Department of Transportation (TxDOT) and Dallas Area Rapid Transit (DART) have pursued and continue to pursue short-term or interim HOV lane projects that would enhance public transportation and overall mobility. There are currently 48.2 miles of interim HOV lanes operational in the Dallas area, including a barrier-separated contraflow HOV lane on East R.L. Thornton Freeway (IH-30), buffer-separated concurrent flow HOV lanes on Stemmons Freeway (IH-35E North) and Lyndon B. Johnson Freeway (IH-635), and a barrier-separated reversible flow HOV lane on South R. L. Thornton (IH-35E South) connected to a buffer-separated concurrent flow HOV lane on Marvin D. Love (US-67). The objective of this research is to investigate the operational effectiveness of the Dallas area HOV lanes. Issues such as person movement, carpool formation, travel time savings, violation rates, safety, and project cost effectiveness are addressed. By understanding the operational performance and issues of both buffer-separated (concurrent flow) HOV lanes and barrier-separated (movable barrier contraflow or fixed barrier reversible flow) HOV lanes, recommendations can be made on suggested HOV lane implementation guidelines for the Dallas area.

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AN EVALUATION OF DALLAS AREA HOV LANES, YEAR 2002

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I. INTRODUCTION

Limited capital investment for major transportation improvements and growth in metropolitan areas require the most efficient use of the existing transportation system. Provisions of the Clean Air Act Amendments and TEA21 further intensify these concerns. One means to improve mobility is high-occupancy vehicle (HOV) lanes. The concept of an HOV lane is to increase the person-carrying capacity of freeways by providing dedicated lanes for multi-occupant vehicles. By doing so, one HOV lane can serve the travel needs of more people than a freeway lane, thereby increasing the efficiency of the entire system. While a variety of types of HOV lanes have been designed and implemented, a number of issues must be considered for an efficient and effective HOV facility.

BENEFITS OF HIGH-OCCUPANCY VEHICLE LANES

Implementing an HOV lane in a corridor can provide a number of benefits. Some of these benefits include:

<u>Travel time savings for eligible vehicles.</u> Multi-occupant vehicles in the HOV lane are able to bypass the congested "stop-and-go" traffic in the general-purpose lanes.

<u>Trip time reliability for eligible vehicles.</u> The travel speed in an HOV lane is generally near free-flow, which does not cause much variation in the day-to-day travel times on an HOV lane. The travel time, however, in congested conditions on general-purpose lanes can vary greatly from day to day, particularly when incidents occur on the freeway.

<u>Increased person throughput.</u> HOV lanes are an incentive for motorists to form carpools or ride transit buses to utilize the HOV lane benefits. With more occupants in fewer vehicles, the number of people commuting in a freeway corridor can increase.

<u>Reduced fuel consumption and decreased vehicle emissions.</u> The addition of an HOV lane in a corridor allows for free-flow travel for buses and other eligible vehicles who use the lane. In general, with an increase in vehicle speeds from the stop-and-go congested conditions, a reduction in fuel consumption and vehicle emissions results.

<u>Reduced bus operating costs.</u> Transit service convenience can be measured in terms of adherence to a predetermined schedule and the time between buses (bus headways). If buses must travel in congested corridors, the time between consecutive buses can vary greatly from day to day.

HOV lanes reduce the daily variance in time between consecutive buses and may even reduce the number of buses needed on a particular route because of a reduction in trip time.

Increased efficiency for the entire system. As commuters from the general-purpose lanes form carpools or ride buses to obtain the benefits of the HOV lane, excess capacity will exist on the general-purpose lanes. Vehicles that had diverted to arterial streets to avoid the congestion on the freeway may divert back to the freeway. The transfer of vehicles from the general-purpose lanes to the HOV lane and from the arterial streets to the freeway (general-purpose lanes and HOV lane) increases the efficiency of the road system.

IMPLEMENTATION OF HOV LANES IN THE DALLAS AREA

An extensive system of permanent HOV lanes is planned for the Dallas-Fort Worth urbanized area. The North Central Texas Council of Governments (NCTCOG) Mobility 2020 Plan, the long-range transportation plan for the Dallas-Fort Worth area, recommends 225 center-line miles of HOV lanes. Until these permanent treatments can be implemented, the Texas Department of Transportation (TxDOT) and Dallas Area Rapid Transit (DART) have been and continue to pursue short-term or interim HOV lane projects that would enhance public transportation and overall mobility. FHWA considers these projects to be interim projects because they have been retrofitted into the existing freeway facility, resulting in design exceptions from normally required standards.

Figure 1 shows the 54.2 lane-miles of interim HOV lanes that are currently operational in the Dallas area while Table 1 includes the details related to these HOV lanes. A 5.2 mile interim barrier-separated contraflow HOV lane on East R.L. Thornton Freeway (IH-30) opened in September 1991 (Figure 2) while interim buffer-separated concurrent flow HOV lanes opened on Stemmons Freeway (IH-35E North) in September 1996 (Figure 3). The northbound HOV lane is 5.6 miles in length, and the southbound HOV lane is 7.3 miles in length. Interim buffer-separated concurrent flow HOV lanes also opened on Lyndon B. Johnson Freeway (IH-635) in March 1997 (Figure 4). The eastbound HOV lane is 6.7 miles in length and the westbound HOV lane is 6.2 miles in length. Interim buffer-separated concurrent flow HOV lanes opened on Marvin D. Love (US-67) in March 2000 (Figure 5). The southbound and northbound HOV lanes are 2.5 miles in length. In March 2002, an additional section of interim reversible flow HOV lane was opened which ties into the US-67 concurrent flow lanes. The additional section, located on South R.L. Thornton Freeway

(IH-35E South) at the merge with US-67, is a barrier-separated reversible flow HOV lane 6.5 miles in length.

Table 1. Interim HOV Lanes Operating in the Dallas Area.

Corridor	**IH-30 (ERLT)**	**IH-35E North (Stemmons)**	**IH-635 (LBJ)**	**US-67 (Love) / IH-35E South (SRLT)**
Type of Facility	Contraflow	Concurrent Flow	Concurrent Flow	Concurrent Flow (US-67) Reversible Flow (IH-35E)
Opening Date	September 1991	September 1996	March 1997	March 2000 (US-67) March 2002 (IH-35E)
Hours of Operation	6 - 9 AM, 3:30 - 7 PM	24 Hour	24 Hour	24 Hour (US-67) 6 - 9 AM (IH-35E) 3:30 - 7 PM (IH-35E)
Length	5.2 miles EB 5.2 miles WB	5.6 miles NB 7.3 miles SB	6.7 miles EB 6.2 miles WB	2.5 miles NB (US-67) 2.5 miles SB (US-67) 6.5 miles NB (IH-35E) 6.5 miles SB (IH-35E)
Construction Cost (M$)	$17.4M[1]	$9.9M[2]	$16.3M	$18.5M (US-67) $26.0M (IH-35E)
O&E Cost (M$)	$0.6M	$0.2M	$0.2M	$0.3M
Eligibility	Buses, vanpools, 2+ occupant carpools, motorcycles			

Notes:
[1] Includes $12.2M HOV lane construction, $0.2M AM auxiliary lane, and $5.0M PM extension.
[2] Includes a reversible HOV ramp through the IH-635 interchange.

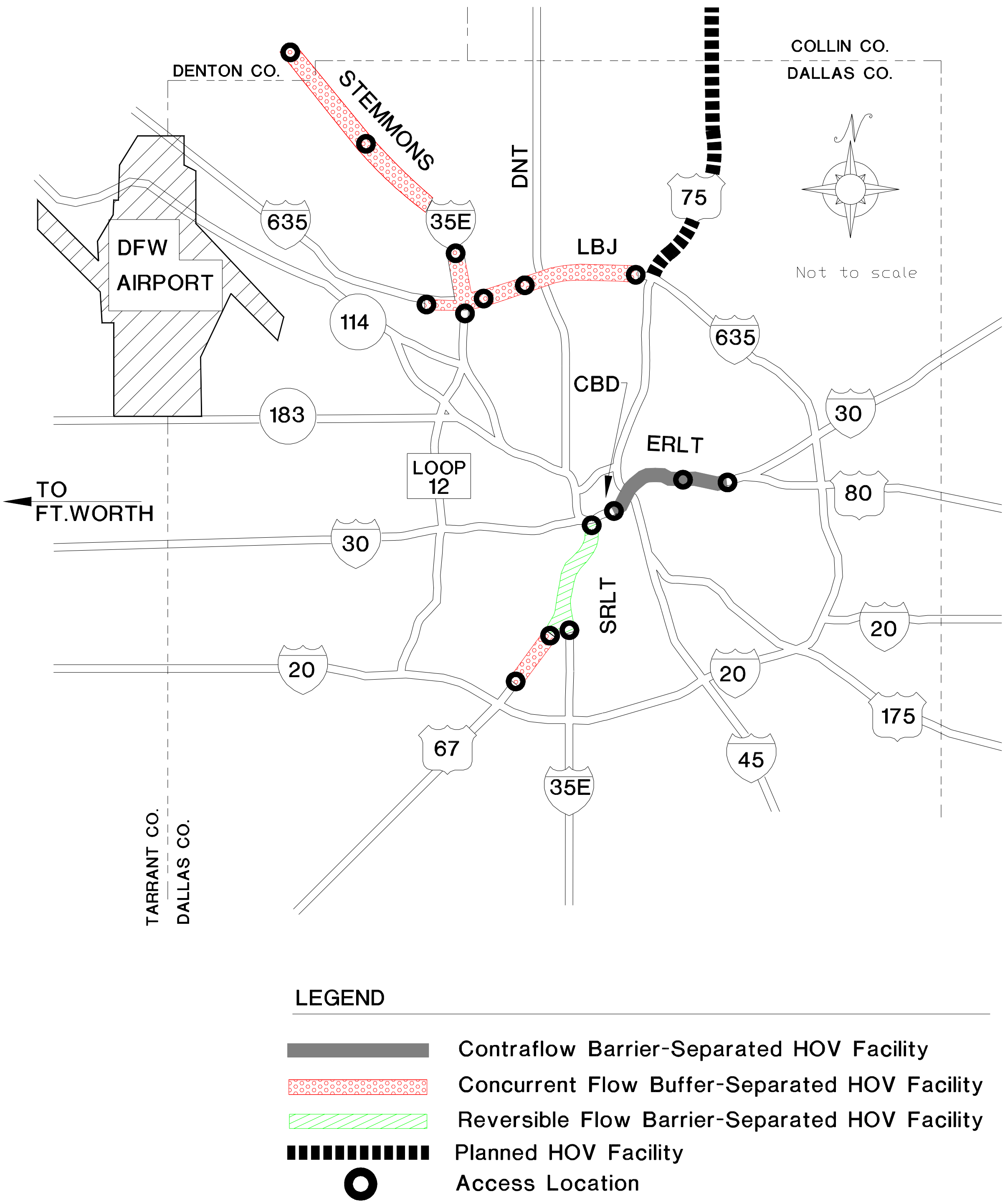


Figure 1. Dallas Area HOV Lanes.

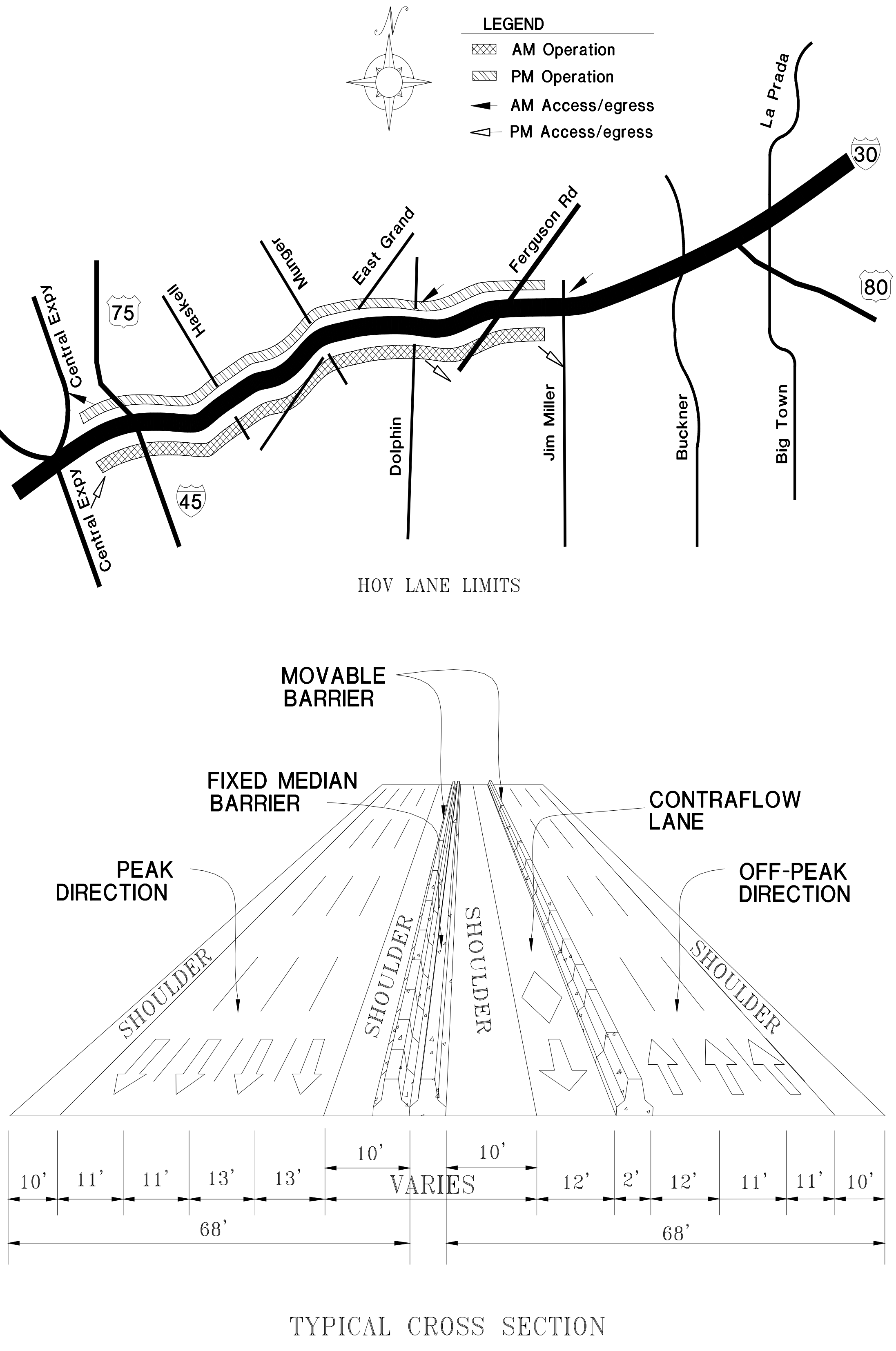


Figure 2. IH-30 (ERLT) Freeway HOV Lane.

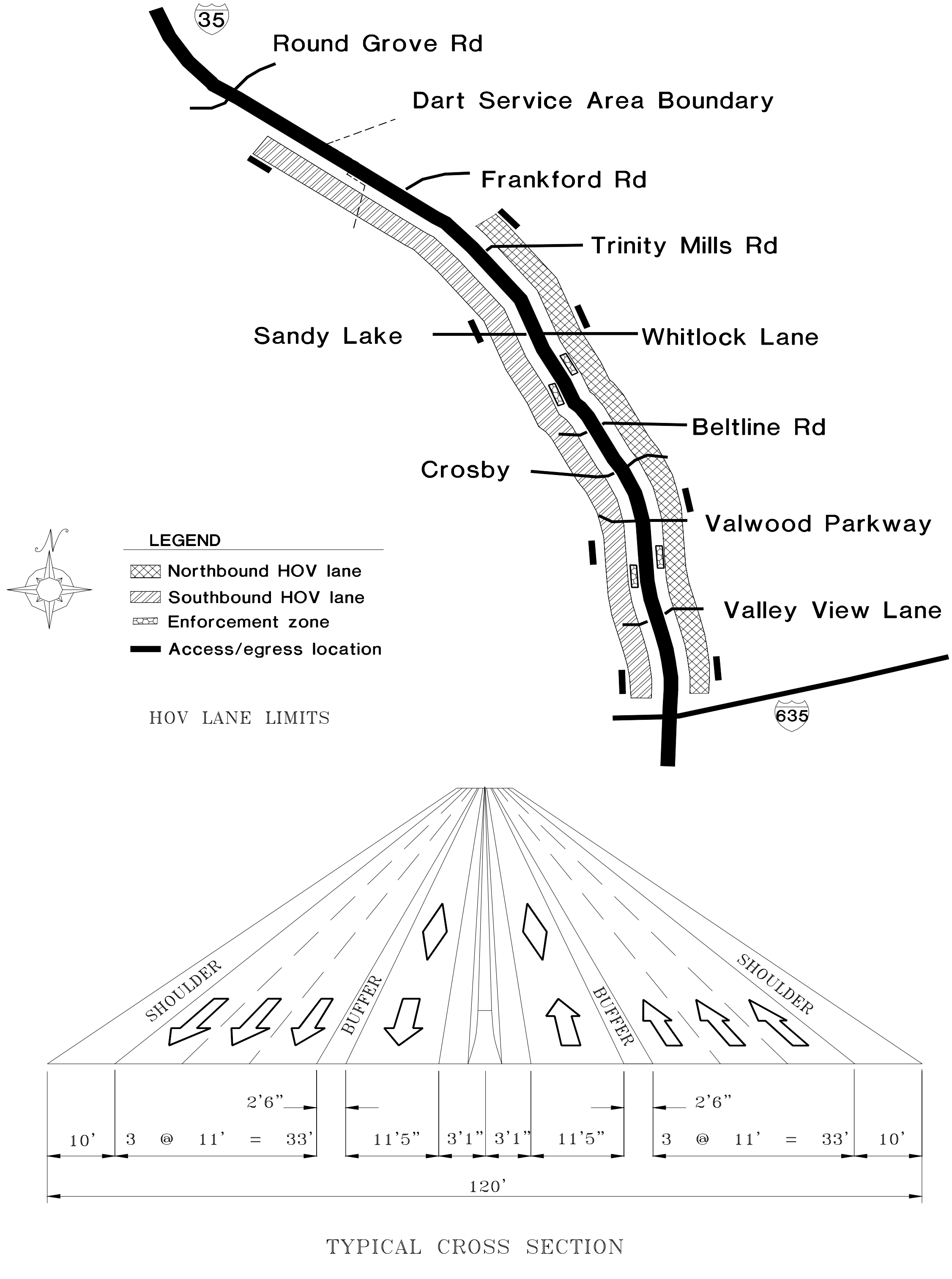


Figure 3. IH-35E North (Stemmons) Freeway HOV Lane.

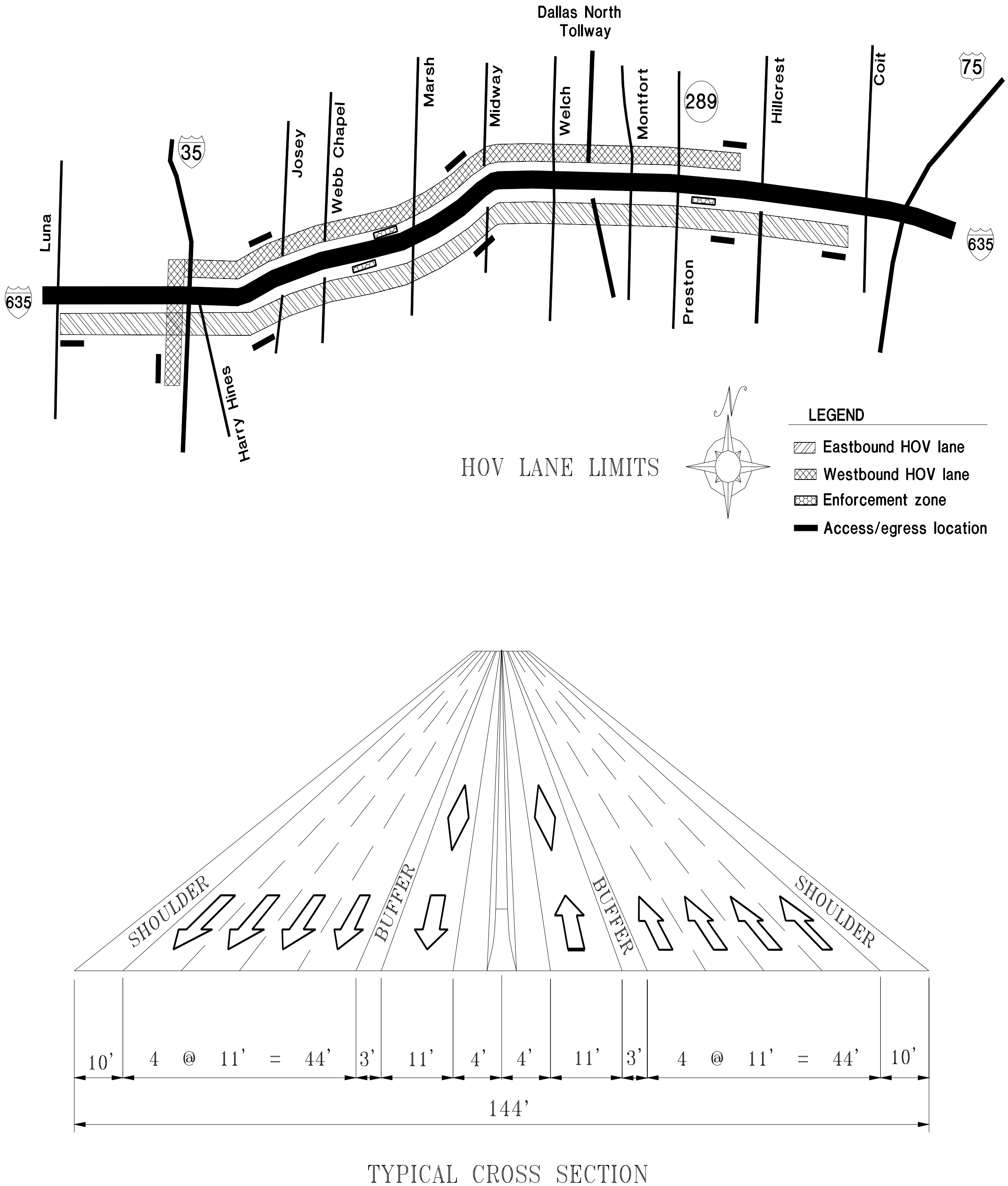


Figure 4. IH-635 (LBJ) Freeway HOV Lane.

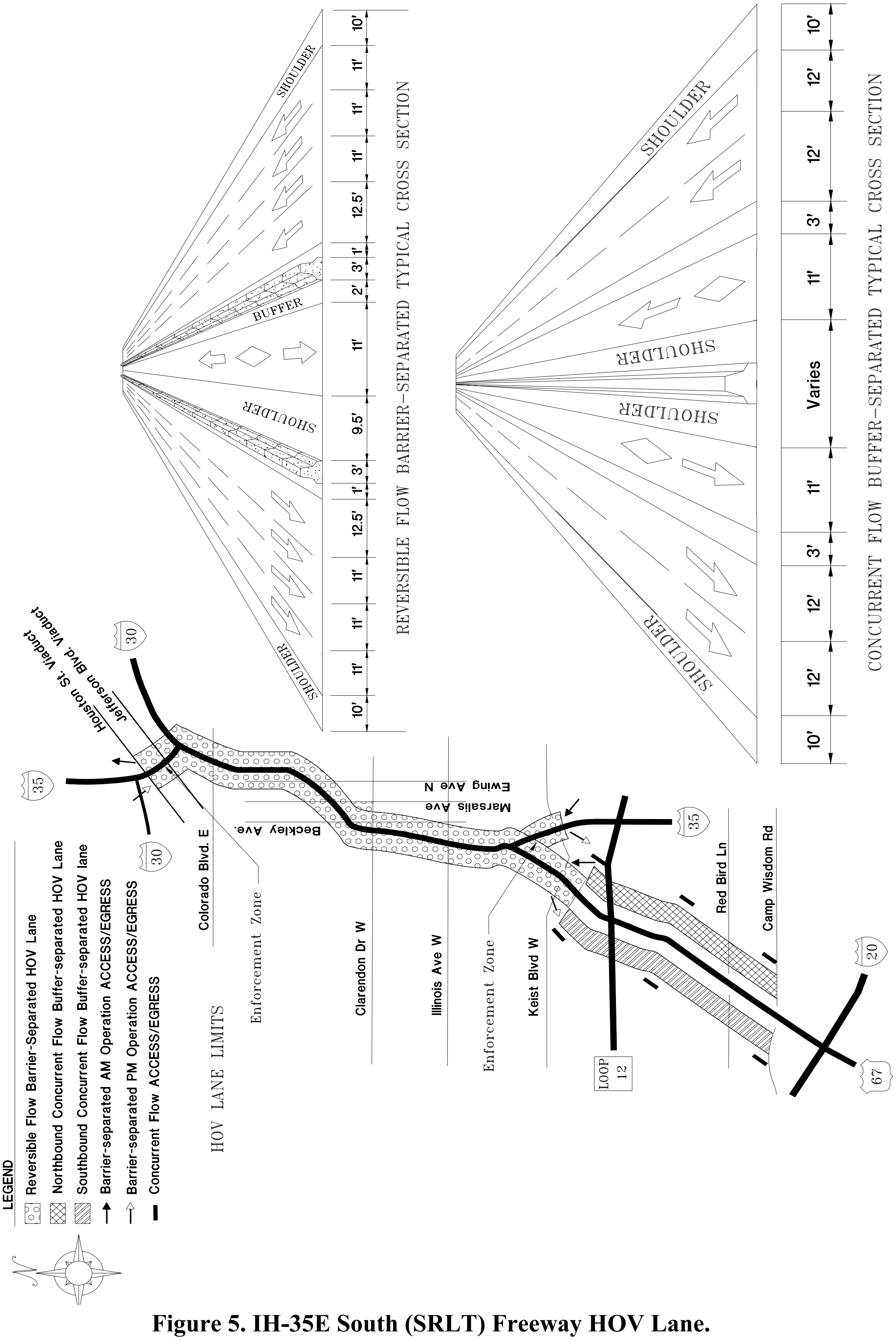


Figure 5. IH-35E South (SRLT) Freeway HOV Lane.

The use of a movable barrier that "borrows" a freeway lane in the off-peak direction and allows it to be used for peak direction HOV lane eligible vehicles creates the IH-30 contraflow lane. The concurrent flow lanes on IH-35E North and IH-635 were created by converting the inside shoulder to an HOV lane. Interim facilities are relatively new in the field of transportation, especially in Texas, and much experimentation is underway to determine optimum operational and design characteristics. Each corridor presents unique challenges in obtaining an operational facility that will attract the formation of carpools and enhance transit ridership. The objective of this research is to investigate the operational effectiveness of the interim HOV lanes in the Dallas area. Additional research concerns particular to concurrent flow lanes include safety, capacity, enforceability, magnitude of violations, appropriate ingress and egress locations, impact on freeway operations, public opinion/acceptance, and effectiveness of 24-hour operation.

Contraflow HOV lanes and concurrent flow HOV lanes have both advantages and disadvantages. The concurrent flow HOV lanes on IH-35E North and IH-635 are the first concurrent flow HOV lanes in Texas; therefore, their operational performance must be monitored and documented. By understanding the operational performance and issues of both buffer-separated (concurrent flow) HOV lanes and barrier-separated (movable barrier contraflow or fixed-barrier reversible flow) HOV lanes, recommendations can be made on suggested HOV lane implementation guidelines for the Dallas area.

II. BACKGROUND

There are approximately 1,000 center-line miles of HOV lanes adjacent to freeway mainlanes in operation in the United States and Canada, and more than eighty percent (80%) of these lanes are concurrent flow facilities. Houston and Dallas are the only cities in Texas that currently have HOV lanes in operation with more proposed for the Austin and San Antonio areas. The first HOV lane in Texas, which opened in August 1979, was the IH-45 (North Freeway) contraflow HOV lane in Houston. HOV lanes now operate on the Southwest (US-59 South), Eastex (US-59 North), Gulf (IH-45), North (IH-45), Katy (IH-10), and Northwest (US-290) freeways. All totaled, Houston has 120 lane-miles of HOV lanes serving the area.

The Dallas area has 48.2 lane-miles of HOV lanes currently in operation on five freeways. The first HOV lane in Dallas opened in October 1991. The IH-30 HOV lane is a barrier-separated contraflow facility which uses a movable barrier. In 1995, buffer-separated HOV lanes were opened in each direction on IH-35E North. The following year buffer-separated HOV lanes were opened on the state's most congested thoroughfare IH-635, also serving traffic in each direction.

The latest addition to the Dallas area HOV lane network extends 9.0 miles between downtown Dallas and Camp Wisdom. Serving the area south of Dallas are reversible barrier-separated HOV lanes along IH-35E South (South R.L. Thornton Freeway) and buffer-separated and reversible barrier-separated HOV lanes along US-67 (Marvin D. Love Freeway). An additional 9 center-line miles of reversible HOV lanes are planned for the north Dallas area on US-75 (North Central Expressway), between IH-635 and the City of Plano, Texas.

The topic of priority lane treatment in Texas has been addressed in several previous major TxDOT research studies including, study 0-1353, "An Evaluation of HOV Lanes in Texas," study 7-1994, "Implementation and Evaluation of Concurrent Flow HOV Lanes in Texas," and study 7-3942, "Investigation of HOV Lane Implementation and Operational Issues" (1,2,3). These studies addressed the evaluation of HOV lanes in Houston and Dallas using trend line data. This allowed detection of changes occurring over time and HOV lane impacts could be isolated by comparing the data with data from control freeways without HOV lanes. The results from these studies and previous studies (documented in such reports as TTI Research Reports 1146-1 through 1146-6F) have been instrumental in the implementation and continued assessment of HOV lanes in both the Houston and Dallas areas.

An evaluation of the impact on a corridor resulting from implementation of an HOV lane requires a substantial amount of data collection. Dallas area HOV lanes served approximately 30.9 million passenger trips in fiscal year 1999 with an average of 100,000 passenger trips each weekday (4). Typical measures of effectiveness include person-throughput, HOV lane utilization, and travel-time savings. Continual monitoring and evaluation provides the basis by which incremental changes are made in system management, facility operation, and support services.

Morning and evening peak period data are currently collected on the HOV lanes in the Dallas District of TxDOT on a monthly basis as part of a DART project. The monthly data collected consist of travel times and person volumes on the HOV lanes and travel times on the adjacent freeway general-purpose lanes. It is documented from experiences in Houston that substantial changes in the corridor occur during the first two to four years of HOV lane operation (5). Increases in HOV lane use tends to level off after four to five years of operation. Usage then increases at a rate comparable to that of the growth rate of adjacent general-purpose lanes. It is critical for the corridors with HOV lanes in Dallas to be monitored frequently to detect corridor changes, particularly in the early years of operation.

RECENT NATIONAL EXPERIENCES

Recent nationwide debate concerning the success of HOV lanes to reduce congestion has been fueled by negative public sentiment that HOV lanes are not serving their purpose. Carpooling has declined nationally by an average of 30 percent in the past two decades. Yet on Texas freeway corridors with mature HOV lanes, there has been an increase in carpooling of 100 percent or greater during the same period (6).

Some areas in the northeast section of the country feel that HOV lanes are under utilized and operate inefficiently at the expense of adjacent general-purpose lanes. HOV lanes on Interstate 80 and 287 in New Jersey were converted to general-purpose lanes in late 1998. The conversion was due to the public's perception that the HOV lanes were unsuccessful in mitigating congestion or solving travel problems within the corridors (7).

A study by the New Jersey Department of Transportation (NJDOT) supported changing the HOV lanes to general-purpose lanes. The study results indicated that HOV facilities were not performing to their original expectations (7). Another study by the North New Jersey Transportation Planning Authority was conducted at the request of the U.S. Department of Transportation. It determined pollution levels, including contributions from automobile emissions, were still within federal requirements (8).

Such research results must be weighed against the many success stories of truly needed HOV lanes with the required characteristics for success. The IH-287 HOV lane was a circumferential route without a central focus or trip attraction. This did not lend itself to express transit use or carpool formation. A planning level study indicated that 450 to 500 vehicles would use the HOV lane from implementation of an employer generated trip reduction program as one of the region's Traffic Demand Management strategies. Unfortunately, the trip reduction program was short lived and left the IH-287 HOV lane with few of the earlier expected users.

The shortcomings of the IH-287 HOV lane negatively impacted the public's perception of the HOV lane concept in general. As a result, the IH-80 HOV lane was also converted to a general-purpose lane even though it drew 800 to 950 vehicles during the peak hour of the first few days of operation. The loss of the IH-80 HOV lane will affect the travel time and trip reliability on the facility since it was projected to operate under congested conditions (Level of Service F) during the peak hour by mid-year 2001. Another study is currently underway to deal with this loss of mobility.

The Washington State Department of Transportation (WSDOT) is investigating the use of HOV lanes during off-peak periods in the Seattle area. This is in response to several state legislative bills focusing on alleviating traffic congestion. Previous legislation in the state proposed that high occupancy vehicle lanes should be completely done away with. But, the possibility of having to repay federal funding used in developing the HOV facilities compelled WSDOT to consider opening HOV lanes to general traffic only during off-peak periods, since part-time operation would not jeopardize federal funding (9).

The WSDOT is considering three options of off-peak use: nighttime operation; weekend operation; or midday operation. The state has studied off-peak use of the HOV lanes and found that demand is fewer than 500 vehicles per hour and demand, as would be expected, drops to almost zero after midnight to about 4 AM. Peak-period use of the HOV lanes is 1,200 vehicles per hour.

Research suggests that Seattle area HOV lanes have been successful according to a study by the Washington State Transportation Center. On IH-405, the HOV lanes provide a morning travel-time savings of 12 minutes and on IH-5, the travel-time savings is seven minutes. The HOV lanes are carrying one-third of all freeway users and in the peak periods, the HOV lanes are moving twice as many people as the general-purpose lanes. Local HOV lane ridership grew 17 percent between the years 1998 to 2000. Many carpools were created during this time frame from users who had previously commuted as single-occupancy vehicles (SOVs) (9).

Conversion of HOV lanes into High Occupancy Toll (HOT) lanes has been a topic of interest for continued use of underutilized facilities for the purpose of congestion relief and for planning purposes. The concept is to offer free access to vehicles with the required number of occupants and allow other vehicles the choice of paying a fee for access. The fee helps manage congestion on the HOT lanes in order to maintain the travel-time savings on the facility for buses and carpools.

HOT lanes basically promote an effective use of available space on HOV lanes. Installation of electronic tolling systems on one or more HOV lanes allows communities the flexibility of varying vehicle eligibility by selling unused capacity in the HOV lane. Houston has experienced success during experiments concerning vehicle throughput on the Katy Freeway (IH-10) HOV lane when using the facility as a peak-hour HOT lane (6). After implementation of the HOT lane concept on IH-15 in San Diego, California, carpooling increased by 13 percent during the first two years of operation, according to a study by San Diego State University.

The Colorado Department of Transportation (CDOT) is conducting a feasibility study on the topic of implementing barrier-separated HOT lanes, where ever needed in the Denver area. The focus of the study is to determine their technical feasibility, public desirability, and the area impacts of converting existing HOV lanes to HOT lanes. The purpose of these "Value Express Lanes" is to maximize the use of HOV lanes by allowing access to SOVs by paying a fee. Carpoolers and those using transit vehicles would continue to use the HOV lanes for free. Recent state legislation is requiring CDOT to implement HOT lanes in the next few years (10).

OTHER ISSUES

Safety Studies (Buffer-Separated HOV Lanes)

The information regarding the safety of HOV projects has been inconclusive. Some studies have concluded that concurrent flow buffer-separated lanes are as safe as other types of projects, while other studies have indicated a safety concern with concurrent flow HOV projects. The largest safety concern with concurrent flow HOV lanes is the potential speed differential between the HOV lane and the general-purpose lanes. Research suggests that safety issues may arise when the speed differential is greater than 25 mph. This finding is consistent with the AASHTO report, "A Policy on Geometric Design of Highways and Streets," which suggests that the greater a vehicle deviates from this average speed on a highway, the greater its chances of becoming involved in a traffic accident (11).

A study was conducted comparing the frequency and characteristics of accidents before and after an HOV lane was added to Riverside Freeway State Route 91 (SR 91) in the Los Angeles area. The HOV lane was created by taking the inside shoulder of the roadway. The study concluded that the HOV project did not have an adverse affect on the safety of the corridor, and the changes in accident characteristics are attributed to the change in location and timing of traffic congestion (12).

Another study conducted by California Polytechnic State University reported the effects HOV lanes have on the safety of selected California freeways. The study suggested the observed accident pattern resulted from differences in traffic flow and congestion rather than geometric and operational characteristics of the HOV facilities (13). The accident "hot spots" during peak periods on freeways with and without HOV lanes are a result of localized congestion (13).

As already discussed, the previous studies on the safety of concurrent flow HOV lanes are inconclusive. There have been several highly successful concurrent flow HOV lane projects and several that have not been as successful. Due to the uniqueness of these facilities, caution should be used when designing these facilities, especially when design values are at or near the minimum recommended design values. Special care should be used when designing access and egress locations to minimize the potential for accidents. Typically, these are the locations with a higher frequency of accidents. The number of traffic accidents that occur in the period of time immediately after a facility is opened may be high because drivers are not familiar with HOV operations and facilities. It may take several weeks for the drivers to become familiar with the facility, especially if the design requires taking the inside shoulder. After the first several weeks or operation, the number of traffic accidents should stabilize.

Safety Studies (Barrier-Separated HOV Lanes)

Traffic accidents in the general-purpose lanes do not typically disrupt operation of barrier-separated HOV lanes. Separated roadways protect the HOV traffic and the general-purpose lanes from the considerable speed differential that may exist between the two traffic streams with concurrent flow HOV lanes (14). However, there has been some concern that physically separated roadways are detrimental to traffic flow when an incident occurs in either the HOV lane or mixed-flow facility, as the barrier limits the ability of traffic to maneuver around an incident (14).

Violation Studies

Concurrent flow HOV lanes generally have a lower compliance rate than other types of HOV lanes regardless of the amount of enforcement (14). These facilities have the potential to become as congested as the mainlanes when a high violation rate occurs. If these facilities become congested, there is less incentive to form carpools or to continue to utilize an existing carpool.

Separated roadways generally have a low violation rate because the characteristics of these facilities deter potential violators. Due to the physical separation from the general-purpose lanes with controlled access points, violators who are spotted in the HOV lane will not have immediate access to the general-purpose lanes. Evidence of violator deterrence has been documented on California barrier-separated HOV facilities where the violation rate is lower than any other mainlane HOV facilities in the state.

III. DATA COLLECTION METHODOLOGY

To evaluate and monitor HOV lanes, it is necessary to collect a substantial amount of operational data on the HOV lanes and the adjacent freeway general-purpose lanes. This section describes the types of data that have been collected to evaluate the effectiveness of the Dallas area HOV lanes.

Most of the HOV facilities in Houston have been operating for several years, resulting in "mature" facilities with little change from year to year; therefore, these facilities are only monitored on a semiannual basis. In Houston, experience has indicated that there is a significant amount of change in the corridor during the first two to four years that an HOV lane is operational (5). After this time period, a facility is considered "mature." It is, therefore, essential that the corridors in Dallas with new HOV lanes initially be monitored frequently to detect corridor changes.

FIELD DATA COLLECTION

Monthly and semiannual data collection is conducted to monitor the operational performance of the HOV lanes. The data are collected in the peak direction of the corridor. During the morning (AM) peak period, IH-30, IH-35E North, and IH-35E South have approximately a 70 percent directional peak inbound (westbound, southbound, and northbound, respectively). A reverse pattern occurs during the afternoon (PM) peak period. IH-635 in the vicinity of the HOV lane, however, has nearly an equal directional split during the AM and PM peak periods. Data are, therefore, collected in both the eastbound and westbound directions during both peak periods. This section will describe the monthly and semiannual field data collection effort.

Monthly Data Collection

Since the Dallas area HOV lanes are relatively new facilities, DART requested that they be monitored on a monthly basis. Texas Transportation Institute is under contract with DART to collect AM peak period (6:00 AM to 9:00 AM) and PM peak period (3:30 PM to 7:00 PM) travel time runs and vehicle occupancy counts in the peak direction on the five HOV lanes in the Dallas area. Observers stationed on the side of the freeway record HOV lane vehicle occupancy counts and the travel time runs are collected using the floating car method. Travel time runs are also conducted on the adjacent freeway mainlanes for each facility that has an HOV lane. By comparing the travel time runs on the HOV lane with the freeway general-purpose lanes, travel time savings (HOV lane benefits) can be calculated. The vehicle occupancy counts are used to monitor changes in HOV lane occupancy usage and violation rates. In addition, automatic counters are placed on the IH-35E North and IH-635 HOV lanes and on the concurrent-flow section of the IH-35E South HOV lane to obtain daily volume of traffic on the HOV lanes. (Daily counts are not needed on the IH-30 HOV lane because the HOV lane is only opened during the peak period.) The number of vehicles parked in the park-and-ride lots located near the HOV lanes is also monitored on a monthly basis.

Semiannual Data Collection

In addition to the monthly data collection, AM and PM peak period vehicle occupancy counts are collected semiannually on the general-purpose lanes of the four corridors that have HOV lanes during the months of September and March. Researchers use these occupancy counts to monitor corridor-wide impacts of HOV lanes during the peak period. These two months of data collection are summarized in separate technical memorandums and are provided to TxDOT and others (15,16).

ACCIDENT DATA

Annual accident data are available from the Texas Department of Public Safety (DPS) through the Texas Accident Data Files. The accident data can typically be used to calculate accident rates before and after the HOV lanes were operational. In addition, the accident data can be plotted by location (milepoint) to determine the areas where a significant number of accidents are occurring. If there is a significant difference in the pattern of accidents before and after the HOV lane opened, these differences may be attributed to the HOV lane. The geometric and operational characteristics of the HOV lane may provide insight into the high accident location(s). However, there is currently a several-month delay in the coding of the data into the Accident Data Files. A little more than two years of "after" data were available for the two concurrent flow HOV lanes. The available data have been summarized as part of this project, but they are very preliminary at this point and additional data will be evaluated as they become available. A follow-up TxDOT research project (0-4434: Safety Evaluation of HOV Lane Design Elements) is currently being conducted to address this issue.

IV. OPERATIONAL PERFORMANCE OF DALLAS AREA HOV LANES

The operational performance of each HOV lane will be described in this section which is divided into the following sub-sections: vehicle and person volumes and vehicle occupancy, speeds and travel times, transit operation impacts, cost effectiveness, enforcement and violations, safety, air quality, and public acceptance. Many of the comparisons consist of "before" HOV lane data with "after" HOV lane data. The "before" data consist of an average of four to six quarterly data collection periods prior to the construction of the HOV lanes in each corridor, as discussed in the "Data Collection Methodology" section of this report. The "after" data are an average of data collected since the HOV lanes became operational.

VEHICLE AND PERSON VOLUMES AND OCCUPANCY

One of the primary objectives of HOV lanes is to increase person-throughput. This objective is accomplished when individuals form carpools or ride transit buses. With more occupants in fewer vehicles, the vehicle occupancy (number of persons in a vehicle) increases, enabling more people to use the facility. This section describes the trends in vehicle and person volumes and occupancy on the HOV lanes since they opened. Figures 6 and 7 provide peak hour HOV lane vehicle and person trips, respectively, over time for each of the HOV lane facilities in Dallas. The peak hour vehicle and person trends on the IH-30 HOV facility, which opened in 1991, has remained constant over the past several years. The peak hour vehicle and person trends on the IH-635 and IH-35E North HOV facilities have seen a slight decrease over time and this may be attributed to the opening of the SH-190 facility, a toll facility that runs parallel to the IH-635 corridor, which may have diverted some of the traffic away from these two corridors. Other factors which may have attributed to this likely include major construction in the corridors and economic issues in this region (e.g., the airline industry, high-tech industries, etc.). The newest facility, IH-35E South, has seen a steady increase in peak hour vehicle and person trips since the facility was opened. This HOV facility is still maturing and is expected to see an increase in ridership with time. Figures 8 and 9 provide total daily HOV lane vehicle and person trips, respectively, over time for each of the HOV lane facilities. Total daily trends of vehicle and person trips on all HOV lane facilities have seen a steady increase of usage over time, with the exception of the IH-635 corridor. Again, this may be attributed to the opening of the SH-190 parallel facility.

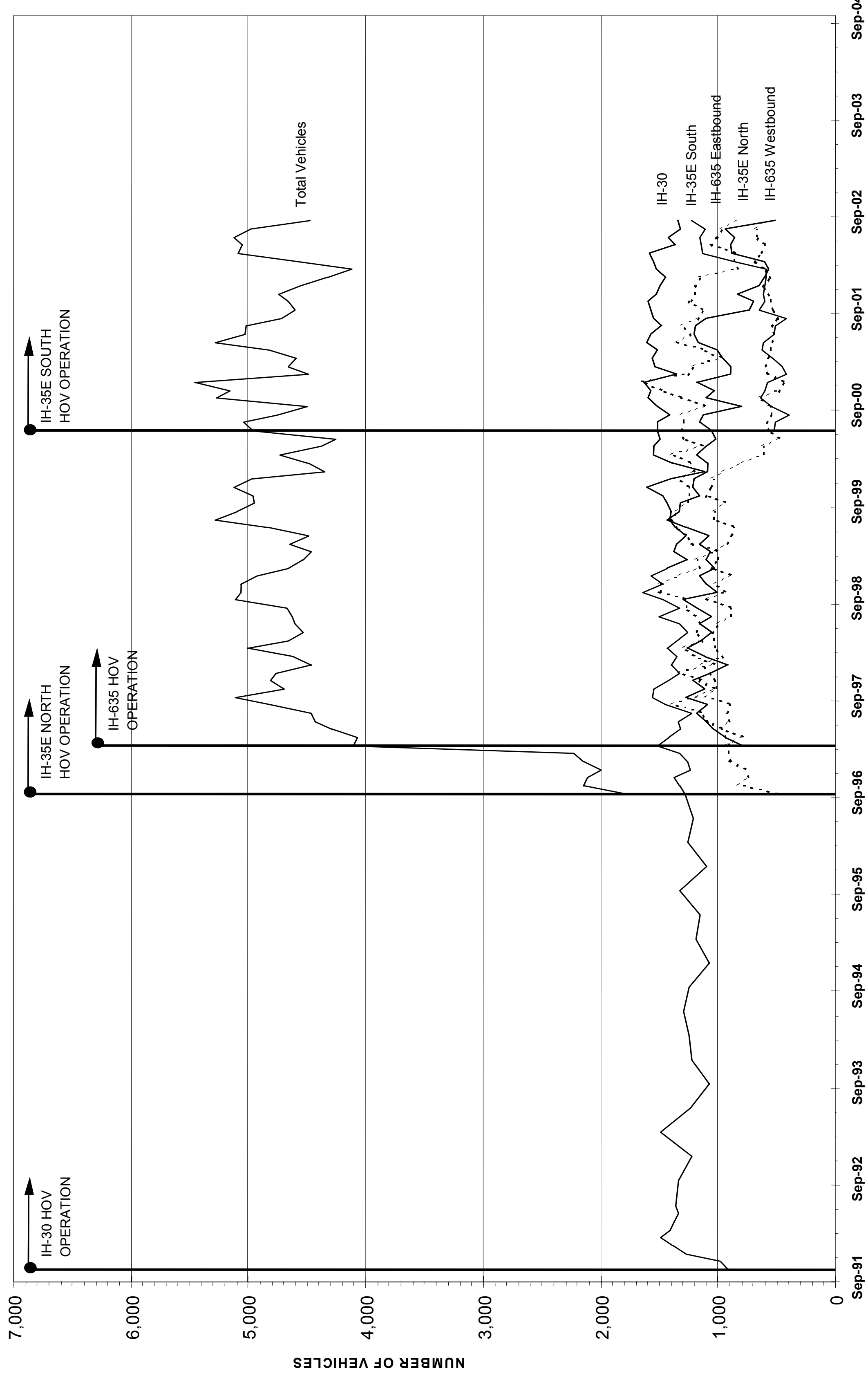


Figure 6. Peak Hour HOV Lane Vehicles.

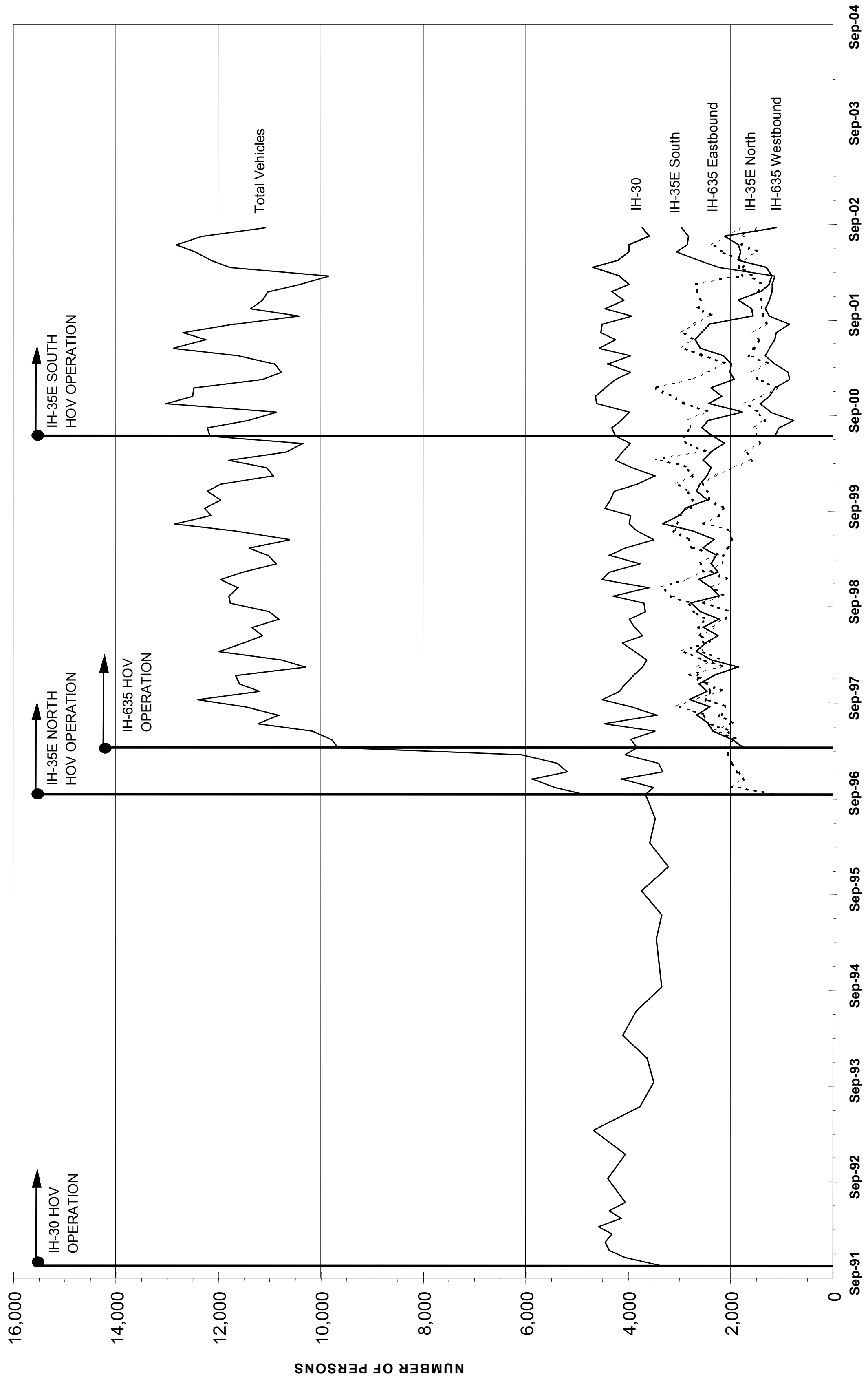


Figure 7. Peak Hour HOV Lane Persons.

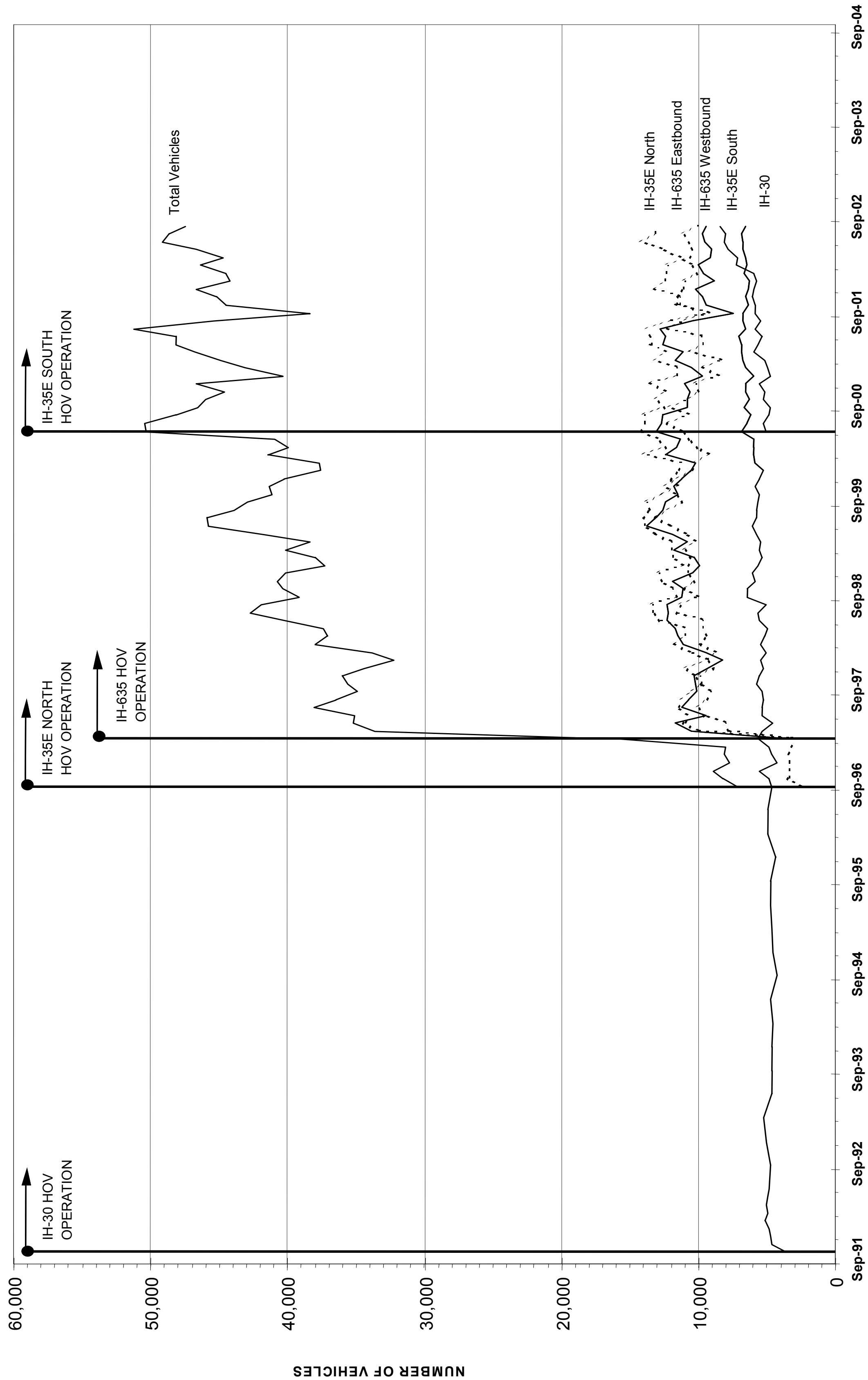


Figure 8. Total Daily HOV Lane Vehicles.

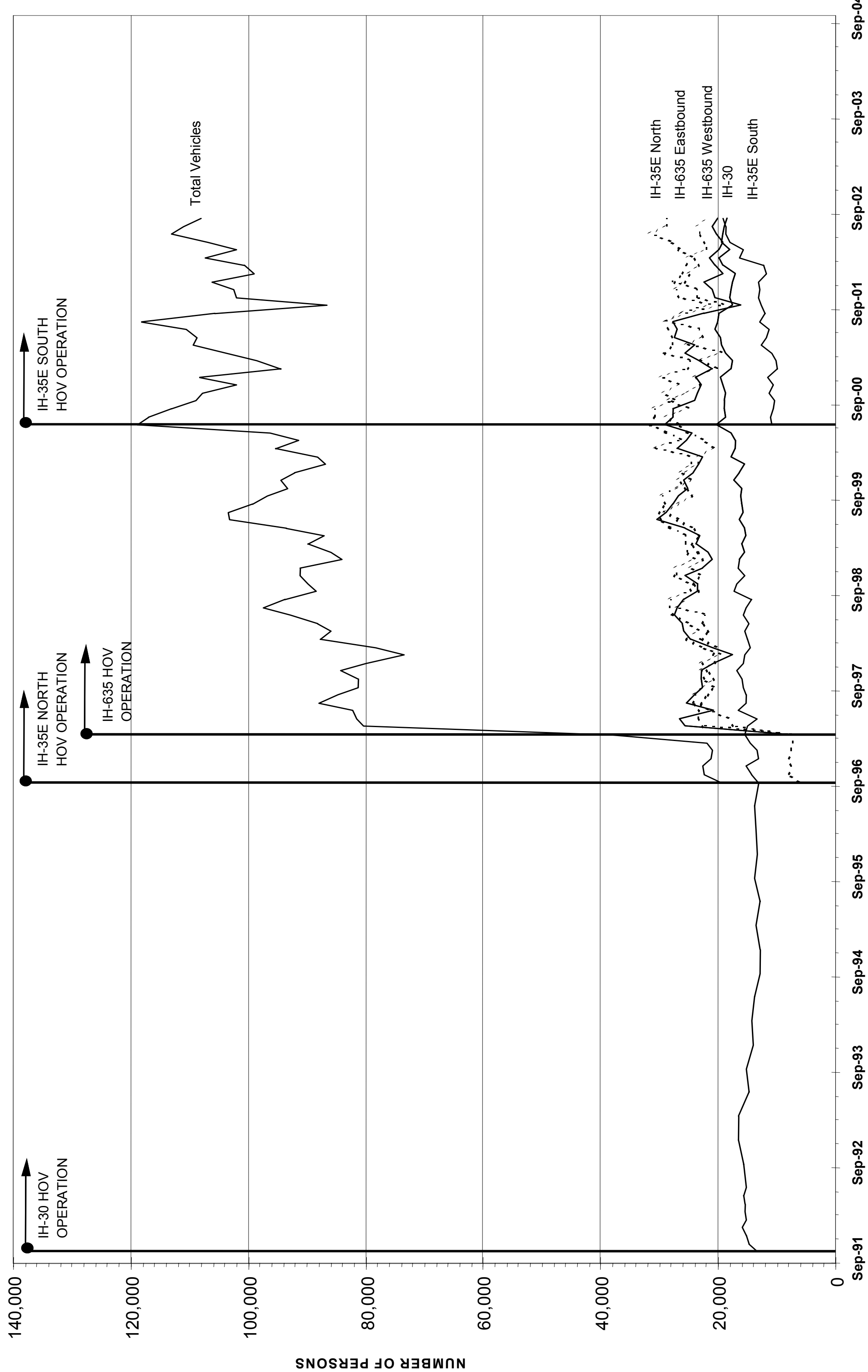


Figure 9. Total Daily HOV Lane Persons.

Vehicle Volumes

One of the objectives of HOV lanes is to increase *person*-throughput rather than *vehicle*-throughput in the corridor. It is, therefore, not very useful to analyze the number of vehicles using a facility. It is, however, important to investigate the number of carpool (multi-occupant) vehicles utilizing a facility. An increase in the number of multi-occupant vehicles on a facility indicates an increase in the person-throughput of a facility. Figure 10 shows the number of two-or-more person (2+) carpools on each of the facilities before and after the HOV lane opened. "Before" data consists of six averaged quarterly collection periods prior to HOV lane construction and "after" data consists of averaged collection periods since HOV lane opening. After each HOV lane was opened, a significant increase in the number of 2+ carpools on each of the facilities resulted. As shown in Figure 11, the percent increase in carpools ranged from 88 percent on eastbound IH-635 to 238 percent on IH-35E North. An analysis of the carpool volumes indicates that the implementation of HOV lanes has resulted in a substantial increase in the number of carpools in each corridor.

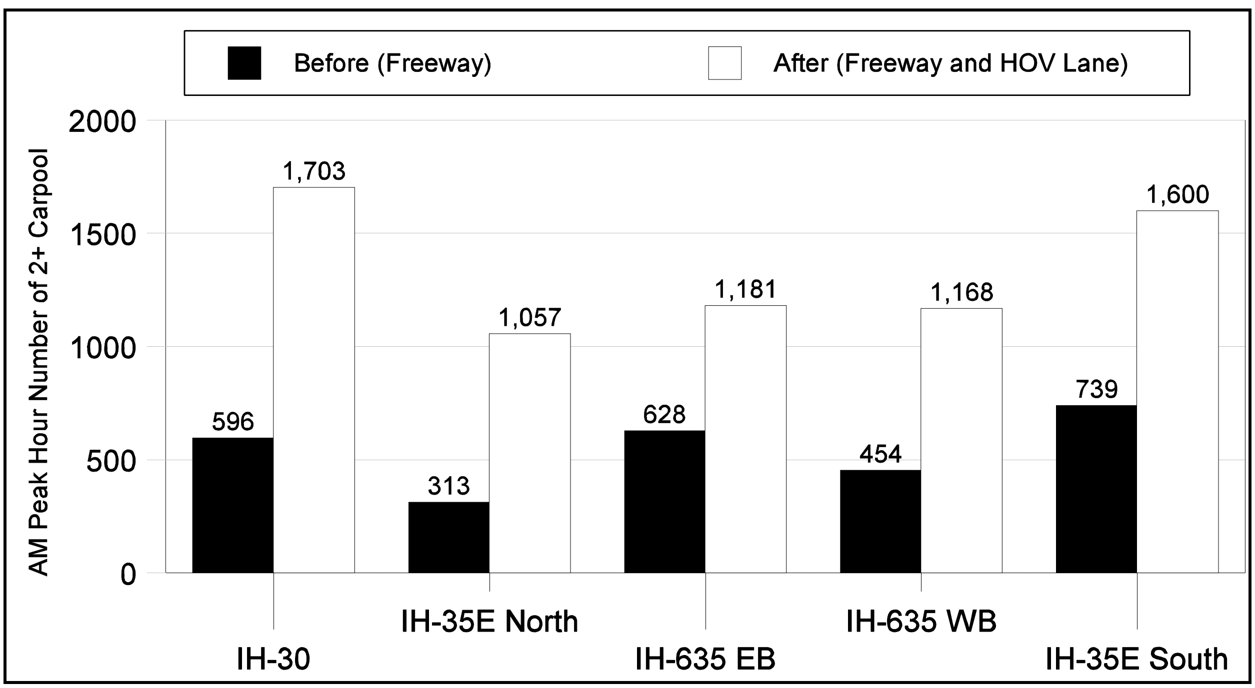


Figure 10. Change in AM Peak Hour Number of Carpools.

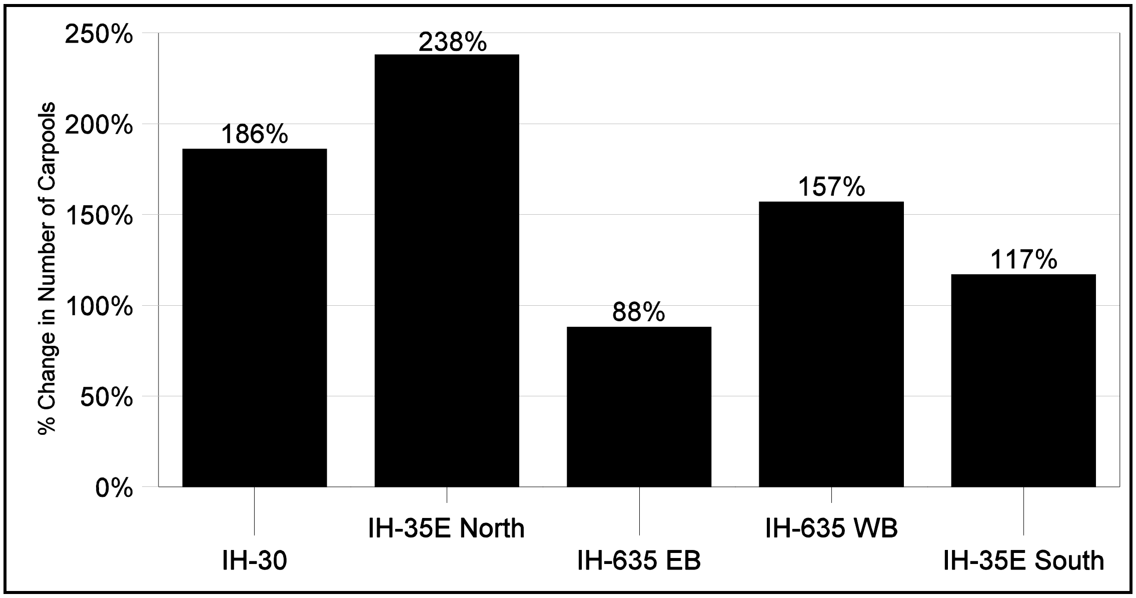


Figure 11. Percent Change in AM Peak Hour Number of Carpools.

Person Volumes

As previously mentioned, HOV lanes should increase person-throughput. Figure 12 shows the AM peak hour before and after person volumes. The total person volume has increased in each corridor since the opening of HOV lanes.

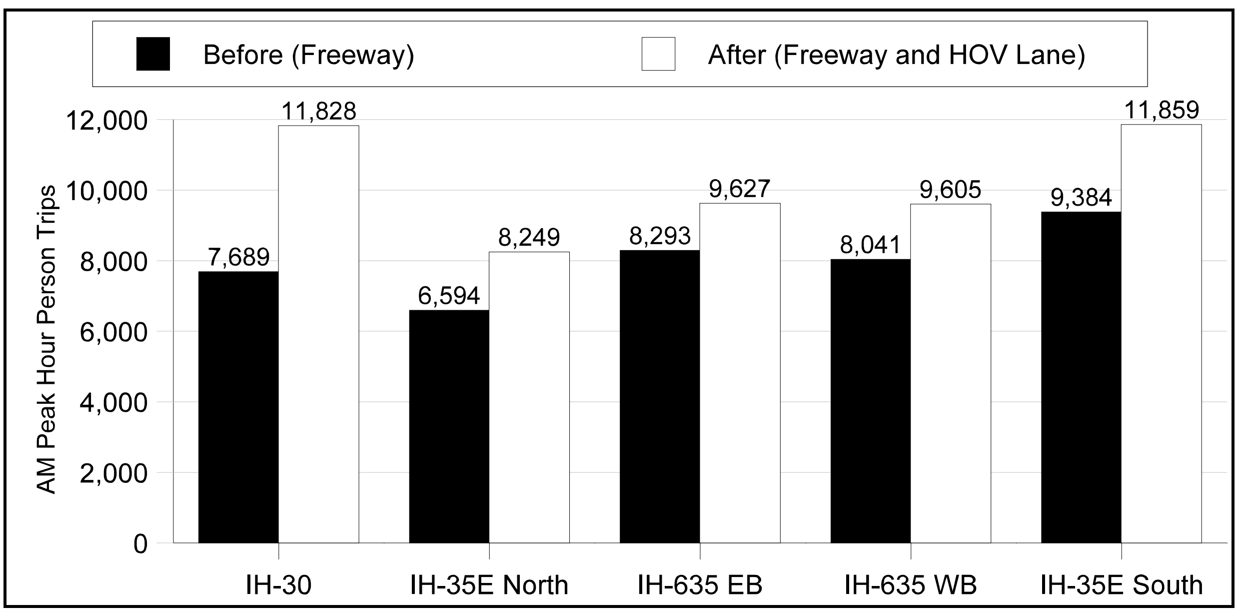


Figure 12. Change in AM Peak Hour Person Trips.

One guideline for HOV lanes is that an HOV lane should carry at least as many people as an adjacent freeway mainlane. Although there likely will be fewer vehicles in the HOV lane than in a general-purpose lane, the *number of people* in an HOV lane should be greater than the average number of people per mainlane. Figure 13 shows the peak hour person volume per lane for each of the HOV lanes and adjacent general-purpose lanes. The IH-30 HOV lane carries more than twice the number of persons as an adjacent freeway lane during the peak hour, while the number of people in the IH-35E North HOV lane is similar to an adjacent freeway lane, and the IH-635 eastbound and westbound and the IH-35E South HOV lanes are greater than an adjacent freeway lane. It is important to note that there are approximately 50 DART buses that utilize the IH-30 HOV lane during the peak hour, while only 10 buses utilize the IH-35E North HOV lane and 15 buses utilize the IH-35E South HOV lane. There are currently no fixed DART bus routes on the IH-635 HOV lanes. The presence of transit routes significantly increases the person-carrying capacity of a facility.

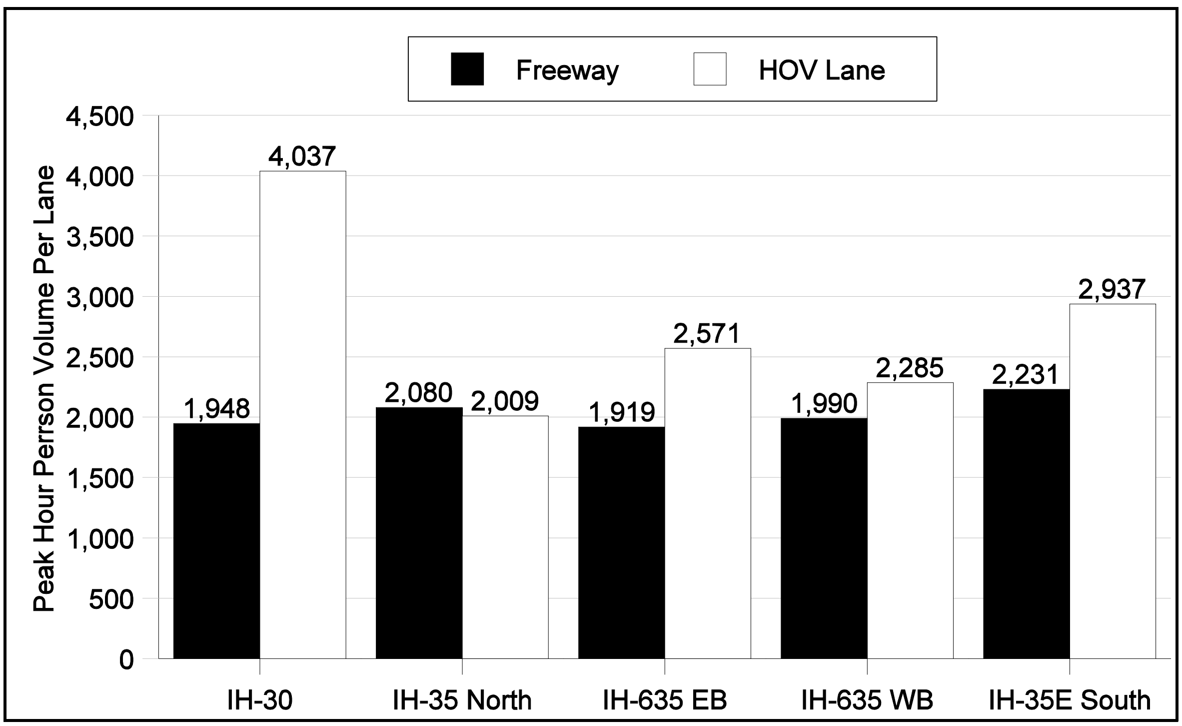


Figure 13. Peak Hour Person Volume Per Lane.

Occupancy

Figures 14 and 15, respectively, show the average peak hour automobile and vehicle occupancy for the freeways with an HOV lane.

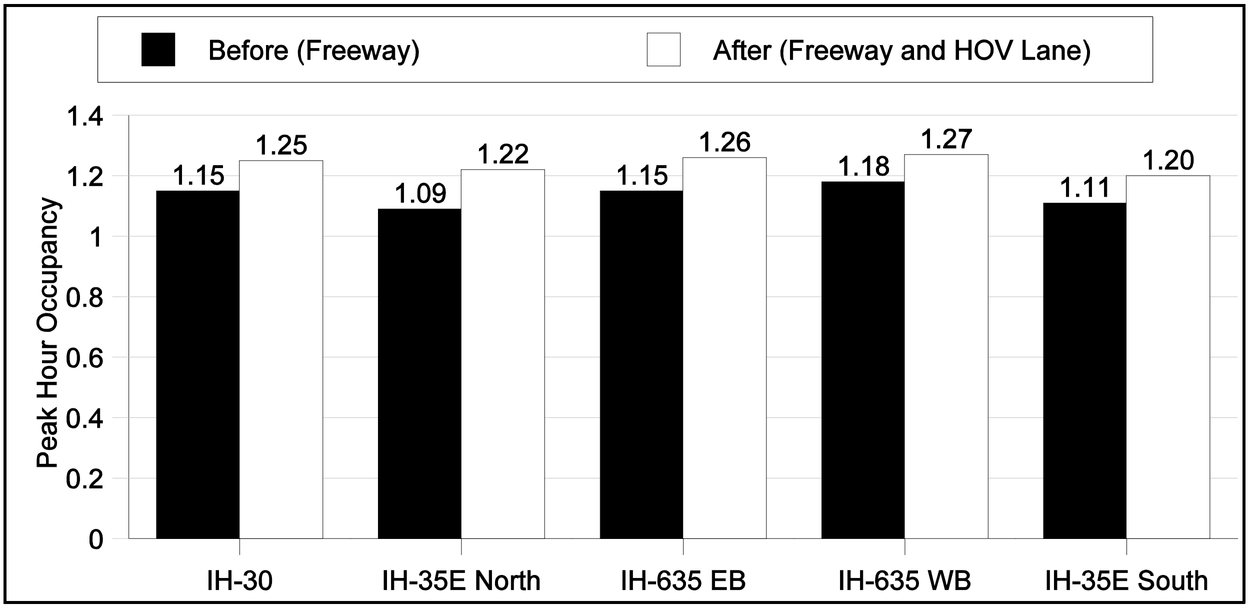


Figure 14. Change in Average Automobile Occupancy.

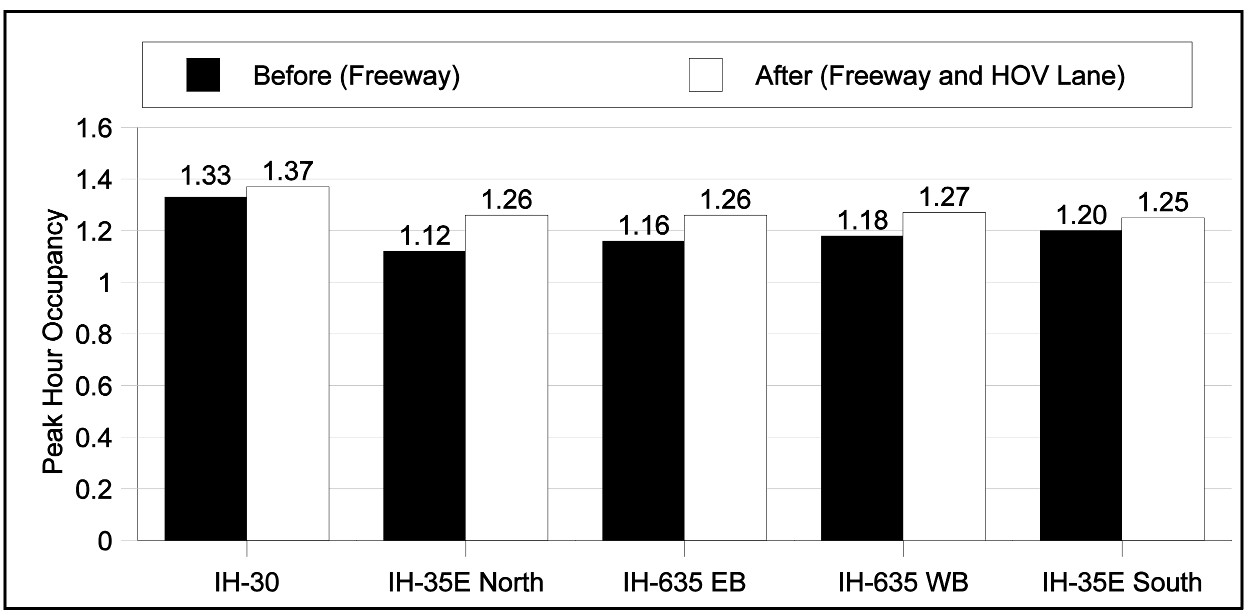


Figure 15. Change in Average Vehicle Occupancy.

Because of the presence of several bus routes on IH-30, both the average vehicle occupancy and the average automobile occupancy were evaluated so that an unbiased comparison could be made between the occupancy rates in each corridor. The five facilities with an HOV lane show a similar increase in the average automobile occupancy rate after the HOV lane was implemented.

Change in automobile occupancy is one method to determine if motorists are forming carpools to utilize the benefits of an HOV lane. The percent change in average automobile occupancy after HOV lanes were opened on IH-30, IH-35E North, IH-635, and IH-35E South is shown in Figure 16.

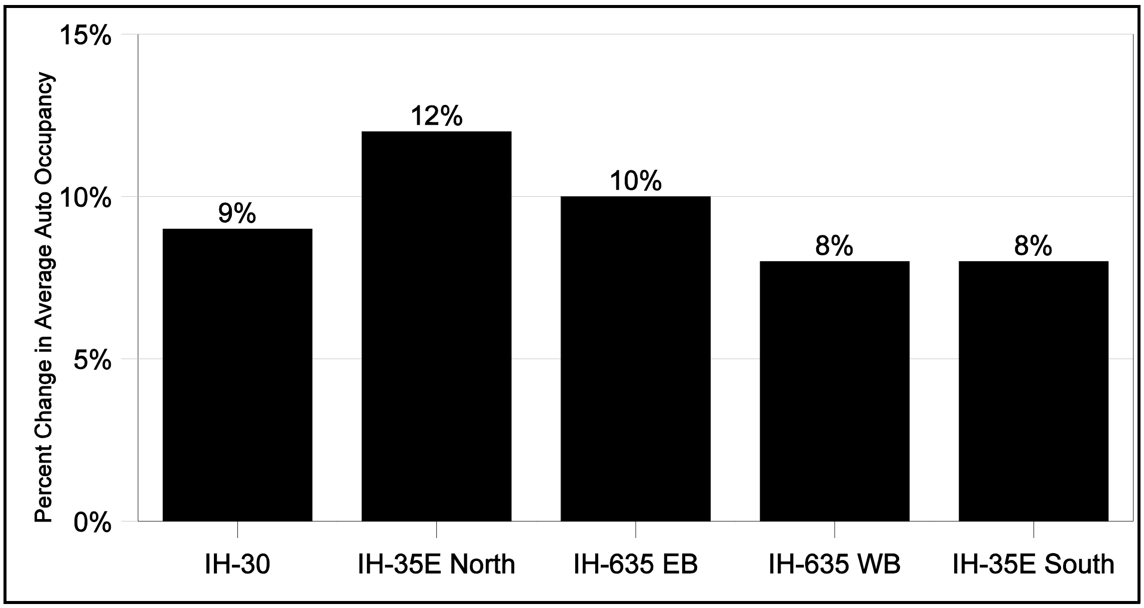


Figure 16. Percent Change in Average Automobile Occupancy.

All five freeways with an HOV lane have an 8 to 12 percent increase in the average automobile occupancy. The increase in average automobile occupancy indicates that motorists are carpooling to gain the benefits of traveling in an HOV lane.

The operational data for the IH-30, IH-35E North, IH-635, and IH-35E South freeways indicate an increase in the person trips and automobile and vehicle occupancy on each facility after an HOV lane opened.

SPEEDS AND TRAVEL TIMES

Operating speeds and travel time savings are two factors that are important to motorists who utilize the HOV lane. HOV lane users expect to travel faster than vehicles in the adjacent general-purpose lanes, thus saving commuting time. This section summarizes the speed and travel time characteristics of the Dallas area facilities with HOV lanes.

Speeds

A guideline for HOV lanes is that the lane should not negatively impact the mainlanes. If implementing an HOV lane causes travel speeds on the adjacent mainlanes to decrease, the efficiency of the roadway system would be diminished and there will be public opposition to the project. Figure 17 shows the peak hour travel speeds on the HOV lanes and adjacent mainlanes.

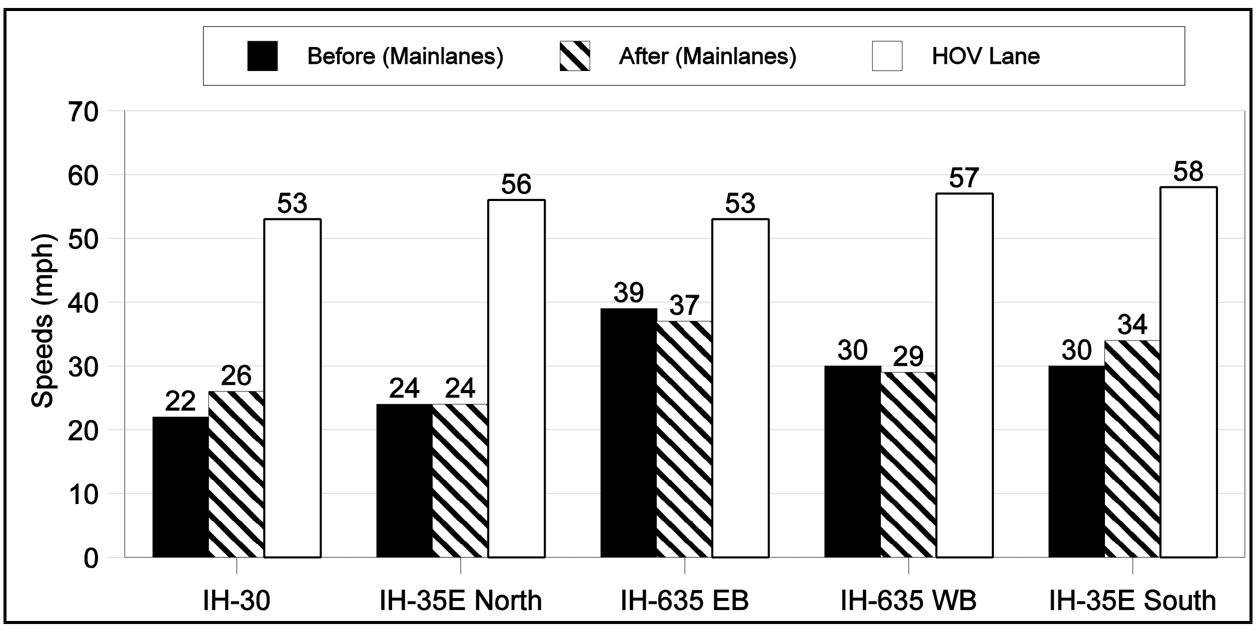


Figure 17. Change in AM Peak Hour Roadway Operating Speeds.

Implementation of the HOV lanes in the Dallas area appears to have essentially no impact (positive or negative) on the mainlane operating speeds. In addition, on each of the facilities, the HOV lane speeds were significantly higher than the speeds on the adjacent general-purpose lanes.

Travel Times

Travel time savings are directly related to operating speed. Researchers found that to encourage the formation of carpools or to increase bus utilization, a minimum of five minutes of total travel time savings over the general-purpose lanes is required. Travel time savings are easiest benefits for passengers to measure directly; therefore, it is imperative that the HOV lane provide users travel time savings over the general-purpose lanes. The peak hour travel time savings on incident-free days for each of the five HOV lanes are shown in Figure 18. This travel time savings actually underestimates the *average* weekday travel time savings due to incidents on the freeway mainlanes. An incident on the freeway mainlanes would likely increase the travel time on the mainlanes; however, it may or may not have an impact on the HOV lane travel times, depending on the type of incident. In general, the HOV lanes save motorists more than five minutes over the general-purpose lanes on incident-free days.

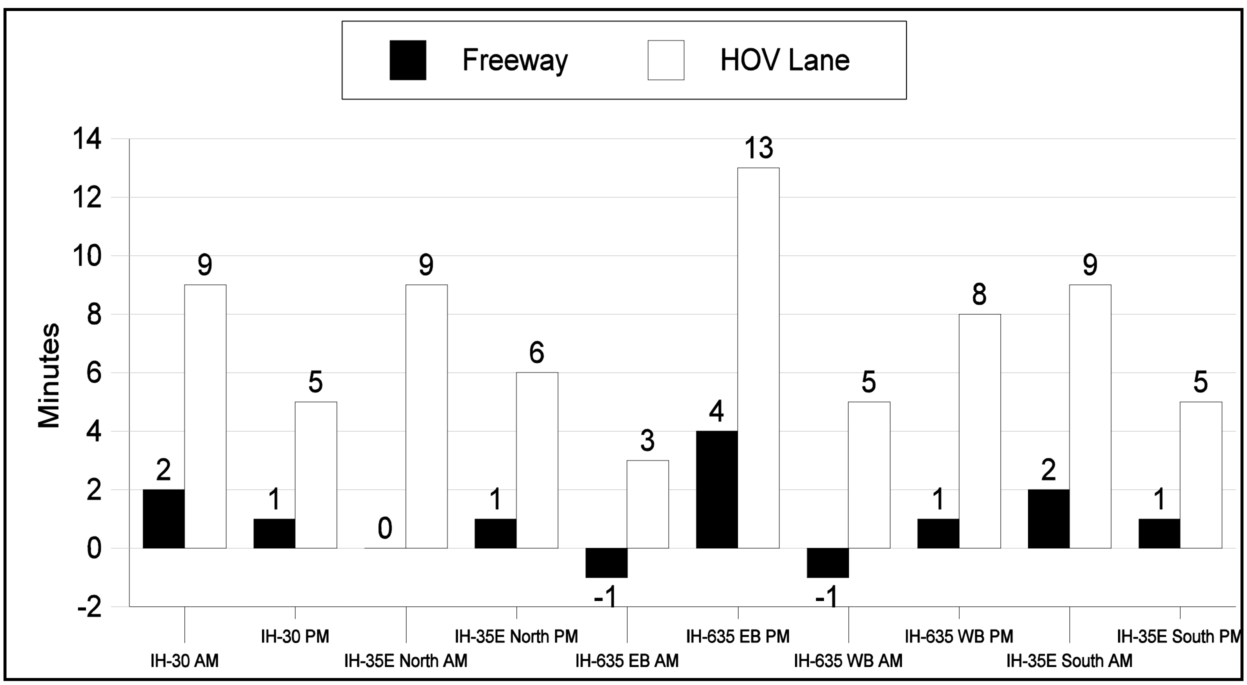


Figure 18. Peak Hour Travel Time Savings After HOV Lane Opening.

Perceived travel time savings may be of greater importance than actual travel time savings. A survey of IH-30 motorists in 1995 determined that the transit users perceived travel time savings as 13 minutes during the AM peak and 12 minutes in the PM peak (17). Similarly, the IH-30 carpoolers perceived they saved 16 minutes during the AM peak and 13 minutes in the PM peak over the general-purpose lanes. At this time, there has not been a motorist survey conducted on either the IH-35E North corridor, the IH-635 corridor, or the IH-35E South corridor.

TRANSIT OPERATION IMPACTS

Potential HOV lane impacts on transit operations may affect transit route and transit ridership, which are discussed in the next section. The IH-635 corridor currently does not have any fixed transit bus routes using the HOV lanes on a regular basis.

Transit Routes

Bus operating speeds have more than doubled since the opening of the HOV lanes on IH-30, IH-35E North, and IH-35E South during the AM and PM peak hours, as shown in the "Speeds and Travel Times" section of this report. In the IH-30 corridor, which has approximately 50 DART buses using the HOV lane during the peak hour, the result is that the operating cost of DART buses using the lane has been reduced by approximately $402,000 per year because fewer buses are required to run the "before" HOV lane routes due to the travel time savings and trip time reliability. Additionally, the bus schedule times have been reduced by six minutes on IH-30 during the AM and PM peak hours as a result of the travel time savings previously discussed. The cost of operating DART buses on IH-35E North has also been reduced by approximately $185,000 per year as a result of implementation of the HOV lane. The cost of operating DART buses on IH-35E South is not available for this report due to the short time of duration that the HOV lane has been operational.

COST EFFECTIVENESS

Tables 2, 3, 4, and 5 show the cost effectiveness of each of the four HOV lanes over 10 years of operation or projected out to 10 years. The tables show the benefit/cost ratio at the end of each fiscal year (September through August) with the exception of the IH-635 and IH-35E South HOV lanes. The HOV lane on IH-635 opened half-way into fiscal year 1997, so the benefits are for six months in 1997 and for six months in the final year (2007), for a total of 10 years. The HOV lane on IH-35E South partly opened half-way into fiscal year 2000 with a concurrent flow section, so the benefits are for six months in 2000 and for six months in the final year (2010), for a total of 10 years. The benefits are based on the travel time savings afforded to users of the HOV and, in the case of the IH-30 HOV lane, include benefits to persons on the adjacent freeway general-purpose lanes as they realized a travel time savings with the implementation of the lane. The benefits are based on measured travel time savings through fiscal year 2001. Benefits in future years are assumed to be the same as fiscal year 2001 benefits. The value of time used is \$13.22 per person. No travel time savings benefits for persons on the adjacent freeway general-purpose lanes were realized in the IH-635 and IH-35E North corridors. However, travel time savings benefits for persons on the adjacent freeway general-purpose lanes were realized on the IH-35E South corridor. All HOV lane projects are cost effective and have attained a benefit cost ratio greater than 1.0 within the first five years of operation, with the exception of the IH-35E South reversible HOV lane which is projected to be cost effective within the first six years of operation. Substantially higher construction costs were incurred with the IH-35E South HOV lane due to the reversible barrier-separated HOV lane configuration chosen.

Table 2. IH-30 (ERLT) Freeway HOV Lane Benefit/Cost Analysis.[1]

Benefits and Costs (Million Dollars)[2]						
Comment	Fiscal Year	Capital Cost	Operation/ Enforcement	HOV Lane Benefits	Mainlane Benefits	B/C Ratio
Initial construction	1992	12.2	0.60	2.85	2.64	0.43
	1993	-	0.60	2.89	3.68	0.88
	1994[3]	-	0.60	2.66	2.45	1.19
AM auxiliary lane	1995	0.2	0.60	3.28	3.92	1.57
PM extension	1996[4]	5.0	0.60	2.99	3.31	1.46
	1997	-	0.60	3.47	2.88	1.68
	1998	-	0.60	4.00	3.00	1.92
	1999	-	0.60	4.12	3.12	2.14
	2000	-	0.60	4.38	3.38	2.51
	2001	-	0.60	4.70	3.70	2.94

Notes:
[1]HOV lane opened in September 1991.
[2]Benefits include \$402,000 DART bus operating costs per year.
[3]AM auxiliary lane opened in July 1994.
[4]PM extension opened in February 1996.

Table 3. IH-35E North (Stemmons) Freeway HOV Lane Benefit/Cost Analysis.[1]

Benefits and Costs (Million Dollars)[2]						
Comment	Fiscal Year	Capital Cost	Operation/ Enforcement	HOV Lane Benefits	Mainlane Benefits	B/C Ratio
HOV lane	1997	7.0				
S-Ramp		2.9	0.20	2.59	0.00	0.26
	1998	-	0.20	2.67	0.00	0.50
	1999	-	0.20	2.42	0.00	0.71
	2000	-	0.20	2.18	0.00	0.81
	2001	-	0.20	2.30	0.00	1.02
	2002	-	0.20	2.14	0.00	1.09
	2003	-	0.20	2.14	0.00	1.23
	2004	-	0.20	2.14	0.00	1.36
	2005	-	0.20	2.14	0.00	1.48
	2006	-	0.20	2.14	0.00	1.59

Notes:
[1]HOV lane opened in September 1996.
[2]Benefits include $185,000 DART bus operating costs per year.

Table 4. IH-635 (LBJ) Freeway HOV Lane Benefit/Cost Analysis.[1]

Benefits and Costs (Million Dollars)						
Comment	Fiscal Year	Capital Cost	Operation/ Enforcement	HOV Lane Benefits	Mainlane Benefits	B/C Ratio
Initial construction	1997[2]	16.3	0.10	4.84	0.00	0.30
	1998	-	0.20	9.23	0.00	0.83
	1999	-	0.20	9.60	0.00	1.35
	2000	-	0.20	8.72	0.00	1.67
	2001	-	0.20	8.73	0.00	2.09
	2002	-	0.20	8.45	0.00	2.40
	2003	-	0.20	8.45	0.00	2.76
	2004	-	0.20	8.45	0.00	3.11
	2005	-	0.20	8.45	0.00	3.42
	2006	-	0.20	8.45	0.00	3.73
	2007[3]	-	0.10	4.23	0.00	3.89

Notes:
[1]HOV lane opened in March 1997.
[2]Includes 3rd and 4th quarters of FY 1997 only (6 months).
[3]Includes 1st and 2nd quarters of FY 2007 only (6 months).

Table 5. IH-35E (SRLT) Freeway HOV Lane Benefit/Cost Analysis.[1]

Benefits and Costs (Million Dollars)						
Comment	Fiscal Year	Capital Cost	Operation/ Enforcement	HOV Lane Benefits	Mainlane Benefits	B/C Ratio
Concurrent Flow Operational	2000[2]	18.5	0.15	0.12	NA[3]	0.00
	2001	-	0.30	0.29	NA	0.03
Reversible Flow Operational	2002	26.0	0.30	2.27	5.78	0.24
	2003	-	0.30	2.27	5.78	0.42
	2004	-	0.30	2.27	5.78	0.58
	2005	-	0.30	2.27	5.78	0.73
	2006	-	0.30	2.27	5.78	0.87
	2007	-	0.30	2.27	5.78	1.01
	2008	-	0.30	2.27	5.78	1.13
	2009	-	0.30	2.27	5.78	1.25
	2010[4]	-	0.15	1.14	2.89	2.80

Notes:
[1]HOV lane opened in March 2000.
[2]Includes 3rd and 4th quarters of FY 2000 only (6 months).
[3]Not Available.
[4]Includes 1st and 2nd quarters of FY 2010 only (6 months).

ENFORCEMENT AND VIOLATIONS

DART transit police enforce the HOV lanes. Although the number of enforcement officers monitoring the lanes varies, the IH-35E North and IH-635 HOV lanes are routinely enforced by a combination of roving and stationary enforcement in squad cars and motorcycles during the peak periods and sporadically during the off-peak periods.

More officers, however, are required to enforce the concurrent flow lanes than the barrier-separated contraflow lane on IH-30. The IH-30 HOV lane is effectively enforced by two transit police officers, while the concurrent flow lanes require three to four officers each during the peak periods.

The peak hour violation rate for each of the HOV facilities is shown in Figure 19. Because of the presence of enforcement officers on the facility, the violation rates on the HOV lanes have been relatively low. The violation rate on the IH-30 HOV lane, which is barrier-separated, is significantly lower than the rate of the concurrent flow HOV lanes. The violations rates on the concurrent flow lanes, however, are at the lower end of typical nationally reported concurrent flow HOV lane violation rates, ranging between 5 and 40 percent. Violation rates on IH-35E South are within expected values.

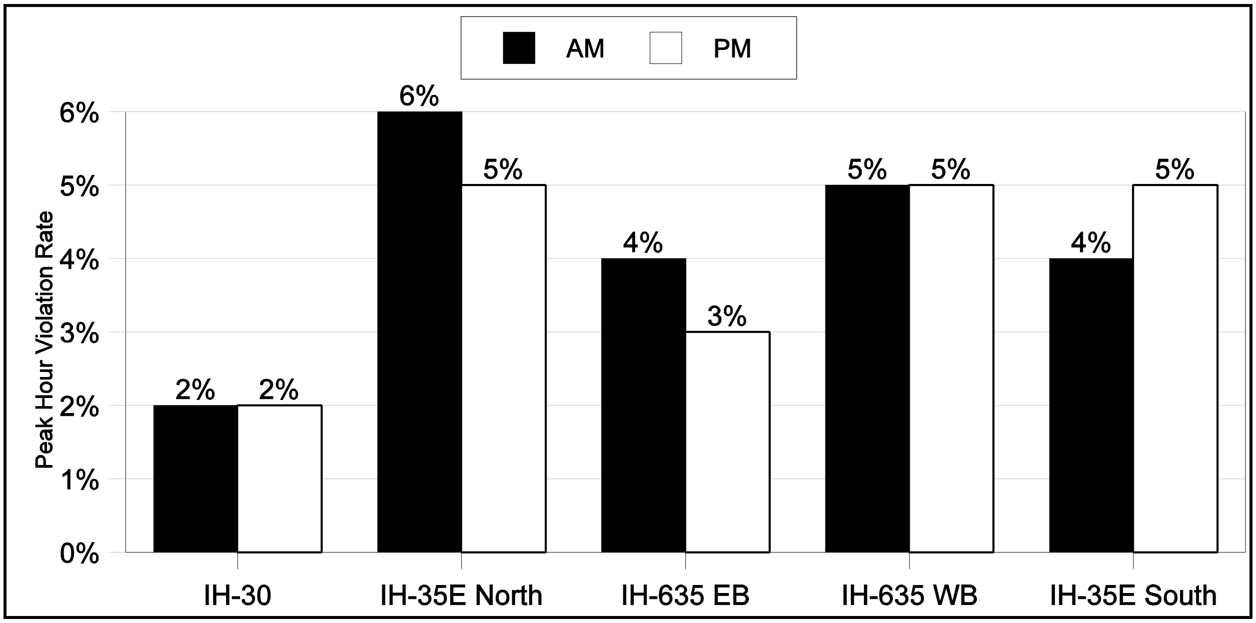


Figure 19. Observed Occupancy Violation Rates.

In addition to traditional HOV lane enforcement methods, a public telephone hotline (HERO) for reporting HOV lane violators, similar to the program in the Seattle area, is currently being studied by DART for implementation. The HERO program consists of a dedicated phone number for motorists to report HOV lane violators and identifies specific individuals who need additional information about the benefits of HOV lanes.

HOV LANE SAFETY

Safety of Dallas Area Freeway Corridors with an HOV Lane

An analysis of "before"and "after" crash data is necessary to evaluate the safety impacts of barrier- versus buffer-separated facilities. Crash rates are an effective means of measuring highway safety trends or crash potential based on the concept of vehicle exposure measured in vehicle-miles traveled (VMT). Combined injury and fatality related annual, two-way crash rates (crashes per 100 Million VMT) for the three corridors of interest in this research are shown in Tables 6, 7, and 8. The data were obtained and summarized from the TxDOT Master Accident/Crash Data Files.

The data were reduced further to determine the annual, peak period crash numbers over several years. TTI traffic volume data from various years were used to obtain peak period crash rates for use in additional comparisons. The tables also show the yearly crashes split by direction, severity of injury, day type, and noted lane location.

Some general conclusions can be drawn from Table 6 concerning safety. Construction within the corridor seems to have contributed to an increase in crash rates and the rates are slightly lower during peak periods. The IH-30 HOV lane began operation in 1991 and the locations for individual crashes in the "before" condition are shown in Figure 20. The locations for individual crashes in the "after" condition are shown both for the short-term (1994) and the long-term (1998) in Figure 21. A before-and-after comparison of corridor crash rates for IH-30 do not indicate anything significant. However, a review of locations for individual crashes in the "after" condition indicates increased crashes near to the entrance for the westbound HOV lane at Jim Miller Road in the morning peak period. At this location, the westbound general-purpose lanes are congested during the morning peak period. Vehicles may be involved in crashes while trying to weave across the general-purpose lanes to access the barrier-separated HOV lane.

Table 6. IH-30 (ERLT) Freeway Corridor Crash Rates.

IH-30 with Contraflow Barrier-Separated HOV Lane From US-75 to Jim Miller Rd. (Cont. Sect.: 0009-11 From Milepoint 4.5 to 10.1)									
	Injury- and Fatality-Related Crashes								
Year	Total Crashes	Peak Period	EB/WB	Nonserious/ Serious[1]	Weekday/ Weekend	Mainlane/ HOV	Vehicle-Miles Traveled (100 Mil VMT)[2]	Crash Rate (Crashes/ 100 Mil VMT)	Peak Period Crash Rate TTI Vol. Used
90[3]	**149**	-	69/80	129/20	99/50	149/na	**2.47**	**60**	-
91	**178**	-	87/91	163/15	121/57	178/na	**2.54**	**70**	-
92[4]	**182**	51	102/80	169/13	124/58	182/0	**2.46**	**74**	Unavailable[6]
93[5]	**201**	59	94/107	181/20	142/59	200/1	**2.46**	**82**	Unavailable[6]
94	**234**	68	102/132	219/15	151/83	230/4	**2.28**	**103**	Unavailable[6]
95	**270**	-	159/111	247/23	187/83	269/1	**2.28**	**118**	-
96	**276**	-	153/123	255/21	194/82	275/1	**2.41**	**115**	-
97	**232**	-	121/111	221/11	156/76	231/1	**2.67**	**87**	-
98	**192**	63	91/101	180/12	131/61	191/1	**2.61**	**74**	63
99	**222**	76	104/118	200/22	153/69	218/4	**2.61**	**84**	83

Notes:
[1]Nonserious = Possible or Non-incompacitating Injury, Serious = Incompacitating Injury or Fatality.
[2]Yearly corridor VMT calculation for 1992-1999 includes HOV lane vehicles.
[3]HOV lane construction began 12/90 and ended 9/91.
[4]Major roadway reconstruction occurred during five of the first six years of HOV lane operation.
[5]Reconstruction of Fair Park bridge began 5/93 and ended 2/96.
[6]Due to construction, no peak period data were collected.

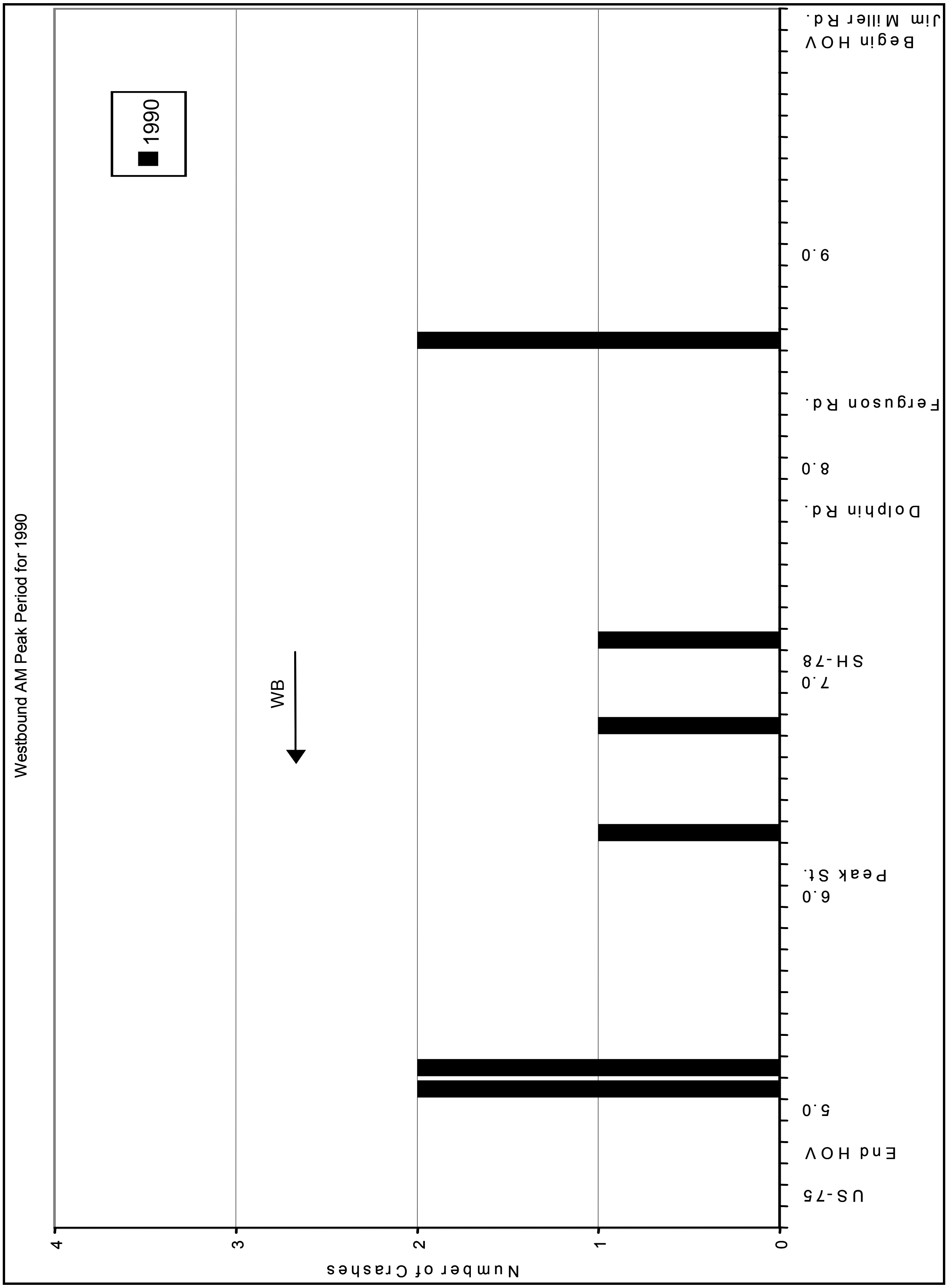


Figure 20. IH-30 (ERLT) Fatality and Injury Crash Data by Location for 1990.

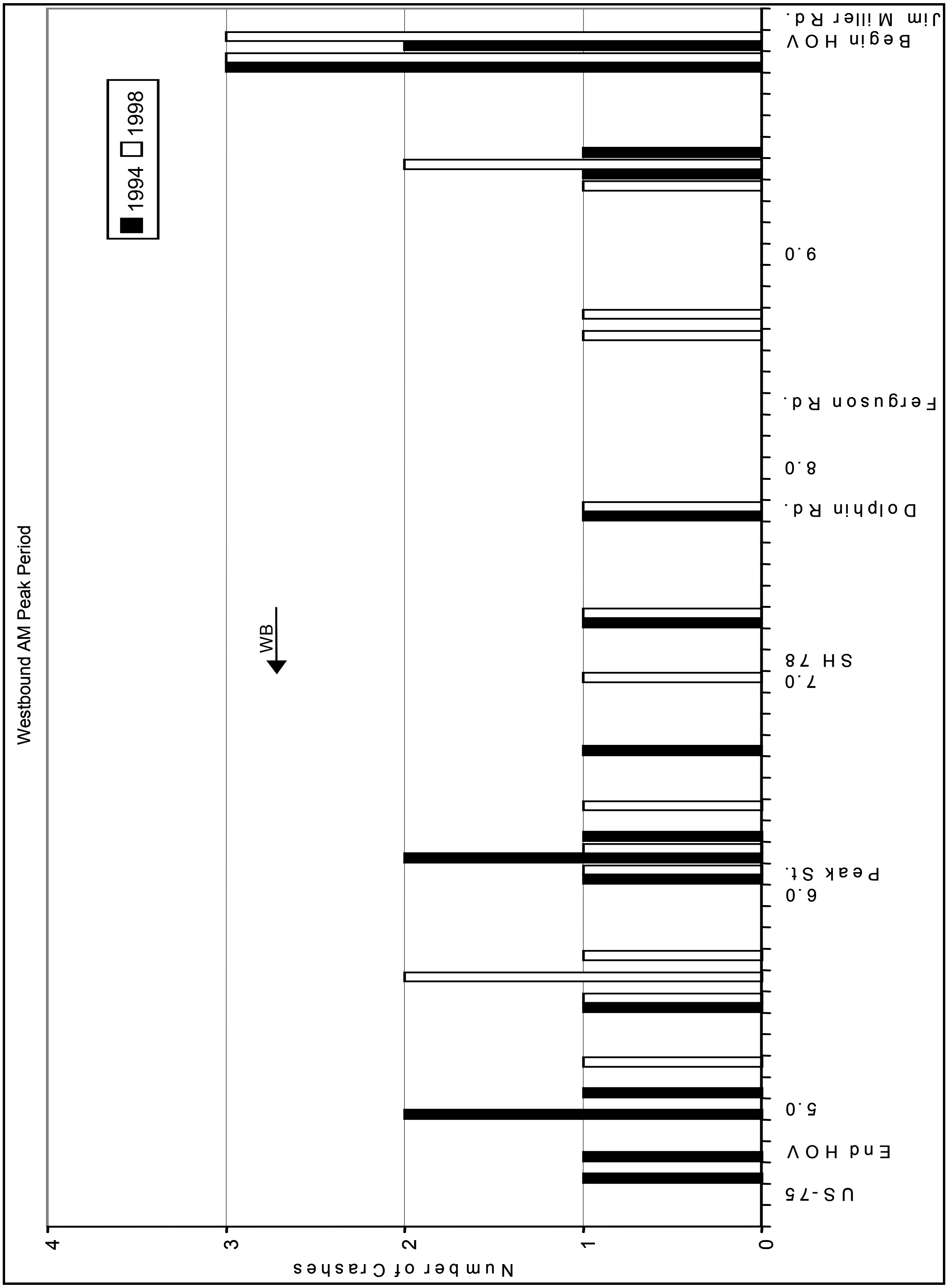


Figure 21. IH-30 (ERLT) Fatality and Injury Crash Data by Location for 1994 and 1998.

Table 7 shows a before-and-after comparison of corridor crash rates for IH-35E. There is an increase in corridor crash rates for the most recent years studied, which are after installation of the buffer-separated HOV lanes. Also, the crash rates in the "after" condition have increased for peak travel periods. A review of locations for individual crashes in the "after" condition indicates increased crashes related to the northbound intermediate access location for the HOV lane between IH-635 and Valley View Ln. (Figure 22). Vehicles may be involved in crashes while trying to weave between the HOV lane and the inner general-purpose lane during the evening peak period.

Table 7. Injury- and Fatality-Related Crash Rates on IH-35E North.

IH-35E North with Concurrent Flow Buffer-Separated HOV Lanes From IH-635 to Dallas Co. Line (Cont. Sect.: 0196-03 From Milepoint 28.5 to 34.5)									
	Injury- and Fatality-Related Crashes								
Year	Total Crashes	Peak Period	EB/WB	Nonserious/ Serious[1]	Weekday/ Weekend	Mainlane/ HOV	Vehicle-Miles Traveled (100 Mil VMT)[2]	Crash Rate (Crashes/100 Mil VMT)	Peak Period Crash Rate TTI Vol. Used
90	**74**	-	38/36	69/5	54/20	74/na	**2.57**	**29**	**-**
91	**75**	-	40/35	67/8	50/25	75/na	**2.55**	**29**	**-**
92	**64**	-	35/29	52/12	53/11	64/na	**2.64**	**24**	-
93	**104**	37	57/47	95/9	70/34	104/na	**2.64**	**39**	45
94	**110**	35	61/49	94/16	78/32	110/na	**2.7**	**40**	53
Construction of HOV Lanes[3]									
97	**157 (Const.)**	-	85/72	150/7	117/40	154/3	**2.98**	**53**	**-**
98	**162**	54	87/74	145/17	119/43	157/5	**3.49**	**46**	67
99	**162**	65	85/77	155/7	123/39	158/4	**3.43**	**47**	78

Notes:
[1]Nonserious = possible or non-incompacitating injury, Serious = incompacitating injury or fatality.
[2]Yearly Corridor VMT calculation for 1997-1999 includes HOV lane vehicles.
[3]HOV Lane Construction began 6/95 and ended 9/96.

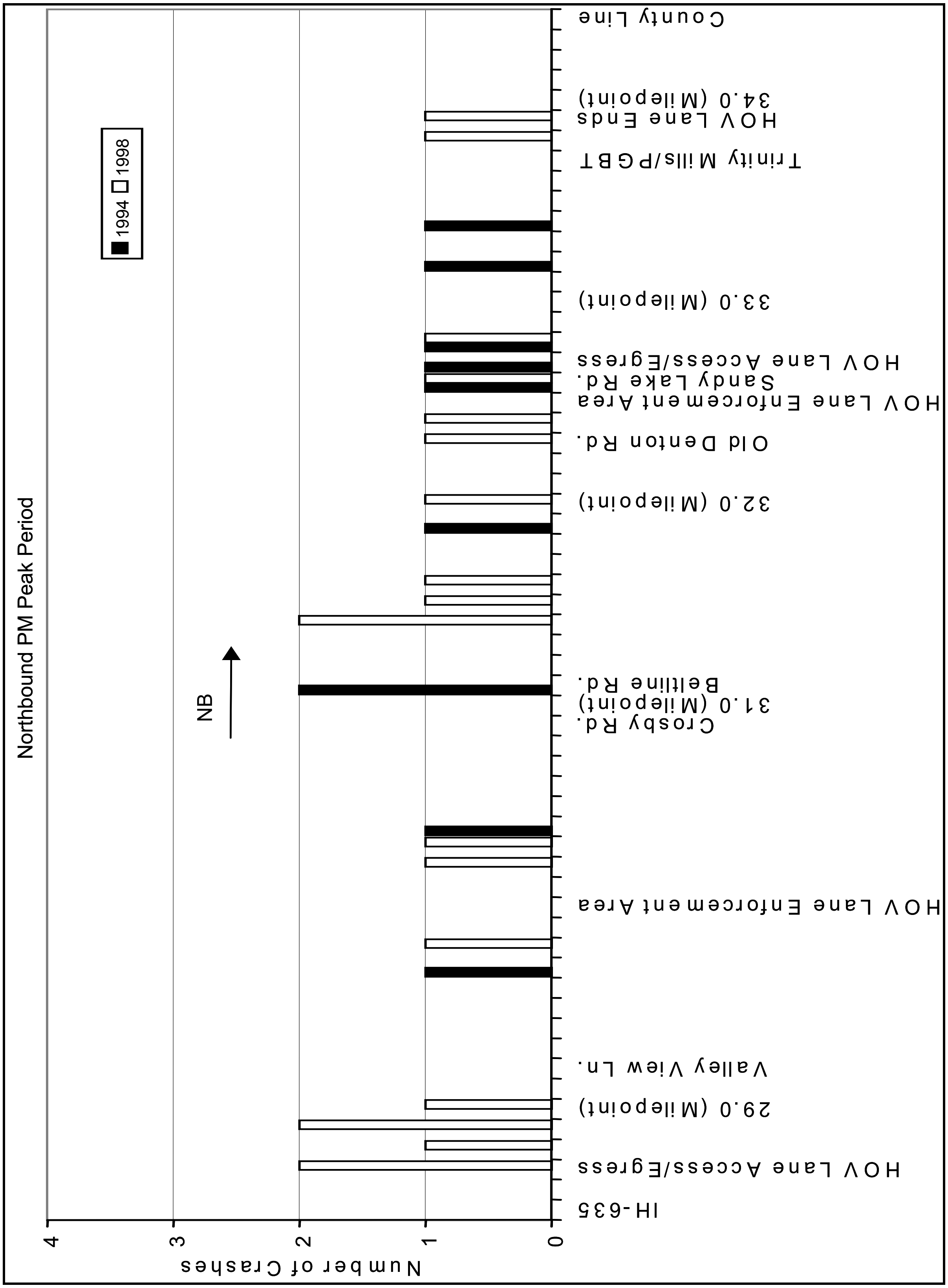


Figure 22. IH-35E (Stemmons) Fatality and Injury Crash Data by Location.

Table 8 shows a before-and-after comparison or corridor crash rates for IH-635. There is an increase in crash rates for the years after installation of the buffer-separated HOV lanes, including the crash rates during peak travel periods. A review of locations for individual crashes in the "after" condition indicates increased crashes related to the HOV lane enforcement area between Marsh Ln. and Webb Chapel Rd. that affects westbound traffic in both the morning and evening peak periods (Figures 23 and 24). Illegal vehicles in the HOV lane may be involved in crashes while trying to quickly exit the lane at a non-approved location prior to the enforcement area.

Table 8. Injury- and Fatality-Related Crash Rates on IH-635.

IH-635 with Concurrent Flow Buffer-Separated HOV Lanes From US-75 to IH-35E North (Cont. Sect.: 2374-01 From Milepoint 6.5 to 14.5)									
	Injury- and Fatality-Related Crashes								
Year	Total Crashes	Peak Period	EB/WB	Nonserious/ Serious[1]	Weekday/ Weekend	Mainlane/ HOV	Vehicle-Miles Traveled (100 Mil VMT)[2]	Crash Rate (Crashes/100 Mil VMT)	Peak Period Crash Rate TTI Vol. Used
90	**264**	-	138/126	236/28	193/71	264/na	**5.48**	**48**	-
91	**282**	-	152/130	256/26	186/96	282/na	**5.95**	**47**	-
92	**245**	84	107/138	227/18	176/69	245/na	**6.06**	**40**	-
93	**241**	78	131/110	228/13	181/60	241/na	**6.06**	**40**	-
94	**283**	93	142/141	375/16	216/67	283/na	**6.60**	**43**	55
Construction of HOV Lanes[3]									
97Jul-Dec	**225 Jul-Dec**	-	118/107	210/15	180/45	220/5	**3.45 Jul-Dec**	**65**	-
98	**476**	184	242/234	451/25	375/101	457/19	**7.53**	**63**	94
99	**434**	146	218/216	403/31	337/97	419/15	**7.42**	**59**	77

Notes:
[1]Nonserious = Possible or Non-incompacitating Injury, Serious = Incompacitating Injury or Fatality.
[2]Corridor VMT calculation for 1997-1999 includes HOV lane vehicles.
[3]HOV Lane Construction Began 6/95 and Ended 3/97.

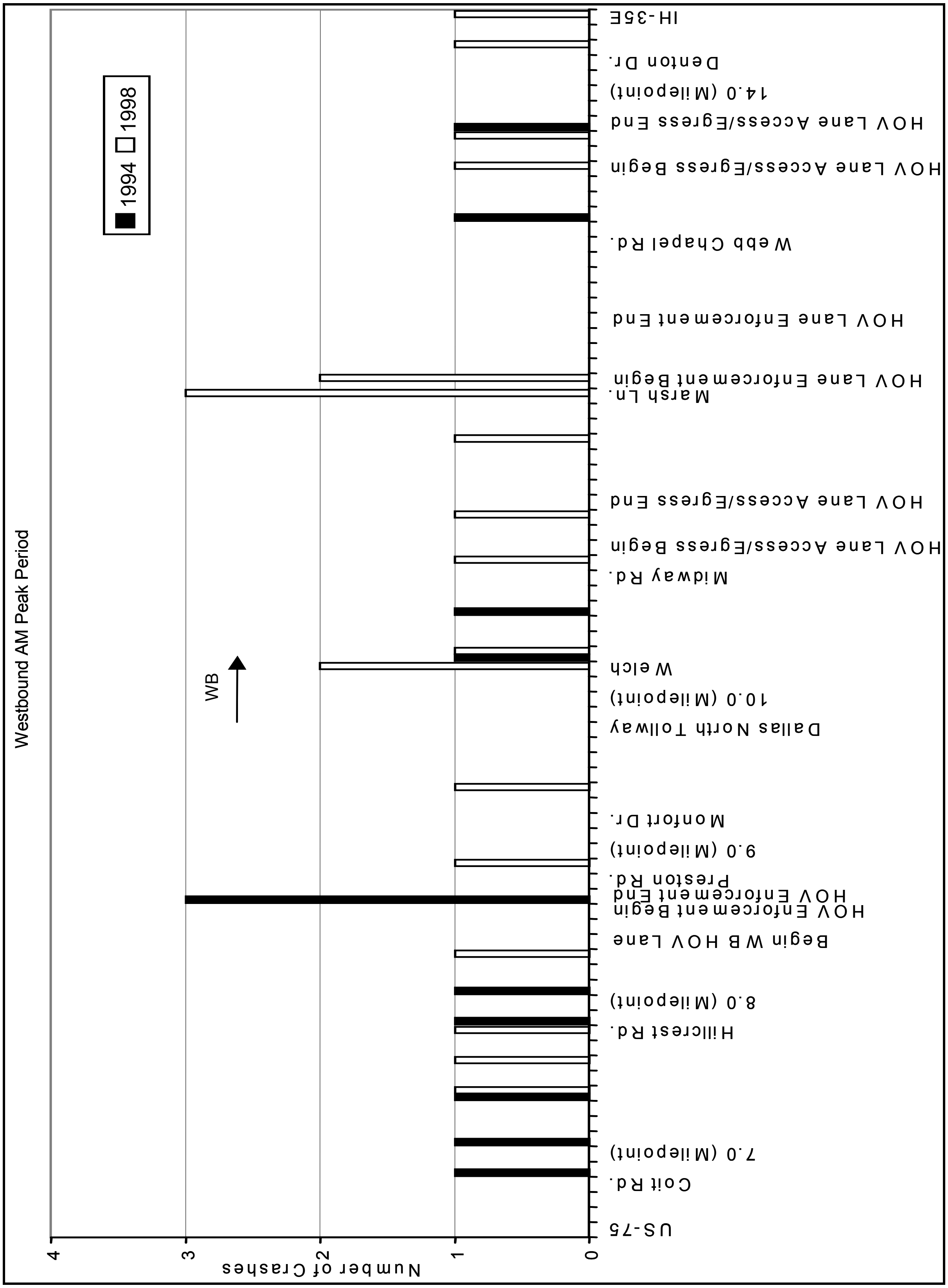


Figure 23. IH-635 (LBJ) Fatality and Injury Crash Data by Location - AM Peak Period.

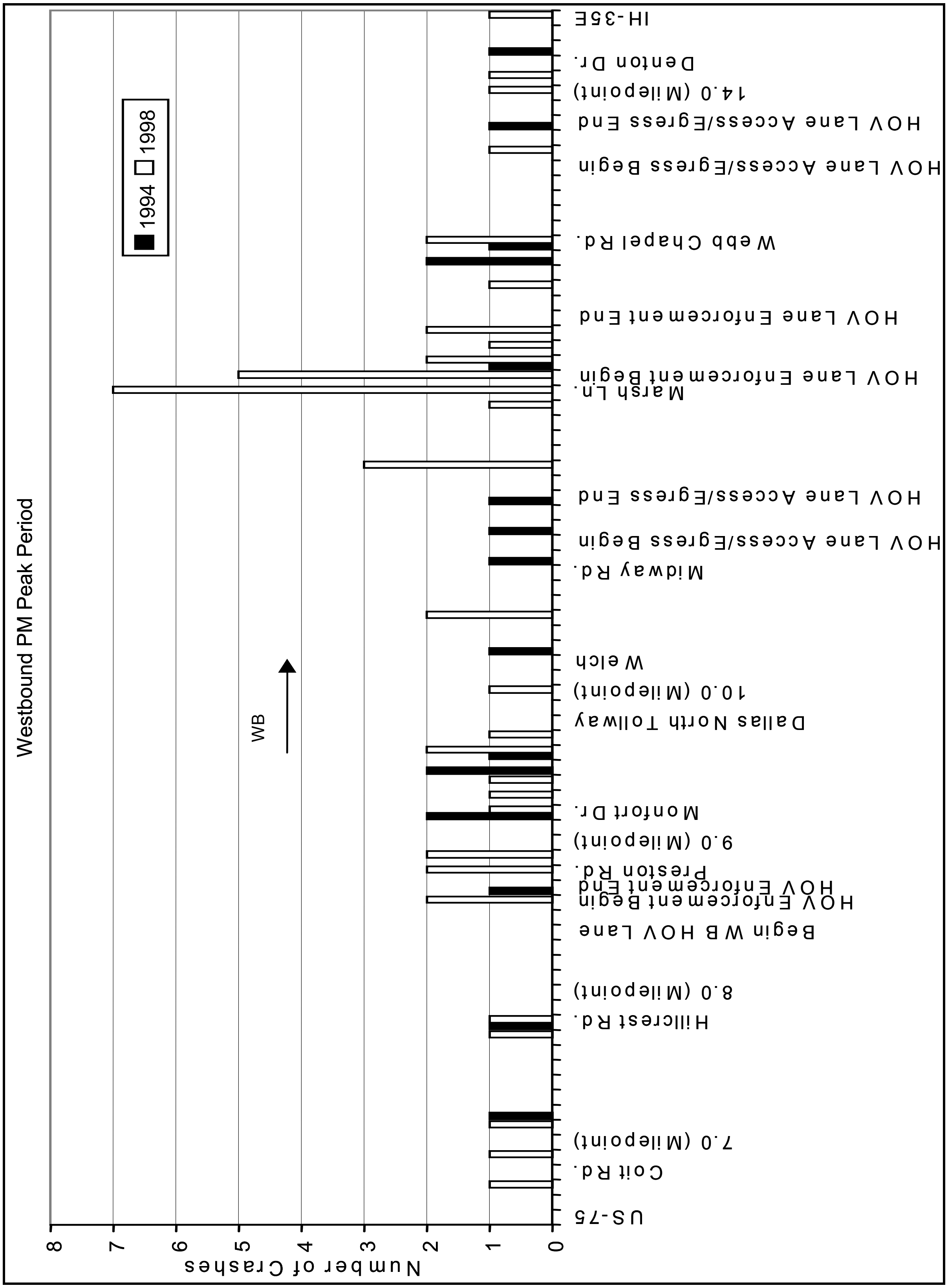


Figure 24. IH-635 (LBJ) Fatality and Injury Crash Data by Location - PM Peak Period.

Researchers were able to determine possible causes for a portion of the total crashes in each of the three corridors discussed. However, these reasons do not account for the overall increase in crashes occurring throughout the corridors with buffer-separated HOV lanes. Several factors were identified early in this research that may have contributed to an increase in crash rates for those corridors. Researchers set out to pinpoint which factor or combination of factors was responsible for the increase in crash rates. The possible contributing factors are as follows:

- Buffer-separated HOV lanes have been implemented.
- There is no longer an inside shoulder.
- General-purpose lanes have been reduced from 12 feet to 11 feet wide.
- Speed limit increased in 1996 during the analysis period for this research.
- Police presence increased for enforcement of HOV lane requirements.
- TxDOT stopped including property damage only (PDO) crashes in the crash database in 1995, possibly causing severe PDO crashes to then be coded as possible injury crashes.

The contribution of losing the inside shoulder and reducing lane widths on general-purpose lanes towards an increase in crash rates was addressed with the data available. These design elements as part of HOV lane facilities are topics of considerable interest within this research. Tables 9 and 10 show crash rates of two control corridors that do not provide inside shoulders. The inside shoulder of IH-35E North (south of IH-635) was removed in 1992 in order that an additional general-purpose lane could be added. The portion of SH-183 used in this research was not designed with inside shoulders.

Table 9. Injury- and Fatality-Related Crash Rates on IH-35E North (South of IH-635).

IH-35E North (south of IH-635) Control Corridor without Inside Shoulders From Royal Lane to Loop 12 (Cont. Sect.: 0196-03 From Milepoint 25.6 to 27.5)			
	Injury- and Fatality-Related Crashes		
YEAR	Total Crashes	Vehicle-Miles Traveled (100 Mil VMT)	Crash Rate (Crashes/100 Mil VMT)
1990	73	1.18	62
1991	46	1.27	36
1992[1] (Const.)	86	1.27	68
1993	80	1.27	63
1994	87	1.40	62
1995	105	1.40	75
1996 (Const.)	119	1.34	89
1997 (Const.)	141	1.39	101
1998	135	1.53	88
1999	109	1.56	70

Note:
[1]Inside shoulders removed in 1992.

Table 10. Injury- and Fatality-Related Crash Rates on SH-183.

SH-183 Control Corridor without Inside Shoulders From Story Rd. to Loop 12 (Cont. Sect.: 0094-03 From Milepoint 4.2 to 7.9)			
	Injury- and Fatality-Related Crashes		
YEAR	Total Crashes	Vehicle-Miles Traveled (100 Mil VMT)	Crash Rate (Crashes/100 Mil VMT)
1990	114	1.67	68
1991	114	1.69	67
1992	124	1.73	71
1993	150	1.74	86
1994	146	1.35	108
1995	137	1.35	101
1996	142	1.35	105
1997	158	1.37	115
1998	132	1.41	93
1999	141	1.48	96

A third example where the inside shoulder has been removed is IH-635 between US-75 and Skillman Ave. in only the eastbound direction. The shoulder removal allowed an additional general-purpose lane to be added. Crash rates for this corridor are shown in Table 11.

Table 11. Injury- and Fatality-Related Crash Rates on IH-635 (East of US-75).

IH-635 (East of US-75) Eastbound Inside Shoulders Removed in 1996 From US-75 to Skillman Ave. (Cont. Sect.: 2374-01 From Milepoint 3.6 to 6.2)			
	Injury- and Fatality-Related Crashes		
YEAR	Total Crashes	Vehicle-Miles Traveled (100 Mil VMT)	Crash Rate (Crashes/100 Mil VMT)
1990	59	0.66	89
1991	59	0.75	79
1992	57	0.78	73
1993	56	0.78	72
1994	52	0.83	63
Construction[1]			
1997	100	0.86	116
1998	79	0.97	81
1999	80	0.95	84

Note:
[1]Shoulder removal began 8/95 and ended 3/96.

A comprehensive review of crash rates from each of these corridors was unsuccessful in pinpointing a single cause for increased crash rates in the buffer-separated HOV lane corridors. Loss of inside shoulder or a reduction in general-purpose lane widths does not appear to contribute singularly to increases in crash rates. Rather, it is due to the combination of the factors outlined earlier. However, researchers were able to intuitively develop other possible contributing factors specific to buffer-separated HOV lanes. These factors are as follows:

- speed differential between HOV lane and general-purpose lanes;
- vehicles weaving from lane to lane for access to and from the HOV lane; and
- law enforcement activities related to the HOV lane, which may require lane changing.

Researchers are able to conclude that crash rates have increased in recent years for the corridors that have a buffer-separated HOV lane within the Dallas area. This increase is a result of a number of combined factors outlined in this research.

Safety Comparison with Similar Freeway Corridors in Texas

Crash rates allow an analyst to make inferences about the safety of highways. Identification of trends may be based on year to year comparisons of crash rates for a particular corridor or statistical comparison with an average crash rate calculated for similar corridors. The rate quality control method of crash rate analysis allows comparison of the crash rate for a particular corridor with an average crash rate for similar corridors. Then, the rates are analyzed to determine if differences are statistically significant. The rate quality control method identifies a corridor as prone to crashes if it satisfies the following inequality:

CORRIDOR CRASH RATE > CRITICAL CRASH RATE

The critical crash rate is determined with the following equation:

$$R_C = \overline{R} + K \times \sqrt{\overline{R}/V} + 1/(2 \times V)$$

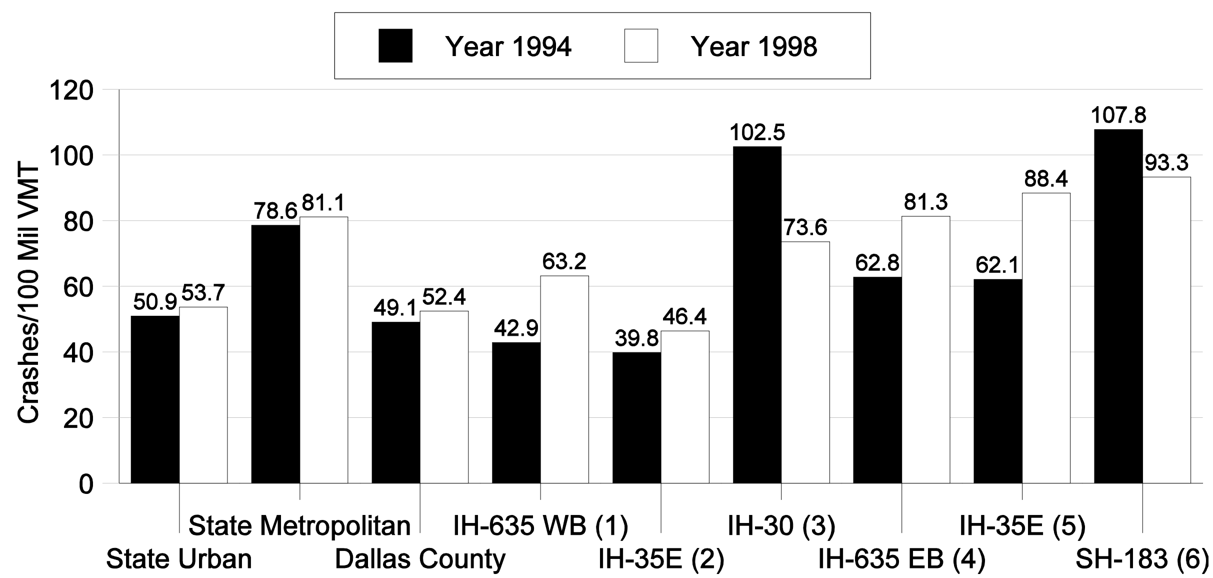
Where, R_C = critical crash rate

$\overline{R}$ = average or mean crash rate for multiple corridors with characteristics similar to those of the corridor under analysis

V = corridor traffic noted in 100 million of vehicle-miles traveled (100 Mil VMT)

K = constant corresponding to level-of-confidence (LOC) in the analysis findings (For this analysis: LOC = 99% or $K = 2.327$)

For this analysis, $\overline{R}$ is computed using three definitions from the TxDOT Master Accident/Crash Data Files to group multiple corridors of similar characteristics. The three groupings include State Urban Interstate Highways, State Metropolitan Areas Interstate Highways, and Dallas County Interstate Highways. State Urban Interstate Highways include all interstate highways in a small urban setting (5000+) within Texas. State Metropolitan Areas Interstate Highways restricts the prior definition to include only the areas with the five largest cities in Texas (Dallas, Fort Worth, Houston, San Antonio, and Austin) which includes the counties of Dallas, Tarrant, Collin, Harris, Bexar, Travis, and Williamson. The final group is restricted even further to include only Dallas County Interstate Highways. A graphical representation of these crash rates and corridor crash rates is shown in Figure 25. The years of 1994 and 1998 were chosen as representative of corridor characteristics before-and-after the areawide implementation of interim HOV lanes within Dallas County with the notable exception of IH-30 where the HOV lane has been in operation since 1991.



Notes:
1. US-75 to IH-35E North.
2. IH-635 to Dallas/Denton County Line.
3. US-75 to Jim Miller Road.
4. US-75 to Skillman Avenue. Inside shoulder was removed in 1996.
5. Royal Lane to Loop 12. Control corridor without inside shoulders.
6. Story Road to Loop 12. Control corridor without inside shoulders.

Figure 25. Injury- and Fatality-Related Crash Rate Comparison on Interstate Highways in Texas.

The rate quality control method of crash rate analysis was applied to the corridors with barrier- and buffer-separated HOV lanes and the two control corridors for the years of 1994 and 1998. Critical crash rates were developed for State Urban Interstate Highways, State Metropolitan Areas Interstate Highways (Dallas, Tarrant, Collin, Harris, Bexar, Travis, and Williamson Counties), and Dallas County Interstate Highways only. These critical crash rates along with corridor crash rates are shown in Table 12.

Table 12. Corridor Crash Rate Analysis.

Critical Crash Rates Determination Using the Rate Quality Control Method[1]									
	State Urban Interstate Highway Crash Rates			State Metropolitan[2] Interstate Highway Crash Rates			Dallas County Interstate Highway Crash Rates		
Year	Crashes	100 Mil VMT	I & F[3] Related (Crashes/100 Mil VMT)	Crashes	100 Mil VMT	I & F Related (Crashes/ 100 Mil VMT)	Crashes	100 Mil VMT	I & F Related (Crashes/ 100 Mil VMT)
1992	12,084	23.6	51.1	9,761	12.4	78.8	2,379	5.3	44.8
1993	12,985	23.6	54.9	10,493	12.4	84.7	2,554	5.3	48.1
1994	13,767	27.1	50.9	11,165	14.2	78.6	2,855	5.8	49.1
AVG	**12,945**	**24.8**	**52.2**	**10,473**	**13.0**	**80.6**	**2,596**	**5.5**	**47.4**
1997	17,248	30.0	57.4	13,795	16.0	86.5	3,688	6.4	57.5
1998	17,112	31.9	53.7	13,687	16.9	81.1	3,620	6.9	52.4
1999	16,482	32.0	51.5	13,209	17.1	77.3	3,516	6.9	51.0
AVG	**16,987**	**31.3**	**54.1**	**13,564**	**16.6**	**81.5**	**3,608**	**6.7**	**53.6**

Year	I & F Related Location Crash Rate			Critical Crash Rates on Interstate Highways			Location Rate Greater Than Any Critical Rate?
	Crashes	100 Mil VMT	Crashes/100 Mil VMT	State Urban (Crashes/100 Mil VMT)	State Metropolitan[2] (Crashes/100 Mil VMT)	Dallas County (Crashes/100 Mil VMT)	
IH-635 with Concurrent-flow Buffer-Separated HOV Lanes from US-75 to IH-35E North (Control Section: 2374-01 from Milepoint 6.5 to 14.5)							
1994	283	6.60	42.9	58.9	88.8	53.7	No
1998	476	7.52	63.2	69.4	89.3	59.8	Yes
IH-35E North with Concurrent-flow Buffer-Separated HOV Lanes from IH-635 to Dallas/Denton Co. Line (Control Section: 0196-03 from Milepoint 28.5 to 34.5)							
1994	110	2.76	39.8	62.5	93.3	57.2	No
1998	162	3.49	46.4	63.4	92.9	62.8	No
IH-30 with Contraflow Barrier-Separated HOV Lanes from US-75 to Jim Miller Road (Control Section: 0009-11 from Milepoint 4.5 to 10.1)							
1994	234	2.28	102.5	63.6	94.6	58.2	Yes
1998	192	2.61	73.6	64.9	94.7	64.3	Yes
IH-35E South Control Corridor without Inside Shoulders from Royal Lane to Loop 12 (Control Section: 0196-03 from Milepoint 25.6 to 27.5)							
1994	87	1.40	62.1	66.8	98.6	61.3	Yes
1998	135	1.52	88.4	68.3	98.9	67.7	Yes
SH-183 Control Corridor without Inside Shoulders from Story Road to Loop 12 (Control Section: 0094-03 from Milepoint 4.2 to 7.9)							
1994	146	1.35	107.8	67.1	98.9	61.5	Yes
1998	132	1.41	93.3	68.9	99.5	68.2	Yes

Notes:
[1]ITE Manual of Traffic Engineering Studies, 4th Edition.
[2]State metropolitan areas include only Dallas, Tarrant, Collin, Harris, Bexar, Travis, and Williamson Counties.
[3]I&F = Injury and Fatality

Summary of Findings for HOV Lane Safety

The yearly crash rates for Dallas area freeways with a buffer-separated HOV lane have increased in the years after the HOV lane was implemented. Also, there is a more pronounced crash rate increase during the peak travel periods. The reason for the increase is a combination of a number of factors outlined in this research and not simply a single factor. However, a review of locations for individual crashes indicates at least a portion of the crash rate increase can be attributed to conflicts at intermediate access locations and lane changes by illegal users of the HOV lane as they approach enforcement areas. The crash rates for Dallas area freeways with buffer-separated HOV lanes are unremarkable when they are compared with similar freeways in Texas.

The yearly crash rates for the Dallas area freeway with a barrier-separated HOV seems to have been most affected by other various construction projects within the corridor. The notable difference for the corridor is the decrease in crash rate during the peak travel periods.

Using the rate quality control method of crash rate analysis, the IH-635corridor appears not to have been prone to crashes in 1994 but was prone to crashes in 1998. It should be noted that this is only true when making comparisons with the critical crash rates from state urban interstate highways and Dallas County interstate highways. When compared to State Metropolitan Areas Interstate Highways, which includes only specific counties, the crash rate analysis does not indicate the corridor was prone to crashes in either 1994 or 1998.

The IH-35E North corridor was not prone to crashes in 1994 or 1998. The corridor's crash rates are lower than critical crash rates developed for each of the three groupings of multiple corridors with similar characteristics.

The IH-30 corridor was prone to crashes in 1994 and 1998 with the corridor crash rate noticeably higher in 1994. This tendency is most likely due to construction in the corridor and bridge reconstruction over the Fair Park area (IH-30 from IH-45 to Haskell Avenue), which started in 1993 and was later completed in 1996.

AIR QUALITY

As previously mentioned, one of the benefits of HOV lanes is a reduction in fuel consumption and vehicle emissions as vehicle speeds increase from stop-and-go congested conditions. A study conducted by NCTCOG estimated the reduction in vehicle emissions from the implementation of each of the HOV lanes in the Dallas area (18). This reduction is based on changes in travel patterns for three groups of commuters: new carpools formed from single-occupant vehicles to use the HOV lane, existing carpools in the mainlanes utilizing the HOV lane, and drivers on the parallel arterials switching to use the mainlanes. Researchers estimate that the volatile organic compound (VOC) emissions are reduced by 51.4 lb/day on IH-30, 109.9 lb/day on IH-35E North, and 236.7 lb/day on IH-635 due to the HOV lane(s) on each of these facilities. No attempt has been made to refine or verify the estimates since NCTCOG staff used operational data supplied by TTI to estimate the emissions.

PUBLIC ACCEPTANCE

In 1995, a survey of IH-30 carpoolers and bus riders using the HOV lane and motorists in the general-purpose lanes was conducted to determine motorists' attitudes regarding commuter travel behavior (17). The primary reasons cited for using transit service were that it is cheaper and more convenient than driving, while the primary reasons for carpooling were that it is cheaper than driving alone and saves time.

DART and TxDOT have been very receptive to public comments about the HOV lanes, and they have been continually improving operations. After the IH-30 HOV lane was opened, DART switched a bus route from an arterial to the freeway HOV lane to gain the travel time savings. In July 1994, to improve AM operations, an auxiliary lane was added at the terminus of the westbound HOV lane. In addition, in February 1996, the eastbound HOV lane for PM operations was extended from Dolphin Road to Jim Miller Road to mitigate recurrent congestion at Dolphin Road.

When the IH-635 HOV lane was opened, motorists from the Dallas North Tollway could not access the westbound IH-635 HOV lane. Because of public response, another access location was added to provide access from the tollway to the westbound HOV lane.

It is anticipated that a survey of HOV lane users and nonusers will be conducted on IH-35E North and IH-635 to assess the public opinion of concurrent flow lanes.

V. OTHER BARRIER- VERSUS BUFFER-SEPARATED HOV LANE ISSUES

In addition to the quantitative issues associated with barrier-separated and buffer-separated HOV lanes, there are also several qualitative issues that must be considered. These qualitative issues include design requirements, implementation time, capacity, access/egress, and flexibility, which are discussed in this section.

DESIGN REQUIREMENTS

Barrier-separated HOV lanes or separated roadways are generally implemented in corridors with a high HOV demand. The benefits of an HOV project must outweigh the cost of building a separated roadway for HOVs. In addition, separated roadways usually require more right-of-way than other types of HOV facilities because of acceleration and deceleration lanes at access/egress areas and wider areas to allow for direct connect ramps. This, many times, makes it difficult to retrofit these types of facilities into existing cross sections.

Buffer-separated or concurrent flow HOV lanes generally require less right-of-way (ROW) than separated roadways. These facilities are typically located on the inside lane of the freeway; however, they can be the outside lane of the freeway, although non-HOV traffic would need to access the HOV lane to enter and exit the freeway, which is undesirable.

IMPLEMENTATION TIME

Separated roadways generally take the longest time to implement. The additional time is required for designing permanent structures, obtaining needed ROW, and obtaining funding for the project, similar to any long-term construction project. The implementation time for concurrent flow HOV lanes is relatively short, particularly when an inside freeway shoulder already exists. Many concurrent flow HOV projects can be accommodated in the existing ROW by converting the inside shoulder to an HOV lane. In addition, reducing the general-purpose lane widths or shifting the lanes may be required to provide a buffer or enforcement area along the facility.

CAPACITY

The vehicular capacity of any facility is dependent on many factors, including design speed, lane width, and the presence of vehicles other than passenger cars in the traffic stream. Differences in capacity specific to the generic comparison of barrier- versus buffer-separated lanes can be attributed to the number of and the design of access/egress areas and the offset to either a barrier or general-purpose lane traffic. The capacity of an HOV facility is in the 1500 to 1700 vph range to ensure free-flow operations before considering the buffer- and barrier-separated issues that impact capacity.

Concurrent flow lanes with continuous access and egress will have continuous merging of high- and low-speed traffic, which will reduce the capacity of the facility (1200-1400 vph). Limited access via a painted buffer will focus this merging activity to specific areas and should improve operations. However, without acceleration and deceleration lanes, which typically are provided at barrier-separated access/egress areas, operations and capacity will be negatively impacted.

The reduction in capacity due to an offset of less than 6 feet to a fixed barrier can be quantified using procedures in the Highway Capacity Manual (19). The capacity reduction for a buffer-separated lane with an offset of less than 6 feet to a congested general-purpose freeway lane, however, is not known and is beyond the scope of this research to determine.

ACCESS/EGRESS

Access to separated roadways is controlled and more limited than on concurrent flow facilities, which provide safe and efficient operations. Access can be provided with direct connector ramps to/from transit centers, park-and-ride lots, and frontage roads, or by slip ramps to/from the freeway mainlanes or frontage road. In addition, the barriers provide effective delineation of entrance and exit points (14).

On separate facilities, carpools must travel the entire distance on the HOV lane; however, on concurrent flow facilities, carpools can travel the entire HOV facility or just a portion of the facility, as dictated by their origin and destination. The access to concurrent flow facilities is much less restrictive than separate roadway facilities. On concurrent flow facilities, access may be provided continuously along the facility or restricted to certain locations, as delineated by pavement markings. The amount of access along the facility should be a decision based on safety and traffic operation concerns. Frequent access increases the potential number of carpoolers but also decreases operational effectiveness.

Concurrent flow HOV lanes are typically the inside lane on the freeway. Therefore, vehicles entering the freeway (generally a right-hand entrance ramp) must weave across several congested freeway lanes to access a median HOV lane and then weave across several congested freeway lanes to exit the freeway (generally a right-hand exit ramp). The weaving to/from the freeway ramps and HOV lane limits the distance that carpools can travel in the HOV lane; therefore, concurrent flow HOV lanes are typically longer distance projects. This weaving maneuver has the potential to negatively affect the mainlane traffic operations. Additionally, if there are left-side entrance or exit ramps, provisions must be made to allow general traffic to use the HOV lane in the proximity of the ramp, which, from a traffic operations standpoint, is not a desirable design.

INCIDENT MANAGEMENT

Incident management is an issue that designers must address in all freeway corridors. Incident management in corridors with concurrent flow HOV lanes is especially critical. HOV lane users who do not regularly gain a travel time savings and trip time reliability may choose not to continue to use the HOV lane. Incidents that occur on the freeway general-purpose lanes can, and have, blocked the concurrent flow HOV lane because of the lack of a physical barrier separating the HOV lane and adjacent general-purpose lanes. DART has personnel that patrol the HOV lanes and respond to all incidents that occur on the facilities.

FLEXIBILITY

A separate roadway facility allows for flexibility in the criteria for eligible users because of the limited access. On the other hand, concurrent flow HOV lanes have flexibility in design) these projects can be interim projects that are retrofitted in the existing cross section, or they can be designed as long-term permanent facilities.

Hours of Operation (24-Hour versus Peak Period Operation)

Typically, barrier-separated HOV lanes are reversible, so they can serve the peak direction commuting traffic; therefore, they usually cannot operate 24-hours a day. Buffer-separated HOV lanes offer the option to either operate 24 hours a day or peak periods only and be used as general-purpose lanes or shoulders during certain hours (non-peak) of the day. Drawbacks of a "part-time" buffer-separated lane, however, may include confusion for commuters, more difficult enforcement and incident management, and increased signing needs.

The two concurrent flow HOV lanes in the Dallas area currently operate 24 hours a day. The typical vehicle and person volumes for each hour of the day are shown in Figures 26 through 29. The traffic patterns on IH-35E North are such that approximately 70 percent of the total corridor traffic is traveling southbound (inbound) during the morning peak period, and the opposite occurs during the evening peak period in the northbound (outbound) direction. There is no recurrent congestion in the off-peak direction or outside of the peak periods on the freeway general-purpose lanes but the HOV lanes are being utilized throughout the day as shown in Figures 26 and 27.

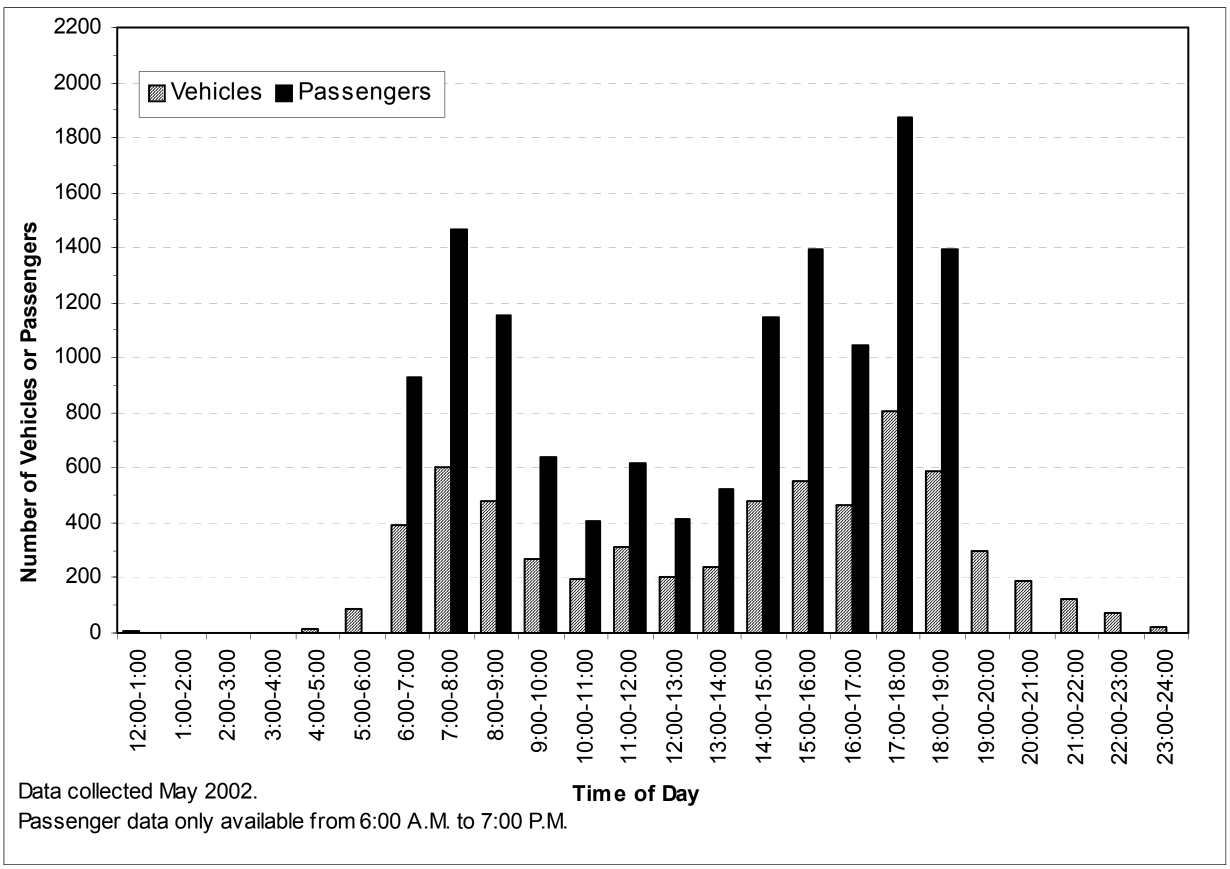


Figure 26. IH-35E North (Stemmons) Freeway Southbound HOV Lane Hourly Volumes.

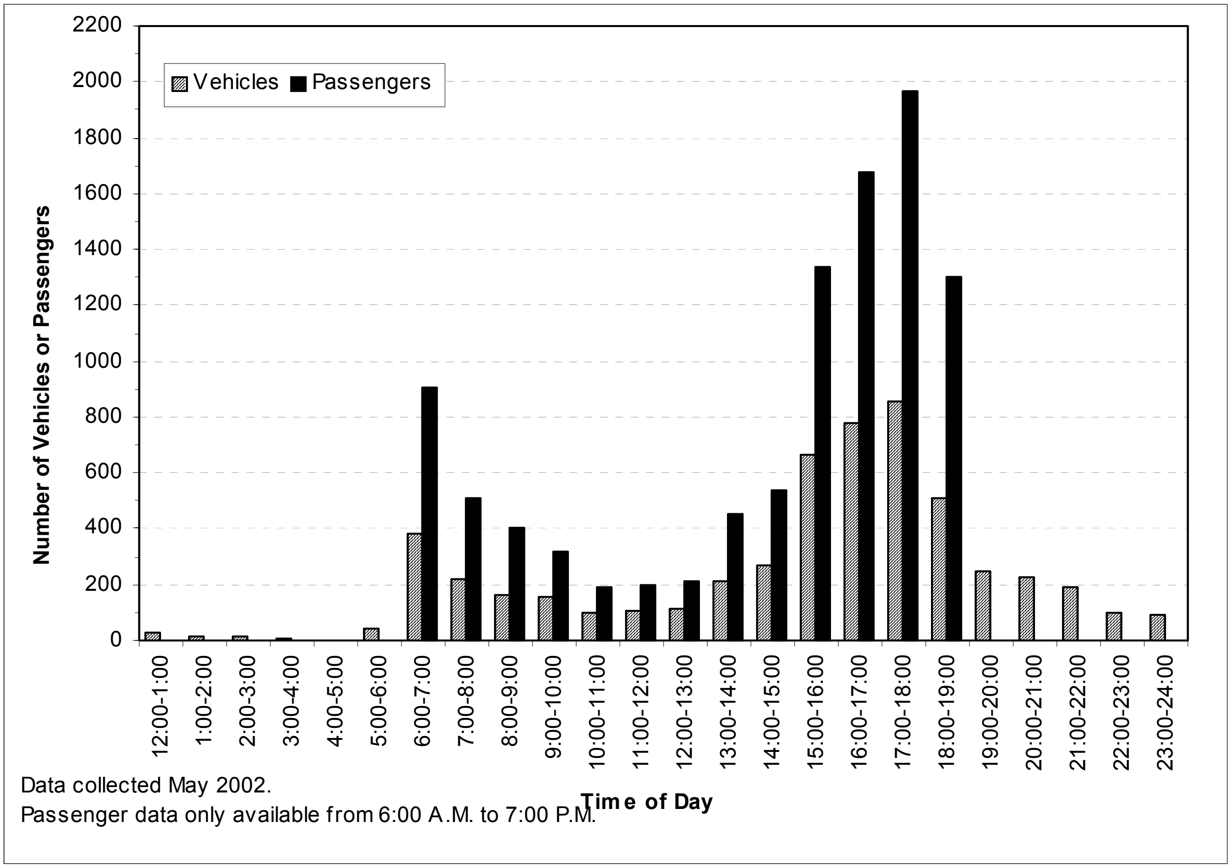


Figure 27. IH-35E North (Stemmons) Freeway Northbound HOV Lane Hourly Volumes.

IH-635, however, has a nearly equal amount of corridor traffic traveling in each direction during the morning and evening peak periods. There is also some recurrent congestion outside of the peak periods. In addition to the peak periods, the HOV lanes on IH-635 are being utilized during the off-peak periods, as shown in Figures 28 and 29. No attempt has been made to quantify any benefits as a result of the off-peak period usage.

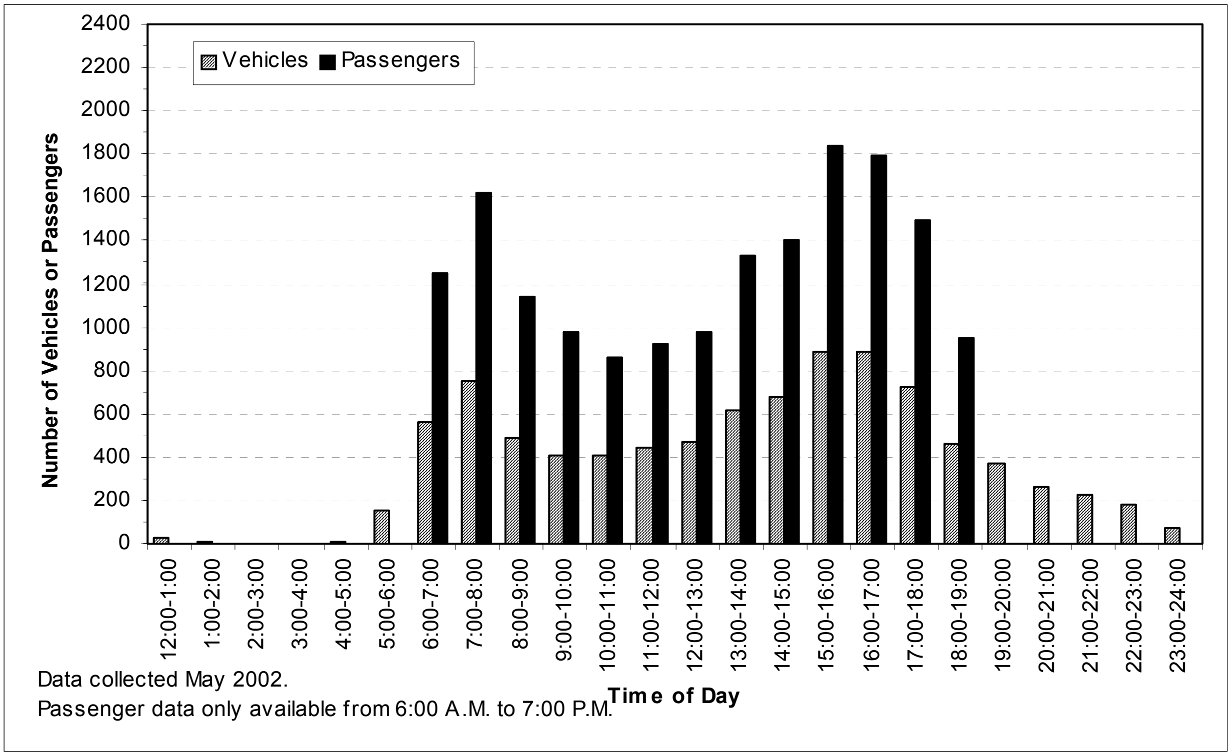


Figure 28. IH-635 (LBJ) Freeway Westbound HOV Lane Hourly Volumes.

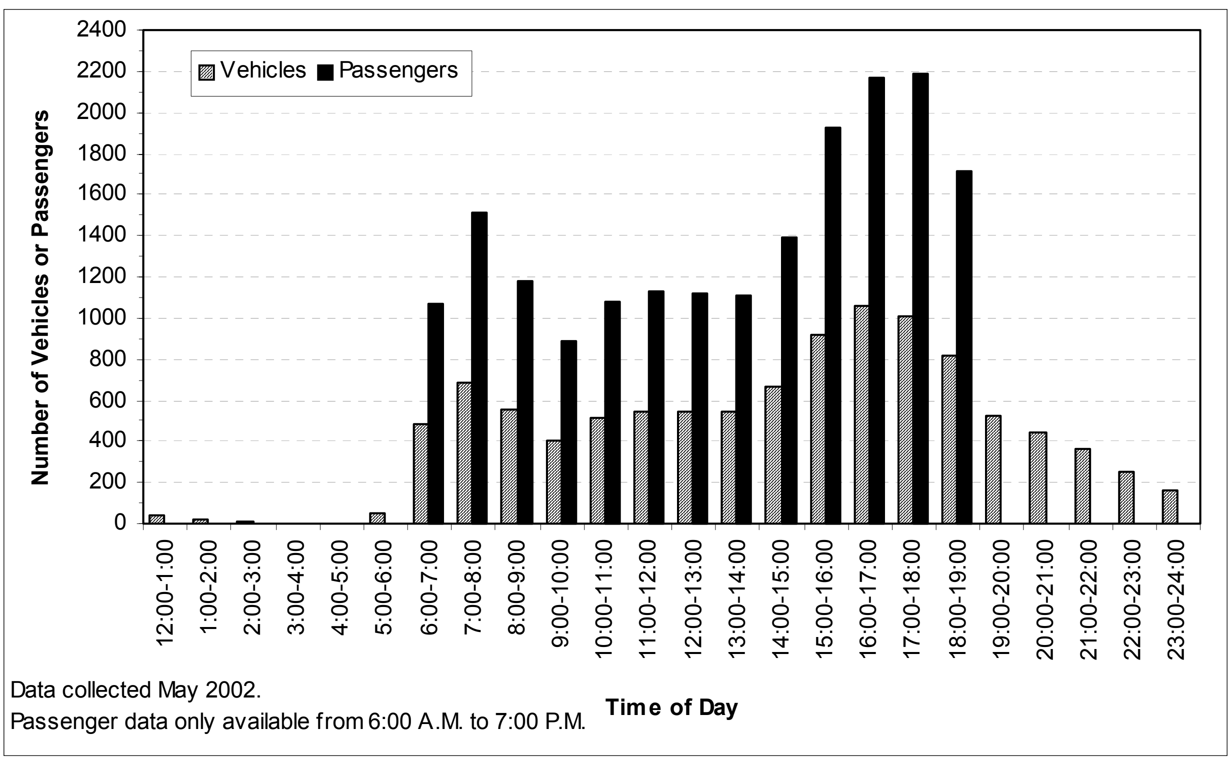


Figure 29. IH-635 (LBJ) Freeway Eastbound HOV Lane Hourly Volumes.

Toll Applications

Congestion pricing can be more easily implemented on barrier-separated HOV lanes, due to their limited access, to allow non-HOV lane eligible vehicles to pay a toll to use the facility during certain time periods. However, congestion pricing can not be easily implemented on buffer-separated (concurrent flow) HOV lanes due to the lack of physical separation. If there was no physical separation between the HOV lane and the general-purpose lanes, drivers may weave between the HOV lane and the general-purpose lane to avoid toll booths or toll tag readers. Because of this, it is not recommended that any type of congestion pricing be implemented on the concurrent flow HOV lanes in the Dallas area. Additionally, as discussed in the previous section, a need does not currently exist for congestion pricing based on the HOV lane volumes and congestion patterns in the two corridors.

SUMMARY OF QUALITATIVE ISSUES

Table 13 shows a summary of the qualitative issues previously discussed.

Table 13. Qualitative HOV Lane Issues.

Characteristic	Barrier-Separated	Buffer-Separated
Design Requirements	High HOV demand Wide cross section needed	Require less right-of-way
Implementation Time	Longest time to implement	Relatively short
Capacity	1500 vph to 1700 vph	1200 vph to 1400 vph
Access	Limited	May be unlimited
Flexibility	Flexibility in eligible users May include congestion pricing	Possible off-peak use as general-purpose lanes

VI. CONCLUSIONS

The goal of this research was to investigate the operational effectiveness of the new concurrent flow HOV lanes in the Dallas area as well as to assess the effectiveness of concurrent flow (buffer-separated) versus contraflow (barrier-separated) HOV lanes in the Dallas area. As shown in Table 14 and the data summary in Tables 15 through 20, the concurrent flow lanes have generated a substantial number of carpools, have increased the person movement in the corridor, have increased the occupancy rate in the corridor, and have not negatively impacted the operation of the adjacent freeway general-purpose lanes. Experience from Houston, however, indicates that two to four years of operation of a facility is required before a complete and thorough assessment can be made.

Table 14. Summary of HOV Lane Measures of Effectiveness.

Measure	IH-30	IH-35E N	IH-635 EB	IH-635 WB	IH-35E S
Has there been an increase in the number of carpools in the corridor?	U [	U [	U [	U [	U [
Does the HOV lane carry as many people as an adjacent general-purpose lane?	U [	U-	U [	U	U [
Has the person volume increased at least as much as the percent increase in number of lanes?	U [	U	U	U	U
Has the occupancy rate in the corridor increased?	U [	U [	U [	U [	U [
In terms of speed, has the HOV lane not negatively impacted the general-purpose lanes?	U [	U [	U	U [	U [
Are the HOV lanes saving HOV lane vehicles at least 5 minutes of travel time?	U [	U [	U	U [	U [
Are the HOV lanes providing motorists at least one minute per mile travel time savings?	U [	U [	U	U	U [

Note:
The table addresses the AM peak hour.

All five HOV lane projects are cost effective and have attained, or are projected to attain, a benefit cost ratio greater than 1.0 within the first five years of operation. While this appears to indicate that either type of HOV lane is acceptable, other issues must be considered, such as the safety of a non-barrier-separated lane.

A before-and-after analysis of crash data was conducted to evaluate the safety impacts of barrier- versus buffer-separated facilities. Crash rates for the IH-35E North and IH-635 corridors have experienced an increase in the analysis years after implementation of buffer-separated HOV lanes and there is a more pronounced increase during peak travel periods. However, the crash rates for these corridors are comparable to crash rates for similar freeway corridors in each of the state's major metropolitan areas. Several factors have been identified, which may have contributed to the increase in crash rates for the corridors with buffer-separated HOV lanes. The reason for the increase is a combination of a number of factors and not simply a single characteristic. However, a review of individual crashes indicated reasons for at least a portion of the crash rate increase for the corridors overall. For IH-35E North, there appears to be a link between crash potential and the weaving maneuver between the HOV lane and the general-purpose lane at an intermediate access location. For IH-635, there appears to be a link between crash potential and lane changes by illegal users of the HOV lane as they approach enforcement areas. Future safety research for pinpointing the most critical factors contributing to crashes in buffer-separated HOV lanes will require a microscopic analysis of particular crashes and their circumstances.

Table 15. IH-35E North (Stemmons) Directional Corridor Operational Data.

Operational Data	"Before"[1] (Mainlanes)	"After"[2] (Mainlanes & HOV)	Percent Change
VEHICLE VOLUMES			
TOTAL			
AM Peak Hour-Southbound	5,965	6,763	13%
PM Peak Hour-Northbound	5,902	6,262	6%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour-Southbound	313	1,057	238%
PM Peak Hour-Northbound	465	1,129	143%
DART BUS			
AM Peak Hour-Southbound	8	9	13%
PM Peak Hour-Northbound	5	9	80%
PERSON VOLUMES			
TOTAL			
AM Peak Hour-Southbound	6,594	8,249	25%
PM Peak Hour-Northbound	6,607	7,874	19%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour-Southbound	651	2,243	245%
PM Peak Hour-Northbound	992	2,416	144%
DART BUS			
AM Peak Hour-Southbound	261	267	2%
PM Peak Hour-Northbound	137	265	93%
OCCUPANCY RATE			
AUTOMOBILE			
AM Peak Hour-Southbound	1.06	1.18	11%
PM Peak Hour-Northbound	1.09	1.22	12%
VEHICLE			
AM Peak Hour-Southbound	1.11	1.22	10%
PM Peak Hour-Northbound	1.12	1.26	12%
Operational Data	**"Before" (Mainlanes)**	**"After" (Mainlanes)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour-Southbound	16.60	16.62	0%
PM Peak Hour-Northbound	12.10	11.67	-4%
SPEEDS (MILES PER HOUR)			
AM Peak Hour-Southbound	24	24	0%
PM Peak Hour-Northbound	28	29	4%
Operational Data	**"Before" (Mainlanes)**	**"After" (HOV Lane)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour-Southbound	16.60	7.26	-56%
PM Peak Hour-Northbound	12.10	6.49	-46%
SPEEDS (MILES PER HOUR)			
AM Peak Hour-Southbound	24	56	133%
PM Peak Hour-Northbound	28	52	86%
PARK-AND-RIDE LOT USAGE[3]	526	649	23%

Notes:
[1]"Before" data are an average of September 1993 to March 1995 data.
[2]"After" data are an average of December 1996 to March 2001 data.
[3]"Before" are data from March 1992 to June 1996, while "After" are data from September 1996 to March 2002.

Table 16. IH-30 (ERLT) Freeway Directional Corridor Operational Data.

Operational Data	"Before"[1] (Mainlanes)	"After"[2] (Mainlanes & HOV)	Percent Change
VEHICLE VOLUMES			
TOTAL			
AM Peak Hour-Westbound	5,692	8,748	54%
PM Peak Hour-Eastbound	7,104	8,924	26%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour-Westbound	596	1,703	186%
PM Peak Hour-Eastbound	954	1,868	96%
DART BUS			
AM Peak Hour-Westbound	40	42	5%
PM Peak Hour-Eastbound	40	44	10%
PERSON VOLUMES			
TOTAL			
AM Peak Hour-Westbound	7,689	11,828	54%
PM Peak Hour-Eastbound	9,549	12,255	28%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour-Westbound	1,290	3,608	180%
PM Peak Hour-Eastbound	2,059	4,026	96%
DART BUS			
AM Peak Hour-Westbound	1,262	1,104	-13%
PM Peak Hour-Eastbound	1,314	1,099	-16%
OCCUPANCY RATE			
AUTOMOBILE			
AM Peak Hour-Westbound	1.13	1.23	9%
PM Peak Hour-Eastbound	1.15	1.25	9%
VEHICLE			
AM Peak Hour-Westbound	1.33	1.35	2%
PM Peak Hour-Eastbound	1.33	1.37	3%
Operational Data	**"Before" (Mainlanes)**	**"After" (Mainlanes)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour-Westbound	14.70	12.47	-15%
PM Peak Hour-Eastbound	11.2 [3]	10.11	-10%
SPEEDS (MILES PER HOUR)			
AM Peak Hour-Westbound	22	26	18%
PM Peak Hour-Eastbound	29 [3]	33	14%
Operational Data	**"Before" (Mainlanes)**	**"After" (HOV Lane)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour-Westbound	14.70	6.19	-58%
PM Peak Hour-Eastbound	11.2 [3]	6.25	-44%
SPEEDS (MILES PER HOUR)			
AM Peak Hour-Westbound	22	53	141%
PM Peak Hour-Eastbound	29 [3]	53	83%
PARK-AND-RIDE LOT USAGE	859	897	4%

Notes:
[1]"Before" data are an average of data collected from October 1989 to June 1991.
[2]"After" data are an average of data collected from June 1996 to March 2002.
[3]"Before" are an average of December 1991 to December 1992 data to account for the extension of the PM HOV lane limits.

Table 17. IH-635 (LBJ) Freeway Eastbound Corridor Operational Data.

Operational Data	"Before"[1] (Mainlanes)	"After"[2] (Mainlanes & HOV)	Percent Change
VEHICLE VOLUMES			
TOTAL			
AM Peak Hour	7,486	8,160	9%
PM Peak Hour	7,175	8,129	13%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour	628	1,181	88%
PM Peak Hour	868	1,630	88%
DART BUS			
AM Peak Hour	1	2	100%
PM Peak Hour	2	2	0%
PERSON VOLUMES			
TOTAL			
AM Peak Hour	8,293	9,627	16%
PM Peak Hour	8,311	10,245	23%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour	1,368	2,546	86%
PM Peak Hour	1,887	3,585	90%
DART BUS			
AM Peak Hour	0	15	??
PM Peak Hour	8	18	125%
OCCUPANCY RATE			
AUTOMOBILE			
AM Peak Hour	1.11	1.18	6%
PM Peak Hour	1.15	1.26	10%
VEHICLE			
AM Peak Hour	1.11	1.18	6%
PM Peak Hour	1.16	1.26	9%
Operational Data	**"Before" (Mainlanes)**	**"After" (Mainlanes)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour	9.70	10.46	8%
PM Peak Hour	21.20	17.42	-18%
SPEEDS (MILES PER HOUR)			
AM Peak Hour	39	37	-5%
PM Peak Hour	18	22	22%
Operational Data	**"Before" (Mainlanes)**	**"After" (HOV Lane)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour	9.70	7.25	-25%
PM Peak Hour	21.20	8.08	-62%
SPEEDS (MILES PER HOUR)			
AM Peak Hour	39	53	36%
PM Peak Hour	18	48	167%
PARK-AND-RIDE LOT USAGE	1,112	1,356	22%

Notes:
[1]"Before" data are an average of data collected from June 1994 to June 1995.
[2]"After" data are an average of data collected from June 1997 to March 2002.

Table 18. IH-635 (LBJ) Freeway Westbound Corridor Operational Data.

Operational Data	"Before"[1] (Mainlanes)	"After"[2] (Mainlanes & HOV)	Percent Change
VEHICLE VOLUMES			
TOTAL			
AM Peak Hour	7,428	8,229	11%
PM Peak Hour	7,902	8,115	3%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour	454	1,222	169%
PM Peak Hour	1,166	1,808	55%
DART BUS			
AM Peak Hour	2	2	0%
PM Peak Hour	1	2	100%
PERSON VOLUMES			
TOTAL			
AM Peak Hour	8,041	9,605	19%
PM Peak Hour	9,312	10,246	10%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour	982	2,516	156%
PM Peak Hour	2,503	3,867	54%
DART BUS			
AM Peak Hour	8	18	125%
PM Peak Hour	0	11	??
OCCUPANCY RATE			
AUTOMOBILE			
AM Peak Hour	1.07	1.17	9%
PM Peak Hour	1.18	1.27	8%
VEHICLE			
AM Peak Hour	1.08	1.18	9%
PM Peak Hour	1.18	1.27	8%
Operational Data	**"Before" (Mainlanes)**	**"After" (Mainlanes)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour	11.20	12.12	8%
PM Peak Hour	13.60	12.98	-5%
SPEEDS (MILES PER HOUR)			
AM Peak Hour	30	29	-3%
PM Peak Hour	25	27	8%
Operational Data	**"Before" (Mainlanes)**	**"After" (HOV Lane)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour	11.20	5.91	-47%
PM Peak Hour	13.60	6.01	-56%
SPEEDS (MILES PER HOUR)			
AM Peak Hour	30	57	90%
PM Peak Hour	25	56	124%
PARK-AND-RIDE LOT USAGE	1,112	1,356	22%

Notes:

[1]"Before" data are an average of data collected from June 1994 to June 1995.

[2]"After" data are an average of data collected from June 1997 to March 2002.

Table 19. IH-35E South (SRLT) Directional Corridor Operational Data.

Operational Data	"Before"[1] (Mainlanes)	"After"[2] (Mainlanes & HOV)	Percent Change
VEHICLE VOLUMES			
TOTAL			
AM Peak Hour - Northbound	7,790	9,468	22%
PM Peak Hour - Southbound	7,522	9,128	21%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour - Northbound	739	1,600	117%
PM Peak Hour - Southbound	1,133	1,698	50%
DART BUS			
AM Peak Hour - Northbound	28	19	-32%
PM Peak Hour - Southbound	22	20	-9%
PERSON VOLUMES			
TOTAL			
AM Peak Hour - Northbound	9,384	11,859	26%
PM Peak Hour - Southbound	9,323	11,630	25%
2+ OCCUPANT AUTOMOBILES			
AM Peak Hour - Northbound	1,572	3,397	116%
PM Peak Hour - Southbound	2,422	3,621	50%
DART BUS			
AM Peak Hour - Northbound	613	540	-12%
PM Peak Hour - Southbound	466	500	7%
OCCUPANCY RATE			
AUTOMOBILE			
AM Peak Hour - Northbound	1.11	1.20	8%
PM Peak Hour - Southbound	1.18	1.22	3%
VEHICLE			
AM Peak Hour - Northbound	1.20	1.25	4%
PM Peak Hour - Southbound	1.24	1.27	2%
Operational Data	**"Before" (Mainlanes)**	**"After" (Mainlanes)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour - Northbound	18.23	15.92	-13%
PM Peak Hour - Southbound	14.43	13.20	-9%
SPEEDS (MILES PER HOUR)			
AM Peak Hour - Northbound	30	34	13%
PM Peak Hour - Southbound	37	40	8%
Operational Data	**"Before" (Mainlanes)**	**"After" (HOV Lane)**	**Percent Change**
TRAVEL TIME (MINUTES)			
AM Peak Hour - Northbound	18.23	9.38	-49%
PM Peak Hour - Southbound	14.43	9.45	-35%
SPEEDS (MILES PER HOUR)			
AM Peak Hour - Northbound	30	58	93%
PM Peak Hour - Southbound	37	56	51%
PARK-AND-RIDE LOT USAGE[3]	451	600	33%

Notes:
[1]"Before" data are an average of March 1996 to March 1998 data.
[2]"After" data are March 2002 data.
[3]"Before" are March 1996 to March 1998 data, while "After" are March 2002 to August 2002 data.

Table 20. HOV Lane Operational Data.

	Contraflow	Concurrent Flow			Reversible Flow
Characteristic	**IH-30**	**IH-35E North**	**IH-635 EB**	**IH-635 WB**	**IH-35E South**
GENERAL					
Opening Date	September 1991	September 1996	March 1997	March 1997	March 2002
Operating Hours	WB: 6-9 AM EB: 3:30-7 PM	24 hrs/day	24 hrs/day	24 hrs/day	Reversible Flow: NB: 6-9 AM SB: 3:30-7 PM Concurrent Flow: 24 hrs/day
Length (miles)	EB: 5.2 WB: 5.2	NB: 5.6 SB: 7.3	6.7	6.2	NB: 9.0 SB: 8.9
VEHICLE VOLUMES					
Total					
AM Peak Hour	1,427	851	703	875	1,221
AM Peak Period	2,990	1,833	1,790	2,194	2,659
PM Peak Hour	1,249	841	1,155	1,059	920
PM Peak Period	2,687	1,925	3,149	2,797	1,957
24-Hour	5,993	10,861	13,685	11,797	8,394
Carpool					
AM Peak Hour	1,334	780	664	815	1,151
AM Peak Period	2,775	1,666	1,687	2,051	2,494
PM Peak Hour	1,161	781	1,094	986	846
PM Peak Period	2,486	1,773	2,981	2,601	1,785
DART Bus					
AM Peak Hour	41	9	1	1	15
AM Peak Period	98	21	2	4	34
PM Peak Hour	41	9	1	1	16
PM Peak Period	90	19	2	4	28
Vanpools, MC, and Other Buses					
AM Peak Hour	18	15	11	18	11
AM Peak Period	43	38	29	47	51
PM Peak Hour	17	13	25	16	15
PM Peak Period	38	40	67	41	33
PERSON VOLUMES					
Total					
AM Peak Hour	4,037	2,009	1,482	1,906	2,937
AM Peak Period	8,563	4,330	3,769	4,777	6,439
PM Peak Hour	3,667	2,012	2,571	2,285	2,391
PM Peak Period	7,647	4,542	6,987	6,011	4,821
24-Hour	17,087	22,152	28,685	25,557	19,108
Carpool					
AM Peak Hour	2,818	1,666	1,411	1,762	2,424
AM Peak Period	5,854	3,548	3,593	4,437	5,228
PM Peak Hour	2,489	1,668	2,425	2,168	1,792
PM Peak Period	5,361	3,785	6,599	5,703	3,810

Table 20. HOV Lane Operational Data (continued).

Characteristic	Contraflow IH-30	Concurrent Flow IH-35E North	Concurrent Flow IH-635 EB	Concurrent Flow IH-635 WB	Reversible Flow IH-35E South
PERSON VOLUMES					
DART Bus					
AM Peak Hour	1,094	254	8	17	450
AM Peak Period	2,419	556	17	38	960
PM Peak Hour	1,077	261	8	4	490
PM Peak Period	2,061	527	22	8	740
Vanpools, MC, and Other Buses					
AM Peak Hour	92	42	35	86	19
AM Peak Period	216	118	87	210	171
PM Peak Hour	71	45	101	57	66
PM Peak Period	152	136	266	149	160
OCCUPANCY RATES					
Automobile					
AM Peak Hour	2.10	2.07	2.09	2.12	2.06
AM Peak Period	2.09	2.07	2.09	2.13	2.06
PM Peak Hour	2.13	2.08	2.21	2.14	2.09
PM Peak Period	2.14	2.08	2.20	2.14	2.09
Vehicle					
AM Peak Hour	2.83	2.36	2.11	2.18	2.41
AM Peak Period	2.86	2.36	2.11	2.18	2.42
PM Peak Hour	2.94	2.39	2.23	2.16	2.60
PM Peak Period	2.85	2.36	2.22	2.15	2.46
ENFORCEMENT					
AM Peak Hour Violation Rate	2%	6%	4%	5%	4%
AM Peak Period Violation Rate	2%	6%	4%	4%	3%
PM Peak Hour Violation Rate	2%	5%	3%	5%	5%
PM Peak Period Violation Rate	3%	5%	3%	5%	6%
OTHER					
Construction Cost	$17.4 M	$9.9 M	$16.3 M		$44.5 M
Construction Cost Per Mile	$1.67 M	$0.8 M	$1.28 M		$4.94 M
Operation & Enforcement	$0.6 M	$0.2 M	$0.2 M		$0.3 M
COST/YEAR					
FY 2000 Annual HOV Benefits	$8.4 M	$2.1 M	$8.5 M		$8.1 M
Operating Years to be Cost Effective	2.4 years	4.8 years	1.8 years		5.9 years

Notes:
[1]Daily total (24-hour) counts are collected with automatic vehicle counters on the HOV lane with an applied observed occupancy rate to estimate the number of passengers.

REFERENCES

1. W.R. Stockton, G.F. Daniels, D.A. Skowronek, and D.W. Fenno. *An Evaluation of High-Occupancy Vehicle Lanes in Texas, 1997*, Research Report 1353-6, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1999.

2. D.A. Skowronek, A.M. Stoddard, S.E. Ranft, and C.H. Walters. *Highway Planning and Operations for the Dallas District: Implementation and Evaluation of Concurrent Flow HOV Lanes in Texas*, Research Report 1994-13, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1997.

3. D.A. Skowronek, S.E. Ranft, and J.D. Slack. *Investigation of HOV Lane Implementation and Operational Issues*, Research Report 7-3942, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1999.

4. Dallas Area Rapid Transit, *The DART Report*, Winter 1999, (http://www.dart.org).

5. K.F. Turnbull, R.H. Henk, and D.L. Christiansen. *Suggested Procedures for Evaluating the Effectiveness of Freeway HOV Facilities,* Research Report 925-2, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1991.

6. W.R. Stockton, G.F. Daniels, D.A. Skowronek, and D.W. Fenno. *The ABC's of HOV: The Texas Experience*, Research Report 1353-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1999.

7. J. Obenberger and B. Rupert. *Issues to Consider in the Operation of High Occupancy Vehicle (HOV) Lanes*, Transportation Research Board Paper 00-1632, National Research Council, Washington D.C., 1999.

8. *IH-287 and IH-80 HOV Reassessment Final Report*, unpublished, New Jersey Department of Transportation, October 22, 1998.

9. *Washington State Considers Opening HOV Lanes to General Traffic on Weekends*, The Urban Transportation Monitor, pp. 1-2, Volume 14, Number 6, March 31, 2000.

10. Colorado Department of Transportation. *CDOT Value Express Lanes Feasibility Study*, (http://www.valuelanes.com/projectdocs.html).

11. *A Policy on Geometric Design of Highways and Streets,* American Association of State Highway and Transportation Officials. Washington, D.C., 1990.

REFERENCES

12. T.F. Golob, W.W. Recker, and D.W. Levine. *Safety of High-Occupancy Vehicle Lanes Without Physical Separation.* ASCE Journal of Transportation Engineering, 115, pp. 591-607, 1989.

13. S. Hockaday, E. Sullivan, N. Devadoss, J. Daly, and A. Chatziiouanou. *High-Occupancy Vehicle Lane Safety.* Submitted to the State of California Department of Transportation by California Polytechnic State University. Contract Number 51P278, TR 92-107. September 1992.

14. C.A. Fuhs. *High-Occupancy Vehicle Facilities. A Planning, Design, and Operation Manual.* Parsons-Brinkerhoff, Inc. New York, New York, 1990.

15. D.A. Skowronek and T.J. Pietrucha. *Dallas Area High Occupancy Vehicle Lanes, September 2000 Operational Summary*. Texas Transportation Institute, The Texas A&M University System, Arlington, Texas, September 2000.

16. D.A. Skowronek and T.J. Pietrucha. *Dallas Area High Occupancy Vehicle Lanes, March 2001 Operational Summary*. Texas Transportation Institute, The Texas A&M University System, Arlington, Texas, March 2001.

17. K.F. Turnbull, P.A. Turner, and N.F. Lindquist. *Investigation of Land Use, Development, and Parking Policies to Support the Use of High-Occupancy Vehicles in Texas.* Research Report 1361-1F. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1995.

18. North Central Council of Governments. *Transportation Control Measures Effectiveness Study.* (An Analysis of Transportation Control Measures Implemented for the 15 Percent Rate of Progress State Implementation Plan in the Dallas-Fort Worth Ozone Nonattainment Area.), Prepared for the Texas Natural Resource Conservation Commission, August 1996.

19. *Highway Capacity Manual.* Transportation Research Board, Special Report 209, National Research Council, Washington D.C., 1994.