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16. Abstract

This report documents the results of the second year of Project 0-4740, Improved Quantification of High-Occupancy Vehicle (HOV) Lane Delay Savings. Year two contained three tasks:

- Task 4: document methodologies used for improved quantification of HOV lane travel time savings including incident conditions, which meets the requirements for Product 0-4740-P1;
- Task 5: prepare guidelines for opening HOV lanes to all traffic during mainlane incidents, which meets the requirements for Product 0-4740-P2; and
- Task 6: investigate an automated strategy to continue revising estimated HOV lane delay savings, which meets the requirements for Product 0-4740-P3.

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IMPROVED QUANTIFICATION OF HIGH-OCCUPANCY VEHICLE (HOV) LANE DELAY SAVINGS: YEAR TWO RESULTS

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CHAPTER 1: INTRODUCTION

This report documents the results of the second year of Texas Department of Transportation Research Project 0-4740, *Improved Quantification of High-Occupancy Vehicle (HOV) Lane Delay Savings*. Year two contained three tasks: Task 4, Task 5, and Task 6.

TASK 4: METHODOLOGIES FOR IMPROVED QUANTIFICATION OF HIGH-OCCUPANCY VEHICLE (HOV) LANE TRAVEL TIME SAVINGS

The goal of this project was to improve the quantification of HOV lane travel time savings by accounting for incident conditions in the evaluation. HOV lanes are commonly evaluated using travel time studies that are typically conducted infrequently and under non-incident conditions due to cost and manpower of conducting manual studies.

Due to the high occurrence of incidents in large urban areas where HOV lanes are more likely to be implemented, travel time studies conducted under non-incident conditions underestimate the true benefit of the HOV lanes. In Houston, in 2003, there were an average of only 17 percent of morning peak periods and 10 percent of afternoon peak periods found to be incident free in the four HOV corridors studied.

The first year of this project examined the impact of mainlane incidents on peak period travel time saving benefits provided by HOV lanes. Data from the HOV systems in Houston and Dallas were used for this study. Researchers studied barrier-separated HOV lanes for the Houston analysis, while studying a buffer-separated HOV lane for the Dallas analysis.

This task presents the methodologies used in the first year's analyses. This task is divided into two sections. The first section presents two methodologies used in the Houston analyses, while the second section presents the methodology used in the Dallas analysis. The methodologies were kept as similar as possible from the beginning of the project; however, differences in types and quantity of available data caused some variations in methodologies between the two analyses.

The analysis followed the same basic procedures listed below:

- Collect incidents and analyze by characteristics,
- Categorize incidents into incident matrix by (duration and severity),
  - Create School in / School out matrices (Houston only),
  - Gather travel times on general-purpose (GP) lanes and (HOV) lanes,
  - Calculate the travel time difference between the GP and HOV,
- Summarize the travel times for each cell of each matrix, and
- Quantify the economic benefits of HOV lane delay savings (Houston only)

The differences between the Houston and Dallas methodologies are summarized in Table 1.

Table 1. Contrast of Houston and Dallas Methodologies.

Attribute	Houston	Dallas Analysis
HOV Configuration	Barrier Separated	Buffer Separated
Travel Time	AVI (Link Travel Time)	VIDS (Spot Speed)
Corridors/Freeways	4	1
Source	RIMS Database	Video (Manual Reduction)
Total Incidents	1 Year (9,506)	4 Months (569)
Incidents Studied	346	64

RIMS = Regional Incident Management System
VIDS = Video Imaging Detection System

TASK 5: GUIDELINES FOR OPENING HOV LANES TO ALL TRAFFIC DURING MAINLANE INCIDENTS

Incident management has a rich history of research and implementation for general-purpose lanes on controlled-access freeways and highways. The past 10 years have seen the advent of technological solutions for centralized traffic and incident management, improving the timeliness of first response teams. In the same 10-year time frame, high-occupancy vehicle lane miles have more than doubled, from approximately 1,300 lane miles in 1995 to over 2,500 in 2000, and are forecasted to be 3,100 in 2005. It is evident by the public policy support for new facilities that HOV lanes have proven themselves capable of providing a premium level of service and reliability.

To use the HOV facilities, users must adhere to the facility's particular occupancy and use policies. Most freeway-based HOV lanes apply a two-person-or-more (HOV 2+) occupancy policy, generating a level of demand that justifies the HOV lane without it becoming overloaded or congested (*1*). These policies may cause an inconvenience to the user, such as traveling additional mileage to pick up a carpool partner. As a result, the user must weigh the value of time gained from the HOV lane versus the cost of time as a result of inconvenience.

In many ways, HOV lanes in any given corridor are selling the possibility of recurring congestion or a minor incident in adjacent general-purpose lanes in return for an uncongested trip in the HOV facility. The expectation, in return for accepting some inconvenience associated with the trip, is that the use of the HOV lane will provide some travel time savings. However, severe congestion or incidents in the general-purpose lanes have tended to cause animosity on the part of the general public toward HOV lanes if they are underutilized (*1*).

Local governments and agencies must balance the dual, and sometimes conflicting, demands of incident management in the general-purpose lanes and use of the HOV lanes. Diversion of general-purpose lane traffic during incidents to underutilized HOV lanes is applied occasionally throughout the nation. Unlike incident management on general-purpose lanes, standards for diversion decisions are lacking at most HOV lane operations (*2*).

The purpose of this task is to provide guidelines for diverting GP traffic to HOV lanes during GP lane incident conditions. It builds upon the information already collected for TxDOT Project 0-4740 and utilizes the recommendations established by Research Report 0-4160-17, Incident Management for Managed Lanes, which was developed for TxDOT Project 0-4160, Operating Freeways with Managed Lanes (*2*).

This task addresses the following questions:

- How is traffic diversion for incident management currently applied on HOV lanes?
- Are travel time savings or other benefits calculable for such decisions?
- What scenarios can be developed to help TxDOT determine the appropriateness of a diversion decision?
- What guidelines can be established to guide diversion decisions through the various scenarios?

TASK 6: INVESTIGATION OF AN AUTOMATED STRATEGY TO CONTINUE REVISING ESTIMATED HOV LANE DELAY SAVINGS

The main objective of this task is to provide an outline, plan, or tool to automatically calculate high-occupancy vehicle lane benefits. The calculated benefits can be used to provide traveler information, operations and planning information, and documentation to quantify the benefits of traffic management functions as they relate to HOV lane operations. Travelers can use the information to effectively plan their trips prior to departure or en route. Traffic management personnel can utilize the information to document the benefits of incident management, intelligent transportation system devices, and emergency management. Operations managers and planners can quantify the utilization of the transportation facilities, use the information to manage existing systems to their fullest, and plan for expansion or new facilities. The same information can provide decision makers with a tool to continually monitor how well the HOV system is performing based on operational and historical data. Continual monitoring will allow a systematic measurement to determine how changes in operation and/or events affect the system.

Implementation of the automation strategy in the Houston region involves the development of software components that accomplish the following:

- provide an interface to automate the calculation of HOV and mainlane travel time differences customizable by facility, date, and time; and
- report the duration and severity of incidents using the above criteria on the facility selected by the user.

The automation strategy utilizes existing automatic vehicle identification (AVI) based travel time data from the Houston TranStar traffic management system to automate the calculation of HOV and mainlane travel times. In addition, incident information from Houston's Regional Incident Management System (RIMS) will be used for the automated reporting of incidents.

CHAPTER 2:
METHODOLOGIES FOR IMPROVED QUANTIFICATION OF HIGH-OCCUPANCY VEHICLE (HOV) LANE TRAVEL TIME SAVINGS

HOUSTON METHODOLOGIES

Two types of analyses were performed in the Houston study. The first analysis looked at the impact of a range of types of individual incidents on HOV lane peak period travel time savings. The second analysis quantified the time and dollar value of the HOV lane peak period travel time savings over the course of the year 2003. Both analyses included studies of the HOV lanes in the IH-10 Katy, IH-45 North, IH-45 Gulf, and US-59 Southwest Freeway corridors.

Individual Incident Analysis Methodology

The individual incident analysis portion of the Houston analysis focuses on the impact of mainlane incidents on HOV lane travel time savings, i.e., how much additional travel time savings Houston HOV lanes provided during incident conditions. The remainder of this section describes the methodology used in this analysis.

Data Resources

The data used in this analysis came from two principal sources. The documentation of individual incidents as well as all accompanying information needed in the analysis were logged and archived in the RIMS database. All speed data used in the analysis were obtained through archived AVI files. Both systems were developed for, and are under the operation of, Houston's traffic management center, Houston TranStar.

Travel Time Analysis Overview

The process used to analyze the travel time data by incident is best described by Figure 1. There are nine steps in the process:

1. Select corridors and develop the incident matrix.
2. Calculate corridor mainlane and HOV travel times using the Travel Time Generator in five minute increments.
3. Calculate the travel time difference for each incident.
4. Average each travel time difference for each incident within each incident matrix cell.
5. Create a matrix of average travel time differences, stratified by incident duration and lanes blocked.
6. Calculate the set of time period matrices (a-e) for each of the four freeways listed in Figure 1 for the total of 20 matrices by freeway and time period:
    a. AM School In,
    b. AM School Out,
    c. PM School In,
    d. PM School Out, and
    e. Combined.

7. Generate a combined corridor (freeway) average by averaging each cell in a given time period matrix.
8. Generate a combined corridors and combined duration average.
9. Generate a weighted average for all corridors, all durations, all time periods, and all blockage types.

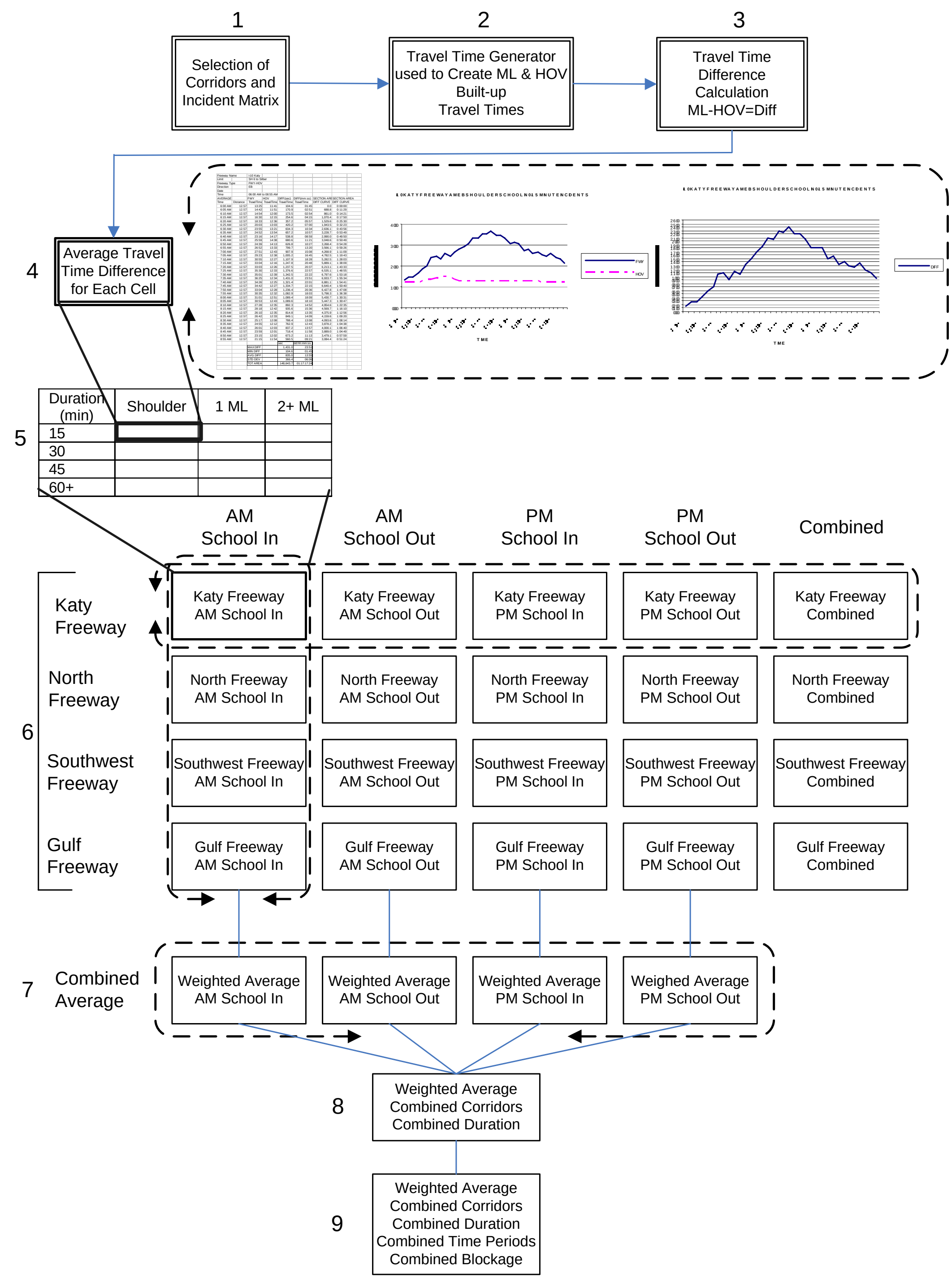


Figure 1. Overview of Steps in Individual Incident Analysis.

Development of the Incident Matrix

In order for researchers to be able to quantify the HOV lane travel time savings for a range of incident types, researchers developed an incident matrix into which to stratify the incidents selected for analysis. A number of factors were considered in the development of the incident matrix including the following:

- time of day,
- time of year,
- longitudinal location of incident,
- cross-section location of incident,
- number of lanes blocked,
- duration of incident, and
- corridor characteristics.

It was determined that the primary factors that should be used in the incident matrix were incident duration and extent of blockage. The remaining factors were taken into consideration through the analysis methodology. Table 2 presents the incident matrix developed as a function of duration of incident and extent of blockage. The categories for lanes blocked initially included a 3+ mainlanes column; however, due to the scarcity of 3+ mainlanes blocked incidents, they were combined with the two mainlanes column to form a 2+ mainlanes column. Although using five incident duration categories in the matrix could result in empty or small sample size cells, it was determined in sponsor meetings that the incident duration categories should not be reduced. The following paragraphs in this section describe how researchers accounted for the remaining aforementioned incident factors.

Table 2. Incident Matrix.

Incident Duration (minutes)	Lanes Blocked		
	Shoulder	1 Mainlane	2+ Mainlanes
0-15			
16-30			
31-45			
46-60			
60+			

The time of day an incident occurs is highly correlated with the extent of the impact that can be expected on resulting congestion and delay. Incidents occurring during off-peak hours have much less impact on traffic operations for a given type of incident than if the same incident occurred during peak hours. For this reason, researchers decided to focus on incidents occurring during peak hours. Based on traffic data from the Houston area, peak hours were defined as 6:00 to 9:00 AM and 3:30 to 6:30 PM.

The time an incident occurs within the peak period can also have an impact on the delay experienced by the motorist. Incidents occurring during the middle of the peak period have a much greater impact than those occurring at the tails of the peak period. Initially, a window of influence was investigated; however, it was difficult to determine when the influence of the incident ended. In most cases, it was difficult to determine if the speeds ever returned to “normal” congestion. Therefore, researchers analyzed travel times during the entire peak period, 6:00 to 9:00 AM and 3:30 to 6:30 PM.

Time of year as an influencing factor is largely a function of whether school is in session or not. Mainlane travel times when school is out of session are typically lower than when school is in session. To account for these potential differences, a comparison using non-incident travel time data was made to determine if mainlane travel times when school was in session or out of session were statistically significant or not. The purpose of this analysis was to determine if researchers should split the incident matrix into two matrices, one containing incidents occurring when school is in session and one containing incidents occurring when school is out of session.

The longitudinal location of incidents was also considered a factor. Incidents outside the limits of the HOV lane facility were not considered in this analysis, as their impact on operations within the limits of the facility would typically be negligible except for cases involving severe incidents. A major incident upstream of the study limits would actually serve as a bottleneck, reducing mainlane demand in the study section and actually lowering mainlane travel times. A major incident downstream of the study limits would only impact operations within the study section if queuing backed up into the study section. These incidents, as well as incidents occurring outside of HOV lane hours of operation, were eliminated from consideration in the filtering process of identifying candidate incidents. Researchers also decided to eliminate incidents from consideration that occurred in the initial section of the analysis corridor since potential incident queuing would not be captured and, thus, the full extent of mainlane delay due to the incident not captured. Researchers examined each corridor individually to establish this upstream buffer area. In general, this buffer area was approximately the first 1-mile section from the upstream corridor limit.

The location of an incident with respect to cross section is categorized in the incident database as a shoulder, one or more mainlanes, an HOV lane, ramp or interchange, frontage road, or a combination thereof. Some number of incidents were logged as not blocking any lanes at all, which could be a result of operator action (omitting the incident location during the logging of the incident), a weather-related event such as flooding, or debris on the roadway that may not physically block a lane of traffic. The focus of this research was limited to incidents occurring on the mainlanes and shoulders of the mainlanes. A relatively small percentage of incidents occurred on ramps and frontage roads, but since the nature of their impact on travel time savings between HOV lanes and mainlanes is, in general, less than for that of incidents occurring on mainlanes and mainlane shoulders, they were not examined in this project. Similarly, a small percentage of incidents involving multiple roadway categories were not included in the analysis since the relationships to delay savings are obscured by the multitude of combinations and relatively small sample size associated with each type of combination, i.e., ramp and frontage road, mainlane and frontage road, etc. Incidents occurring on the HOV lane were also not included in the analysis since the focus of this project was determining the travel time savings provided by the HOV lane during mainlane incidents.

Researchers also thought that differences in corridor characteristics could be a factor in the delay savings provided by the HOV lane. The only way to account for these differences was to analyze each corridor separately, thus creating four incident matrices for IH-10 Katy, IH-45

North, IH-45 Gulf, and US-59 Southwest Freeway. Corridor differences that could impact delay savings include:

- length of HOV lane facility,
- location of HOV lane access points,
- mainlane/HOV lane speed limits (not necessarily the same),
- corridor alignment, and
- mainlane/HOV average daily travel (ADT).

Selection of Candidate Incidents

A total of 31,687 entries were made in the RIMS database during 2003. Eliminating 22,181 multiple records resulted in a total of 9,506 individual incidents. The multiple records are used to record stages of an incident, such as when the incident is detected, when the status of the number of lanes blocked changes, and when the incident is cleared. A unique incident identification number is assigned to each incident, and multiple entries under this identification number can be made to note the changes in the incident. A comparison with Department of Public Safety accident records was used to verify the frequency of incidents logged in the database.

A two-part process filtered the pool of incidents down to the incidents suitable for analysis in this research. Table 3 details the first process used to identify candidate incidents for further analysis. This process filtered the pool of incidents from 9,506 incidents down to 1,036 incidents for further consideration, representing approximately 11 percent of the total incidents logged in 2003.

Table 3 shows the step-by-step process used in this first filter process. Incidents were removed that occurred on corridors without HOV lanes and corridors that had HOV lanes but where incidents were outside the hours of operation of the HOV lane, outside the limits of the HOV lane, and in the opposite direction of flow of the HOV lane. Incidents from the US-59 Eastex and US-290 Northwest Freeway corridors were also eliminated due to the low number of incidents logged in those corridors. Incidents that did not occur on the mainlanes or shoulders of the mainlanes were also eliminated since those categories were eliminated from consideration during the development of the incident matrix.

The resulting distribution of 1,036 incidents by corridor and extent of blockage is shown in Table 4. The decision to remove US-59 Eastex and US-290 Northwest Freeway corridors from the analysis was largely due to the limited number of incidents in the database for these corridors. Using the same selection criteria used to identify the incidents in the four corridors in Table 4, the resulting candidate incidents for these two corridors were identified as shown in Table 5. Due to the limited sample of candidate incidents identified, insufficient incidents would exist to fill out the incident matrix for these corridors. The candidate incidents for the four corridors in Table 4 represent 89 percent of the candidate incidents for all six corridors in Tables 4 and 5.

Table 3. Data Reduction Technique to Identify Candidate Incidents.

Action	Number of Incidents Eliminated	Percent of Incidents Eliminated	Number of Remaining Incidents
Number of individual incidents in 2003 RIMS database			9,506
Incidents on roadways without HOV lanes	−2,959	31%	6,547
Incidents on roadways with HOV lanes, but occurring outside of HOV hours of operation	−1,094	12%	5,453
Incidents on roadways with HOV lanes, during HOV hours of operation, but occurring outside the limits of the HOV lane	−1,148	12%	4,305
Incidents on roadways with HOV lanes, during HOV hours of operation, within the limits of the HOV lane, but occurring in the opposite direction of flow of the HOV lane	−1,537	16%	2,768
Incidents on HOV lanes	−655	7%	2,113
Incidents in US-59 Eastex and US-290 Northwest Freeway corridors	−252	3%	1,861
Incidents on both shoulders and mainlanes	−235	2%	1,626
Incidents on neither shoulders nor mainlanes	−491	5%	1,135
Incidents on combination of shoulder or mainlanes with ramps, frontage road, HOV lane, or occurring on the weekend	−99	1%	1,036
Total candidate incidents: incidents occurring on roadways with HOV lanes, during HOV hours of operation, within the limits of the HOV lane, in the direction of flow of the HOV lane, on roadway mainlane(s) or shoulder, on weekdays, in the Katy, North, Gulf, and Southwest Freeway corridors			1,036
Total	8,470	89%	1,036

Table 4. Candidate Incidents from First Filter Process for Study Corridors.

Corridor	Shoulder	1 Mainlane	2+ Mainlanes	Total
IH-10 Katy	56	173	22	251
IH-45 North	82	205	48	335
IH-45 Gulf	55	137	26	218
US-59 Southwest	70	135	27	232
Total	263	650	123	1,036

Table 5. Candidate Incidents from First Filter Process for Non-Study Corridors.

Corridor	Shoulder	1 Mainlane	2+ Mainlanes	Total
US-59 Eastex	10	9	11	30
US-290 Northwest	21	69	14	104
Total	31	78	25	134

The candidate incidents in Table 4 were subsequently filtered through a second process to identify the incidents that were subsequently analyzed in this research. Researchers focused on incidents occurring and cleared within the AM peak period of 6:00 to 9:00 AM and the PM peak period of 3:30 to 6:30 PM. Thus, incidents occurring during the off-peak hours were filtered out. Also, since the full impact of incidents occurring during the analysis peak period but cleared outside of the peak period would not be captured, only incidents occurring and cleared during the peak period were analyzed. Another step in this filtering process was to eliminate incidents from the analysis that occurred in the initial section of the study corridor (typically approximately 1 mile) since incident-related queuing would potentially not be fully captured. In a small number of cases, multiple candidate incidents occurred within the same peak period and same corridor. Only the most major of the multiple incidents were analyzed in this project. The final step of the second filtering process was to eliminate incidents for which sufficient AVI data were not available.

Table 6 shows the number of incidents by corridor that were filtered out during the second filtering process. The order shown in the table is the order incidents were filtered, i.e., first for off-peak, then for longitudinal location (initial section of corridor), then for multiple incidents, and finally for insufficient mainlane AVI data.

Table 6. Incidents Removed during Secondary Filtering Process.

Corridor	Candidate Incidents	Removed Off-Peak		Removed Longitudinal		Multiple Incidents		Incomplete Mainlane AVI Data		Total Removed		Total Remaining	
	#	#	%	#	%	#	%	#	%	#	%	#	%
Katy	251	115	46	13	5	15	6	29	12	172	69	79	31
North	335	139	41	31	9	23	7	37	11	230	69	105	31
Gulf	218	92	42	3	1	11	5	23	11	129	59	89	41
Southwest	232	99	43	15	6	12	5	38	16	164	71	68	29
Total	1,036	445	43	62	6	61	6	127	12	695	67	341	33

Thus, a total of 341 incidents were analyzed in this research. The total number of incidents analyzed by corridor was:

- IH-10 Katy Freeway Corridor – 79 incidents,
- IH-45 North Freeway Corridor – 105 incidents,
- IH-45 Gulf Freeway Corridor – 89 incidents, and
- US-59 Southwest Freeway Corridor – 68 incidents.

Analysis of Non-Incident Travel Times for School Days versus Non-School Days

Prior to conducting the analysis of travel times during mainlane incident conditions, researchers explored the impact of school being in or out of session on mainlane travel times. Only travel time data on non-incident days for both the HOV and mainlanes were used in this comparison to eliminate the impact of incidents on travel times. Researchers identified the AM and PM peak periods during 2003 for each corridor in which an incident occurred neither on the HOV lane nor the mainlanes.

The premise for this comparison was the possibility that travel times are statistically significantly different on the mainlanes when school is in or out of session. In the event the differences are statistically significant, researchers proposed splitting the matrix for each corridor into two matrices. The purpose of this decision was to isolate the impact of incidents on travel times rather than obscure them with other significant travel time factors. For example, the potential exists that a travel time savings provided by the HOV lane on a minor incident day when school is out of session could be less than the travel time savings provided on a non-incident day when school is in session. The HOV lane would still be providing a savings over the mainlanes during incident conditions, but this difference could be obscured if the impact of whether school was in session or not was significant.

Table 7 shows the number of non-incident peak periods by corridor for the AM peak period or the PM peak period that were incident free on both the HOV lane and mainlanes. The table does not show the number of days that were incident free in both the AM and PM peak periods on the same day. Using data for days that were either incident free in the AM or PM peak period expanded the data sample available to analyze.

Table 7. Non-Incident Days Used in School Open/School Closed Comparison.

	Katy		North		Gulf		Southwest	
	AM	PM	AM	PM	AM	PM	AM	PM
Total Non-Incident Peak Periods	124	103	141	105	146	111	161	123
Weekend Days	81	68	85	73	89	73	96	81
Conflict Days	7	10	9	10	10	10	17	14
Total Non-Incident Weekday Peak Periods	36	25	47	22	47	28	48	28
School Open	24	20	33	17	28	19	34	18
School Closed	12	5	14	5	19	9	14	10

The first row of data in Table 7 shows the total number of non-incident AM and PM peak periods. From these days the number of non-incident weekend days (second row) was eliminated since all HOV lanes with the exception of the Katy Freeway HOV lane are closed on weekends. The third row shows the number of conflict days eliminated. Conflict days include days where the HOV lanes are closed due to major holidays such as New Year's Day, Memorial Day, July 4th, Labor Day, Thanksgiving Day, and Christmas Day, as well as days where conflicting school schedules existed, i.e., some schools in the corridor were in session, while others were closed. The fourth row shows the total number of incident-free weekday peak periods. The non-incident peak periods are categorized in the bottom two rows as school open and school closed. As seen in the last two rows of Table 7, the sample size of peak periods that were incident free during 2003 is very small. Averaging the data for the four corridors, only 17 percent of AM weekday peak periods were incident free, while only 10 percent of weekday PM peak periods were incident free. Researchers ran the Travel Time Generator (discussed in the next section) for each of these days and performed statistical analyses.

The results of the multivariate repeated measures analyses appear in Table 8. The *p*-values in the table denote the probability that there is no interaction between school days and start time. In other words, if school days have no effect on travel time, then the variation in travel time with respect to start time should be the same whether school is in session or not. Any *p*-values in the table less than 0.05 can be considered evidence that school days are influencing travel time; these significant values are shown in bold. All morning peak period travel times were found to be significantly influenced by school days; this effect was most pronounced for the North Freeway. Nearly all of the evening peak period travel times were unaffected by school days, with the exception of the Southwest Freeway corridor. In the case of the Katy corridor PM analysis, insufficient data were available to perform the statistical test.

Table 8. Results of Tests for Effects of School Days on Travel Times.

Corridor	Peak Period	***P-values for the Effect*** School × Start Time	Type of School Effect
Katy	AM	**0.0381**	Multiplicative
	PM	NA	NA
Gulf	AM	**0.0171**	Multiplicative
	PM	0.1278	None
North	AM	**0.0019**	Multiplicative
	PM	0.7006	None
Southwest	AM	**0.0379**	Multiplicative
	PM	**0.0198**	Multiplicative

Note: Any *p*-values in the table less than 0.05 can be considered evidence that school days are influencing travel time; these significant values are shown in bold.
NA = Insufficient data available to perform statistical test

Based on the results of this analysis, the initial matrix was split into five incident matrices per corridor. The initial combined matrix was also analyzed. The five matrices are:

- AM School In,
- AM School Out,
- PM School In,
- PM School Out, and
- Combined.

AVI System and Travel Time Generator Software

AVI System

The researchers used Houston's AVI system as the data source for the analysis of travel times and speeds presented in this project. AVI-based data are ideal for providing direct travel time computations between two points on a roadway. The TxDOT-installed AVI system has been operational in the Houston area since 1993. Since that time, coverage has gradually expanded to include more than 230 directional freeway miles and 61 HOV lane miles. The system is equipped with over 240 individual reader "checkpoints." Today, approximately 65 percent of Houston-area freeways are instrumented with AVI sensors, with coverage focused on the busiest corridors.

The AVI system uses vehicles equipped with transponder tags as probes. The Houston system uses tags distributed by the Harris County Toll Road Authority's (HCTRA) "EZ-Tag" toll collection system. In order to calculate reliable travel times using transponder tags, a sufficient number of tagged vehicles must be present along the instrumented roadways. With HCTRA's existing tag infrastructure, the Houston area has excellent tag penetration (or density), with more than 1 million tags distributed throughout the region. Transponder tag readers or checkpoints are placed at approximately 1.2 to 5.0 mile intervals along the freeway and tollway system.

To obtain complete cross-section coverage, the AVI readers have an array of antennas that span the entire cross section of a roadway (in some cases using a single sign bridge and in other cases multiple sign bridges) to capture all lanes. The readers detect probe vehicles as they pass checkpoints within the system. The tag identification number, reader location identifier, and exact date and time are transmitted wirelessly to a tag reader each time a probe vehicle passes a checkpoint. Upon receiving tag reads, the reader sends them to an AVI data processing software component over a dial-up telephone line. As a tagged vehicle passes successive reader locations along a route, the data processing component is able to determine accurate point-to-point travel times and speeds using the unique identification of the transponder tag. Tag read data are confidential and used anonymously for the purpose of developing travel time and speed data. This information is provided to personnel at Houston TranStar for use in detecting freeway congestion, and to the public through media reports, displays on selected roadside electronic message signs, and on the Houston TranStar website (http://traffic.houstontranstar.org). The AVI system architecture is shown in Figure 2.

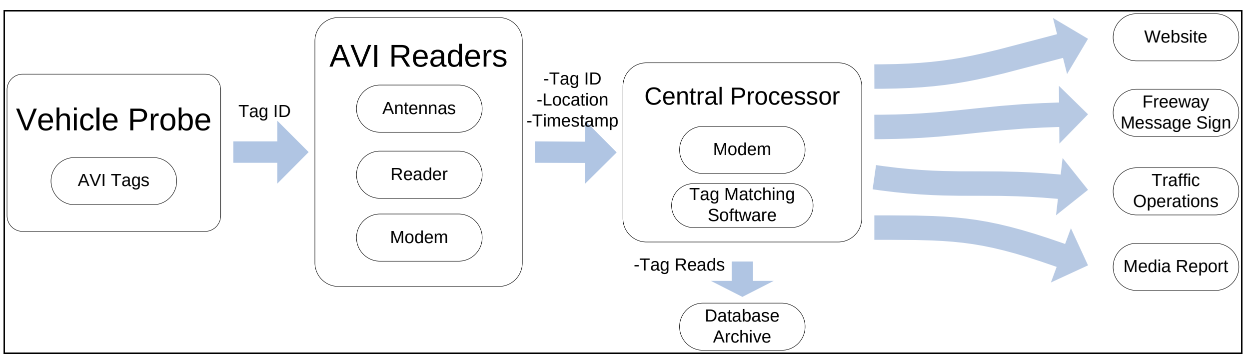


Figure 2. AVI System Architecture.

Determining travel times between AVI readers involves matching tags that pass successive reader locations. With accurate distances between the reader locations, the system can easily obtain average vehicle speeds and travel times. Utilizing SAS Institute's Analytics Software Development Package, the Texas Transportation Institute (TTI) developed a routine that determines travel times between AVI readers using archived raw tag read data. First, the routine reads each raw tag read into memory. After the raw tag data are read, the tag reads are "matched" between successive readers. Using the distance between each reader, the travel time and speed are calculated and the results are output to a dataset. For this project, individual travel times and speeds were aggregated into five-minute averages. A five-minute average is an average of all speed and travel time samples for a freeway segment during a given five-minute interval. Figure 3 is a sample of a dataset containing five-minute averages for an AVI reader segment.

	READDATE	TIMEPER1	STARTCP	ENDCP	DIST	_FREQ_	TRAVTIME	STD_DEV	SPEED
1	15857	0	0	1	3.95	13	214	16.896745249	66.448598131
2	15857	300	0	1	3.95	15	215.46666667	7.308181977	65.996287129
3	15857	600	0	1	3.95	12	208.91666667	17.547122703	68.065416833
4	15857	900	0	1	3.95	13	205.30769231	17.080127904	69.261895841
5	15857	1200	0	1	3.95	8	205.5	23.850726254	69.197080292

Figure 3. Sample AVI Five Minute Averages.

The first two columns of data are the date and time in SAS offset format. Note that the time (TIMEPER1) reflects the number of seconds after midnight. For example, “0” represents 12:00 AM and “300” represents 12:05 AM. Since the averages are aggregated into five minute intervals, each row represents a five-minute period, beginning at the time indicated in column two. The third (SARTCP) and fourth (ENDCP) data columns represent the starting and ending reader location numbers, respectively. The fifth column (DIST) is the distance, in miles, between the readers. The sixth column (_FREQ_) is the number of samples used in the average, followed by the travel time (TRAVTIME) in seconds, the standard deviation (STD_DEV) of the travel time, and the average speed (SPEED) in miles per hour.

Travel Time Generator Software

AVI data provide travel times on predetermined roadway segments based on the location of the readers. For this project, it was required that travel times be calculated for entire freeway corridors rather than for individual AVI reader segments. Figure 4 shows the difference between the project requirements and what AVI data provide by default.

The freeway corridor shown in Figure 4 contains three AVI reader locations resulting in two AVI reader segments: A to B and B to C. By matching AVI tag reads, a travel time average can be calculated for each segment. The archived, AVI-based travel time data contain roadway segment travel times in this format, based on the location of the readers. For this project, a true travel time was required from Reader A to a location downstream of Reader C. As a result, the AVI-based travel time data do not directly correlate to the data required in the project. First of all, the start and end points of the corridor are not the same as the start and end points of the AVI reader locations. Second, adding together link-based travel times from the two AVI segments depicted in Figure 4 does not necessarily represent the true travel time of a probe vehicle traversing the entire freeway corridor. This variance is because of the difference in time that the probe vehicles pass each reader.

Assume a probe vehicle begins at Reader A at 12:00 AM, passes Reader B at 12:05 AM, and reaches Reader C at 12:10 AM. Adding together aggregated five minute averages from 12:00 to 12:05 for each segment will not result in an accurate depiction of a travel time for the entire corridor since the probe began traversing the second segment at 12:05 AM. A more accurate method to represent a true travel time is to add together averages from 12:00 AM for the first segment and 12:05 AM for the second segment. This method can be described as a "built-up" AVI travel time, and it consists of aggregating multiple AVI segments and adding each segment travel time to the previous start time. Using the raw AVI data, tags *could* be matched between Reader A and Reader C; however, the data sample sizes would be much lower since many vehicle probes could exit the freeway between those readers.

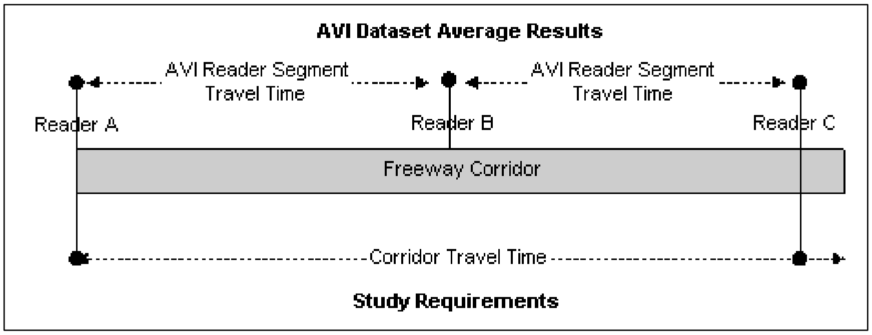


Figure 4. AVI Travel Time Data versus Project Requirements.

In order to produce "built-up" travel times for entire freeway corridors using existing AVI data, TTI developed a software component that utilizes the logic mentioned above. The component was designed with the following requirements.

- Aggregate existing AVI-based link travel times into five minute averages to produce a "built-up" travel time report along a freeway corridor.
- Provide the user with the ability to enter factors that can be used in travel time calculations to compensate for the differences between AVI start and end points and project corridor start and end points.
- Compensate for missing AVI data by averaging existing speeds from adjacent time periods for the specific link missing.
- Produce an on-screen and delimited output file for each travel time generated, making it simple to import the data into external programs such as Microsoft Excel®.
- Provide the user with an easy-to-use, web-based interface with the ability to configure the travel time reports by corridor, direction, AVI segments used, date, and start time.

The component was developed using Microsoft ASP.NET®, an applications development framework for the web. It accesses the travel time datasets generated by SAS using Open Database Connectivity (ODBC). The application can be accessed from any approved network client using a standard web browser such as Microsoft Internet Explorer®. The user interface of the Travel Time Generator component is shown in Figure 5.

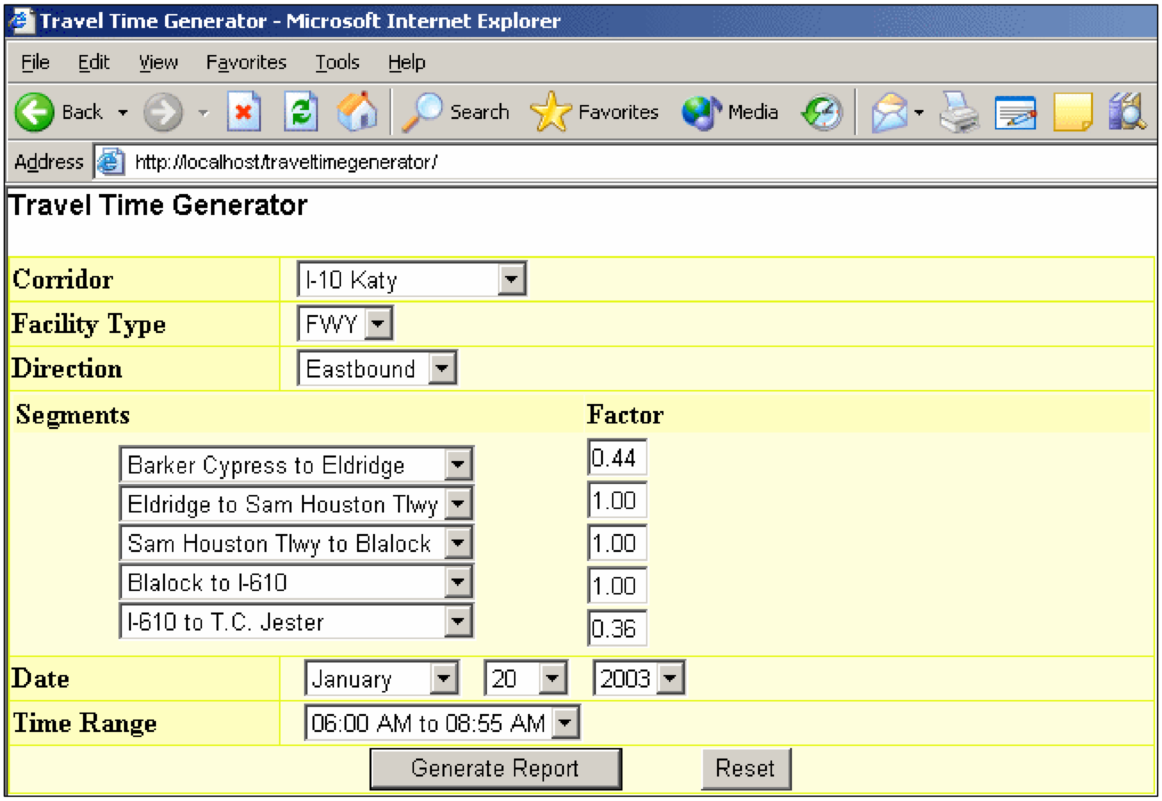


Figure 5. Travel Time Generator User Interface.

Users are given the option to choose a freeway corridor, facility type (mainlanes or HOV), and direction of travel. AVI segments for the selected corridor then appear automatically. A factor textbox for each AVI segment allows users to customize the percentage of a travel time that is used in generating the report. This factor aids in compensating for the difference in start and end points between AVI segments and the corridor. For example, in Figure 6 (bottom row), 44 percent of the Barker-Cypress to Eldridge travel time is used in the calculation, 100 percent of the middle segments are used, and 36 percent of IH-610 to T.C. Jester is used. In this case, the project corridor began downstream of the beginning of the first AVI segment and ended before the end of the last AVI segment. These segment factors define data within the limits of the HOV lane, i.e., western extension to eastern extension. More information on the development of AVI segment factors is presented in the following section. The user can then select the date and time range from which to generate the report. Currently, reports can be generated for the time periods used in this study: either 6:00 AM to 9:00 AM or 3:30 PM to 6:30 PM.

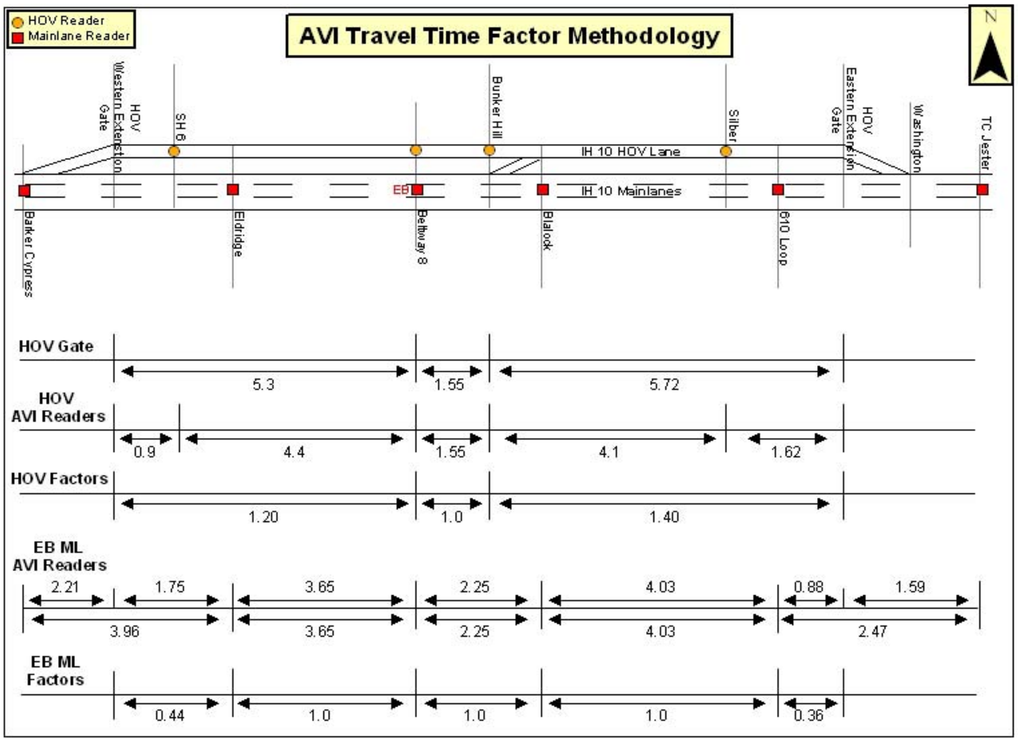


Figure 6. AVI Travel Time Factor Methodology.

When the user clicks the "Generate Report" button, the application begins building travel time reports based on the inputs from the form. Using the aggregated, five minute travel time averages, the application adds together travel times from all the AVI segments specified on the form and multiplies each segment time by the segment factor percentage using the built-up method described earlier.

Figure 7 shows the resulting Travel Time Generator summary report. This summary shows the travel times for the corridor for each five minute period start time as well as an hourly average travel time. The summary report is followed by a detailed view of each five minute travel time summary. Each detailed view shows the AVI sensor locations, start times, AVI segment distances, travel times, speeds, data sample sizes, and standard deviations of the travel times, as shown in Figure 8. To compensate for missing data in an AVI segment, the application searches for existing data up to 15 minutes before and after the missing data appear for that specific segment. Each travel time found during those time periods is averaged to use in place of the missing data. In Figure 8, on the 6:05 AM report, the data on the AVI segment from Blalock to IH-610 are missing. In this case, travel times were found in the adjacent 10-minute time periods and averaged to fill the gap. The report indicates that the data were generated using this technique by highlighting the line in gray.

I-10 Katy HOV EB - SH 6 to Silber
on Monday 1/20/2003 from 6:00 AM to 8:55 AM

Start Time	6:00	6:05	6:10	6:15	6:20	6:25	6:30	6:35	6:40	6:45	6:50	6:55	Average
Travel Time	11:26	11:23	11:47	12:18	12:03	12:09	12:10	12:06	12:15	11:52	12:20	12:00	**11:59**

Start Time	7:00	7:05	7:10	7:15	7:20	7:25	7:30	7:35	7:40	7:45	7:50	7:55	Average
Travel Time	11:25	11:38	11:34	11:18	11:10	11:14	11:43	11:08	11:19	11:21	11:32	11:46	**11:26**

Start Time	8:00	8:05	8:10	8:15	8:20	8:25	8:30	8:35	8:40	8:45	8:50	8:55	Average
Travel Time	11:37	11:28	11:28	11:36	11:57	11:57	11:04	11:26	11:01	11:11	11:08	11:32	**11:27**

Figure 7. Travel Time Generator Onscreen Summary Report.

6:05 AM Report

Sensor Locations	Start Time (h:mm)	Distance (mi.)	Travel Time (m:ss)	Speed (mph)	Sample Size	Standard Deviation
Barker Cypress to Eldridge	6:05 AM	1.74	1:30	70	24	13
Eldridge to Sam Houston Tlwy	6:05 AM	3.65	3:10	69	14	16
Sam Houston Tlwy to Blalock	6:05 AM	2.25	1:57	69	1	0
Blalock to I-610	6:05 AM	4.05	4:07	59	2	19
I-610 to T.C. Jester	6:05 AM	0.88	0:49	65	7	9
Route Totals		**12.57**	**11:33**	**65**	**48**	

6:10 AM Report

Sensor Locations	Start Time (h:mm)	Distance (mi.)	Travel Time (m:ss)	Speed (mph)	Sample Size	Standard Deviation
Barker Cypress to Eldridge	6:10 AM	1.74	1:38	64	15	13
Eldridge to Sam Houston Tlwy	6:10 AM	3.65	3:15	67	21	17
Sam Houston Tlwy to Blalock	6:10 AM	2.25	1:48	75	3	8
Blalock to I-610	6:10 AM	4.05	4:14	57	2	16
I-610 to T.C. Jester	6:10 AM	0.88	0:48	66	10	10
Route Totals		**12.57**	**11:43**	**64**	**51**	

Figure 8. Travel Time Generator Detailed Report.

For each report generated by the user, two text files are saved containing the data in the report. The files consist of the report summary and the report details, respectively. Each file is space and comma delimited, making it easy to import into a database or spreadsheet for further analysis. The file names are uniquely generated using the corridor, facility type, and date to prevent them from being overwritten each time the software is used.

Development of AVI Segment Factors

As mentioned in the previous section, one issue encountered when comparing HOV lane travel times with mainlane travel times is the fact the AVI readers are not always at the same locations for the HOV lane and mainlanes and are never at the limits of the HOV lane, which is the desired corridor length for this project. The segment factors were created to adjust travel times for the exterior links in the corridor for the HOV lane and mainlanes to create an estimate of the travel time for the limits of the HOV lane. The HOV lane AVI readers are located within the limits of the HOV lane (in Figure 6, 0.9 mile east of the HOV gate); thus, the travel time between actual readers is not representative of the travel time desired for the entire HOV facility, i.e., from HOV gate to HOV gate. The mainlane readers may be located at different places than the HOV lane readers, but there is always a reader upstream and downstream of the HOV lane limits. Thus, using the upstream reader would over-represent the travel time, while using the downstream reader would underestimate the travel time for comparable HOV gate to HOV gate travel times.

As shown previously, Figure 6 graphically represents how researchers used segment factors to extrapolate travel times for both the HOV lane and mainlanes to be representative of HOV gate to HOV gate travel times (labeled "Eastern Extension Gate" and "Western Extension Gate"). The top of the figure illustrates the Katy Freeway eastbound mainlanes and HOV lane, showing the location of the HOV entrance and exit gates as well as major cross streets. There are four AVI readers on the Katy Freeway HOV lane located at SH-6, Beltway 8, Bunker Hill, and Silber. As seen in the line labeled "HOV AVI Readers," the SH-6 reader is located 0.9 mile east of the Western Gate, while the Silber reader is located 1.62 miles west of the Eastern Gate. The segment factors are then used to extrapolate the equivalent travel times for the exterior links for the desired distance. The actual link between the HOV lane AVI readers between SH-6 and Beltway 8 is 4.4 miles. The desired distance from the HOV lane gate to Beltway 8 is 5.3 miles; thus, a segment factor of 1.2 is used (5.3/4.4 = 1.2). All interior segments have a factor of 1.0 since the actual travel time for the entire segment is used for calculating the corridor travel time. The actual link between the HOV lane AVI readers between Bunker Hill and Silber is 4.1 miles. The desired distance from Bunker Hill to the Eastern Gate is a distance of 5.72 miles; thus, a segment factor of 1.40 is used (5.72/4.1 = 1.40).

Factors greater than 1.0 are used for the HOV lanes to extend the distance represented by the travel time to the limits of the HOV lane. Since there are readers on the mainlanes upstream and downstream of the HOV limits, mainlane segment factors less than 1.0 were calculated to use the portion of the travel time representative of the location of the HOV lane gate within the segment. Tables 9 and 10 show the factors calculated for the Katy Freeway HOV lane and mainlane segment links in both directions. Similar tables for the other three corridors in this project are provided in Appendix A of Technical Report 0-4740-1, *Quantification of Incident and Non-Incident Travel Time Savings for Barrier-Separated High-Occupancy Vehicle (HOV) Lanes in Houston, Texas* (*10*). These factors were incorporated into the development of the Travel Time Generator.

Table 9. Katy Freeway HOV Lane Segment Factors – HOV Gate to HOV Gate.

Segment	Eastbound (EB) HOV Lane			Westbound (WB) HOV Lane		
	Segment Length (miles)	Modified Length (miles)	Segment Factor	Segment Length (miles)	Modified Length (miles)	Segment Factor
SH-6 to Tollway	4.40	5.30	1.20	4.40	5.30	1.20
Tollway to Bunker Hill	1.55	1.55	1.00	1.55	1.55	1.00
Bunker Hill to Silber	4.10	5.72	1.40	4.10	5.72	1.40

Table 10. Katy Freeway Mainlane Segment Factors – HOV Gate to HOV Gate.

Segment	EB Mainlanes			WB Mainlanes		
	Segment Length (miles)	Modified Length (miles)	Segment Factor	Segment Length (miles)	Modified Length (miles)	Segment Factor
Barker Cypress to Eldridge	3.96	1.75	0.44	4.50	2.29	0.51
Eldridge to Tollway	3.65	3.65	1.00	2.90	2.90	1.00
Tollway to Blalock	2.25	2.25	1.00	2.90	2.90	1.00
Blalock to Loop 610	4.03	4.03	1.00	3.65	3.65	1.00
Loop 610 to T.C. Jester	2.47	0.88	0.36	2.40	0.81	0.34

Analyzing Selected Incidents

The Travel Time Generator Software was run for the peak period of the days of each incident in each cell of the corridor matrices. The results were displayed on-screen as well as written to text files. Figure 9 illustrates a portion of an individual incident summary report text file. The file contains all pertinent identification information such as freeway corridor, corridor limits, facility type (mainlanes or HOV lane), direction of flow, date, and time period. The columns of the report show the period start time, distance (which is the corridor length since it is the summation of all segments in the corridor), travel time in seconds, speed in mph, number of AVI tag reads making up the sample, and the sum of the number of segments that had estimated data (using a smoothing technique).

Development of HOV Lane Baseline Travel Time Curves

Researchers initially intended to compare mainlane and HOV lane travel time data for the same day that each mainlane incident occurred. Because of the extent of HOV lane AVI data missing, we were unable to make this comparison; the sample size of incident days with both good/usable mainlane and HOV lane data on the same day would have drastically reduced the analysis sample size. In response, researchers created a set of baseline HOV lane travel time data files and curves to compare with individual incident mainlane travel time files.

```
Freeway Name, IH-10 Katy
Limit, Barker Cypress to T.C. Jester
Freeway Type, FWY
Direction, EB
Date, 05/08/2003
Time, 06:00 AM to 08:55 AM

Time,      Distance, TravelTime,  Speed,  Sample, GeneratedData
06:00 AM,   12.57,     823,        55       73,        1
06:05 AM,   12.57,     880,        51,      72,        2
06:10 AM,   12.57,     919,        49,      65,        1
06:15 AM,   12.57,     964,        47,      102,       0
06:20 AM,   12.57,    1090,        42,      44,        0
06:25 AM,   12.57,    1154,        39,      72,        0
06:30 AM,   12.57,    1095,        41,      32,        0
```

Figure 9. Illustration of an Individual Incident Summary Report.

A combination of the HOV lane travel time data files was averaged together, which represented HOV lane travel times during mainlane incident conditions, and used for the travel time comparisons. For example, the data from the 6:00 AM five minute time period for all HOV files during mainlane incident conditions that contained data in this cell were averaged together to create the baseline speed and travel time data points for each time period and segment. Although the data were averaged to create the baseline HOV lane travel times, the sample size of data available was still limited with the exception of the Katy Freeway HOV lane; however, since the variability of travel times on the HOV lanes is low, it is still assumed to be representative.

The effects of HOV drivers' rubbernecking of mainlane incidents were assumed to be localized and have minimal effect on the overall HOV corridor travel time. However, to account for the potential rubbernecking effect, available HOV lane data during mainlane incidents were used in the development of the baseline curves. In the case of the Southwest Freeway, there were still time periods with data not available even using the averaging technique. A "best fit" line was used with the existing data points to create the baseline used for the Southwest Freeway HOV lane travel times.

Summarization of Files

Once the individual detailed report and summary files were generated, they were stored in a directory structure that mirrors the incident matrix. As previously mentioned, incidents were classified for each corridor into five matrices:

- AM School In,
- AM School Out,
- PM School In,
- PM School Out, and
- Combined.

The directory folders corresponded to the cells of each incident matrix and consisted of mainlane incident travel time data to be compared with the corresponding HOV travel time data. Each cell in the corridor matrices was comprised of data from 0 to 40 incidents. Due to the large volume of data, a semi-automated process was developed utilizing several different Excel macros and templates to more efficiently analyze the data. As mentioned, the original intention was to compare the mainlane incident travel time data with the HOV travel time data for the same day. Initially, an Excel macro was developed to compare each five minute period of the mainlane travel time to the HOV travel time for the same day. From these five minute differences, a range of statistics was generated including the average, maximum, minimum, and area between the two curves. The differences in travel time were written to a file, and the difference from a particular cell was gathered and averaged. Due to the limited HOV lane AVI data, this process was later adjusted to incorporate the comparison of the difference between the average mainlane travel times during mainlane incidents in a cell to a baseline HOV travel time in the corresponding cell.

Mainlane versus HOV Lane Travel Time Comparison

After the summarization of data files, a series of graphs and tables were developed to aid in the travel time analysis. One table and two graphs were developed to represent the average mainlane and HOV lane travel time data for each cell in each corridor matrix. Examples of the table and two graphs are shown in Table 11 and Figures 10 and 11.

The travel time comparison table shows the freeway travel time, HOV travel time, a travel time comparison, and the area between the two travel time curves. A summary of the average, maximum, and minimum travel time differences, standard deviation, and area between the curves is shown at the bottom of the table. Figure 10 shows the mainlane and HOV travel time during the AM peak period. Figure 11 shows the difference between the two curves, i.e., the travel time savings provided by the HOV lane. These graphs are very beneficial in determining the travel time difference trends. The average travel time differences in the tables tend to wash out the appearance of savings in the travel time difference due to the fact that it is the average over the entire three-hour peak period, rather than only peak hour savings as reported in some studies or the maximum travel time savings. For this reason, the maximum travel time savings values shown in the table and the graphs of travel time differences are useful in showing how HOV lane benefits are often much greater than the reported average savings.

An area method of delay calculation was used to calculate the area between the mainlane and the HOV travel time curves. Integration by parts was used to determine the area using the calculated difference between the two lines as the “Y” value and the five minute time period for the “X” value. This shape is a trapezoid, so X*Y/2 was used to determine the area for each segment. The segments were totaled to determine the total area under the curve for the peak period. The area method provides the most analytical method for measuring the difference between the two curves, but it is less intuitive than the maximum, minimum, and average travel time measure. This method does hold promise and with time might be utilized in future comparisons.

Table 11. Travel Time Comparison Table.

Freeway Name		I-10 Katy					
Limit		SH-6 to Silber					
Freeway Type		FWY-HOV					
Direction		EB					
Date							
Time		06:00 AM to 08:55 AM					
AVERAGE		FWY	HOV	DIFF(sec)	DIFF(mm:ss)	SECTION AREA	SECTION AREA
Time	Distance	TravelTime	TravelTime	TravelTime	TravelTime	DIFF CURVE	DIFF CURVE
6:00 AM	12.57	13:25	11:41	104.6	01:45	0.0	0:00:00
6:05 AM	12.57	14:42	11:51	170.9	02:51	688.8	0:11:29
6:10 AM	12.57	14:54	12:00	173.5	02:54	861.0	0:14:21
6:15 AM	12.57	16:30	12:15	254.6	04:15	1,070.4	0:17:50
6:20 AM	12.57	18:33	12:36	357.2	05:57	1,529.6	0:25:30
6:25 AM	12.57	20:03	13:03	420.2	07:00	1,943.5	0:32:23
6:30 AM	12.57	23:55	13:21	634.3	10:34	2,636.1	0:43:56
6:35 AM	12.57	24:52	13:54	657.2	10:57	3,228.7	0:53:49
6:40 AM	12.57	23:16	14:17	538.8	08:59	2,990.0	0:49:50
6:45 AM	12.57	25:59	14:38	680.6	11:21	3,048.6	0:50:49
6:50 AM	12.57	24:39	14:13	626.8	10:27	3,268.4	0:54:28
6:55 AM	12.57	26:52	13:33	799.7	13:20	3,566.1	0:59:26
7:00 AM	12.57	27:51	12:43	907.9	15:08	4,268.9	1:11:09
7:05 AM	12.57	29:23	12:38	1,005.2	16:45	4,782.5	1:19:43
7:10 AM	12.57	30:55	12:27	1,107.9	18:28	5,282.5	1:28:03
7:15 AM	12.57	33:04	12:16	1,247.8	20:48	5,889.1	1:38:09
7:20 AM	12.57	33:03	12:26	1,237.5	20:37	6,213.1	1:43:33
7:25 AM	12.57	35:30	12:33	1,376.6	22:57	6,535.1	1:48:55
7:30 AM	12.57	35:01	12:39	1,342.5	22:22	6,797.6	1:53:18
7:35 AM	12.57	36:25	12:34	1,431.0	23:51	6,933.7	1:55:34
7:40 AM	12.57	34:26	12:25	1,321.4	22:01	6,881.1	1:54:41
7:45 AM	12.57	34:42	12:27	1,334.7	22:15	6,640.4	1:50:40
7:50 AM	12.57	33:04	12:28	1,236.4	20:36	6,427.8	1:47:08
7:55 AM	12.57	30:35	12:32	1,082.9	18:03	5,798.3	1:36:38
8:00 AM	12.57	31:01	12:51	1,089.4	18:09	5,430.7	1:30:31
8:05 AM	12.57	30:53	12:43	1,089.6	18:10	5,447.3	1:30:47
8:10 AM	12.57	27:28	12:35	892.3	14:52	4,954.6	1:22:35
8:15 AM	12.57	28:18	12:42	935.6	15:36	4,569.7	1:16:10
8:20 AM	12.57	26:10	12:35	814.8	13:35	4,375.9	1:12:56
8:25 AM	12.57	26:42	12:33	849.1	14:09	4,159.6	1:09:20
8:30 AM	12.57	25:17	12:08	788.4	13:08	4,093.6	1:08:14
8:35 AM	12.57	24:55	12:12	762.9	12:43	3,878.2	1:04:38
8:40 AM	12.57	26:01	12:03	837.2	13:57	4,000.1	1:06:40
8:45 AM	12.57	23:59	12:01	718.4	11:58	3,889.0	1:04:49
8:50 AM	12.57	23:15	12:02	673.2	11:13	3,479.1	0:57:59
8:55 AM	12.57	21:15	11:54	560.5	09:21	3,084.4	0:51:24

	sec	dd:hh:mm:ss
MAX DIFF	1,431.0	23:51
MIN DIFF	104.6	01:45
AVG DIFF	835.0	13:55
STD DEV	366.4	06:06
TOT AREA	148,643.7	01:17:17:24

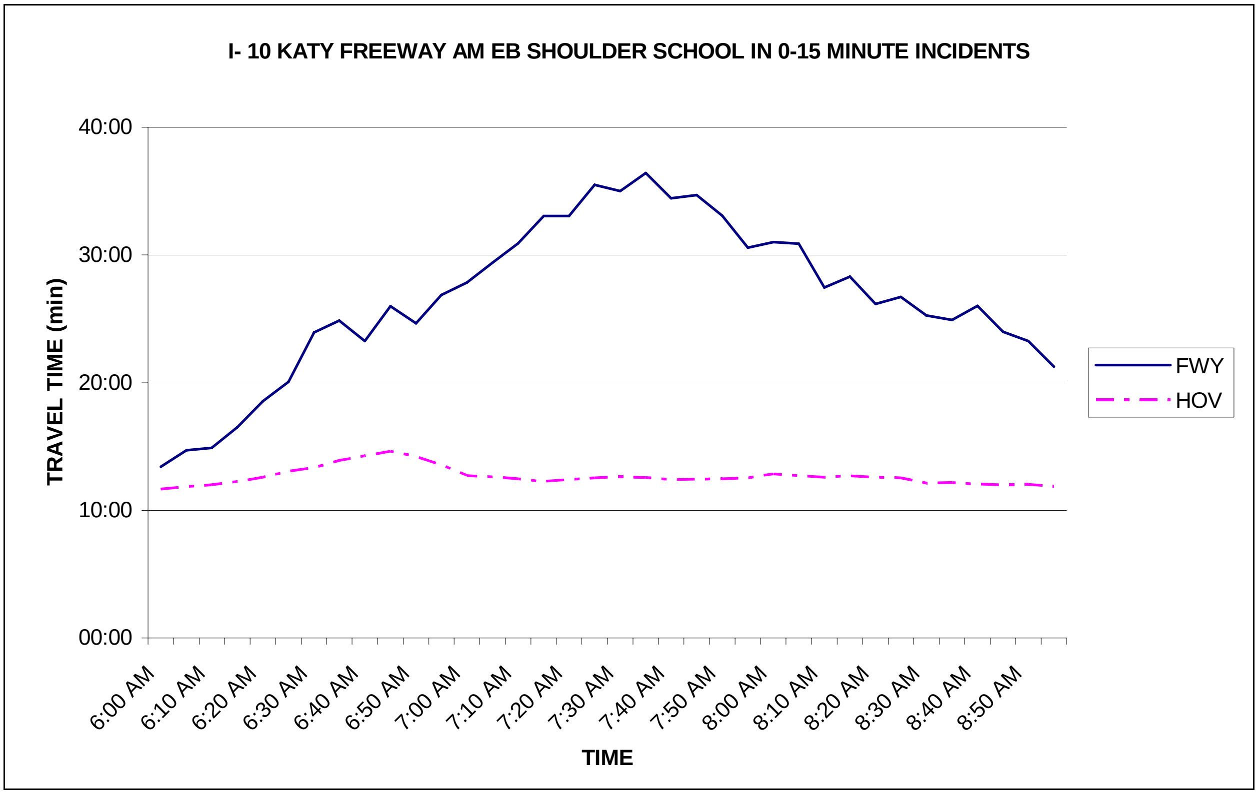


Figure 10. Mainlane versus HOV Lane Travel Times.

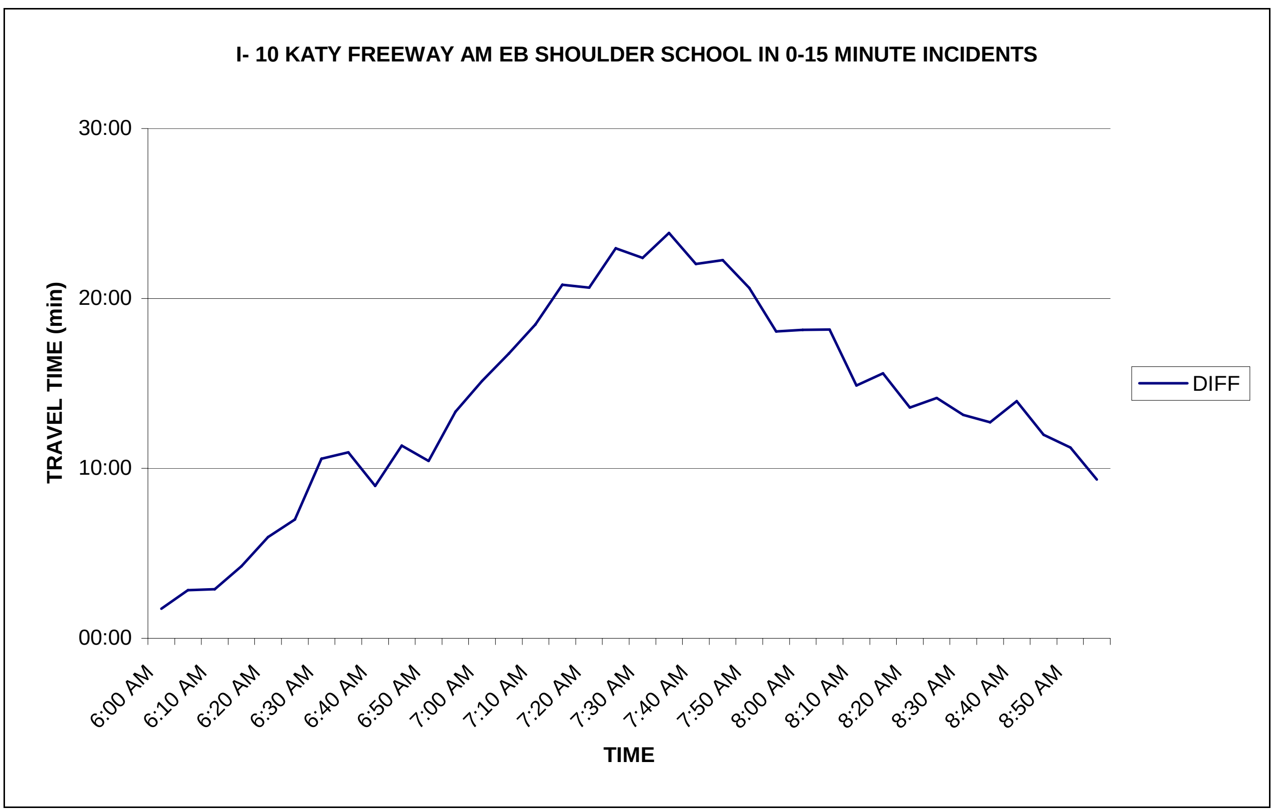


Figure 11. HOV Lane Travel Time Savings.

If the mainlane travel time is less than the HOV travel time, the values are negative and thus are shown below the HOV lane curve. This situation occasionally occurs at the beginning or ending of a peak period where the mainlanes operate at free-flow conditions. Additionally, even though the HOV lane would be operating at free-flow conditions during those time periods as well, the one-lane design of the HOV lane prevents vehicles from passing slower moving vehicles. The full set of tables and graphs for each analysis cell of each corridor matrix is contained in Appendix B of the first years report. For ease of locating the tables and graphs for a particular matrix cell, the first page in Appendix B of the first years report presents the matrix for each corridor with the page number of the graph associated with each cell. Cells that contained no incidents that could be used in the analysis are indicated with an "NA" in the cell.

Incident Matrix Cell Averages

Once the data for each incident were processed through the Travel Time Generator Software, the results were averaged for the number of incidents within each cell of the incident matrix. An example is shown in Table 12. This figure represents the combined incident matrix for the Katy Freeway, showing incident duration versus extent of lane blockage (shoulder, one lane, or two or more lanes). For each cell (each incident duration and extent of blockage), various statistics were calculated and presented. These statistics include the number of incidents included in each cell, the average HOV travel time savings, the maximum HOV lane travel time savings (of any incident in the cell), the average minimum HOV lane travel time savings, as well as the average deviation. The two lines below these cells show the average for all incidents within that category of blockage as well as the percent difference between the incident travel time and non-incident travel time. For comparison, the average non-incident HOV travel time savings are provided at the bottom of the table. It should again be pointed out that the values in the average HOV lane travel time savings cells are those over the entire three hour peak period and that HOV lane travel time savings are much higher during the incidents as seen in the maximum HOV lane travel time savings cells.

Table 12. Katy Freeway HOV Travel Time Savings (Combined Weighted Averages).

	LANES BLOCKED														
Incident	SHOULDER					1 MAINLANE					2+ MAINLANES				
Duration	INC	AVG	MAX	MIN	DEV	INC	AVG	MAX	MIN	DEV	INC	AVG	MAX	MIN	DEV
min		mm:ss	mm:ss	mm:ss	mm:ss		mm:ss	mm:ss	mm:ss	mm:ss		mm:ss	mm:ss	mm:ss	mm:ss
0-15	**5**	19:30	32:04	07:09	07:16	**20**	13:54	22:43	06:15	05:09	**3**	21:42	35:59	08:56	08:52
16-30	**5**	12:46	22:27	05:25	05:00	**11**	17:42	29:28	05:55	07:15	**1**	28:20	08:40	05:53	21:02
31-45	**3**	19:57	32:00	10:26	07:26	**12**	19:34	32:40	05:56	08:17	**0**				
46-60	**0**					**6**	34:32	38:29	09:34	08:55	**2**	17:09	26:26	03:20	06:57
61+	**3**	15:08	25:19	05:56	05:52	**2**	12:55	23:17	03:14	05:44	**1**	35:21	04:05	00:57	19:11
Avg		16:40	27:47	07:00	06:20		18:27	28:23	06:22	06:48		23:18	41:56	05:46	11:32
% Diff		33%	41%	70%	35%		48%	45%	55%	45%		87%	113%	40%	146%

	NON-INCIDENT			
INC	AVG	MAX	MIN	DEV
60	12:29	19:39	04:07	04:41

Blank cells indicate no incidents for that matrix cell

Annual Benefit Quantification Analysis Methodology

The annual analysis estimated the annual savings, in terms of time and dollars, provided by the four HOV lanes studied in this project during the AM and PM peak periods. This analysis was done using January to December 2003 AVI data. Thus, both incident and non-incident conditions in the proportion they occurred during 2003 are accounted for in the calculation. The steps listed below were used in this analysis.

Step 1 – Filter AVI Data

The first step was to filter the AVI data. The dataset included data for every day of the year (excluding dates or partial dates where technical issues such as downed readers or communication errors caused data to be missing). Since this evaluation compares mainlane travel times with HOV travel times, dates the HOV lanes were not open were filtered out. These dates included all weekends as well as a number of holidays. In the event of any major weather events such as flooding, hurricane, etc., that non-typical data would be filtered as well.

Step 2 – Calculate Mainlane and HOV Lane Annual Average AM and PM Peak Period Travel Times

From the filtered dataset created in Step 1, the annual average AM and PM peak period corridor travel times were calculated for the mainlanes and HOV lanes. For this analysis, the AM peak period was defined as 6:00 to 9:00 AM and the PM peak period from 3:30 to 6:30 PM.

Step 3 – Calculate Annual Average AM and PM Peak Period HOV Lane Travel Time Savings

$$\begin{matrix}\text{HOV Lane}\\ \text{Travel Time}\\ \text{Savings (minutes)}\end{matrix} = \begin{matrix}\text{Average Peak}\\ \text{Period Mainlane}\\ \text{Travel Time (minutes)}\end{matrix} - \begin{matrix}\text{Average Peak}\\ \text{Period HOV}\\ \text{Travel Time (minutes)}\end{matrix}$$

Step 4 – Calculate Annual Average Weekday Person-Trips on the HOV Lanes by Corridor

In order to put the savings in terms of person-minutes, the HOV travel time savings were multiplied by the annual average number of HOV person-trips in each corridor. At present, manual HOV person counts are conducted by TTI during March, June, September, and December of each year. The number of person-trips for these four data collection periods in 2003 was used to calculate the annual average weekday person-trips for each corridor.

Step 5 – Calculate Annual Average HOV Peak Period Person-Minute Travel Time Savings

The annual average peak period HOV lane travel time savings are multiplied by the average peak period number of HOV person-trips to obtain the number of person-minutes saved by the HOV lanes.

$$\begin{matrix}\text{Annual Average}\\ \text{HOV Travel}\\ \text{Time Savings (minutes)}\end{matrix} \times \begin{matrix}\text{Annual Average}\\ \text{Weekday HOV}\\ \text{Person-Trips}\end{matrix} = \begin{matrix}\text{Annual Average Peak}\\ \text{Period Person-Minutes}\\ \text{Travel Time Savings}\end{matrix}$$

Step 6 – Convert Annual Average Peak Period Person-Minute Travel Time Savings to Annual Average Peak Period Person-Hour Travel Time Savings

The annual average peak period person-minute travel time savings is divided by 60 (60 minutes in one hour) to arrive at the annual average peak period person-hour travel time savings.

Step 7 – Calculate Annual Average HOV Peak Period Dollar Value Savings

$$\begin{array}{c}\text{Annual Average}\\ \text{Peak Period}\\ \text{HOV Travel}\\ \text{Time Savings}\\ \text{(person-hours)}\end{array} \times \$13.56 \times \begin{array}{c}\text{Number}\\ \text{of AVI}\\ \text{Days}\end{array} = \begin{array}{c}\text{Annual}\\ \text{Average Peak}\\ \text{Period Dollar}\\ \text{Value Savings}\\ (\$)\end{array}$$

The annual average peak period HOV travel time savings is multiplied by the dollar value of time of $13.56 and the number of AVI days used in the annual calculations to arrive at an annual average dollar value of HOV lane savings per peak period.

The value of time was originally derived by TTI in 1985 using a speed-choice model. The 1985 value of time was determined to be $8.03 per person-hour. This figure has been updated annually based on the consumer price index (CPI). This value is then extracted out to quantify the benefit on an annual basis by multiplying the average daily savings by the number of non-holiday weekdays. In 2003, the number of non-holiday, non-major weather event weekdays was 253 days.

Table 13 illustrates the process and steps used in this annual benefit quantification analysis.

Table 13. Quantification of Houston HOV Lane Annual Savings.

Freeway	Direction	Peak Period*	Mainlane Peak Period Travel Time	HOV Peak Period Travel Time	Peak Period Travel Time Savings	Percent Difference	Average Peak Period HOV	Average Peak Period Savings	Average Peak Period Savings	Average Peak Period Savings	Annual Savings
			(minutes)	(minutes)	(minutes)		(person-trips)	(minutes)	(hours)	($)**	($)
North	SB	AM	24.27	19.73	4.54	18.7	13,037	59,175	986	$13,374	$3,383,505
North	NB	PM	23.64	18.59	5.05	21.4	12,316	62,238	1,037	$14,066	$3,558,626
Gulf	NB	AM	20.66	14.49	6.17	29.9	8,684	53,612	894	$12,116	$3,065,401
Gulf	SB	PM	20.32	14.21	6.11	30.1	7,534	46,024	767	$10,401	$2,631,543
Katy	EB	AM	24.77	12.90	11.87	47.9	11,478	136,285	2,271	$30,800	$7,792,514
Katy	WB	PM	32.18	13.40	18.78	58.4	11,822	222,031	3,701	$50,179	$12,695,308
Southwest	EB	AM	18.04	13.67	4.37	24.2	10,143	44,321	739	$10,017	$2,534,178
Southwest	WB	PM	17.33	13.40	3.93	22.7	9,421	37,064	618	$8,376	$2,119,251
TOTALS							**84,435**		**11,012**	**$149,329**	**$37,780,326**

* Peak periods are 6:00 to 9:00 AM & 3:30 to 6:30 PM

** = avg. peak period savings (hours) × $13.56/hour value of time savings

DALLAS METHODOLOGY

This document provides guidance in quantifying the additional travel time benefit when the IH-635 buffer-separated HOV lane is not affected by a mainlane incident and the decrease in benefit when the HOV lane is affected by the mainlane incident. It is based on the results of a research project sponsored by the Texas Department of Transportation to assist in evaluating the effectiveness of buffer-separated concurrent-flow HOV lanes in the Dallas District. Comprehensive reports were prepared to document the results of the study (*3*, *4*).

Intelligent Transportation System (ITS) Coverage

Closed Circuit Television

The IH-635 corridor is electronically monitored from the DalTrans Transportation Management Satellite Center, the transportation management center (TMC) of the TxDOT Dallas District. The goal of DalTrans is to improve the region's mobility, reduce congestion, and improve safety for multiple corridors in the region. Operations personnel can detect unplanned incidents by periodically scanning the traffic images from the closed circuit television (CCTV) cameras. Incident detection may also be provided to the TMC by external sources such as 911 calls, police scanners, the Courtesy Patrols, or coordination with the Dallas Sheriff's Office (DSO) and the Dallas Fire Department.

The northern section of IH-635 is outfitted with eight CCTV cameras of various spacing. These eight cameras have the ability to pan, tilt, and zoom on locations throughout the corridor to scan for incident occurrence or verify reported incidents. Figure 12 shows the locations of these cameras with their identifying names of Luna, Harry Hines, Josey, Pedestrian Bridge, Rosser, Welch, Montfort, and Preston.

Autoscope Network

TxDOT also monitors traffic characteristics of various corridors using a video image detection system (VIDS), known as Autoscope. The Autoscope system uses equipment set up to look over a section of highway and detect various types of traffic data over certain time intervals. This system can detect and record corridor vehicle volumes and vehicle speeds for each of the individual travel lanes or for multiple lanes combined. The Autoscope equipment is in the same location as the CCTV cameras, as indicated in Figure 12.

Data Collection

Data collection efforts for this research required use of the DalTrans CCTV cameras and the Autoscope system along IH-635. The research team was already familiar with both systems from previous work efforts involving Dallas-area freeways. By cross-referencing recordings of video data for incidents in the corridor with speed data available from the Autoscope system, a reasonable determination of travel times and delay was possible for the HOV lanes and the general-purpose lanes. The research team used this information to calculate the change in travel time savings for users of the HOV lane when an incident occurred on the general-purpose lanes only, as well as those that affected the HOV lane.

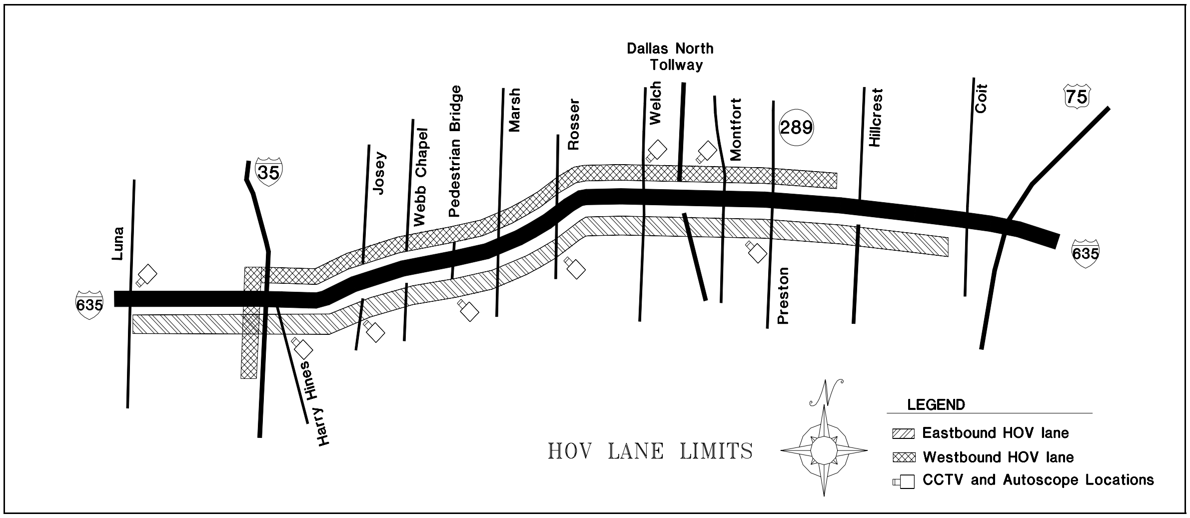


Figure 12. IH-635 (LBJ Freeway) CCTV Camera and Autoscope Locations.

Daltrans CCTV Cameras

Methodology

Visual confirmation of incidents along the IH-635 corridor was achieved by using the eight different camera views of CCTV from DalTrans on the weekdays over the five-month period from September 2003 through January 2004. The camera views used are designated as Luna, Harry Hines, Josey, Pedestrian Bridge, Rosser, Welch, Montfort, and Preston. The eight views were recorded using two video cassette recorders (VCR), four views per video cassette recorder in a quad-screen format, during the AM and PM peak periods as shown in Figure 13. The AM peak period was from 6:00 AM to 9:00 AM and the PM peak period was from 4:00 PM to 7:00 PM. The two VCRs were kept in the DalTrans electronic equipment room for the duration of the data collection period. No weekend data were recorded or required given the scope of the research effort.

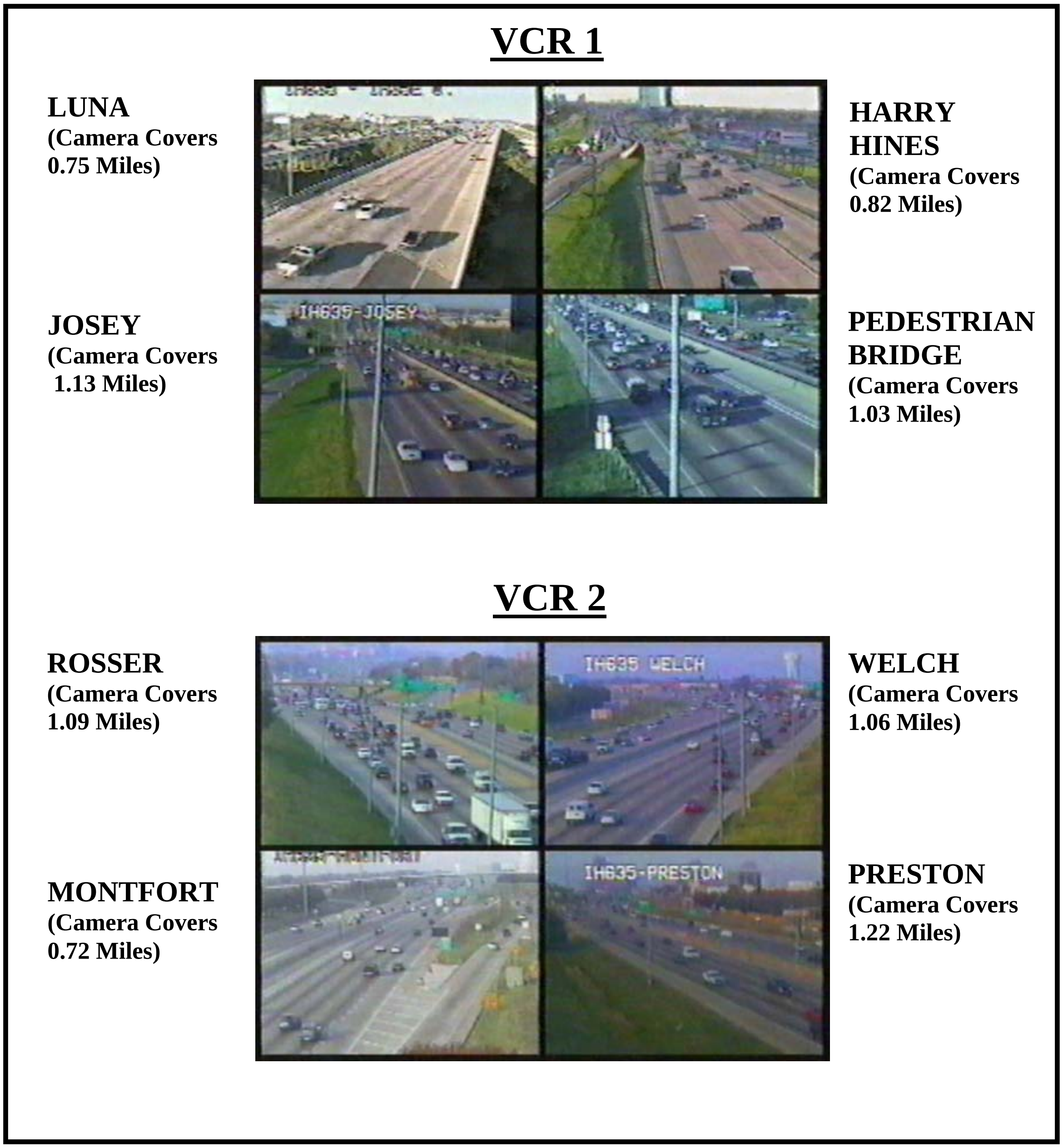


Figure 13. DalTrans Camera Views.

Video Data Reduction

Every two weeks during the data collection period, the recorded video data were retrieved from DalTrans by the research team, and each videotape was reviewed to identify incidents. The incidents for this analysis were defined as any event that reduced the freeway capacity, including major or minor traffic crashes, stalled vehicles, spilled loads, and stopped or slowed vehicles on the general-purpose lanes, the HOV lane, or the shoulder areas. Characteristics of each incident were documented by the research team and included the location, date, beginning and ending time in which there was visual confirmation, lane blockage, and type of incident along with other pertinent information.

Categorization of Incidents

A total of 569 incidents were recorded during the weekday peak periods on IH-635 from September 18, 2003, through January 19, 2004 (6:00 to 9:00 AM and 4:00 to 7:00 PM), for this project. This number equates to 88 weekdays of recorded peak period video data. It should be noted that there were 17 weekdays during the data collection period where video data were unavailable due to technical problems with DalTrans equipment, thereby leaving 71 weekdays of usable video data. Thus, the total number of incidents from this data collection effort is actually less than the true number of incidents that occurred during this calendar period. Table 14 shows the incidents categorized by the resulting type of lane blockage and the length of time for blockage that were available from the data collection effort.

Incidents that were observed blocking one of the general-purpose lanes are the most prevalent and result in limiting the vehicle capacity of the freeway general-purpose lanes. Incidents that block the inside shoulder (IS), the outside shoulder (OS), and the inside shoulder enforcement area (ISEA) usually have less impact on traffic movement in the corridor. Of the 569 incidents, 499 were either on the inside or outside shoulder or the inside shoulder enforcement area.

Table 14. Incident Lane(s) Blockage and Duration.

CCTV Observed Blockage Time (minutes)	ISEA	IS	HOV Lane	HOV Lane & Lane 1	2+ Lanes	1 Lane	OS	Other	Total
0-15	20	20	6	2	0	23	238	1	310
16-30	4	3	2	2	1	8	28	1	49
31-45	0	1	2	5	0	2	27	3	40
46-60	0	4	2	2	0	1	14	0	23
61+	1	9	2	1	0	2	130	2	147
Total	25	37	14	12	1	36	437	7	569

The primary objective of reviewing the videotapes was to observe incidents occurring in the general-purpose lanes. However, there were a number of incidents that were observed to block the HOV lane in some manner. This blockage results in limiting the person-movement capacity of the facility and has a direct impact on the travel time savings and reliability of the HOV lane. Even more detrimental to the mobility of the corridor was the number of incidents observed blocking both the HOV lane and Lane 1 of the general-purpose lanes, which is immediately adjacent to the HOV lane.

Autoscope

A total of 569 incidents were recorded during the weekday peak periods on IH-635 from September 18, 2003, through January 19, 2004. Characteristics of each incident were documented by the research team, including the location, date, beginning and ending time in which there was visual confirmation, lane blockage, type of incident, and other pertinent information. With this critical information, the research team was able to acquire the corresponding speed and vehicle volume data for the corridor, which had been previously archived by TxDOT from the Autoscope system. Although TxDOT has CCTV cameras at eight locations along this corridor, only six of those locations are outfitted with Autoscope equipment. These six locations are identified as Josey, Pedestrian Bridge, Rosser, Welch, Montfort, and Preston.

Methodology

TxDOT provided the research team with archived Autoscope data in two installments in Microsoft Access® database format. The first installment covered the time period from September 2003 to mid-November 2003. The second installment covered the time period from mid-December 2003 through January 2004. The archived data from mid-November to mid-December 2003 was irretrievable from the database. Of the 569 incidents, 154 incidents occurred during the same calendar time frame as the lost Autoscope speed data.

Data Reduction

The Access database of the archived Autoscope data contained information from all active Autoscope equipment locations from around the Dallas freeway system. The data concerning only the IH-635 corridor were parsed out for ease in manipulating the data. The data were then separated to coincide with the six separate Autoscope locations of interest along the corridor. The research team was able to move forward with the data analysis by having the data in this simplified format.

Data Analysis

Introduction

Incidents that blocked one or more of the general-purpose lanes or the HOV lane were the main focus of the analysis with shoulder incidents of little consequence given the scope of this research. A number of incidents were identified by the research team from the list of 569 incidents as good candidates for further analysis of travel time and delay characteristics. The goal was to compare the speed and travel time characteristics of these incident days with data collected on typical non-incident days. The data from non-incident days served as the baseline information for the analysis.

General-Purpose Lanes Baseline

The baseline data for the IH-635 corridor or the typical non-incident day traffic characteristics are needed to compare to traffic data gathered during the occurrence of an incident. Unfortunately, the IH-635 corridor routinely experiences one or more incidents somewhere along the corridor almost everyday during peak periods. However, a review of the list of incidents documented from late September 2003 to mid-January 2004 shows that no incidents were visually confirmed for 16 different peak period time periods, some of which were for the AM peak period with the remaining for the PM peak period. These 16 time periods would provide the needed non-incident day data to develop the baselines.

Corridor Typical Day Determination

Upon first review, the research team anticipated that the 16 time periods should have provided 10 time periods for the AM peak period baseline and six time periods for the PM peak period baseline for all six Autoscope locations along the corridor. However, this was not the case. Autoscope data were missing from the electronic Access database for many of the locations during these particular time periods. As a result, the baseline for each location and each time period was developed using anywhere from two to six time periods. Although the baselines were developed using limited data, the research team felt that the baselines were adequate for comparison with incident data based on previous knowledge of speed characteristics for the corridor from previous research *(5)*.

Typical Day Graphical Representation

By using the data from the days without incidents, the research team was able to develop a total of 24 different baselines for the corridor. The total 24 was for the six locations by AM or PM peak period and by direction, either eastbound or westbound. Figure 14 shows an example of one of the typical non-incident day baselines used in the analysis. This example is for the Autoscope data from the Preston site during the AM peak period in the westbound direction for the general-purpose lanes only. The graph shows the instantaneous traffic speeds at different time periods converted to travel time and weighted by the length of camera coverage. The peaks on the graph indicate the times of lowest speeds and the highest travel times occurring for this section of roadway.

On incident-free days, the speed on the HOV lanes is expected to remain relatively stable throughout the peak period. Historical data indicate that the HOV lane is usually moving at around 60 mph *(5)*. This speed is converted to travel time and represented on the graph as simply a constant travel time to compare to the general-purpose lane travel times. On the graph, for a particular time period, the difference between the line for the general-purpose lanes travel time and the line for the HOV lane travel time represents the typical travel time savings available to HOV lane users on incident-free days for that particular location. For instance, an HOV lane user can expect to save a maximum of approximately 0.6 minutes, or 36 seconds, over a 1.2 mile section near Preston in the westbound direction at 7:45 AM on a typical non-incident day for that five minute time increment.

Representative Incident for General-Purpose Lane Blockage

Increased General-Purpose Lane Delay

The increased delay due to incidents on the general-purpose lanes equates to increased travel time savings for HOV lane users that are unaffected by the incident. This savings is due to the decreased speeds on the general-purpose lanes while the HOV lane speeds remain relatively unchanged. By including the data for decreased general-purpose lane speeds on the baseline graph, the research team was able to visualize and better understand the impact of incidents with respect to travel time in the corridor.

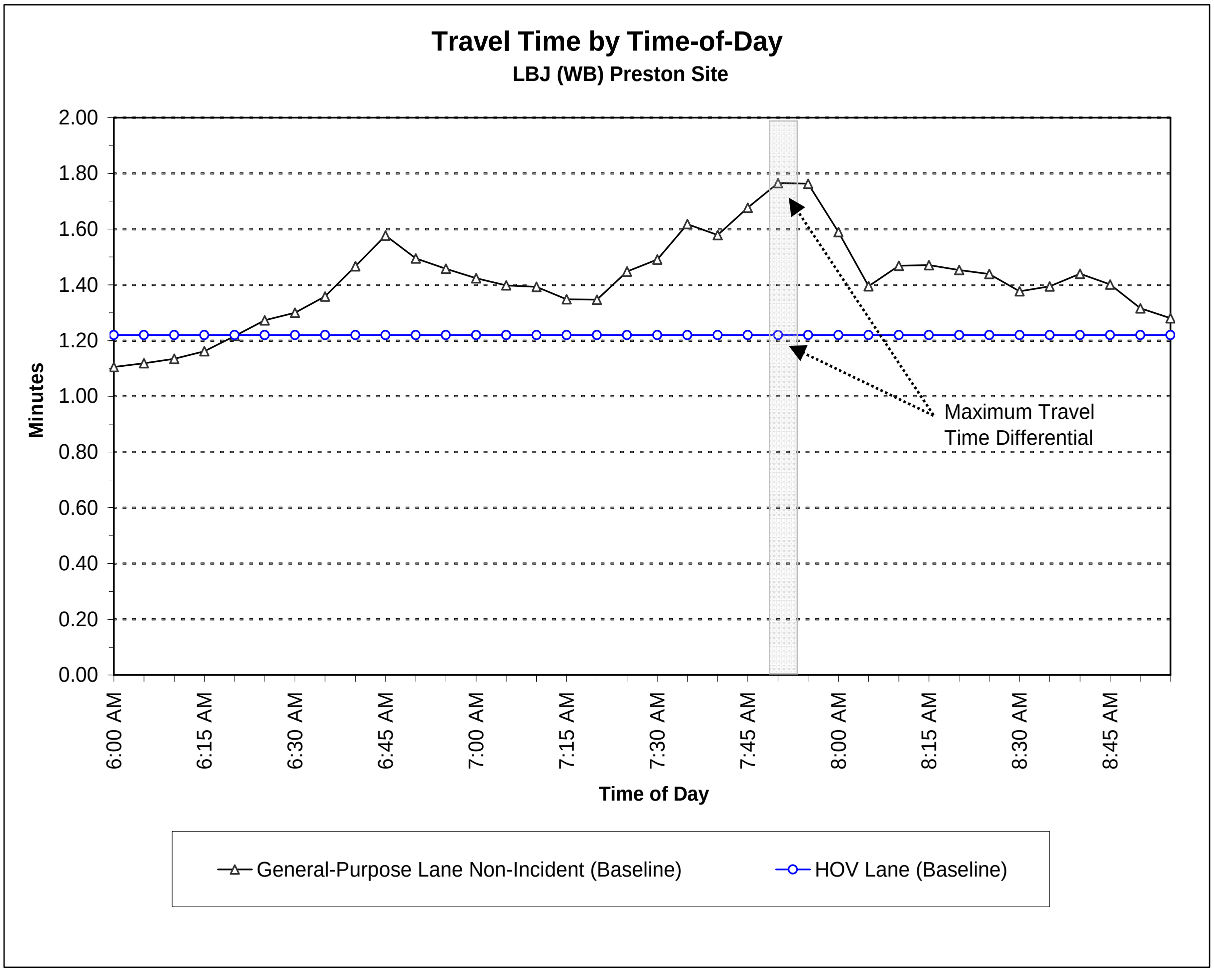


Figure 14. Baseline Delay.

General-Purpose Lane Delay Graphical Representation

Figure 15 portrays a typical example of a general-purpose lane incident and the impact on travel time as compared to the typical non-incident general-purpose lanes day and the typical travel times on the HOV lane. This particular incident resulted in blocking two general-purpose lanes and was visually detected using the CCTV cameras at the Preston location by DalTrans personnel at 6:17 AM. By viewing the Autoscope data from the graph, it would seem that the incident actually occurred at 6:15 AM. Since two lanes were blocked, the speed on the general-purpose lanes quickly slowed and increased the travel time as shown on the graph. The incident was cleared from the roadway at 6:44 AM, and the general-purpose lanes were back to normal operation by about 7:00 AM.

The highest peak on the general-purpose lane incident data represents the greatest slowdown in speeds and the longest travel times. The difference in the peak and the corresponding data point on the line representing typical non-incident general-purpose lane conditions gives the additional delay on the general-purpose lanes during an incident. For this example, this difference equates to an additional 4.2 minutes travel time savings westbound at Preston at 6:50 AM for the HOV lane users during that five minute time increment.

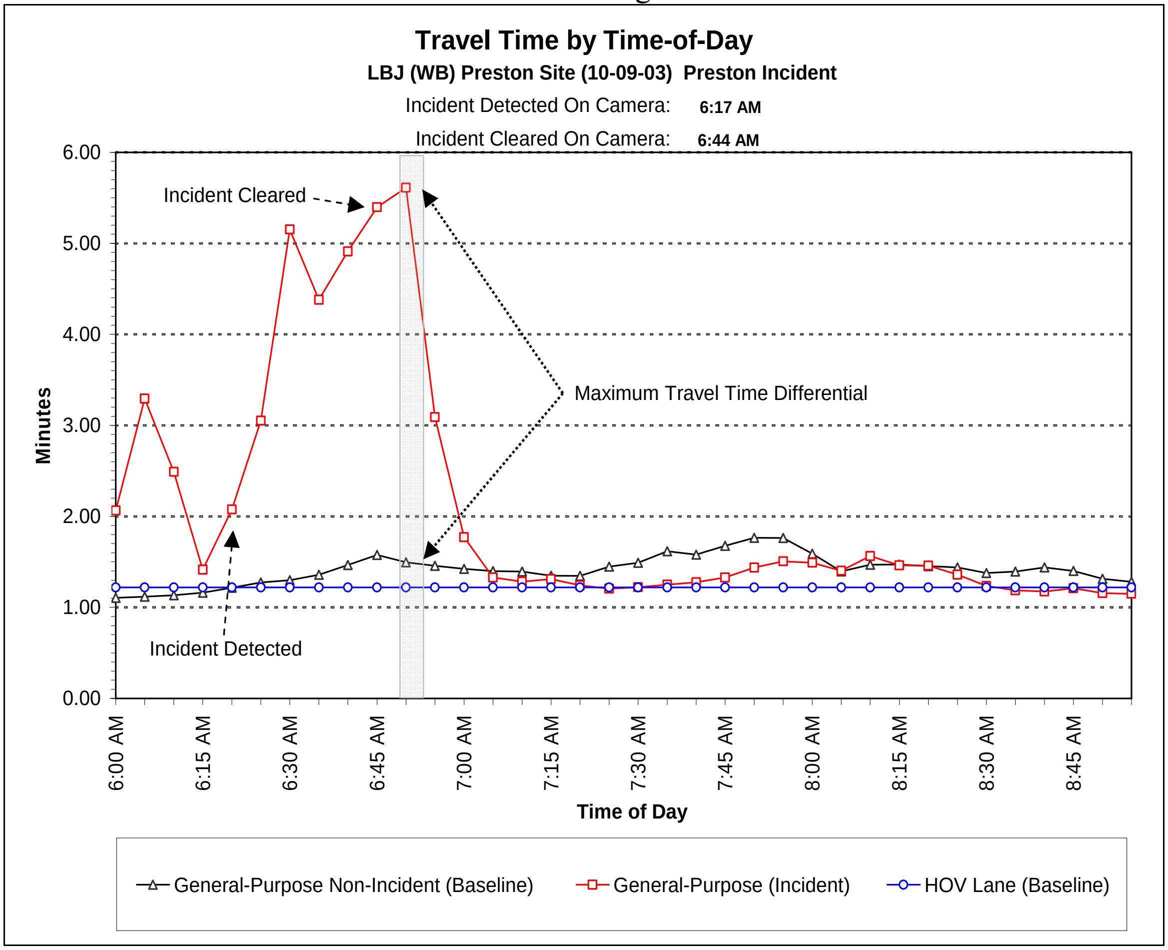


Figure 15. Incident Causing General-Purpose Lanes Delay.

General-Purpose Lanes Delay Calculated for Representative Incidents

Table 15 shows the calculated additional delay for representative incidents chosen for the analysis. There were a limited number of usable incidents due to the limited amount of data from the Autoscope database. Therefore, each cell of the table corresponds to data characteristics of one particular incident. The data in the table represent the difference in the peak or maximum recorded general-purpose lane travel time due to the incident and the corresponding data for the typical (baseline) non-incident days on the general-purpose lanes. Simply stated, these data represent the maximum additional delay each and every vehicle in the general-purpose lanes is experiencing as a result of the incident for the one camera location where the incident can be visually monitored, roughly over a one-mile section. Conversely, these data represent the additional travel time savings offered to each high-occupancy vehicle lane vehicle as a result of an incident in the general-purpose lanes.

Only incidents of 60 minutes or less are shown in Table 15. The research team determined that incidents longer than one hour did not yield reasonable Autoscope speed data that could be directly attributed to the incident. The graphical representations of the extended time frame lane blocking incidents did not match video data of the incident when compared to incidents causing lane blockage of less than 60 minutes. As previously shown in Table 14, there were only five incidents from the data set that resulted in blocking the HOV lane, the HOV lane and Lane 1, or the general-purpose lanes for this incident duration category. With the low number of incidents in this category and the atypical graphs, the research team chose not to continue with further analysis of this category.

Table 15. Additional Incident Delay (Minutes) for General-Purpose Lanes.

	Location of Blockage		
Incident Duration (minutes)	GP Lane (1 Lane Blocked)	GP Lanes (2+ Lanes Blocked)	Outside Shoulder
0-15	1.0	NA	0.6
16-30	1.4	4.1	1.4
31-45	2.1	NA	1.6
46-60	3.7	5.0	1.2

Note: Data for outside shoulder incidents shown for comparison.

Incidents Resulting in Blocking the HOV Lane

HOV Lane Delayed

In the case of concurrent-flow HOV lanes with a painted buffer separation, incidents occurring on the general-purpose lanes can adversely affect the operation of the HOV lane. Recent research conducted by TTI shows that this type of HOV lane design has increased the frequency of injury-related crashes in the corridors studied. The IH-635 corridor was a part of that study as well. The majority of the increase in crashes occurred in the general-purpose lane designated as Lane 1, which is immediately adjacent to the HOV lane (6). Not only are many crashes occurring in Lane 1, it appears that emergency vehicles will purposely block Lane 1 and the HOV lane to provide a safe haven to work the crash when responding to incidents that are only blocking Lane 1. In these cases, the users of the HOV lane do not gain additional travel time benefits due to an incident occurring in the general-purpose lanes. The HOV lane users are affected adversely by having to merge back into the now extremely congested general-purpose lanes; thus, they lose the travel time benefits as well as the trip reliability, which are two of the primary goals of implementing HOV lanes. Obviously, incidents that occur on the HOV lane adversely affect the users by the same reasoning to a lesser degree. However, the HOV lane is actually blocked due to the incident itself and not due to positioning of emergency response vehicles.

HOV Lane Delay Graphical Representation

Figure 16 graphically represents data for a typical example of an incident on the HOV lane and the impact on speeds and travel time on the HOV lane and the general-purpose lanes as compared to the typical non-incident day. The incident was visually detected by the CCTV cameras at the Welch location by DalTrans personnel at 4:00 PM. Since the video recording of the corridor always began in the afternoon at 4:00 PM, the incident had been in place for an undetermined amount of time. Since the HOV lane was blocked, the speeds quickly dropped and the travel time increased for both the HOV lane and the general-purpose lanes as shown on the graph. The incident was cleared at 4:59 PM. The HOV lane travel time returned to normal, and speeds were back to free flow by about 5:10 PM; the general-purpose lanes travel time returned to normal and speeds were free flow by about 5:55 PM.

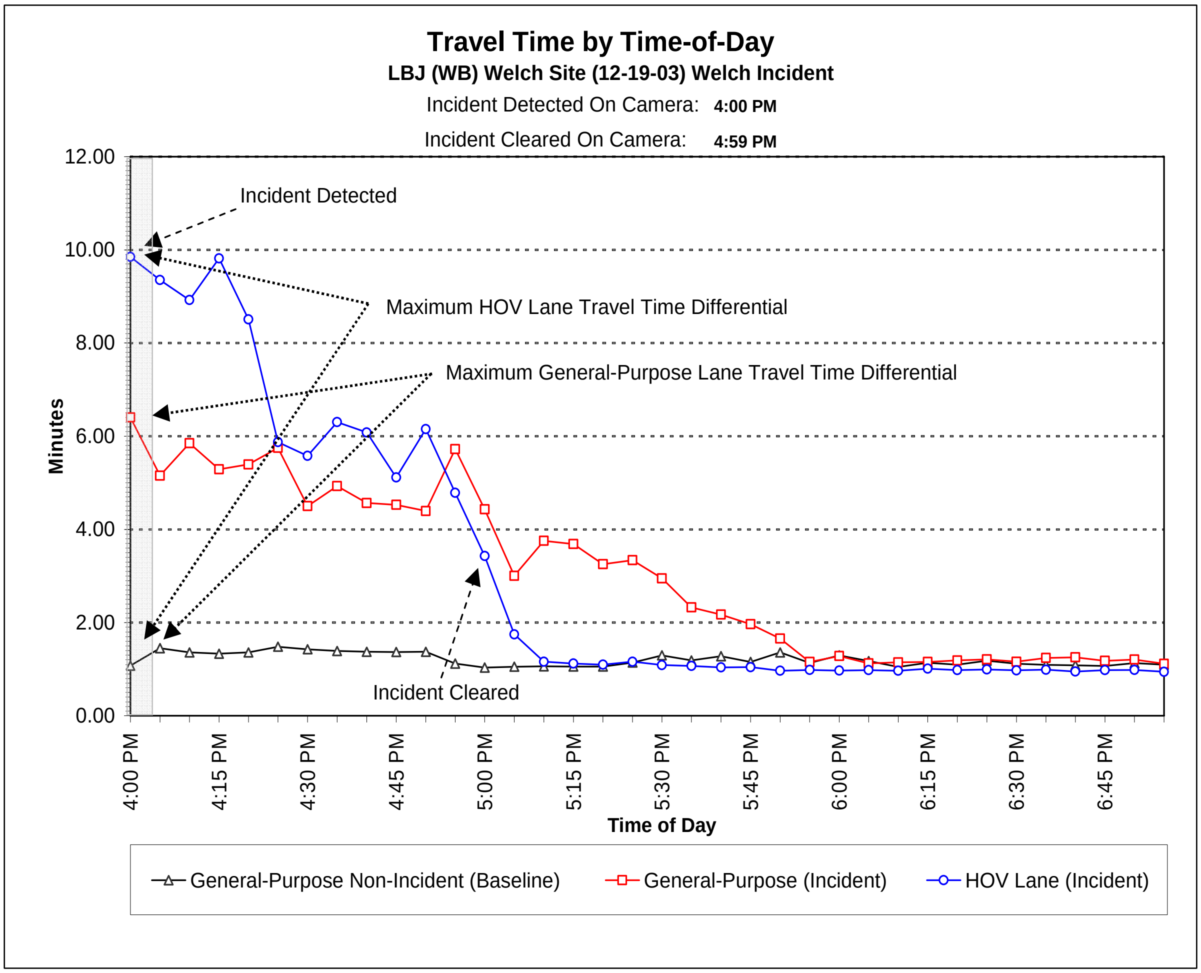


Figure 16. Incident Causing HOV Lane and General-Purpose Lanes Delay.

For this incident, the HOV lane speeds are lower and travel times are shown to be longer than even the general-purpose lanes. In this case, the highest peak on the HOV lane incident data represents the greatest slowdown in speeds and the highest travel times. The difference in the peak and the typical HOV lane speeds and travel time gives the maximum delay to HOV lane users at this camera location. For this example, this equates to 8.8 minutes of travel time delay westbound at Welch at 4:00 PM for the HOV lane users during that five minute time increment.

HOV Lane Delay and General-Purpose Lanes Delay Calculated

Table 16 shows the calculated delay for representative incidents. There were a limited number of usable incidents due to the limited amount of data from the Autoscope database. Therefore, each cell of the table corresponds to data characteristics of one particular incident. For the HOV lane, the data in the table represent the difference in the peak recorded HOV lane travel time due to the incident and the typical HOV lane travel time for non-incident conditions. For the general-purpose lanes, the data in the table represent the peak recorded general-purpose lane travel time due to the incident and the typical general-purpose lanes travel time for non-incident conditions. Only incidents with a duration of less than one hour are shown in the table. The research team determined that incidents with a duration longer than one hour did not yield reasonable Autoscope data that could be directly attributed to the incident.

Table 16. Incidents Delaying (Minutes) HOV Lane and General-Purpose Lanes.

Location of Blockage						
Incident Duration (minutes)	HOV Lane Blocked		HOV Lane and Lane 1 Blocked		Inside Shoulder/ Enforcement Area	
	GP Lane	HOV Lane	GP Lane	HOV Lane	GP Lane	HOV Lane
0-15	3.4	3.8	3.3	2.3	0.2	0.4
16-30	NA	NA	12.9	12.2	0.2	0.0
31-45	4.9	5.6	14.5	14.3	NA	NA
46-60	4.2	8.8	6.7	9.7	NA	NA

Note: Data for inside shoulder/enforcement area incidents shown for comparison.

As seen in Table 16, the incidents involving the HOV lane in some manner result in the HOV lane users actually experiencing more delay than the general-purpose lane users. Incidents with a duration of 45 to 60 minutes in which only the HOV lane is blocked show the HOV lane delay to be twice that of the delay in the general-purpose lanes. Incidents in both the HOV lane and Lane 1 show the HOV lane delay to be about 45 percent more than the general-purpose lanes. Therefore, the HOV lane users are experiencing additional travel time delay near an incident location when the incident impacts the HOV lane operation. This increased delay can be factored into the benefits calculation on both non-incident days and incident delay savings for HOV lane users when a general-purpose lane is blocked.

Upstream Delay Due to Incidents

Upstream Delay for HOV Lane and General-Purpose Lanes

An incident's greatest impact to freeway operations is most obvious in the section of roadway in the vicinity of the incident, as was shown in previous sections. However, there may be additional effects seen upstream of the incident for a great distance. A freeway traffic queue resulting from an incident can extend one or two miles or even further if the required clearance time is very long. The residual effect of an incident can continue long after the incident has been cleared, particularly during peak periods of a congested corridor such as IH-635.

Upstream Delay Graphical Representations

Figure 17 shows data graphically for the Montfort location approximately one mile upstream of the Welch incident blocking the HOV lane presented previously. Again, the Welch incident was visually detected by the CCTV cameras at the Welch location by DalTrans personnel at 4:00 PM, and the incident was cleared at 4:59 PM. At the upstream Montfort location, the HOV lane shows some adverse affects of the incident. However, the users of the HOV lane are still obtaining speed and travel time benefits over that of the general-purpose lanes.

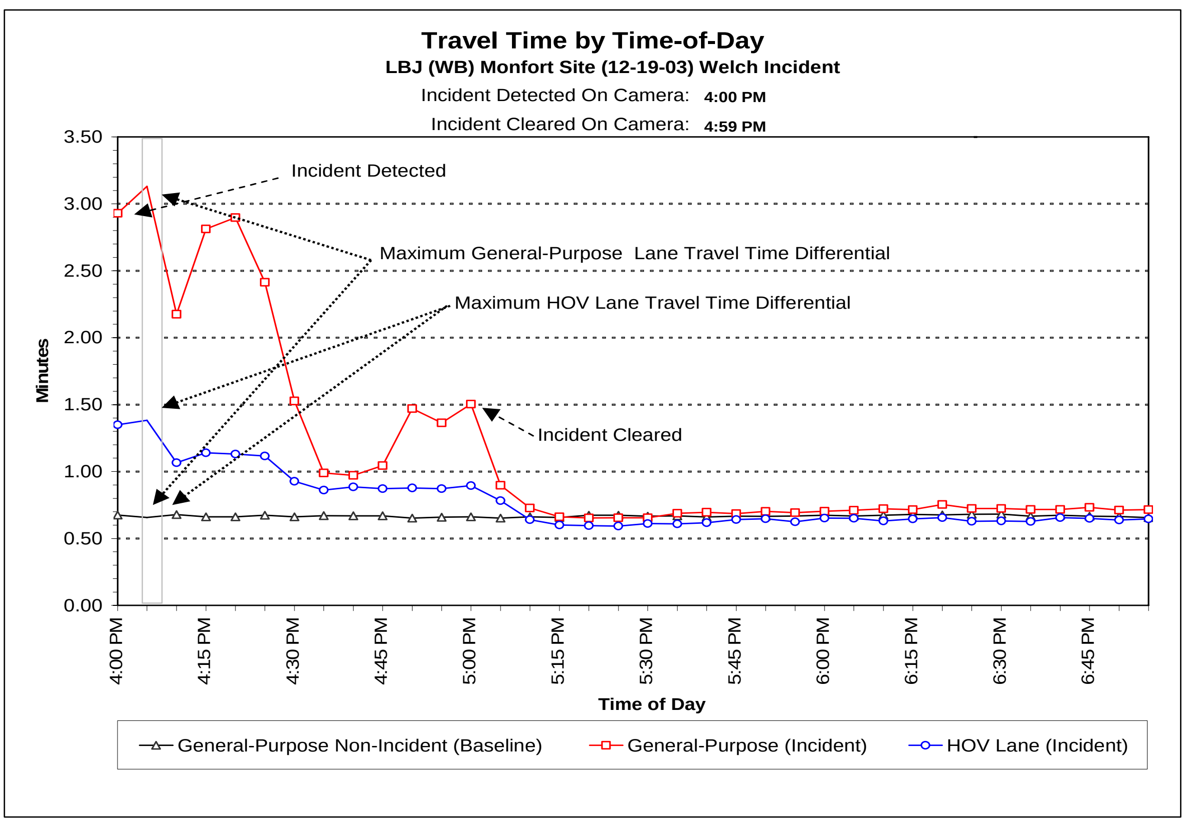


Figure 17. Delay Upstream of Incident – Approximately One Mile.

Figure 18 shows data graphically for the Preston location approximately two miles upstream of the Welch incident blocking the HOV lane. Again, the HOV lane speed and travel time are showing effects of the downstream incident. However, the users of the HOV lane are still getting measurable travel time benefits over that of the general-purpose lanes.

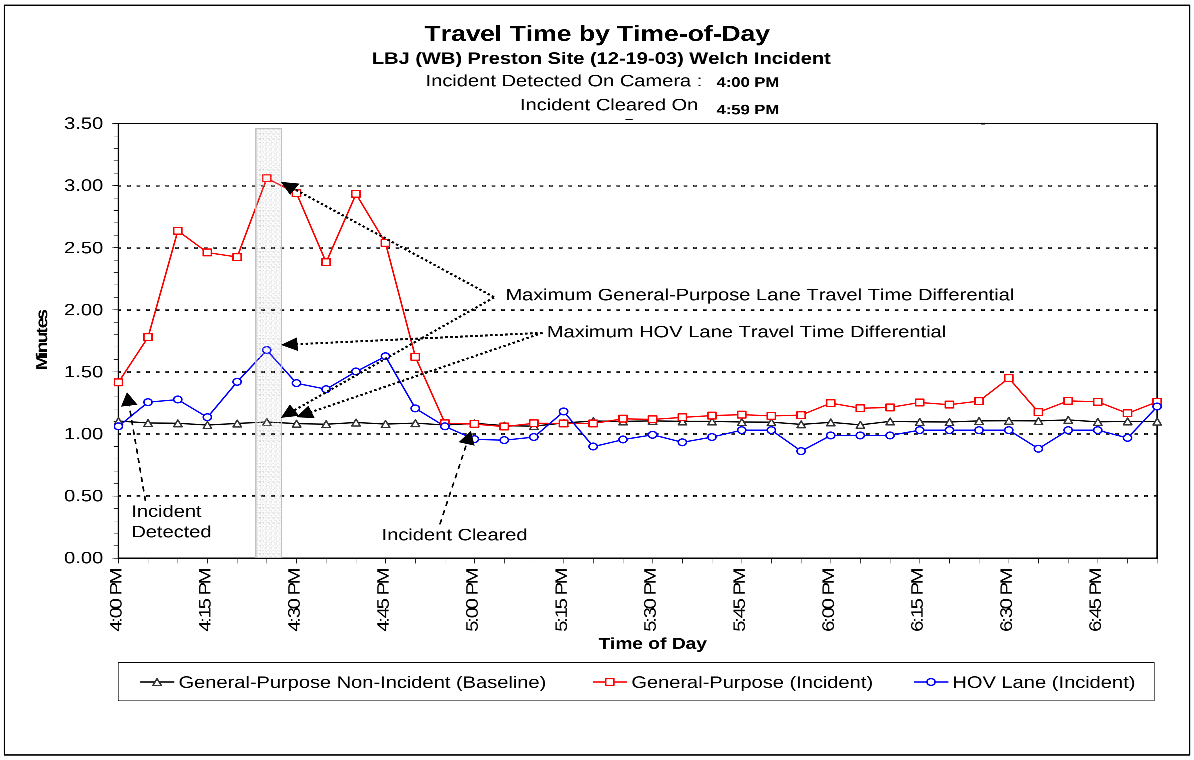


Figure 18. Delay Upstream of Incident – Approximately Two Miles.

Upstream Delay Calculated

Table 17 shows the calculated delay for both the HOV lane and the general-purpose lanes approximately one mile and two miles upstream of representative incidents. As before, each cell in the table corresponds to data characteristics of one particular incident. For the HOV lane, the data in the table represent the difference in the peak recorded HOV lane travel time due to the incident and the typical HOV lane travel time for non-incident conditions. For the general-purpose lanes, the data in the table represent the peak recorded general-purpose lanes travel time due to the incident and the typical general-purpose lanes travel time for non-incident conditions. Data were available two miles upstream for only two incidents, which are in the 46 to 60 minute incident duration category.

As seen in Table 17, one mile or two miles upstream of an incident, the HOV lane users are experiencing an additional travel time benefit whether the incident blocked a general-purpose lane or blocked the HOV lane in some manner. Again, this was not the case in Table 16, which shows delay in the immediate vicinity of an HOV lane-related incident. In that case, the HOV lane users are not experiencing additional travel time savings.

Table 17. Delay (Minutes) Upstream of Incident.

Location of Blockage			
Incident Duration (minutes)	1 Lane Blocked (GP Lane)	HOV Lane Blocked (GP Lane/HOV Lane)	HOV Lane and Lane 1 Blocked (GP Lane/HOV Lane)
0-15	(2.6) - 1 Mile	NA	(3.2/1.6) - 1 Mile
16-30	(0.2) - 1 Mile	NA	NA
31-45	(1.1) - 1 Mile	NA	NA
46-60	(2.5) - 1 Mile (3.8) - 2 Miles	(2.5/0.7) - 1 Mile (2.0/0.5) - 2 Miles	(4.4/3.9) - 1 Mile

NA indicates no data available for matrix cell

Combined Total Delay

Incident Site Delay plus Upstream Delay

Table 18 shows the calculated incident delay plus any other delay that was verified upstream of the incident to give a total quantifiable delay related to the incident. Incidents blocking only general-purpose lanes and not affecting the HOV lane provide data values that can be used for determining additional travel time savings for HOV lane users. For example, the cell for incidents with a lane blockage of 46 to 60 minutes shows additional general-purpose lane delay of almost 10 minutes. Conversely, this equates to an additional travel time savings of 10 minutes for each and every HOV lane vehicle due to an incident in the general-purpose lanes.

Table 18. Total Quantifiable Delay (Minutes).

Location of Blockage						
Incident Duration (minutes)	1 Lane Blocked (GP Lane)	2+ Lanes Blocked (GP Lane)	HOV Lane Blocked		HOV Lane and Lane 1 Blocked	
			GP Lane	HOV Lane	GP Lane	HOV Lane
0-15	3.5	NA	3.4	3.8	6.5	3.9
16-30	1.6	4.1	NA	NA	12.9	12.2
31-45	3.2	NA	4.9	5.6	14.5	14.3
46-60	10.0	5.0	8.6	9.9	11.1	13.6
Average	4.6	4.6	5.6	6.4	11.3	11.0

Table 18 also shows that the total HOV lane delay for incidents involving the HOV lane in some fashion experience approximately the same delay as the general-purpose lanes. Again, the total delay includes the delay experienced one or two miles upstream, if available, which provided additional travel time savings for HOV lane users. Unfortunately, the extreme unusual delay experienced by HOV lane users in the vicinity of an HOV lane related incident overshadows any travel time savings provided upstream.

It should be noted again that the data in Table 18 are representative of only one particular incident per cell. Logically, the delay times should increase for longer blockage times. However, this delay cannot be determined because there were a limited number of incidents for analysis due to the limited amount of Autoscope data.

CHAPTER 3:
GUIDELINES FOR OPENING HOV LANES TO ALL TRAFFIC DURING MAINLANE INCIDENTS

The purpose of this task is to provide guidelines for diverting general purpose traffic to HOV lanes during general purpose lane incident conditions. It builds upon the information already collected for TxDOT Project 0-4740 and utilizes the recommendations established by TxDOT Project 0-4160, Operating Freeways with Managed Lanes (*2*).

This task addresses the following questions:

- How is traffic diversion for incident management currently applied on HOV lanes?
- Are travel time savings or other benefits calculable for such decisions?
- What scenarios can be developed to help TxDOT determine the appropriateness of a diversion decision?
- What guidelines can be established to guide diversion decisions through the various scenarios?

REVIEW OF TRAFFIC DIVERSION APPLICATIONS

The primary data collection for this task consists of telephone-based interviews with incident management specialists for HOV systems in Texas and other states. The purpose of these interviews was to establish the current practice of departments of transportation (DOTs) and other organizations in their application of traffic diversion.

These interviews refresh data originally collected by Hoppers in 1999 that address the question of traffic diversion into HOV lanes (*7*). Hoppers reports on the diversion policies of six regions: Dallas, Houston, Virginia (D.C. area), Minneapolis, Seattle, and Maryland. Hoppers offers guidelines on the development of a diversion plan, recognizing the principal elements will be interagency cooperation, media involvement, and public notification.

In short, the interviews conducted in 2005 did not alter the summary of Hoppers' review. As a result, Table 19 summarizes the current diversion policies and application, adapted from Hoppers.

The specific configuration of an HOV lane may partially determine its suitability for diversion and as a result the criteria that may be applied to it. As noted by the Washington State Department of Transportation, most diversion policies are set for barrier-separated facilities, where the implications of opening a facility to general-purpose traffic have greater consequences (*8*).

The California Department of Transportation specifically highlights the case of a continual-access HOV, typically separated from general-purpose lanes by a striped lane or 4-foot buffer. Continual-access lanes are difficult to enforce for diversion – if an incident occurs in the HOV lane, the drivers typically move into the general-purpose lane without guidance, and if an incident occurs in the general-purpose lanes, many vehicles will knowingly violate use policies to get around the incident. The Department suggests a cooperative decision be made between the California Highway Patrol and the Department regarding whether general-purpose traffic be allowed to divert into the continual-access HOV lanes without penalty. For the case of a barrier-separated HOV facility, multiple general-purpose lanes must be blocked before a diversion decision is eligible, and even then the diversion must be treated with caution if the facility is reversible (*9*).

Table 19. Peer Operator Incident Management Plans.

Region	Agencies	Criteria for Diversion	Motorist Information	Incident Management System
Dallas	DART[1]	No specific criteria	VMSs[2], cones, flags, and media announcements	DFW[3] ITS (dfwtraffic.dot.state.tx.us)
Houston	METRO[4], TxDOT	No specific criteria	VMSs, overhead lane control signals, and media announcements	Houston TranStar (www.houstontranstar.org)
Maryland	MdSHA[5]	No specific criteria	VMSs, highway advisory radio, and media announcements	CHART[6] (www.chart.state.md.us)
Minneapolis	Mn/DOT[7]	No specific criteria	VMSs and media announcements	Regional Transportation Management Center (www.dot.state.mn.us/tmc)
Seattle	WSDOT[8]	No specific criteria	VMSs, portable signs, police direction, and media announcements	Traffic Systems Management Center (www.wsdot.wa.gov/Traffic)
Virginia (D.C. area)	VDOT[9]	50% of mainlanes closed and time to clear incident more than two hours	VMSs, highway advisory radio, police direction, and media announcements	Smart Travel Virginia (www.vdot.virginia.gov/comtravel)

[1]Dallas Area Rapid Transit
[2]Variable message signs
[3]Dallas-Fort Worth
[4]Metropolitan Transit Authority of Harris County
[5]Maryland State Highway Administration
[6]Coordinated Highways Action Response Team
[7]Minnesota Department of Transportation
[8]Washington State Department of Transportation
[9]Virginia Department of Transportation

In Virginia, the Hampton Roads HOV system allows for traffic diversion if blockage in general-purpose lanes has occurred for more than 10 minutes. In this situation, the Virginia Department of Transportation estimates an average travel time savings of four minutes per vehicle (*8*).

Ballard reports extensively on the nature of incident management and diversion, primarily from a survey conducted of managed lanes operators (*2*). For the purpose of Ballard's report, managed lanes were defined to broadly include facilities like HOV lanes, but also toll and truck-permission variants (such as high-occupancy/toll lanes, express toll lanes, and truck-restricted lanes). Of 13 managed lane facilities reporting some form of traffic diversion plan, five were HOV lanes, four were express lanes, one was a toll lane facility, and three were high-occupancy toll (HOT) lanes. Since the principal of "premium access" is shared between all four types of managed lane facilities, they are reported here for use in HOV diversion analysis.

Ballard indicates that most facilities had reviewed its diversion plan after implementation and were satisfied overall with their plans, despite few interagency agreements on diversion (see Table 20) (*2*). Furthermore, Ballard found that all HOV and HOT lane facilities with diversion plans had either eliminated vehicle occupancy and/or vehicle type requirements in diversion incidents.

Table 20. Incident Management Survey of Managed Lane Operators.

Facility Type	Diversion Plan	Review Diversion Plan after Implementation	Interagency Agreements	Satisfaction with Diversion Plan
HOV Lanes	5	4	1	5
Express Lanes	4	2	0	3
Toll Lanes	1	1	1	0
HOT Lanes	3	1	2	3

Ballard explored two specific triggers for diversion plans on managed-lane facilities: incident duration and number of blocked lanes (*2*). For incident duration, responses varied from 10 to 55 minutes. Ten minutes has been the minimum time of duration required by the Federal Administration (FHWA) for traffic diversion; however, other managed lanes report 15 minutes, 30 minutes, and 55 minutes of incident duration for traffic diversion. As for number of blocked lanes, an equal number of respondents indicated one lane of blockage (for two or three lane facilities) and two lanes of blockage (for three or four lane facilities).

DETERMINING TRAVEL TIME SAVINGS FOR TRAFFIC DIVERSION

As noted by many authors, the process of diverting traffic from general-purpose lanes to HOV lanes in incident situations is not without peril to the success of HOV lanes. Since HOV lanes are intended to provide a premium level of service – represented by travel time savings over adjacent general-purpose lanes – to an extent, their business model is dependent upon recurring congestion and/or incidents in general-purpose lanes. Efforts to minimize the effect of incidents upon general-purpose lane users may have the effect of also minimizing the travel time incentive for carpooling, vanpooling, or riding the bus. This diversion may negatively affect the volume of eligible HOV lane users, exacerbating the utilization of these facilities.

Determining the appropriate times to divert general-purpose traffic to HOV lanes will be dependent, in part, upon being able to calculate the travel time savings for traffic diversion. Travel time savings will differ depending upon whether the facility is a barrier-separated or buffer-separated facility.

Barrier Separation

Fenno et al. investigated the travel time savings for HOV users during times of incidents on four barrier-separated Houston-area HOV facilities: Katy (IH-10 West), North (IH-45 North), Gulf (IH-45 South), and Southwest (US-59 South). Figures 19 through 23 summarize the results of their investigation of travel time savings on HOV lanes during times of incidents (*10*).

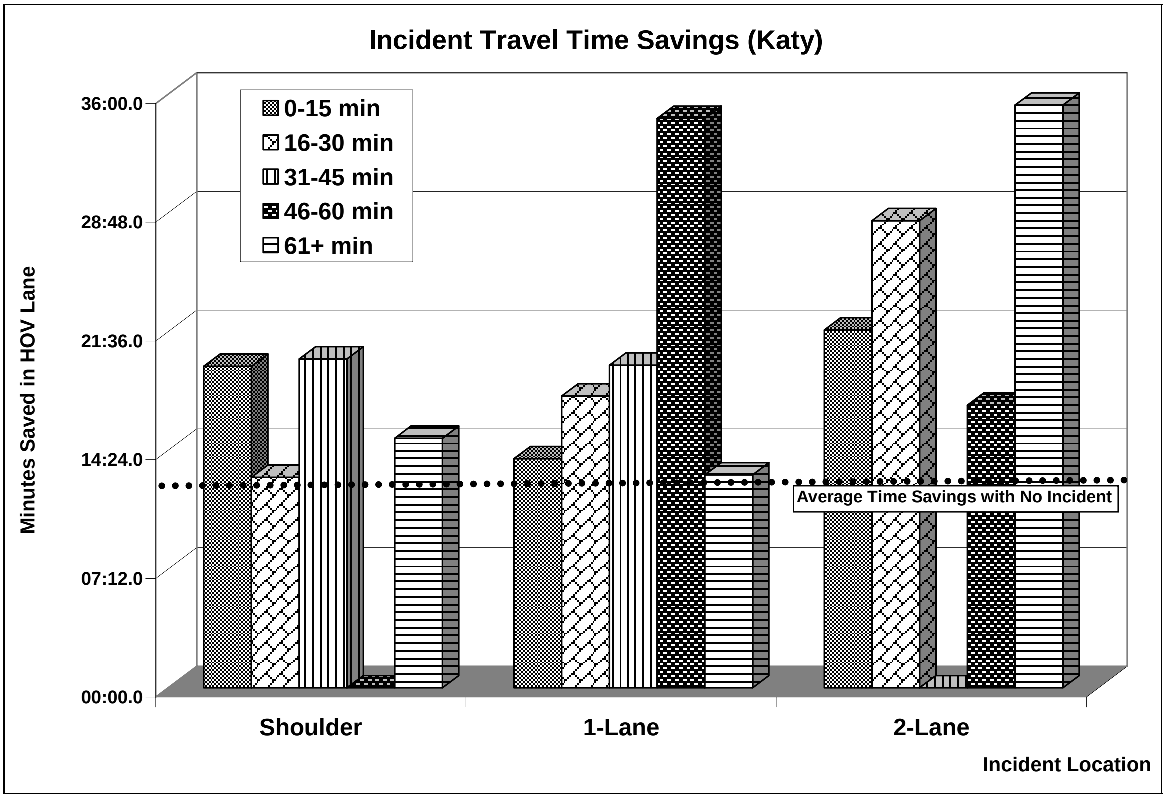


Figure 19. IH-10 Katy Incident Travel Time Savings in HOV Lane.

Figure 20. IH-45 North Incident Travel Time Savings in HOV Lane.

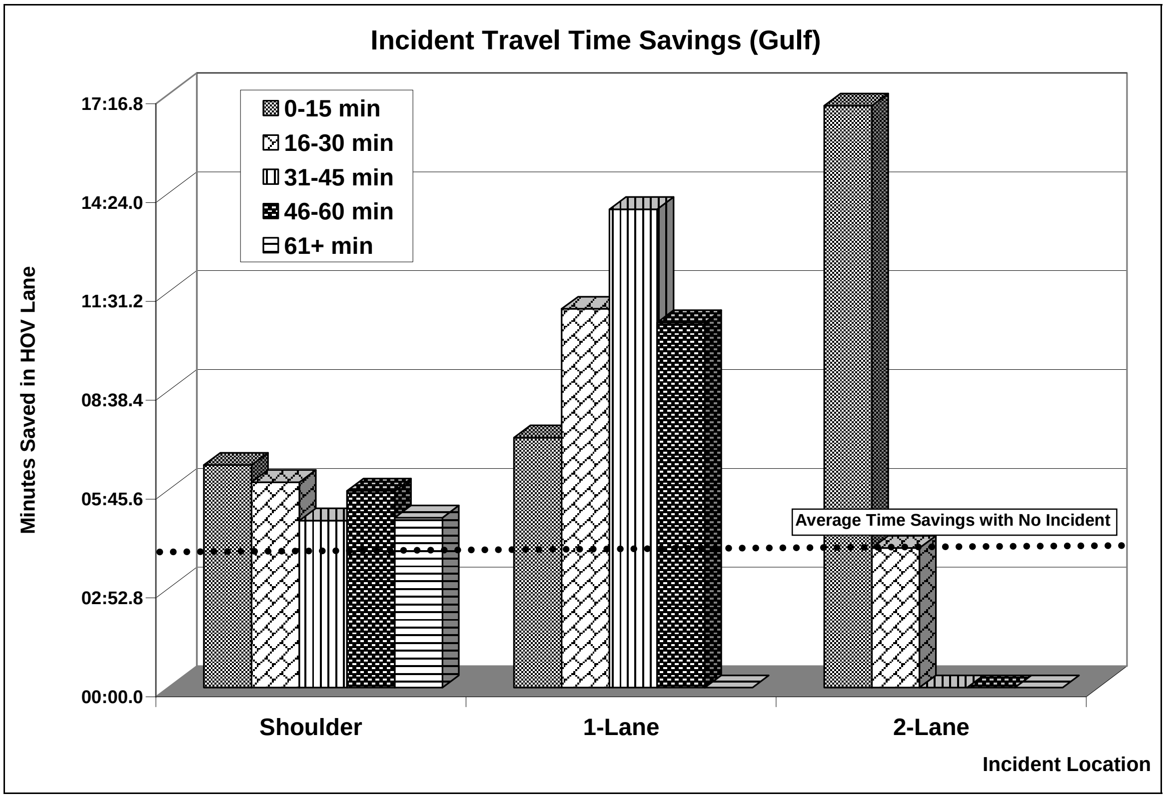


Figure 21. IH-45 Gulf Incident Travel Time Savings in HOV Lane.

Figure 22. US-59 Southwest Incident Travel Time Savings in HOV Lane.

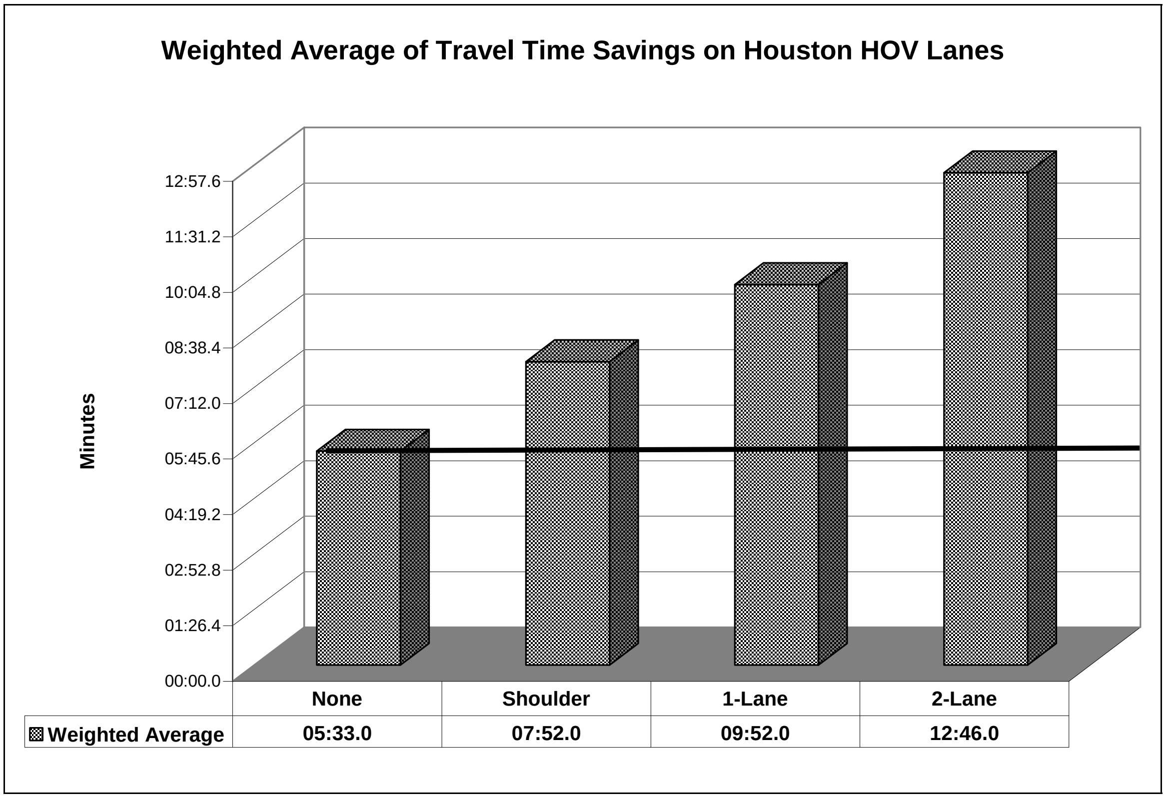
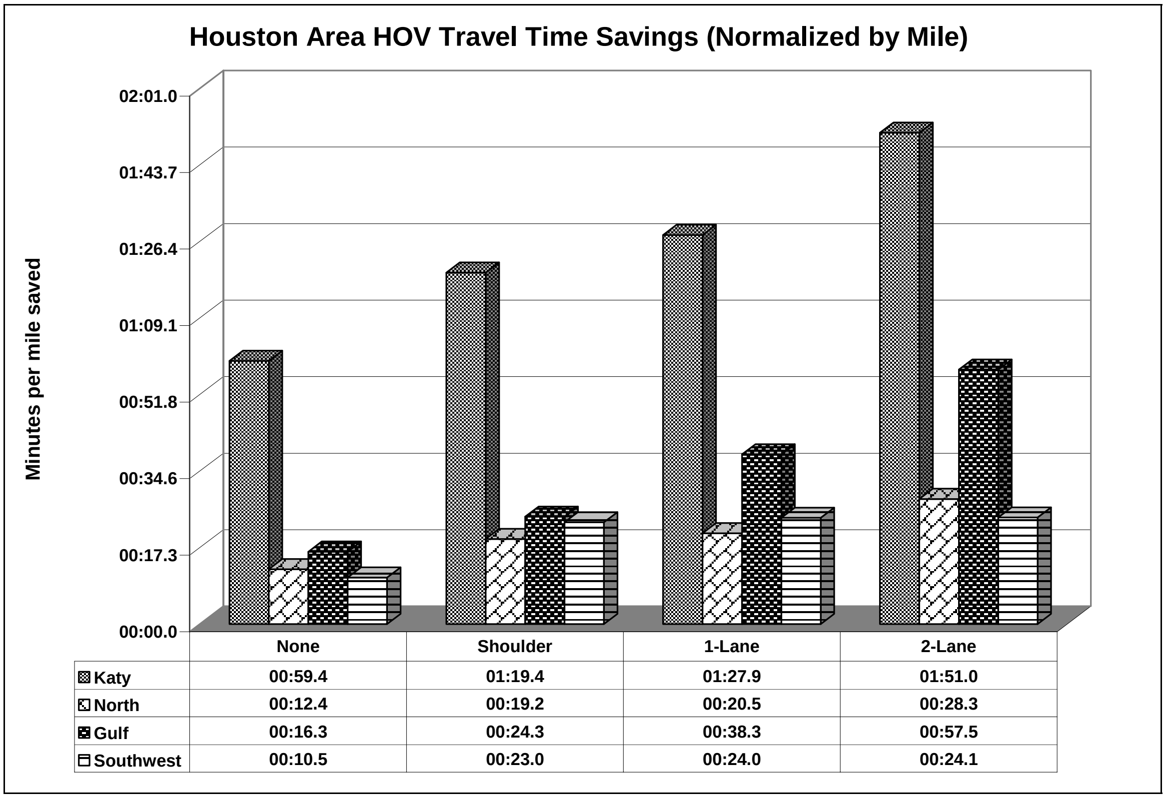


Figure 23. Weighted Average of Incident Travel Time Savings on Houston HOV Lanes.

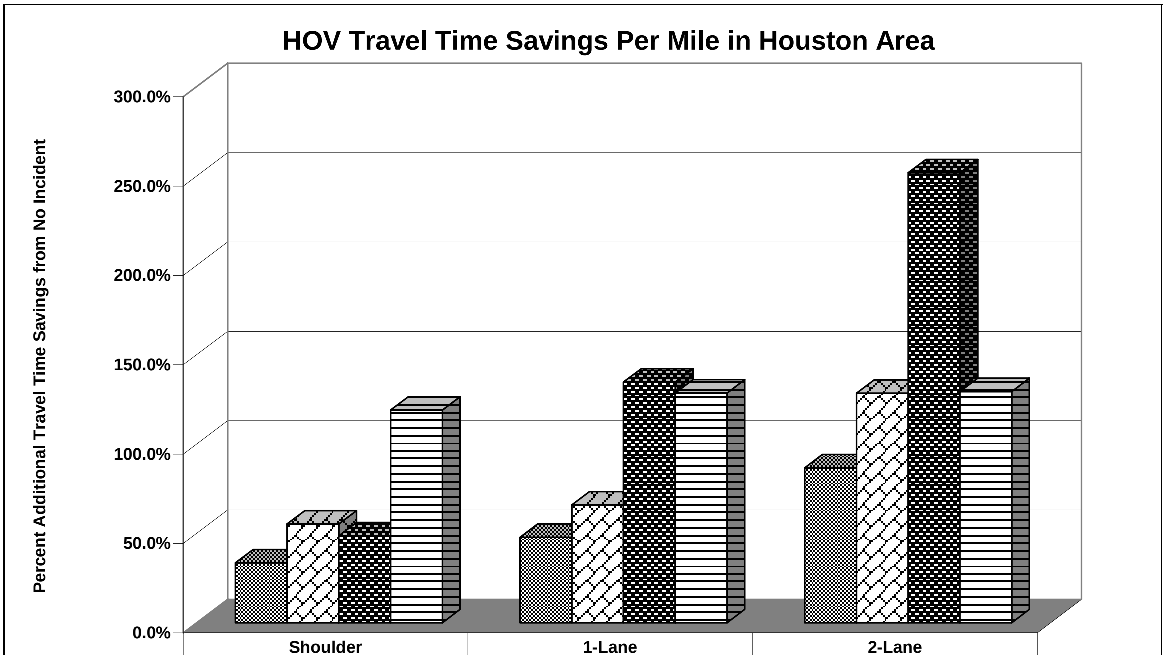
It is evident from the data that travel time savings from the use of a barrier-separated HOV lane can vary significantly between facilities. Figure 24 adjusts the average travel time savings by mile for each facility. Even when normalized by mile, travel time savings are largely dependent upon the overall travel characteristics within a corridor. Regardless of specific travel time savings, the use of HOV lanes on all Houston area facilities demonstrates at least a doubling of time savings in the situation of two-lane incident blockage in the general-purpose lanes.



	None	Shoulder	1-Lane	2-Lane
Katy	00:59.4	01:19.4	01:27.9	01:51.0
North	00:12.4	00:19.2	00:20.5	00:28.3
Gulf	00:16.3	00:24.3	00:38.3	00:57.5
Southwest	00:10.5	00:23.0	00:24.0	00:24.1

Figure 24. Weighted Travel Time Savings Normalized by Mile.

If a diversion decision should only be made in highly unusual circumstances, so as not to undermine the long-term viability and effectiveness of the HOV facility, then it may be appropriate to consider the effects of incidents in comparison to the non-incident travel time savings (which inherently assumes congestion and minor incidents). For the purpose of defining the potential travel time benefit for diversion into HOV lanes during incidents, the Houston data provide an illustration of potential average benefits. When expressed as a percent gain in *average, weighted travel time savings* during incidents, shoulder and one-lane blockage incidents do not typically exceed 100 percent of the non-incident travel time savings when use of the HOV lanes are employed. Indeed, whereas the *average, weighted, non-incident travel time savings* is 5.5 minutes across all HOV facilities, the one-lane blockage *average, weighted travel time savings* is almost 10 minutes. Furthermore, even the two-lane blockage scenario rarely exceeds 150 percent of the non-incident travel time savings, as shown in Figure 25.

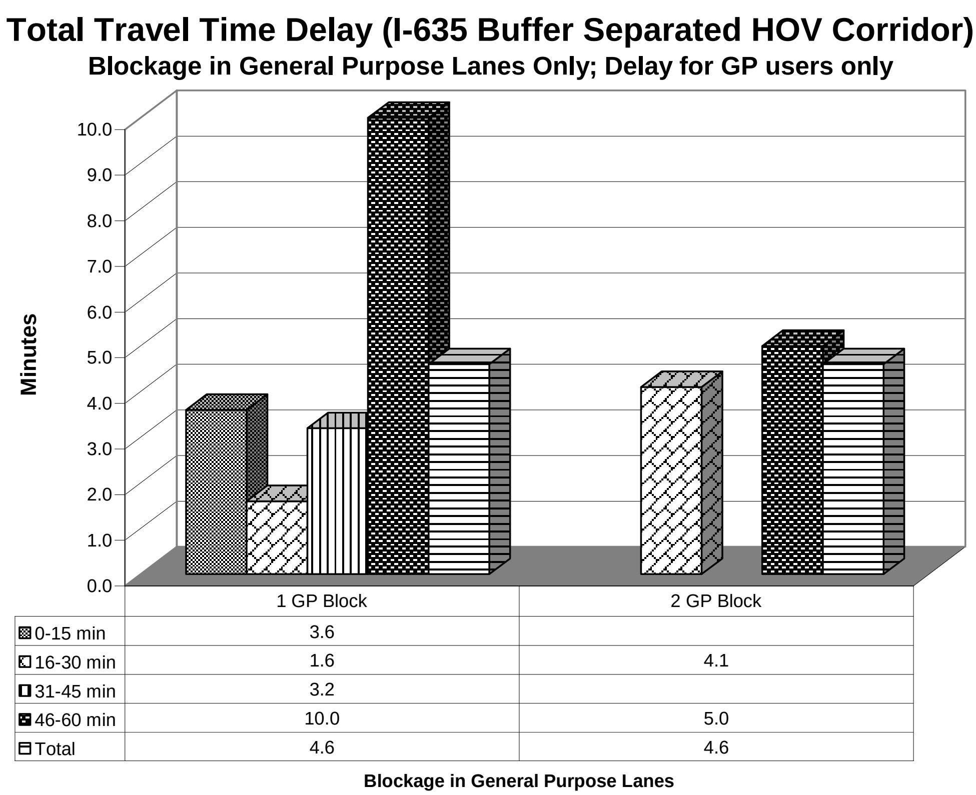


	Shoulder	1-Lane	2-Lane
Katy	33.5%	47.8%	86.6%
North	55.3%	66.0%	128.5%
Gulf	48.6%	134.7%	251.8%
Southwest	119.0%	128.6%	129.4%

Figure 25. HOV Travel Time Savings per Mile Expressed as Percentage.

Buffer Separation

Cothron et al. explored the travel time savings for the buffer-separated IH-635 HOV lanes in north Dallas (*11*). Since buffer-separated HOV lanes are inherently easier to be affected by incidents, their investigation identified scenarios where incidents occurred either in the general-purpose lanes exclusively, the HOV lane exclusively, or a combination of general-purpose and HOV lanes. The average travel time delay by incident duration is provided in Figures 26 to 28.



	1 GP Block	2 GP Block
0-15 min	3.6	
16-30 min	1.6	4.1
31-45 min	3.2	
46-60 min	10.0	5.0
Total	4.6	4.6

Figure 26. Total Travel Time Delay for General-Purpose Lane Users on I-635.

As indicated by the research team, occasions of blockage within the HOV lane, which in turn worsen the travel time advantage for users as opposed to benefit them, are often unrelated to actual incidents. As articulated, incident-response agents will often block the HOV lane to tend to a general-purpose lane incident. This action results not only in unnecessary HOV lane closures but also the removal of diversion scenarios (*11*).

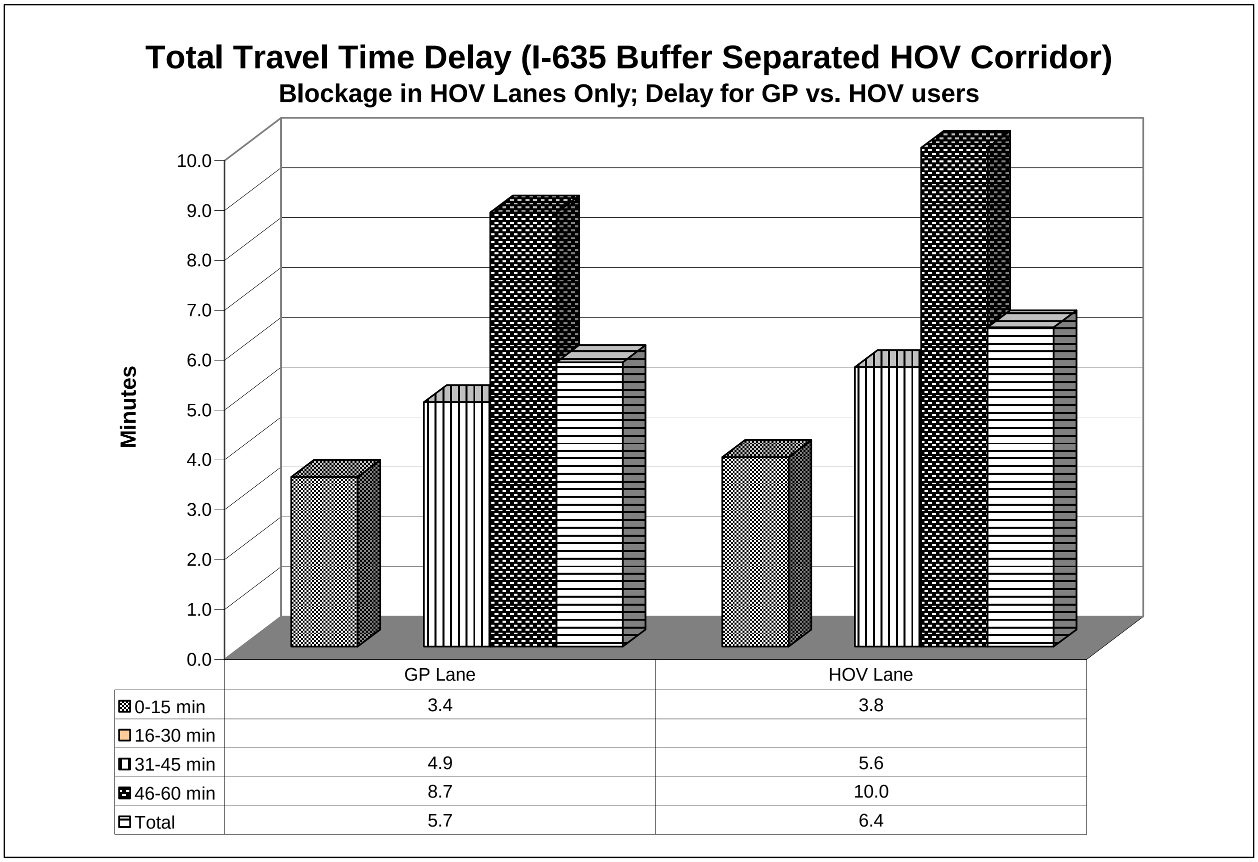


Figure 27. Total Travel Time Delay with HOV Lane Blockage on I-635.

TRAFFIC DIVERSION SCENARIOS

As the likely benefit of diverting general-purpose lane traffic to HOV lanes will differ depending upon the nature of the corridor, providing hard-and-fast numbers (such as Virginia DOT's incident management practice) may not be the most effective means of appropriately identifying diversion applications. Instead, identifying specific types of incidents and surrounding effects may provide better assurance to the traveling public that HOV lanes are opened to general-purpose lane traffic only when they should be opened.

In general, the case for diversion can best be articulated for barrier-separated HOV facilities – access control at ingress points provides incident-response agents easier management and safety of general-purpose traffic access to the HOV lane. Buffer-separated HOV facilities not only suffer from greater travel time uncertainty as a result of diversion (as articulated previously for the case on IH-635) but also greater safety concerns for side-swipe and rear-end crashes as a result of acceleration/deceleration weaving movements (*8*). As such, although the diversion scenarios to be described apply for both barrier-separated and buffer-separated HOV facilities, the guidance process to follow is for *barrier-separated* HOV facilities only. Except in the most extreme general-purpose lane incident circumstances, buffer-separated HOV facilities provide too many challenges to articulate a specific process for approving diversion applications.

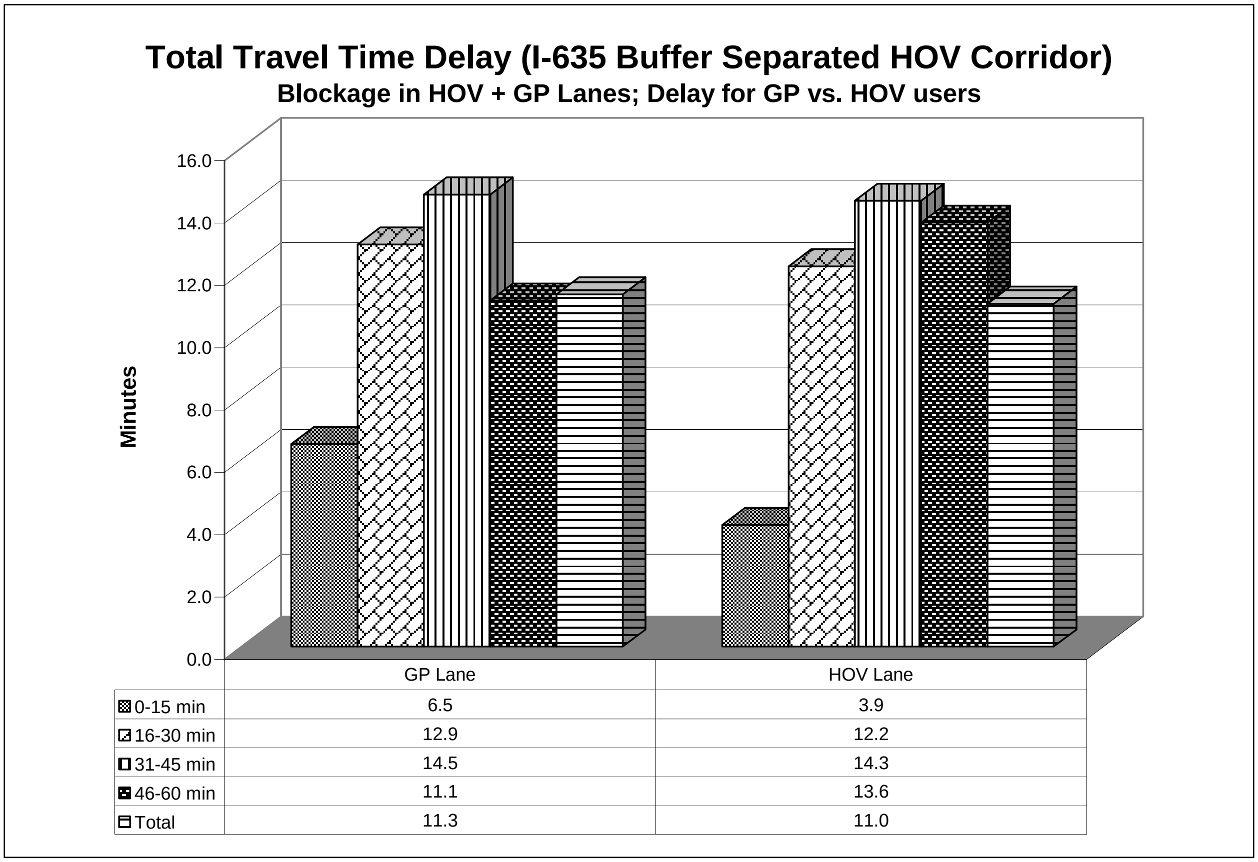


Figure 28. Total Travel Time Delay with HOV and GP Lane Blockage on I-635.

Four attributes can impact the potential range of situations:

- HOV Lane(s) Demand. Is HOV lane volume low or high at the moment of the incident? If low, is it in the beginning of the peak period, when traffic is escalating, or declining after the peak period? If high, is there accommodation for additional traffic?
- General-Purpose Lane(s) Demand. What volume of traffic are the general-purpose lanes carrying? What are the expectations on demand within the next hour, given peak period effects?
- Incident Severity. How long is the incident likely to extend, based upon knowledge regarding vehicle wreckage and/or on-ground injuries?
- Lane Blockage. How many general-purpose lanes are blocked? Where is the blockage located? Is there any blockage to concurrent-flow HOV lanes, if applicable?

The on-the-field determination of these questions can generally be applied to one of 16 potential incident scenarios, as articulated in Table 21.

These 16 scenarios, as applied to guidance on diversion, yield three categories of diversion decisions: positive benefit, no significant benefit, or detrimental effect. Each of these three categories is described below.

Table 21. Prospective HOV Diversion Scenarios.

Scenario	HOV Demand	GP Demand	Severity	Blockage	Effect
A	High	High	High	High	-
B	High	High	Low	High	Negative
C	Low	High	High	High	Positive
D	Low	High	Low	High	Positive
E	High	High	High	Low	-
F	High	High	Low	Low	Negative
G	Low	High	High	Low	Positive
H	Low	High	Low	Low	-
I	High	Moderate	High	High	-
J	High	Moderate	Low	High	Negative
K	Low	Moderate	High	High	Positive
L	Low	Moderate	Low	High	-
M	High	Moderate	High	Low	Negative
N	High	Moderate	Low	Low	Negative
O	Low	Moderate	High	Low	-
P	Low	Moderate	Low	Low	Negative

- Indicates no positive or negative effect

Positive Benefit

The positive benefit scenarios are C, D, G, and K.

All four scenarios that lend themselves to a positive benefit have one thing in common – a low level of HOV volume. Without low HOV volumes, there is no significant capacity available for diversion; hence the corridor is a poor choice for carrying incident-based traffic from the general-purpose lanes. HOV volumes will likely change over the course of the peak period, making situational awareness important, which is addressed in the following section.

Three of the four scenarios also involve high incident severity, implying the incident will extend for a prolonged period of time. Using situational awareness of likely HOV volumes, in-field agents will weigh the expected duration of the incident against the expected HOV volumes. A diversion decision in the case of low incident severity should only occur when the general-purpose lane blockage is likely to be high. In this situation, even if the incident can be cleared relatively quickly, the multiple lane blockages may cause residual upstream traffic congestion for an extended period of time.

No Significant Benefit

The scenarios with no significant benefit are A, E, H, I, L, and O.

These six scenarios identify uncertain benefits of traffic diversion from the general-purpose lanes to HOV lanes. In general, these scenarios can be categorized as “no significant benefit,” but in reality, they may be either positive or detrimental based upon the situation.

For three scenarios, a high level of HOV volume is present. As with the determination of positive benefit, situational awareness is important. If HOV volumes are declining at the time of the incident and are expected to continue declining based upon historic volumes, then in-field agents would be advised to consider the anticipated duration of the incident and the lane blockage in concert with the HOV volume decline. This decision affects scenarios A and I (which involve high incident severity and lane blockage). If the HOV volumes are increasing or are in the midst of peak utilization, diversion is unlikely to provide any significant net benefit.

The remaining three scenarios share the characteristic of low HOV volumes, with either low incident severity or low lane blockage. In the case of moderate general-purpose lane volumes, a high incident duration or lane blockage may warrant diversion depending upon when within the peak period cycle the incident occurs.

Scenario H deserves particular attention. This scenario involves high general-purpose lane volume and low HOV volume, a tempting scenario for in-field agents to divert general-purpose traffic to avoid an incident. However, this scenario also features a low anticipated duration for the incident and low lane blockage – in other words, a typical incident on a congested freeway corridor. FHWA guidance has stated in the case of Virginia that significant travel time delay must be experienced by general-purpose lane traffic before HOV diversion would be permitted. For the Hampton Roads HOV program, this meant a minimum of 10 minutes of travel time delay (*2*). It is unlikely that scenario H, with low incident duration and lane blockage, would meet the definition of significant travel time delay.

Detrimental Effect

The detrimental effect scenarios are B, F, J, M, N, and P.

In all but one of the scenarios, detrimental situations involve diverting traffic to facilities with high HOV volumes (five scenarios) and either low incident severity (four of the scenarios) or low lane blockage (one of the scenarios). No likely positive benefit to travelers would occur since there is no capacity in which to divert traffic.

The final scenario, P, involves low values for all measures, such as a minor incident that occurs outside peak periods. In this scenario, the detrimental effect of the incident upon general-purpose lanes is unlikely to achieve the FHWA-mandated threshold for diversion.

GUIDANCE FOR DETERMINING THE DIVERSION DECISION

The previous section identified 16 traffic and incident scenarios coarsely aggregated in three likely benefit categories. The purpose of this final section is to provide step-by-step guidance to in-field agents for determining which scenario applies to their incident situation. Although the guidance could be built with quantitative data, it is unlikely in-field agents will have access to historical data particular to the corridor or real-time volume information from corridor sensor equipment. As a result, this guidance is directed toward qualitative measures that provide sufficient backing for a diversion decision. For practice, agents should ask themselves the following questions and score appropriately. This process should only require a few moments while in the field, yet it provides accountability for diversion (or non-diversion) decisions. Figure 29 provides a general overview of the process. Albeit sacrificing accuracy, the following calculations use grossly rounded numbers and simplified equations to allow in-field agents the ability to quickly decide on the diversion. The steps below provide the field agent with specific procedures on an HOV diversion decision. A look-up table for use in the field is provided in the appendix.

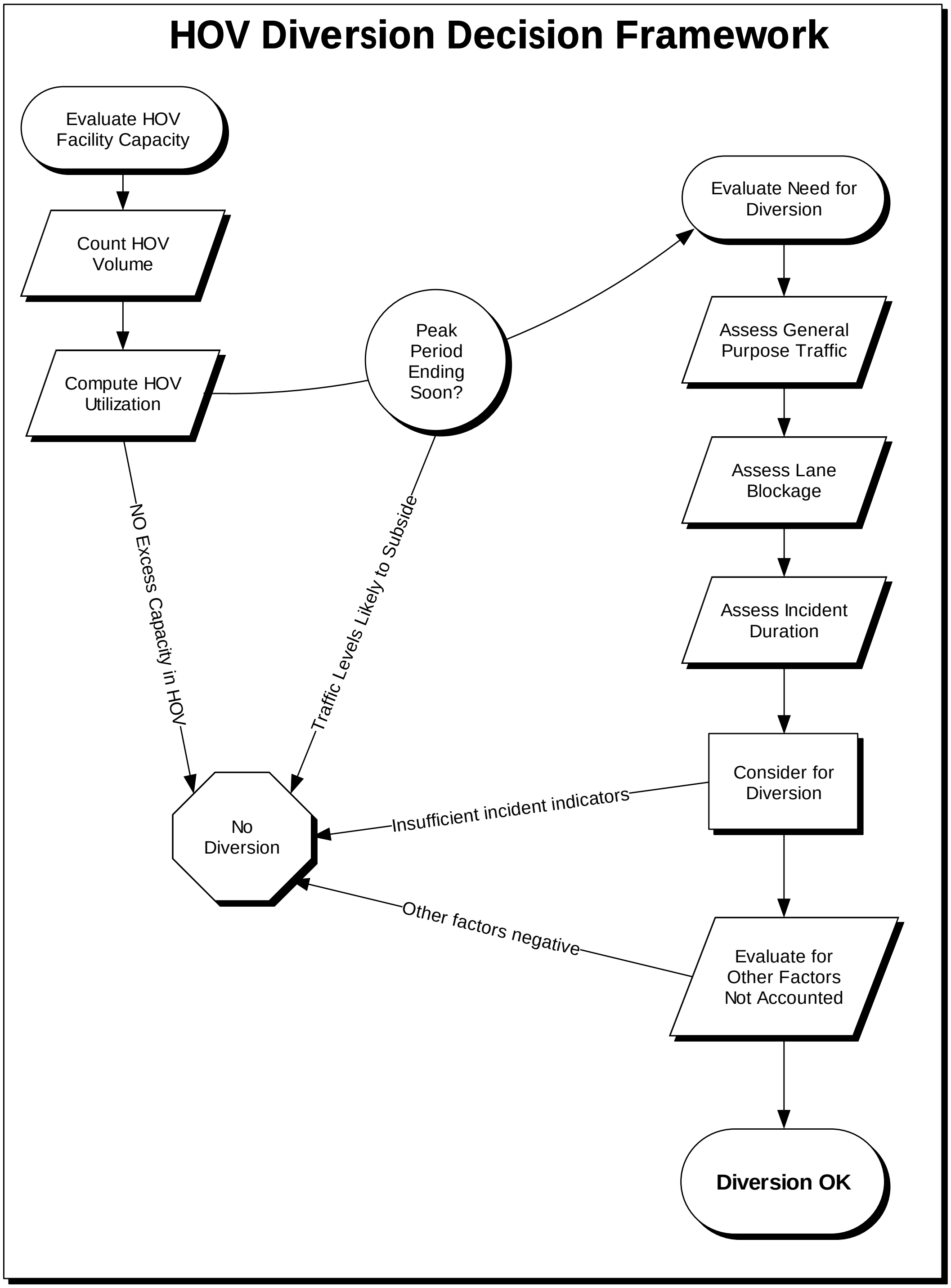


Figure 29. HOV Diversion Decision Process Overview.

Step 1: Initial Assessment for Diversion to HOV Lanes

The concept of excess capacity is subjective to in-field agents without the use of monitoring technology. To quickly assess the availability of capacity, in-field agents will use a one minute vehicle count, requiring personal judgment to determine if the minute is representative of *current* HOV lane traffic.

1-A: Visually count number of vehicles on one lane in the HOV facility for a period of one minute. Although the results from one minute of observations are not generally considered representative samples of HOV traffic, time is of the essence for in-field agents. As a result, a one-minute sample should be accurate *enough* to make a subjective diversion determination.

1-A provides an easy math process for determining the existing volume-to-capacity ratio (percent utilization) for the HOV lanes at the time. As assumed in the process, the typical carrying capacity at free-flow for a freeway lane is in the neighborhood of 1,500 vehicles per hour. As expressed for determining volume to capacity,

$$\textbf{\textit{Volume}} = \boldsymbol{X}\ \frac{\text{vehicles}}{\text{minute}} \qquad \text{where } \boldsymbol{X} = \text{the answer to 1-A}$$

$$\textbf{\textit{Capacity}} = 1500\ \frac{\text{vehicles}}{\text{hour}} \times \frac{1\ \text{hour}}{60\ \text{minutes}}$$

1-B: Calculate the percent utilization for the HOV lane. *Capacity* can be simplified as the ratio of 25 vehicles per 1 minute. The process above yields the percent utilization of the HOV lane by the following equation:

$$\textbf{\textit{Percent Utilization}} = \frac{\textbf{\textit{Volume}}}{\textbf{\textit{Capacity}}} = \frac{\boldsymbol{X}\ \text{vehicles/minute}}{25\ \text{vehicles/ minute}}$$

The answer for 1-B yields the same as the percent utilization and, as such, is the percent utilization for the facility.

If the answer to 1-B is more than 80 percent, then the HOV lane is already accommodating a significant amount of traffic from eligible users, without sufficient excess capacity for diversion. The result would be to cease diversion consideration because none of the "positive effect" scenarios involve high HOV utilization. If 1-B is between 40 and 75 percent, there may be sufficient excess capacity *provided that* HOV traffic is not likely to significantly increase based upon when the incident occurs within the peak period. The following question, 1-C, addresses this situation. If 1-B is less than 40 percent, no additional consideration is necessary, and the in-field agent may proceed to Step 2.

1-C: Will HOV volume likely increase significantly within the next hour, based upon when the incident has occurred within the peak period? If the incident occurs early in the peak period, future HOV traffic volume will likely increase over the measured volume in Step 1-A. As a result, action taken in favor of diversion could undermine the expected HOV volumes later in the peak period. Hence, if HOV traffic is likely to increase within the next hour, it is advisable to cease diversion consideration.

Step 2: Assess General-Purpose Lane Traffic

After ascertaining the availability of excess capacity in the HOV lanes, the in-field agent will next assess general-purpose lane traffic. Rather than require an actual sample traffic count, qualitative observation should be sufficient. The next few questions require the allocation of "points" that will help guide the in-field agent in determining how the facility falls relative to the positive benefit scenarios.

2-A: What is the level of traffic on the general-purpose lanes? Depending upon how the in-field agent would identify traffic, the following points are awarded: heavy volume/congested, moderate volume/some stopping and congestion, low volume/very minor stopping prior to incident.

Step 3: Assess Lane Blockage

Lane blockage is considered in this step, as one of two means of evaluating incident severity. As noted by Fenno et al., diversion benefits are potentially greatest when multiple lanes are blocked *(10)*.

3-A: How many general-purpose lanes will be blocked by the incident *and* incident-response team? The in-field agent should consider partial lane blockages as full blockages. If only the shoulder is blocked, record this as zero lanes.

3-B: How many total general-purpose lanes are available in one direction? HOV lanes are excluded from this measure.

Step 4: Assess Incident Duration

The final step in the specific evaluation is to assess how much time the incident will likely require before full clearance and restoration of travel on the general-purpose lanes. Again, this will be a subjective determination on the part of the in-field agent based upon expertise and knowledge of typical conditions.

4-A: How much time is estimated for the incident and the incident response team to be cleared from the general-purpose lanes? Three possibilities are offered: more than 1 hour, 30 minutes – 60 minutes, or less than 1 hour.

Step 5: Diversion Determination

This step provides the basis for a diversion decision. Using the HOV Lane Diversion Decision Look-Up Table (Appendix), a "positive benefit" scenario (as outlined above) ensues for situations with a checkmark (✓) notation. A "no significant benefit" or "detrimental effect" scenario ensues for situations with a cross mark (✗).

Implementation Considerations

In addition to the guidance for determining diversion provided above, there are two additional considerations that may influence the implementation of diversion decisions. Although these questions do not alter the structure of the guidance, how these questions are answered will help determine the process for diversion:

- **Is the incident occurring in the off-peak direction if the barrier-separated HOV lane is peak direction only?** Contra-flow HOV diversion decisions on barrier-separated facilities are the most difficult of all diversion decisions due to driver expectation and should be only made in the rarest of occasions. Additional in-field manpower may be necessary to ensure a contra-flow diversion decision is conducted safely.

- **Can a diversion decision be made from the traffic management center, as opposed to in-field agents?** The process described here was designed to provide in-field agents with a simple, intuitive means of determining a diversion decision. Much of the data collected by the agent may be already in the possession of the traffic management center. As a result, the TMC may have the ability to make a diversion decision prior to the in-field agent's arrival on the scene.

CHAPTER 4: INVESTIGATION OF AN AUTOMATED STRATEGY TO CONTINUE REVISING ESTIMATED HOV LANE DELAY SAVINGS

The main objective of this task is to provide an outline, plan, or tool to automatically calculate high-occupancy vehicle lane benefits. The calculated benefits can be used to provide traveler information, operations and planning information, and documentation to quantify the benefits of traffic management functions as they relate to HOV lane operations. Travelers can use the information to effectively plan their trip prior to departure or en route. Traffic management personnel can utilize the information to document the benefits of incident management, intelligent transportation system devices, and emergency management. Operations managers and planners can quantify the utilization of the transportation facilities, use the information to manage existing systems to their fullest, and plan for expansion or new facilities. The same information can provide decision makers with a tool to continually monitor how well the HOV system is performing based on operational and historical data. Continual monitoring will allow a systematic measurement to determine how changes in operation and/or events affect the system.

DATA AND DATABASES

The primary data used in determining HOV lane delay savings during incident and non-incident conditions are travel time through the HOV corridor in comparison with the travel time in the mainlanes in the same direction of flow. All travel time data are available through the TranStar historical AVI database, which will be discussed further in the next section. These data are processed through a Travel Time Generator Software program, which is fully functional and was developed during the first year of this project. The other database that is utilized is the TranStar Regional Incident Management System, in which TranStar operators log incidents occurring on the freeway mainlanes, HOV lanes, ramps, interchanges, and frontage roads. By utilizing the two databases, HOV lane delay savings can be quantified during both incident and non-incident conditions. Figure 30 provides a graphical relationship between the data/databases, intermediate calculation processes, and final output.

Data Elements

Travel Time

The main components used in determining HOV benefits are travel time savings and travel time reliability. One of the primary objectives in HOV operations is that the lane should provide travel time savings and a more reliable, consistent trip time than the adjacent general-purpose mainlanes. These savings are typically quantified on a limited basis by comparing the peak period, peak direction travel times of the HOV lane with those of the adjacent mainlanes. Average travel time is an important piece of information, and travel time reliability (travel time range or variation) is also very valuable. The software components used in the automation strategy calculate HOV and mainlane travel time differences and reliability.

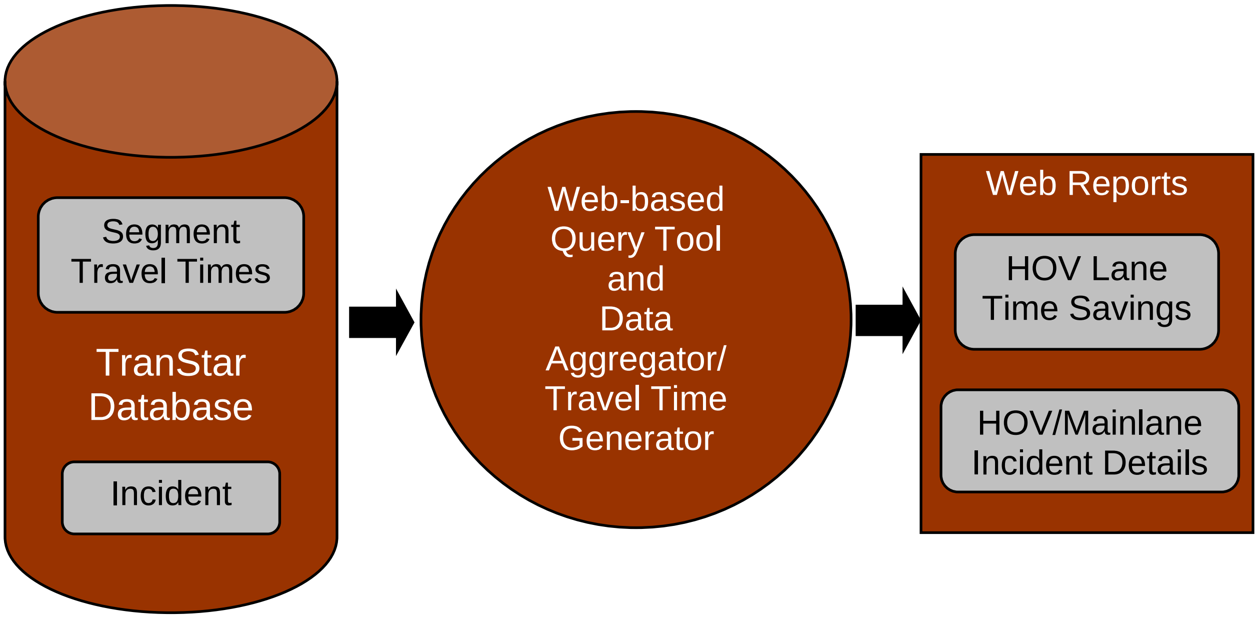


Figure 30. Travel Time Implementation Architecture.

Incidents

Incidents are one of the factors that influence travel time more than anything else. Knowing the frequency, duration, and severity of incidents can provide information that clearly quantifies the increased travel time savings that HOV lanes provide during mainlane incident conditions. The automation strategy aims to summarize incidents to help users more clearly understand the travel time benefit of the HOV lane.

HOUSTON AVI SYSTEM AND TRAVEL TIME GENERATOR SOFTWARE ANALYSIS

The process used to calculate travel time on the general purpose and HOV lane is described fully in Chapter 2, Methodologies for Improved Quantification of High-Occupancy Vehicle (HOV) Lane Travel Time Savings. This process provides the information that drives the query tools and displays explained below.

POTENTIAL GRAPHICAL INTERFACES AND REPORT FORMATS

To semi-automatically estimate HOV lane delay savings for a particular corridor on a particular day or time period, data from the TranStar Database could be queried by corridor date and time. Only minor modifications would need to be made to the existing Travel Time Generator Software program. The web-based interface could look similar to the screen shown in Figure 31. Travel times would be calculated for the entire length of the HOV corridor. The user would select a corridor, date, and time range or select a specific day of week during the date range.

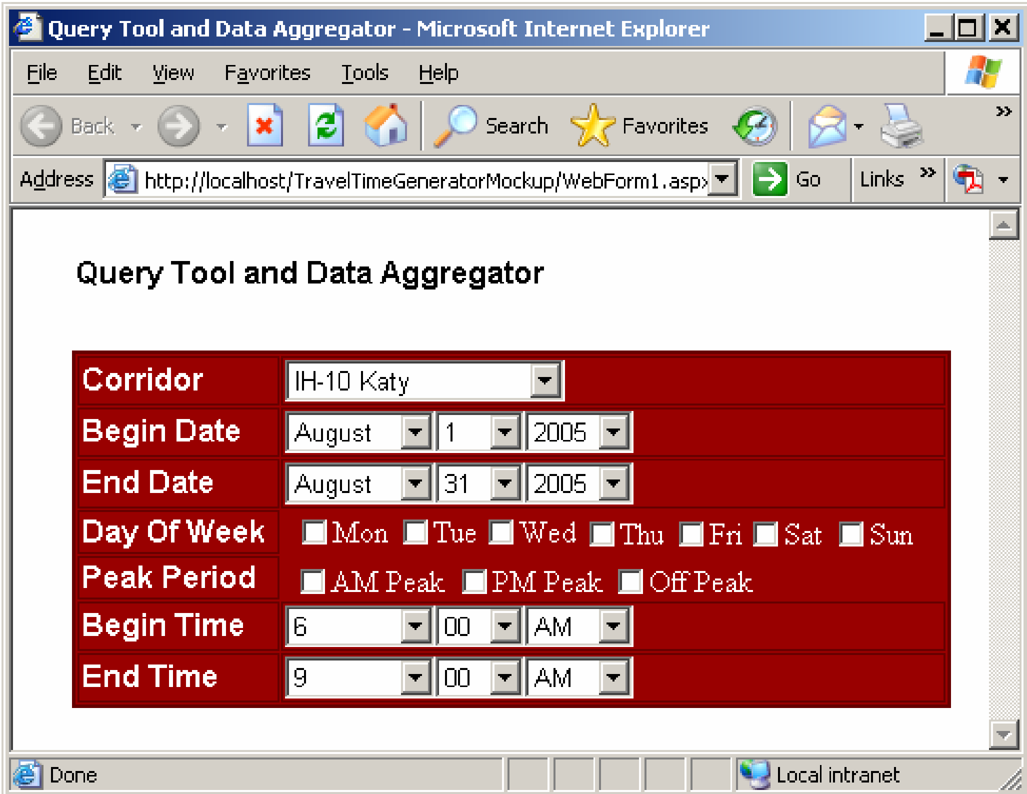
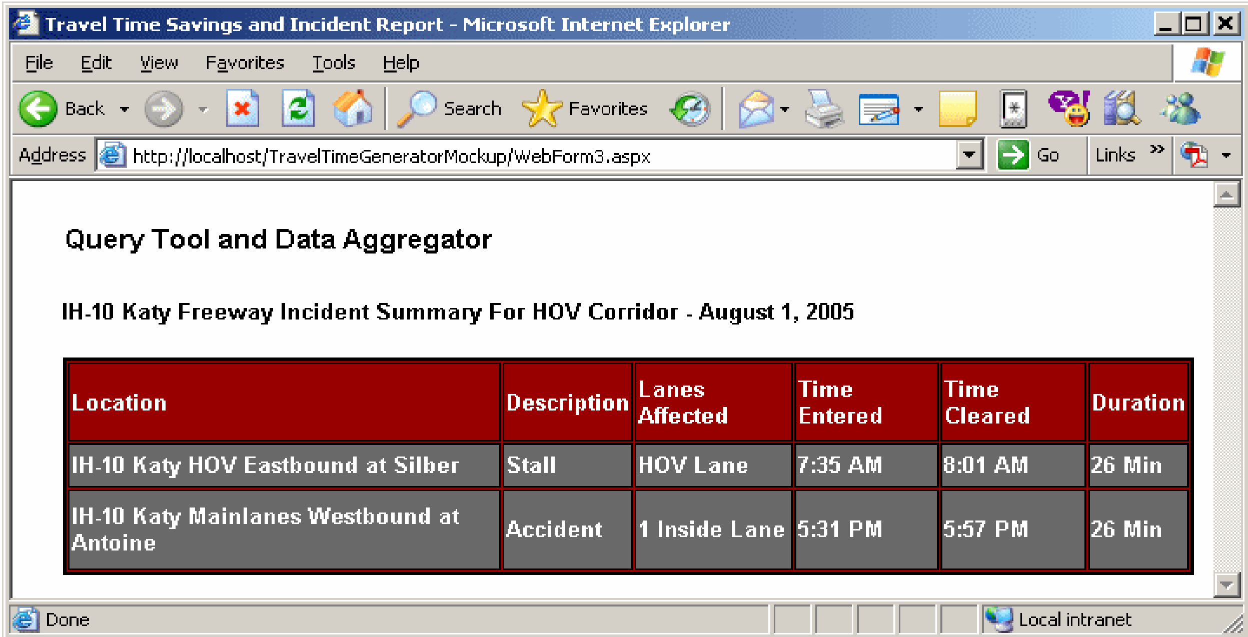


Figure 31. Potential Graphical Interface for HOV Lane Delay Savings Estimate.

The program would then generate a series of reports in tabular and graphical form. These reports would be on-screen and in file format for travel time and incidents. Figures 32 and 33 illustrate examples of what these reports might look like. Figure 32 would provide travel time for the mainlane and the HOV lane as well as the travel time differences between them. Figure 33 shows an example of the incidents from the RIMS database that would be appended to the travel time savings table. The incidents in this table would be filtered to only include incidents occurring during HOV hours of operation, within the limits of the HOV lane, and in the direction of flow of the HOV lane.

Figure 34 provides an example of a graphic that could be automatically generated to show the mainlane and HOV lane travel times, as well as the incident superimposed on the graphic. The shaded area of the incident would indicate the duration of the incident and have text to describe the location and direction of the incident.

These results or outputs could be beneficial for traveler information to determine the benefit or travel time savings that can be gained by using the HOV system. System operators might use this information when trying to determine if an HOV lane should be opened to mainlane traffic due to a mainlane incident. The flow of data for these calculations is briefly explained below and in more detail in the first year report.

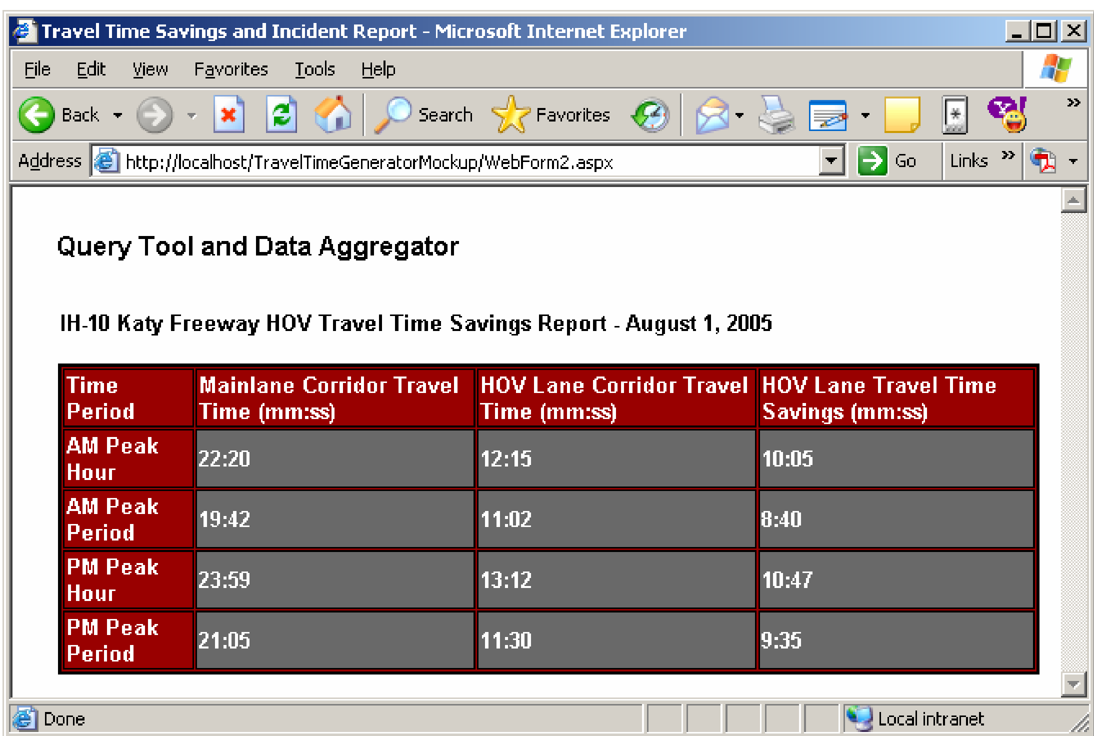


Query Tool and Data Aggregator

IH-10 Katy Freeway Incident Summary For HOV Corridor - August 1, 2005

Location	Description	Lanes Affected	Time Entered	Time Cleared	Duration
IH-10 Katy HOV Eastbound at Silber	Stall	HOV Lane	7:35 AM	8:01 AM	26 Min
IH-10 Katy Mainlanes Westbound at Antoine	Accident	1 Inside Lane	5:31 PM	5:57 PM	26 Min

Figure 32. Potential HOV Lane Travel Time Savings Report Format.



Query Tool and Data Aggregator

IH-10 Katy Freeway HOV Travel Time Savings Report - August 1, 2005

Time Period	Mainlane Corridor Travel Time (mm:ss)	HOV Lane Corridor Travel Time (mm:ss)	HOV Lane Travel Time Savings (mm:ss)
AM Peak Hour	22:20	12:15	10:05
AM Peak Period	19:42	11:02	8:40
PM Peak Hour	23:59	13:12	10:47
PM Peak Period	21:05	11:30	9:35

Figure 33. Potential Incident Summary Report Format.

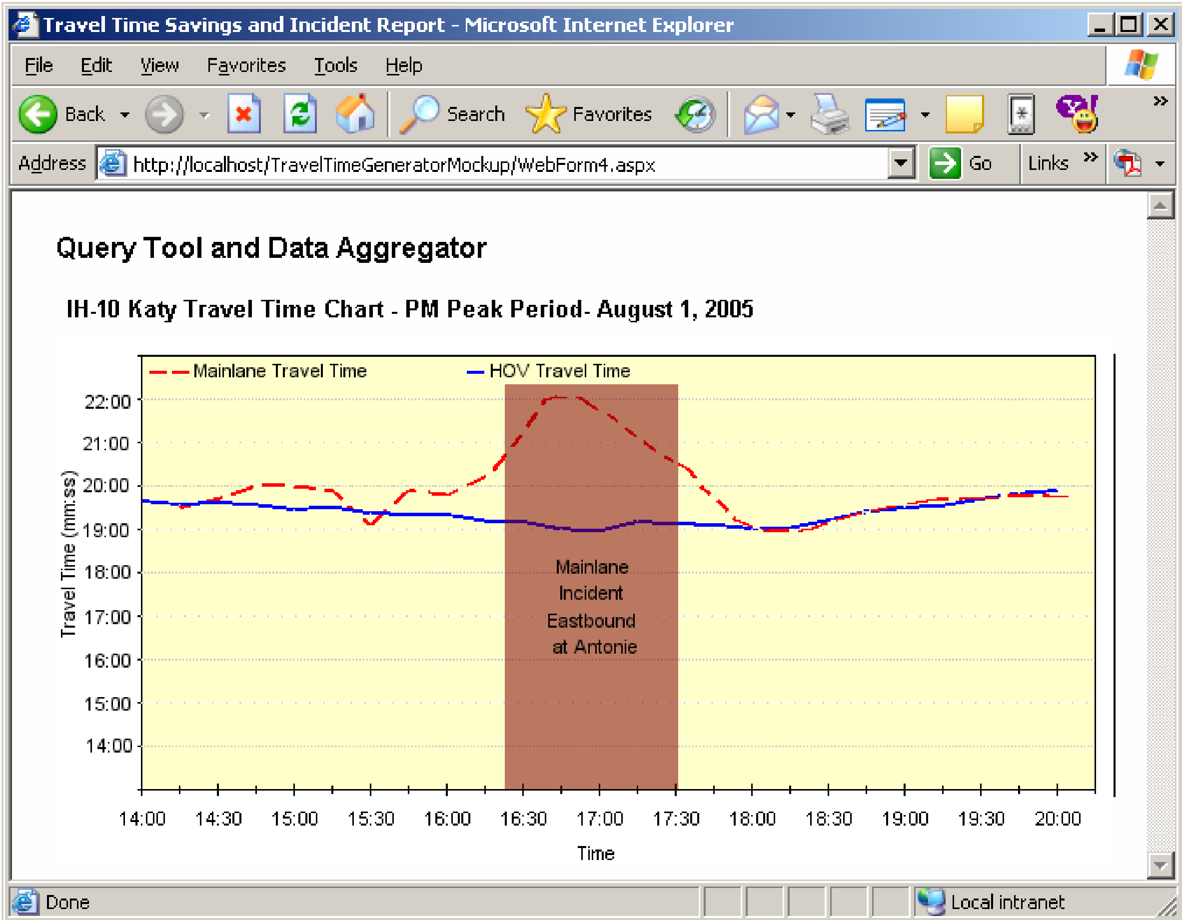


Figure 34. Potential Graph of Mainlane/HOV Lane Travel Times with Incident Duration.

Travel times for the mainlanes and HOV lanes will be generated utilizing data from the AVI system. The Travel Time Generator Software developed in the first year of this project could be used to develop the built-up travel times for both the mainlanes and HOV lanes. The difference between these two corridor measurements would be the building blocks of the output described above. Similar screening and data smoothing processes described in the first year report would still need to be employed to provide clean and complete data for the system performance. Once the mainlane and HOV lane travel times are calculated, the travel time difference, as well as other statistical and travel time reliability calculations, would be made. These measures might include average travel time, standard deviation, coefficient of variance, etc. In addition to tabular calculations, graphical representations could also aid users to better understand and utilize the information more efficiently. Figure 35 shows an example of what these more detailed comparisons might look like. Researchers envision that these processes will run periodically (daily, weekly, monthly, quarterly, and yearly) by facility and system wide but also allow the flexibility to generate user-defined queries. The periodic data are useful to continually monitor the system over time and to identify trends.

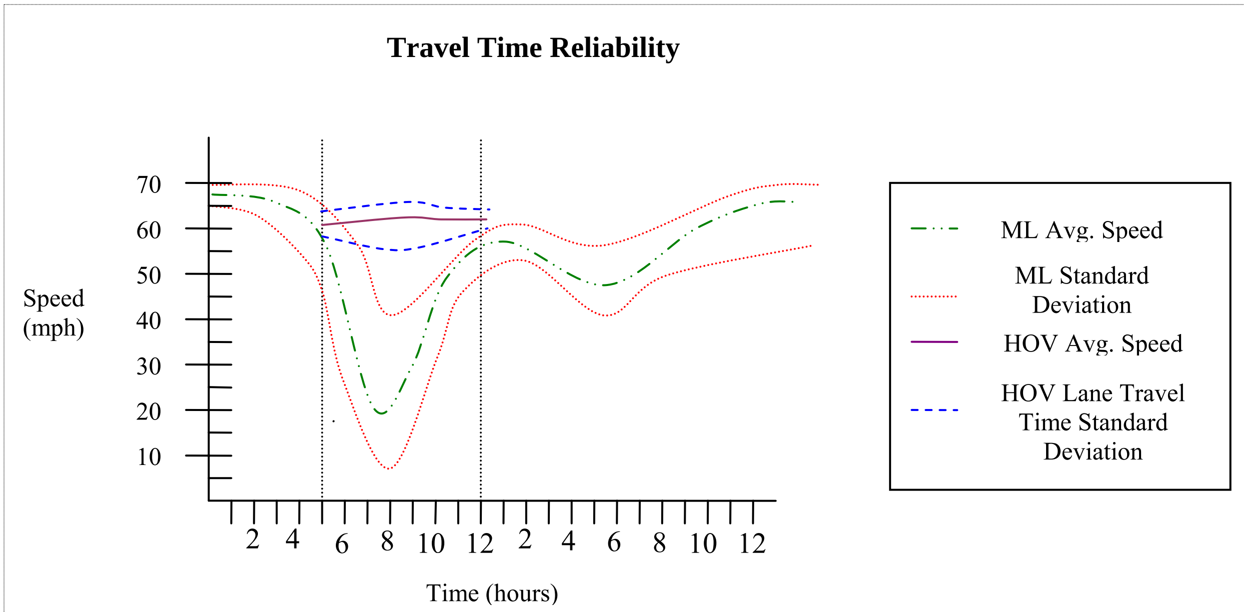


Figure 35. Sample of Mainlane and HOV Travel Time Reliability Graph.

FUTURE SYSTEM IMPROVEMENTS TO IMPROVE ESTIMATES OF HOV LANE DELAY SAVINGS

The interfaces and reports described thus far could be made readily available with minor modifications to the existing Travel Time Generator Software already developed in year one of this project. If it were desired to convert HOV delay savings from terms of minutes and seconds into dollars saved, a few additional modifications would need to be made.

First, the value of time needs to be added to the algorithm. The current value of time used by TxDOT is $13.56/hour. This cost is representative of January 2005 and is updated annually. This cost would need to be updated in the algorithm annually.

The quantification of HOV lane delay savings also uses HOV volumes as an input. At present, HOV volumes are only collected on a quarterly basis. The installation of sensors on the HOV lanes would provide daily volumes and, thus, much more accurate estimates of HOV lane delay savings in monetary terms.

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HOV LANE DIVERSION DECISION LOOK-UP TABLE

3. Number of general-purpose lanes blocked by incident		**1. Available capacity within the HOV lanes**							
		Less than 20 vehicles per lane per minute in HOV lane (80% volume / free-flow capacity)							**More than** 20 vehicles per lane per minute in HOV lane (80% volume / free-flow capacity)
		2. Level of traffic on the general-purpose lanes							
		Heavy			Moderate			Light	
		4. Est. time for incident clearance							
Blocked Lanes	**Total General-Purpose Lanes**	Less than 30 minutes	30 minutes – 1 hour	More than 1 hour	Less than 30 minutes	30 minutes – 1 hour	More than 1 hour		
1	2	✗	✓	✓	✗	✗	✓	✗	✗
1	3	✗	✗	✗	✗	✗	✗	✗	✗
1	4+	✗	✗	✗	✗	✗	✗	✗	✗
2	2	✗	✓	✓	✗	✗	✓	✗	✗
2	3	✗	✓	✓	✗	✗	✓	✗	✗
2	4+	✗	✓	✓	✗	✗	✓	✗	✗
3	3	✗	✓	✓	✗	✓	✓	✗	✗
3	4+	✗	✓	✓	✗	✗	✓	✗	✗

✓	Eligible for HOV opening	✗	Do not open HOV lane unless under extreme circumstances