FINAL REPORT

to

THE FLORIDA DEPARTMENT OF TRANSPORTATION
RESEARCH CENTER

on Project

"Lifting HOV/HOT Lane Eligibility and Shoulder Use
Restrictions for Traffic Incident Management"

FDOT Contract BDK77-977-23 (UF Project 00104311)

December 2013

Transportation Research Center
The University of Florida

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Lifting HOV/HOT Lane Eligibility and Shoulder Use Restrictions for Traffic Incident Management	December 2013
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Yafeng Yin, Lily Elefteriadou, Ziqi Song, Nima Shirmohammadi, Grady Carrick, Alexandra Kondyli	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Transportation Research Center University of Florida 512 Weil Hall, PO Box 116580 Gainesville, FL 32611-6580	
	11. Contract or Grant No.
	FDOT Contract BDK77-977-23

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399	Final, Nov 2012-Dec 2013
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report presents an investigation of the possibility of lifting HOV/HOT lane eligibility and shoulder use restrictions during major incidents on general-purpose (GP) lanes. Using traffic data from FDOT Districts 4 and 6, the impacts of incidents of GP lanes on the operation of HOV/HOT lanes were investigated. A methodology was developed to determine the appropriateness of diverting the GP traffic to HOV/HOT lanes under different incident scenarios. The methodology is theoretically sound and can be easily implemented in a spreadsheet tool requiring only a few critical inputs. The project also reviewed the regulations in Florida concerning the operations of HOV/HOT lanes and concluded that there was no legal obstacle or barrier that prevents opening HOV/HOT lanes to the GP traffic. Consequently, a two-stage decision-making procedure was proposed to implement a diversion plan. The procedure takes advantage of the existing partnership between FDOT and FHP on incident management and should allow quick decision making and ensure the integrity and credibility of the diversion policy. Lastly, the feasibility of shoulder use for incident management as well as simultaneous use of other freeway management techniques such as variable speed limits and ramp metering were investigated.

17. Key Word	18. Distribution Statement
	No restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	112	N/A

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to Messrs. Dong Chen and Paul Clark of the Florida Department of Transportation for the guidance and support that they provided on this project.

EXECUTIVE SUMMARY

High-occupancy-vehicle (HOV) lanes are preferential lanes designated for exclusive use for all or part of a day by vehicles with two or more occupants. They provide travel time savings and offer more reliable and predictable travel times. These incentives may encourage people to carpool or use the public transit system, thereby reducing congestion during peak hours and improving air quality. In Florida, HOV lanes are currently deployed on I-95 in Miami-Dade, Broward, and Palm Beach Counties. The lanes are buffer-separated and operate in both directions during the morning peak (7AM–9AM) and evening peak (4PM–6PM) hours. This HOV facility is the longest in the U.S. constituting a length of 58 miles in each direction (a total of 116 HOV lane miles). On the other hand, high occupancy/toll (HOT) lanes refer to HOV facilities that allow lower occupancy vehicles to pay a toll to gain access. HOT lanes enhance the utilization of HOV lanes by providing an option for motorists to "buy in" or to pay to avoid congestion. FDOT implemented HOT lanes, known as 95 Express, on I-95 in the Miami and Fort Lauderdale regional area. When completed, 95 Express will be 22 miles long, extending from I-95 interchange at SR-112 north to the Broward Boulevard Park and Ride lot.

Traffic incidents impose significant negative impacts on freeway operations, causing traffic delay, yielding higher fuel consumption and emissions, and creating safety concerns. It has been suggested that HOV/HOT lanes may be used to help manage traffic when a major incident or crash has occurred on a general-purpose (GP) lane. The primary objective of this report was to develop guidelines for FDOT to open HOV/HOT lanes to the GP traffic when major incidents occur on GP lanes. The feasibility of opening shoulder was also explored in conjunction with other freeway management techniques.

We first reviewed a broad range of literature on opening HOV/HOT lanes to all traffic in response to incidents on GP lanes. It was found that many federal and state transportation agencies recognize lifting HOV/HOT eligibility restrictions during major incidents as a viable incident management strategy. However, there was no consensus on when and under what conditions the restrictions should be lifted. Many state agencies treat HOV/HOT lanes as a last resort in their incident management plans and rely on the engineering judgment and experience of on-site responders to decide whether to open HOV/HOT lanes to the GP traffic. It appeared that only the Virginia Department of Transportation has clearly defined criteria in place, which are two-hour delay or 50 percent of GP lanes blocked. However, because the effectiveness of opening HOV/HOT lanes depends on many factors, e.g., available capacity of HOV/HOT lanes, traffic demand, incident duration and capacity loss, availability of other diversion routes, and specific lane configurations, a predefined set of criteria may hardly account for every incident situation.

We examined how incidents on GP lanes and the responses to the incidents affected the operations of HOV lanes in FDOT District 4 and HOT lanes in FDOT District 6. Incident delays on HOV and HOT lanes were estimated based on the travel time difference under incident and incident-free conditions for five selected incidents using a large amount of archived data along I-95. The results showed that the number of blocked lanes and the duration of lane blockage were not directly correlated to the magnitude of the impact of an incident on travel time. This led us to caution against the use of either the number of blocked lanes or the duration of the lane

blockage as the sole criterion to decide whether to open HOV/HOT lanes. Results also suggested that HOV lanes are more adversely affected by incident of GP lanes than HOT lanes, which may be explained by different lane separation configurations. It appeared that motorists on GP lanes voluntarily or at the direction of police officers utilize HOV lanes to bypass the incident locations. This implies that the benefit of opening HOV lanes may be relatively limited as compared to opening HOT lanes.

Built upon the above empirical analyses, we further developed a methodology to determine the appropriateness of diverting the GP traffic to HOV/HOT lanes under different incident scenarios. Employing the deterministic queuing analysis technique, we derived closed-form formulas for both vehicle and passenger incident delays. By comparing those delays under the status quo condition with those where HOV/HOT lanes are open to GP traffic after an incident, one can decide whether it is appropriate to open the lanes. The methodology was demonstrated on the aforementioned five selected incident scenarios. The methodology is theoretically sound, and can be easily implemented in any spreadsheet tool requiring only a few critical inputs. However, it remains a challenge for first responders in the field to utilize such a quantitative approach to make diversion decisions in a timely manner.

On the institutional aspect, we reviewed the legal and operational parameters of lifting HOV/HOT lane restrictions in response to incidents on GP lanes. It was found that Florida Statute 316.006(1) authorizes FDOT to manage state roadways; 316.0741 authorizes the agency to regulate HOV lanes by rule and 338.166 charges the agency with establishing variable tolling rates on HOT lanes. The legal authority and role of FDOT is fairly clear with respect to the operations of managed lane facilities. On the other hand, under 321.05, FHP is authorized to regulate, control and direct traffic on roadways. Therefore, both FDOT and FHP appear to have legal authority to lift the HOT/HOV restriction. Their joint application of traffic changes and their collaboration in traffic incident management are legally valid extensions of their respective missions to promote a safe driving environment.

To take advantage of the existing partnership between FDOT and FHP on incident management, we recommend a two-stage decision-making procedure to implement a diversion plan. At the first stage, FHP officers can use rules-of-thumb to make a quick but accountable decision on whether it is appropriate to lift HOV/HOT lane eligibility restrictions after major incidents on GP lanes. If lifting is deemed to be necessary, FHP officers will make a request to FDOT. Engineers at traffic management center can then apply the developed quantitative methodology to conduct a more thorough analysis and approve or disapprove the request accordingly. The procedure should allow quick decision making and is expected to ensure the integrity and credibility of the diversion policy.

Lastly, we explored the shoulder lane use for incident management. A review of existing deployments of the shoulder lane use in Europe and U.S. showed that its benefits during peak periods are considerable in terms of reducing travel times, increasing throughput and improving travel time reliability and safety. However, there are several maintenance and enforcement concerns that pertain to the shoulder lane use. Enforcement issues particularly related to the concurrent implementation of variable speed limits have been identified in the past. Automated enforcement efforts such as those reported in European installations would likely result in increased compliance and would enhance the performance of the strategy. A few minor liability issues have been identified in the literature. From a legal perspective, in Florida, the term

"roadway" may require clarifying language, since the shoulder is currently excluded from the definition of the term as defined in the Florida Statutes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

High-occupancy-vehicle (HOV) lanes are preferential lanes designated for exclusive use by vehicles with two or more occupants for all or part of a day (FHWA, 2008b). They have been advocated by Federal Highway Administration (FHWA) as a cost-effective and environmentally friendly option to help move more people in fewer vehicles along congested routes. The primary goal of HOV lanes is to increase the overall roadway efficiency by improving person-moving capacity and benefiting bus transit. HOV lanes provide travel time savings and also offer more reliable and predictable travel times. These incentives further encourage people to carpool or use public transit system. As a result, HOV lanes may reduce congestion during peak hours and improve air quality.

The deployment of HOV lanes in the U.S. has evolved over 30 years. Chang et al. (2008) identified 345 HOV facilities in operation or under construction across the nation. In Florida, HOV lanes are currently deployed on I-95 in Miami-Dade, Broward, and Palm Beach Counties. The lanes are buffer-separated and operate in both directions during the morning-peak (7AM–9AM) and evening-peak (4PM–6PM) hours. This HOV facility is the longest in the U.S. constituting a length of 58 miles in one direction (a total of 116 HOV lane miles). The facility is enforced by Florida Highway Patrol (FHP), and the shoulder lane next to the HOV lanes serves as the enforcement shoulder. FDOT is converting one portion of the facility into high-occupancy/toll (HOT) lanes. The HOT system will eventually be approximately 22 miles long, extending from I-95 interchange at SR-112 north to the Broward Boulevard Park and Ride lot.

High-occupancy/toll (HOT) lanes refer to HOV facilities that allow lower-occupancy vehicles to pay a toll to gain access. Since the first HOT lane was implemented in 1995 on State Route 91 in Orange County, California, the concept has been becoming popular among governors and transportation officials, in state legislatures and the media. Among other factors, the popularity and wide acceptance of the HOT lane concept are due to the additional option it makes available to motorists and the low utilization of HOV lanes. More specifically, HOT lanes provide motorists an option to "buy in" or to pay to avoid congestion. On the other hand, many have expressed concern about the wasted capacity resulting from a low utilization of many HOV lanes. Thus, converting underutilized HOV lanes to HOT lanes likely creates a win-win situation for both HOT and general-purpose (GP) lane users. FDOT implemented HOT lanes, known as 95 Express, on I-95 in the Miami and Fort Lauderdale regional area. When completed, 95 Express will be approximately 22 miles long, extending from I-95 interchange at SR-112 north to the Broward Boulevard Park and Ride lot. It is being constructed in two phases. Phase 1 extends from SR-112/I-195 to the Golden Glades Interchange. The northbound opened to traffic on July 11, 2008, and tolling began on December 5, 2008. The southbound opened to traffic in late 2009, and tolling began on January 15, 2010. Phase 2, currently under construction, will expand the HOT lanes from the Golden Glades to Broward Boulevard in Broward County.

This report examines the possibility of lifting HOV/HOT eligibility restrictions during certain incidents on general-purpose (GP) lanes. Although FDOT and FHWA have provided guidelines, i.e., FDOT (2006) and FHWA (2010), that discuss a wide range of issues involved in traffic incident management, they do not address this specific incident management element associated with HOV/HOT facilities. It has been suggested that HOV/HOT lanes may be used to help manage traffic when a major incident or crash has occurred on the GP lanes (AASHTO, 2004). Various DOTs throughout the nation have incident management plans that allow for the

1

diversion of GP traffic into HOV HOV/HOT lanes in response to an incident in the GP lanes. However, specific criteria to trigger the diversion plans are not always included. In Florida, there is no established guideline and procedure on opening HOV/HOT lanes to the GP traffic during traffic incidents.

Meanwhile, in several European countries (most notably Netherlands and Germany), agencies allow the use of shoulder by general traffic during congested periods to alleviate congestion. These installations are usually coupled with lower speed limits upstream of the shoulder opening through the use of variable speed limit (VSL) systems (for safety purposes). In the US, these systems have not been implemented, primarily due to concerns with incident response and removal if the shoulder is used by the general traffic. This report will also review previous studies of shoulder use and investigate the feasibility of opening the shoulder to the general traffic considering enforcement issues, as well as simultaneous use of other freeway management techniques.

The remainder of the report is organized as follows:

Chapter 2 reviews the current practices of diverting the GP traffic into managed lanes in response to incidents on GP lanes in four states with the highest HOV mileage around the nation, including California, Washington, Texas, and Virginia. It also reviews the use of HOT lanes for incident management.

Chapter 3 analyzes the traffic data from HOV lanes in FDOT District 4 and HOT lanes in Florida District 6 during incident and non-incident situations. The data are retrieved from STEWARD (Statewide Transportation Engineering Warehouse for Archived Regional Data) hosted by the University of Florida. The intent of the data analysis is to examine how incidents on GP lanes and the responses to the incidents affect the operations of HOV/HOT lanes.

Chapter 4 adopts the deterministic queuing analysis technique to estimate the incident-induced delay and derive closed-form delay formulas with a few input parameters. The incident-induced vehicle and passenger delays can be easily calculated using the formulas. By comparing those delays under the status quo condition with those where HOV/HOT lanes are open to GP traffic after an incident, one can decide whether it is appropriate to open the lanes.

Chapter 5 reviews the legal and operational parameters of lifting HOV/HOT lane restrictions in response to incidents on GP lanes. This chapter also looks into the issues on how FHP will conduct enforcement downstream after the restriction of a HOV/HOT lane is lifted at an incident location, how to inform troopers (using their mobile computers) about changes to the lane restrictions, and documentation of when and where modifications are made to deflect court challenges of tickets.

Chapter 6 develops guidelines to implement a diversion plan. A two-stage decision-making procedure is proposed. The first-stage decision on the diversion is made by FHP officers on the scene based on qualitative decision criteria. If diversion is deemed to be necessary, FHP officers will make a request to FDOT of opening HOV/HOT lanes to the GP traffic. FDOT engineers at a traffic management center (TMC) may then perform a more in-depth quantitative analysis using inputs provided by FHP officers or their own data to make a second-stage decision.

Lastly, Chapter 7 reviews previous studies of shoulder use and investigates the feasibility of opening the shoulder to the general traffic as well as simultaneous use of other freeway management techniques, such as variable speed limit (for safety purposes) and ramp metering.

2 REVIEW OF PRACTICES OF OPENING HOV/HOT LANES FOR TRAFFIC INCIDENT MANAGEMENT

2.1 Introduction

FHWA defined an incident as "any non-recurring event that causes a reduction of roadway capacity or an abnormal increase in demand. Such events include traffic crashes, disabled vehicles, spilled cargo, highway maintenance and reconstruction projects, and special non-emergency events" (FHWA, 2000). For each minute a freeway lane is blocked due to an incident, it approximately takes four minutes for the traffic conditions to return to normal (FHWA, 2010). It is estimated that 25 percent of road congestion can be attributed to traffic incidents (FHWA, 2005). Traffic incidents not only yield tremendous congestion, but also impose adverse safety impacts. Secondary crashes due to congestion caused by a previous crash are estimated to represent 20 percent of all crashes (USDOT, 2007). They are also responsible for 18 percent of all fatalities on freeways. Moreover, between 1997 and 2006, 17 percent of the accidental law enforcement deaths were the result of "struck-by" motor vehicle incidents occurring during activities such as traffic stops, directing traffic and assisting motorists (FHWA, 2010). Therefore, traffic incident management (TIM), defined as a planned and coordinated program to detect and remove incidents and restore traffic capacity as safely and quickly as possible (Carson, 2010), offers tangible benefits to both motorists and transportation agencies.

The primary objective of this chapter is to provide a comprehensive review of practices of diverting the GP traffic into HOV lanes in response to incidents on GP lanes. It also touches on the use of HOT lanes for incident management because FDOT plans to construct a HOT lane network in south Florida. The remainder of the chapter 2 is organized as follows. Section 2.2 provides an overview of HOV lane incident management; Section 2.3 reviews federally funded research on lifting HOV restrictions for incident management; Section 2.4 is an in-depth review of current practices of four state transportation agencies on opening HOV lanes to GP traffic; Section 2.5 introduces two simulation-based studies that evaluate the effectiveness of the diversion strategy; Section 2.6 discusses HOT lane incident management and finally Section 2.7 provides summary and recommendations and then concludes this chapter.

2.2 Overview of HOV Lane Incident Management

Hoppers (1999) conducted a survey of six transportation agencies to understand their practices of diverting GP traffic to HOV lanes during major incidents and severe weather conditions. The survey found that none of the agencies interviewed except Virginia has specific guidelines for incident management responders to follow in determining whether the restrictions on HOV lanes should be lifted during severe situations. Four factors, including the severity of the incident, time of day, impact on the mainline traffic and availability of alternative routes, have been identified to be crucial for the development of general guidelines for diverting GP traffic to HOV lanes.

Daganzo et al. (2002) proposed a dynamic HOV lane designation strategy to reduce freeway congestion. The strategy is not designed specifically for incident management, but it shares the same idea of opening HOV lanes to GP traffic when GP lanes are congested. The primary goal of the dynamic HOV lane strategy is to recover the lost capacity caused by freeway bottlenecks without penalizing HOVs. The HOV lane designation, conveyed to users via variable message signs (VMSs), is dynamically activated depending on the queue present in the HOV lane

upstream of the dynamic section. During off-periods all vehicles could use the section while during on-periods only HOVs are allowed. The HOV designation of the dynamic section is turned off to increase the capacity of the bottleneck segment until a queue of HOVs is detected upstream. The scheme, however, may not be practical due to compliance, enforcement and human-factors issues.

To identify incident management strategies that are particularly applicable to managed lane facilities, e.g., HOV, HOT, and exclusive-use lanes, Ballard (2004) conducted an incident management survey with 82 respondents throughout the nation, who are experienced with multiple types of managed lane facilities. Two specific triggers for the diversion of GP traffic into managed lanes were explored: incident duration and the number of blocked lanes. For incident duration, seven respondents (four HOV and three HOT facility operators) reported that the minimum expected duration of an incident before a diversion plan would be implemented varies from 10 to 55 minutes. Among those who indicated a minimum number of blocked lanes required to deploy a diversion plan, the most common response is two out of three GP lanes must be blocked. As for the duration of diversion, nine of 11 managed lane facility operators indicated that they discontinue diversion plans when the incident is cleared and/or the queue from the incident dissipates. Only two (one HOV and one HOT facility operator) replied that they also discontinue the diversion when operations of the managed lanes deteriorate.

Fenno et al. (2006) carried out telephone-based interviews with incident management specialists for HOV systems in Texas and other states. Their interviews updated and confirmed the data originally obtained by Hoppers (1999). Four attributes that may impact the potential benefits of diverting GP traffic to HOV lanes were determined: HOV lane demand, GP lane demand, incident severity, and lane blockage. A total of 16 traffic and incident scenarios were identified, among which four scenarios that can lead to positive benefits were highlighted. All four scenarios share a common feature: a low level of HOV volume. Three of the four scenarios also involve high incident severity. A diversion decision in low incident severity should only occur when the GP lane blockage is likely to be high. The report also provides qualitative-based guidance to in-field agents for determining which scenario applies to their incident situations.

2.3   Federally Funded Research

The National Cooperative Highway Research Program's (NCHRP) *Report 414: HOV Systems Manual* (TRB, 1998) notes that HOV facilities can be used to assist with managing incidents and accidents on GP lanes or responding to other special circumstances. The use of an HOV lane to help with incident management depends on the type of the facility, access points, and other factors, and should only be considered in response to extreme problems and specific situations in order to maintain the integrity of the HOV facility. In addition, it is important to design an incident management plan that clearly identifies when and under what conditions the HOV facility may be used to help manage traffic, the specific procedures to follow, and the responsibilities of various agencies.

NCHRP Synthesis of *Highway Practice 279: Roadway Incident Diversion Practices* (Dunn et al. 1999) presents a detailed summary of incident diversion practices based on a survey of transportation agencies that have developed and deployed diversion plans. Although the report is not specifically developed in the context of HOV facilities, it does point out that a limited number of agencies maintain alternate route plans that divert traffic from a freeway to a HOV

facility and/or a toll road, and allow for the elimination of HOV restrictions and tolls, respectively.

*Guide for High-*Occupancy *Vehicle (HOV) Facilities* (AASHTO, 2004) suggests that HOV facilities can play a role in incident management on freeways or in corridors. For instance, HOV lanes may be used to help manage traffic when a major incident or crash has occurred on GP lanes. Incidents may include major crashes on the freeway, snowstorms and flooding.

The *Managed* Lanes *Handbook* published by Texas Transportation Institute (TTI) in cooperation with Texas Department of Transportation (TxDOT) and FHWA explores complex and interrelated issues associated with the safe and efficient operation of managed lanes, e.g., HOV, HOT, and exclusive-use lanes (TTI, 2005). The handbook lists four motivating conditions for the interim use of managed lanes, namely, construction and maintenance, special events, major incidents, and emergencies and evacuation. In major incidents, the primary reason of interim use of managed lanes is to reduce congestion in GP lanes, with secondary benefit from improved safety for on-site responders and improved access to the incident scene. The handbook acknowledges that it is challenging to define appropriate incident conditions under which interim managed lanes use is applicable, and these interim use criteria must be tailored to each facility. In general, three aspects should be considered: severity and nature of the incident conditions; time of day, anticipated duration, and anticipated traffic impacts; and availability of alternative facilities or strategies.

A recent FHWA report (Carson, 2010) reviews and assesses various TIM policies, procedures and technologies to identify current best practices in the United States. The report describes task-specific and cross-cutting issues or challenges commonly encountered by TIM responders during the performance of their duties, and effective strategies for overcoming these issues and challenges. One of the task-specific strategies recommended is reserved/special-use lane temporary use policy. During a major incident, it may be useful to suspend reserved or special-use lanes (e.g., HOV, HOT, and toll lanes) restrictions. The additional capacity in the reserved/special-use lane can partly replace the mainline capacity lost because of the incident. The report specifically mentions that it is imperative to have a set of criteria, which define when reserved/special-use lanes should be opened for interim use, to provide consistency. Criteria for interim use of reserved/special-use lanes generally consider the duration it takes to clear an incident and the percentage of reduced capacity caused by the incident.

FHWA published an updated version of the managed lane chapter of *Freeway Management and Operations Handbook* (FHWA, 2011). Although the handbook does not provide detailed procedures for HOV lane incident management, it notes that "mainline incidents can be more effectively addressed by allowing the general traffic to use the managed lane where barriers between the parallel roadways are not present".

2.4 Agency Practices

According to a FHWA report (Chang et al, 2008), there are 345 HOV facilities in operations or under construction across the nation. To be more representative, we decided to review the practices of the top five states that have the largest number of HOV facilities in the United States. Chang et al. (2008) indicated that Minnesota has 83 HOV lane facilities, the second largest inventory of HOV facilities. However, over 75 of them are bus-only shoulder lanes, which are

not a typical type of HOV lanes. Therefore, Minnesota is excluded from our review and only the practices of four states are reviewed in this section.

California

The State of California has a total of 88 HOV facilities and is the state with the largest inventory of HOV facilities (Chang et al., 2008). As of 2012, there are over 1,500 miles of HOV lanes in operations or under construction, and over 700 additional miles are programmed or proposed in the state (Caltrans, 2012).

The California Department of Transportation (Caltrans) summarizes its incident handling procedures on HOV facilities in *High-Occupancy Vehicle Guidelines for Planning, Design and Operations* (Caltrans, 2003). For a major incident in GP lanes, the guideline notes that non-eligible vehicles may use the HOV lane without penalty. The decision on whether to open the HOV facility to GP traffic should be made jointly by Caltrans and California Highway Patrol (CHP). The guideline also highlights that barrier-separated HOV facilities generally should not be used for incident management due to restrictive access points. Diversion of GP traffic to barrier-separated HOV lanes may only be warranted when a major incident blocks multiple GP lanes and takes an extended duration to clear, and it should be particularly cautious for reversible operations.

Washington

The Washington Department of Transportation (WSDOT) is responsible for operating more than 300 lane-miles of HOV facilities in the central Puget Sound region. WSDOT has established a set of performance standards to ensure that the HOV system provides reliable travel time and dependability for carpoolers, vanpoolers and transit users. The current performance standard states that a driver in an HOV lane should be able to maintain an average speed of 45 mph or greater at least 90 percent of the time during the morning and afternoon rush hours. The HOV system enjoys a high level of popularity with the majority of freeway users, and has one of the lowest HOV lane violation rates in the nation (Washington State Transportation Center, 2007). As a result, several HOV facilities in the region are so heavily utilized that they are usually congested during the peak periods and no longer meet the established performance standard.

During an incident, the Washington State Patrol (WSP) commanding officer at the scene and WSDOT in Central Traffic Management work together to decide whether or not to open up HOV lanes to all traffic (WDOT, 2012). The decision is based on many factors, such as the severity of the incident, time of day and the availability of diversion routes other than the HOV lane. If that decision is made, a network of VMSs and portable signs, along with police officers will direct vehicles into the lane. WSDOT normally does not open HOV lanes to single-occupancy vehicles during the peak periods because they want to maintain the credibility of the HOV system to frequent users (Hoppers, 1999).

Texas

Almost all HOV facilities in Texas are concentrated in two metropolitan areas, namely, Dallas and Houston. There are over 30 HOV facilities in operations or under construction and three more facilities are in the planning stages in these two areas (Chang et al., 2008).

The HOV system in Dallas is operated by Dallas Area Rapid Transit (DART). DART allows the diversion of GP traffic to HOV lanes under severe congestion conditions, and does not have specific criteria for the emergency responders to follow to determine whether HOV restrictions should be lifted. That being said, DART strives to maintain the credibility of the HOV lane and only use it for incident management when other measures fail, such as diverting traffic to shoulders or exit ramps. VMSs, cones, flags and media announcements are used to provide drivers the proper instructions to divert to HOV lanes. For concurrent HOV facilities, drivers are expected to merge back to GP lanes once passing the incident scene and occupancy restrictions are enforced again at a reasonable distance from the incident scene (Hoppers, 1999). It is noted that contraflow facilities generally cannot be reversed to divert non-peak direction traffic since there is no emergency access gate for traffic in the non-peak direction and it requires barrier transfer machines to allow non-peak direction traffic into HOV lanes (Blume, 1998).

Houston coordinates its transportation and incident management services through TranStar Traffic Management Center, jointly operated by four government agencies, i.e., TxDOT, Metropolitan Transit Authority of Harris County (METRO), Harris County and the City of Houston. The HOV facilities have been open to the GP traffic in response to heavy rain storms and flooding, as well as major accidents that blocked the freeway GP lanes (TRB, 1998). There are no specific guidelines in place determining whether diversion to HOV lanes is warranted. METRO police personnel can decide to open HOV lanes to the GP traffic if a major incident causes extreme congestion and there is no available alternative route to divert traffic (Hoppers, 1999). For particularly severe incidents in the non-peak direction, contra-flow HOV facilities may be closed and revered to serve non-peak direction traffic (Blume, 1998).

Virginia

The State of Virginia has a set of criteria that clearly define when HOV occupancy restrictions are qualified to be lifted. The Code of Virginia (33.1-46.2) states that "this (HOV) program shall include the temporary lifting of HOV restrictions and the opening of HOV lanes to all traffic when an incident resulting from nonrecurring causes within the general lanes occurs such that a lane of traffic is blocked or is expected to be blocked for 10 minutes or longer. The HOV restrictions for the facility will be reinstated when the general lane is no longer blocked and is available for use." The Virginia Department of Transportation (VDOT) and the state and local police are responsible for traffic incident management on HOV facilities. VDOT makes the decisions to lift HOV restrictions in conjunction with, or at the request of the Virginia State Police Department. Such a request is made by the police only when an accident is deemed to be a major one that takes an extended period of time to clear (VDOT, 2012).

Diverting GP traffic to HOV lanes in response to incidents has been a successful and popular strategy to the general public and local media (Hoppers, 1999). However, VDOT is reluctant to lift HOV restrictions too often because of the concern that lifting the restrictions may discourage

carpooling. Therefore, in practice, the criteria used by VDOT to determine whether HOV restrictions should be lifted are more rigorous than what are defined in the Code of Virginia. It is reported by Hoppers (1999) that if the operation of clearing a major incident lasts longer than two hours or if an incident blocks 50 percent of the mainline in the peak direction then the resections on HOV lanes will be lifted. VDOT informs drivers the information on any changes in the HOV lane restrictions through VMSs.

2.5   Simulation-Based Studies

Although opening HOV lanes to all traffic has been identified as a viable incident management strategy by various stakeholders, only a couple of studies have been conducted in the literature to evaluate the effectiveness of this strategy in alleviating congestion. The difficulty is the lack of field data and the non-recurring nature of traffic incidents. Microscopic traffic simulation models have been playing an important role in evaluation alternative traffic operation schemes, particularly in situations when field data are not readily available.

Liu and Murray-Tuite (2008) used VISSIM (PTV, 2005), a microscopic simulation tool, to evaluate four strategies to mitigate incident-related congestion, i.e., opening HOV lanes to all traffic, smoothing traffic flow by variable speed limits (VSL), diverting traffic by en route rerouting, and diverting traffic via VMSs, The test bed is a medium sized network located in northern Virginia, consisting of 3098 links or connectors and 315 nodes. The study tested four incident scenarios representing different levels of severity of an incident. Opening HOV lanes to all traffic is consistently rated the most effective strategy to mitigate incident-incurred congestion based on four measures of effectiveness defined in the study among all proposed strategies.

Chou and Miller-Hooks (2011) employed a similar simulated-based approach to investigate the potential for mobility improvement in GP lanes as a consequence of diverting traffic around an incident using existing managed lanes. The study simulated the traffic operation in morning peak hours of a stretch of I-270 of seven and a half miles in Maryland, including a continuous-access HOV lane. The impact of diverting traffic into HOV lanes was accessed by systematically designed experiments with 135 combinations of incident scenarios and diversion implementations. Simulation results showed that the benefits to the GP traffic due to the implementation of opening HOV lanes are governed by a number of factors, such as incident duration, number of lanes blocked, and the relative location of the incident scene to diversion access points for non-continuous access facilities. Although the performance of the managed lanes is degraded, the benefits of the diversion to the GP users appear to outweigh additional delay incurred by managed lane users in nearly all incident scenarios, including those in which only one lane is blocked.

2.6   The Use of HOT Lanes for Incident Management

A Guide for HOT Lane Development published by FHWA (Perez and Sciara, 2003) specifies two major reasons for the effective incident management of HOT lanes. First, it is essential to maintain premium travel service conditions on HOT lane facilities, which requires quick response and rapid clearance when incidents occur. Secondly, given that HOT lanes are likely to be separated by physical barriers, vehicles may not be able to navigate around disabled vehicles, introducing the risk that all traffic traveling on the facility comes to a standstill. The guide does not discuss the possibility of opening HOT lanes to the GP traffic when a major incident occurred at the GP lanes.

Managed Lane Handbook (TTI, 2005) suggests two common strategies that may be employed for interim use of managed lanes: suspension of restrictions and suspension of tolls. One direct impact resulting from interim use of HOT lane facilities is toll revenue loss, the amount of which depends on the toll rates and utilization of the HOT lane facility, and the duration of interim use. The handbook also cautions that temporary toll suspension sets a precedent for similar actions in the future, and may result in pressure to suspend tolls from motorists in conditions that do not warrant such an action.

For HOT lane facilities, lower occupancy vehicles are allowed to use HOT lanes by paying a toll. Therefore, the relevant strategy for the use of HOT lanes for incident management is essentially suspension of tolls during major incidents. Legislators in Virginia acknowledge that "in order to alleviate an actual or potential threat or risk to the public's safety, the Department (VDOT) shall facilitate the flow of traffic on or within the vicinity of the toll facility by permitting the temporary suspension of toll collection operations on its facilities." The Code of Virginia (33.1-252) states that "major incidents that may require the temporary suspension of toll collection operations shall include, but not necessarily be limited to (i) natural disasters such as hurricanes, tornadoes, fires, and floods; (ii) accidental releases of hazardous materials such as chemical spills; (iii) major traffic accidents such as multivehicle collisions; and (iv) other incidents deemed to present a risk to public safety. The decision temporarily to suspend toll collection operations shall be made by the (VDOT) Commissioner or his designee." The Florida Turnpike Enterprise usually lifts tolls on its facilities in conjunction with evacuation orders in anticipation of a storm's landfall. The enterprise notes that "such suspensions are not ordered as a courtesy, but rather as a matter of public safety and as a means to facilitate a smooth flow of traffic during larger than normal traffic volumes (Florida Turnpike Enterprise, 2012)." The newly constructed I-85 HOT facility in Georgia has a toll suspension operation procedure specifically for traffic incidents in GP lanes. When toll rate signs display "OPEN TO ALL", HOT lanes are open to all vehicles with less than six axles at no charge, including those without a Peach Pass. This procedure aims at safely diverting traffic around a blockage in GP lanes (Georgia State Road and Tollway Authority, 2012).

To our best knowledge, no specific criteria for suspending tolls on HOT lanes have been documented in the literature. However, the diversion criteria for opening HOV lanes may be also applicable to HOT lane facilities. Technically, it is easy to open a HOT lane to all traffic, given the existing ITS infrastructure for HOT lane operations. However, for a physically separated HOT lane, if there are limited ingress/egress points, opening the lane to all traffic may have more adverse impact on its performance.

2.7 Summary and Recommendations

We have reviewed a broad range of literature on opening HOV lanes to all traffic in response to incidents in GP lanes. It was found that many federal and state transportation agencies recognize lifting HOV restrictions during major incidents as a viable incident management strategy. However, there is no consensus on when and what conditions the restrictions should be lifted. Many state agencies treat HOV lanes as a last resort in their incident management plans and rely on the engineering judgment and experience of on-site responders to decide whether to open HOV lanes to the GP traffic. The practices of selected state transportation agencies are summarized in TABLE 2.1.

It can be observed from TABLE 2.1 Summary of Practices of HOV Restrictions Liftingthat only one state agency, i.e., VDOT, has clearly-defined criteria in place, even though various studies recommended that it is critical to have a set of criteria for responders to follow. The challenge for designing such criteria is evident. It is difficult to specify incident conditions where interim use of HOV lanes is appropriate. If the criteria are set too low, HOV lanes will be often used for incident management, which will undermine their credibility and integrity. On the other hand, if the criteria are too high, the potential benefits of lifting HOV lane restrictions may not be fully explored. The effectiveness of opening HOV lanes depends on many factors, e.g., HOV lane capacity, HOV demand, GP lane capacity, GP demand, incident duration and capacity loss, availability of other diversion routes, and specific lane configurations. A pre-defined set of criteria can hardly account for every incident situation.

TABLE 2.1 Summary of Practices of HOV Restrictions Lifting

City/State	HOV Lane Incident Management Agency	Criteria for HOV Restrictions Lifting	Interagency Cooperation
California	Caltrans	No specific criteria; barrier-separated HOV facilities generally not used	CHP
Washington	WSDOT	No specific criteria; normally during off-peak periods	WSP
Dallas, Texas	DART	No specific criteria; only use when other measures fail, such as diverting traffic to shoulders or exit ramps	N/A
Houston, Texas	TransStar	No specific criteria	TxDOT, METRO, Harris County, the city of Houston
Virginia	VDOT	Two-hour delay or 50 percent of GP lanes blocked	Virginia Sate Police Department

On the other hand, clear guidance is necessary to ensure quick response and consistency in the use of HOV lanes for incident management. To this aim, our recommendations are as follows:

- Instead of defining a set of criteria, it may be feasible to develop a step-by-step procedure or guideline for emergency responders to determine whether lifting HOV restrictions is warranted or not;

- The procedure needs to be generic and flexible enough to accommodate most incident scenarios, and specific thresholds in the procedure should be tailored to each individual facility before the implementation;

- The procedure needs to consider a variety of factors in deciding the diversion of GP traffic into HOV lanes, including availability of other diversion alternatives or routes, HOV lane capacity, HOV demand, GP lane capacity, GP demand, incident duration and capacity loss.

On the suspension of tolls of HOT lanes for incident management, we recommend that such a practice should only be used in extreme situations that are deemed to present a risk to public safety for the following reasons:

- The operation may significantly undermine the value of HOT lanes. One of the reasons why we implement HOT lanes in the first place is to provide motorists including those in lower-occupancy vehicles a reliable and faster option in congested corridors. If HOT lanes are frequently opened to all traffic during incidents, the option is lost when it is needed the most;

- Many HOT lanes are physically separated and there are limited ingress/egress points. Consequently, opening HOT lanes to all traffic may have more adverse impact on motorists using the lanes. The benefit of opening a HOT lane to all traffic during incidents may not be as good as opening a continuous-access HOV lane.

- Some HOT lanes also have a revenue-generating function. Suspending tolls on those facilities too often will compromise such a function.

3 ANALYSIS OF TRAFFIC CONDITIONS OF HOV/HOT LANES IN INCIDENT AND NON-INCIDENT SITUATION

3.1 Introduction

The objective of this chapter is to examine how incidents on GP lanes and the responses to the incidents affect the operations of HOV/HOT lanes. More specifically, we estimate incident delay using traffic data of HOV lanes in FDOT District 4 and HOT lanes in FDOT District 6 during incident and non-incident situations.

Traffic incidents impose significant negative impacts on freeway operations, causing traffic delay, yielding higher fuel consumption and emissions, and creating safety concerns. In the literature, numerous studies have been conducted to investigate those negative impacts, particularly quantifying incident-induced delay, see, e.g., Morales (1987), Skabardonis et al., (1996). However, to the best of our knowledge, none of them has examined quantitatively the impacts of incidents on GP lanes on HOV/HOT lane operations.

The methods used in the literature to estimate incident delay can be broadly classified into three categories, namely deterministic queuing, shock wave analysis and travel time difference approach. Deterministic queuing analysis is the most widely-used, which relies on a queuing diagram consisting of accumulative vehicle arrival and departure curves at an incident location. The area between these two curves represents the delay caused by the incident. The queuing diagram was originally discussed in the context of freeway operations by Moskowitz and Newman (1963). Morales (1987) developed a spreadsheet analytical tool based on the queuing theory to quantify incident delay. Fu (2004) employed the fuzzy set theory to consider the uncertainties involved in the existing queue condition, future traffic arrival and departure patterns. Li et al. (2006) also addressed the stochastic properties of incident duration and capacity reduction within the queuing analysis framework. Despite its popularity, there are a few obstacles for conducting queuing analysis using empirical field data. One major assumption of the approach is that arrivals and departures occur at the same location, i.e., vehicles have no physical length. In reality, especially when major incidents happen, the physical queue length can be substantial. Since the arrival and departure curves should be observed at different detector stations miles apart and there are likely on and off-ramps in between, it is difficult to determine accurately the number of arrivals. The analysis also heavily relies on an accurate estimation of capacity reduction during incidents. Even though empirical data are available for various freeway facilities (e.g., Goolsby, 1971), the remaining capacity changes dynamically throughout the duration of an incident and hence is hard to quantify in practice. Furthermore, the delay estimation is affected by the changes in traffic demand due to the possibility of diversion (Skabardonis et al., 1996).

Another approach to estimate incident delay is shock wave analysis. Lighthill and Whitham (1955) and Richards (1956) proposed that traffic flow can be characterized using flow, density and speed through an analogy with fluid dynamics and demonstrated the existence of traffic shock waves. Al-Deek et al. (1995) described an application of shock wave analysis to estimate freeway incident delay using extensive loop and incident data. Chin (1996) compared the queuing analysis and linear shock wave analysis procedure and concluded that these two approaches produce comparable results. Rakha and Zhang (2005) demonstrated the consistency in delay estimates between queuing theory and shock wave analysis. In fact, theoretically these

two approaches should produce the same results, as pointed out by Lovell and Windover (1999). Although shock wave analysis can provide well-defined theoretical delay estimation, the implementation suffers similar limitations as the above queuing analysis. The intensive data requirements may not be satisfied by the current traffic data collection infrastructure (Wang et al. 2011).

The incident delay is essentially the travel time difference for vehicles to traverse an incident-impacted segment under incident and incident-free conditions. Therefore, estimating incident delay is indeed a travel time estimation problem. Skabardonis et al. (1996) applied the idea to estimate incident delay using data from loop detectors that are continually recorded at close spacing. Quiroga (2000) and Kraus et al. (2006) also proposed similar approaches to measure incident delay. One caveat of this approach is that the calculation of travel time requires speed data, which may not be readily available at freeway facilities using single-loop detectors. This, however, is not an issue for our study sites since all freeway segments investigated are equipped with microwave radar detectors that can provide relatively accurate speed data regardless of weather conditions. We thus adopt the travel time difference approach to estimate incident delays for our case studies.

The remainder of the chapter is organized as follows. Section 3.2 provides an overview of the incident data set. Section 3.3 elaborates the methodology adopted in this study to estimate incident delay and perform detailed analysis on five representative incident cases. Section 3.4 summarizes the findings from the data analyses and concludes Chapter 3.

3.2 Overview of Incident Data

The incident data set is comprised of 7,364 incident records, which were logged between 5/1/2011 and 3/31/2012. Each incident record is provided with several descriptive entries, including event ID, detection date and time, number of blocked lanes and position in the cross section of roadway, minutes to reopen the blocked lanes, and the reported latitude and longitude coordinate of the incident.

Among all the 7,364 incidents, 1,863 occurred on the HOV segments of I-95 in Districts 4 and 6, and 4221 incidents were located on the GP lanes along the segment of 95 Express, a HOT lane facility in District 6. We further conducted the following data processing for HOV and HOT segments:

HOV segment

The first step of data processing for HOV segments was to remove incidents that have not blocked any lane. This reduces the data set to 328 records. Since we attempted to evaluate the impacts of incidents on HOV lane operations, we only focused on those that occurred during the operating hours of HOV lanes, i.e., 7 to 9 AM and 4 to 6 PM on weekdays, which further reduces the data set to 66 incidents. Among those 66 incidents, 46 of them occurred on HOV lanes. We excluded those incidents as the focus of this chapter is to examine the incidents on GP lanes. The final data set consists of 20 incident records. The frequencies of incidents with respect to the number of blocked lanes, after each step of data processing, are presented in TABLE 3.1.

TABLE 3.1 Frequency of Incidents on HOV Segments

Number of blocked lane	After removing incidents with no blocked lane		After removing incidents out of operating hours		After removing incidents on HOV lanes	
	Frequency	Percentage (%)	Frequency	Percentage (%)	Frequency	Percentage (%)
1	148	45.1	33	50	12	60
2	103	31.4	18	27.3	4	20
3	36	11.0	8	12.1	2	10
4	22	6.7	5	7.6	2	10
5	19	5.8	2	3	-	-
Total	328	100	66	100	20	100

The severity of an incident in terms of travel delay depends on the available capacity and traffic demand during the incident. Since the incident data set does not provide any demand information, we considered the number of blocked lanes and the duration to reopen to traffic as crude indicators for incident severity. The reported duration to clear the lane blockage is relatively scattered, ranging from one to 478 min. TABLE 3.2 presents the cross-tabulation for number of blocked lane against the reopening duration.

HOT segment

Similar to HOV segments, the incidents, which are reported no lane blockage, were removed from the data set. This reduces the number of incidents in the data set to 851. Moreover, to be consistent with the above, only incidents that occurred during 7 to 9 AM and 4 to 6 PM were considered. The final incident set contains 203 incident records and all of them occurred on GP lanes. TABLE 3.3 summarizes the frequency of incidents with respect to the number of blocked lanes while

TABLE 3.4 presents the cross-tabulation for number of blocked lane against the reopening duration.

TABLE 3.2 Cross-tabulation of the Number of Blocked Lanes against Reported Time to Reopen on HOV Segments

Number of blocked lanes		Time to reopen							
		0-10	10-20	20-30	30-40	40-50	50-60	60-120	120<
After removing incident without blocked lane	1	51	36	22	10	4	5	9	11
	2	25	14	22	10	11	3	12	5
	3	4	7	6	5	-	3	9	2
	4	6	5	1	3	1	1	4	1
	5	6	3	2	1	-	1	3	2
After removing incident out of operating hour	1	20	9	8	2	3	-	2	-
	2	2	6	8	3	4	-	2	-
	3	1	2	3	1	-	2	1	-
	4	1	2	1	-	1	-	1	-
	5	-	1	-	-	-	-	-	-
After removing incident on HOV lanes	1	6	3	2	1	1	-	2	-
	2	1	1	1	-	1	-	-	-
	3	-	1	-	1	-	1	-	-
	4	1	-	-	-	-	-	-	-
	5	-	-	-	-	-	1	2	-

TABLE 3.3 Frequency of Incidents on HOT Segments

Number of blocked lane	After removing incidents with no blocked lane		After removing incidents during non-peak hours	
	Frequency	Percentage	Frequency	Percentage
1	605	71.7	170	84.2
2	171	20.3	27	13.4
3	49	5.8	3	1.5
4	15	1.8	2	1
5	4	0.5	-	-
Total	844	100	202	100

TABLE 3.4 Cross-tabulation of the Number of Blocked Lanes against Reported Time to Reopen on HOT Segments

	Number of blocked lane	Time to reopen							
		0-10	10-20	20-30	30-40	40-50	50-60	60-120	120<
After removing incident without blocked lane	1	264	179	81	30	15	3	9	24
	2	29	28	41	23	9	13	12	16
	3	2	7	14	11	7	3	5	-
	4	2	2	2	-	1	2	3	3
	5	0	0	1	1	-	-	2	-
After removing incident During non-peak hours	1	72	59	18	11	5	-	4	1
	2	4	4	8	3	3	4	1	-
	3	1	-	-	1	-	1	-	-
	4	-	-	-	-	-	-	2	-
	5	-	-	-	-	-	-	-	-

3.3 Selected Incident Analysis

Selected Incidents

Although many incidents may occur every year, only a very small fraction of them are expected to impose significant impacts on freeway operations and thus warrant lifting the restrictions of HOV/HOT lanes. In this study, we focus on a limited number of major incidents and perform detailed data analysis to gain insights into how those incidents impact on HOV/HOT lane operations quantitatively. Five incidents were selected for the analysis and their basic characteristics are summarized in TABLE 3.5. FIGURE 3.1 shows their geological locations. Three incidents are located in HOV segments while the other two are in the HOT segments.

TABLE 3.5 General Description of Five Selected Incidents

Incident ID	Lane blockage	Lane reopen time (min)	Incident type	Managed lane type	Impacted area	
					Number of detectors	Length (mi)
316748	2 right lanes (of 4 GP lanes) blocked	41	Crash	HOV	14	6.49
324919	2 right lanes (of 4 GP lanes) blocked	19	Crash	HOV	18	8.49
309947	2 right lanes (of 4 GP lanes) blocked	7	Disabled Vehicle	HOV	16	7.92
304026	2 left lanes (of 4 GP lanes) blocked	59	Disabled Vehicle	HOT	7	1.98
310107	3 left lanes (of 4 GP lanes) blocked	37	Crash	HOT	12	4.18

As previously mentioned, we adopted the travel time difference approach (Skabardonis et al., 1996), to estimate incident delay. The approach is intuitive and effective. More importantly, radar detectors along the study corridor have provided relatively accurate traffic speed and volume data, which make the approach particularly suitable for travel time calculations. The traffic data were retrieved from STEWARD (Statewide Transportation Engineering Warehouse for Archived Regional Data) hosted by the University of Florida.
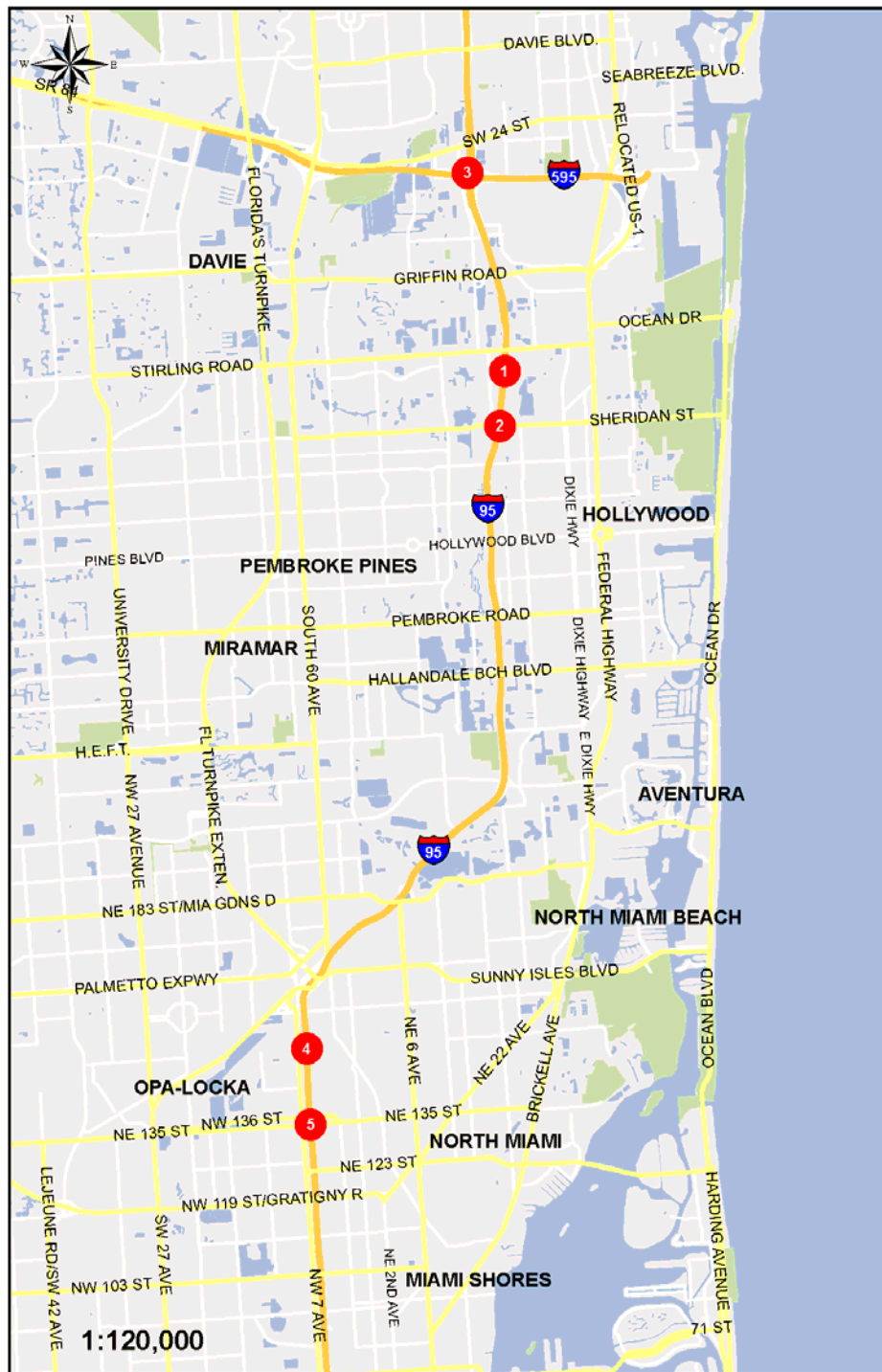
FIGURE 3.1 Locations of Five Selected Incidents

Incident Delay Estimation Approach

Define three sets I, J and M, where I and J include incident-impacted time intervals and segments, respectively, and $M = \{GP, HOV, HOT\}$ includes all three lane types. The incident delay is calculated for each time interval $i \in I$, segment $j \in J$, and lane type $m \in M$ as follows:

$$d_{ijm} = l_j q_{ijm} \left(\frac{1}{v_{ijm}} - \frac{1}{\tilde{v}_{ijm}} \right) \quad \forall 0 < v_{ijm} \leq \tilde{v}_{ijm}$$

where d_{ijm} denotes the incident delay (veh-h) for all vehicles traveling on lane type m of segment j during time interval i, and q_{ijm}, v_{ijm} and $\tilde{v}_{ijm}$ are the number of vehicles during the interval (veh), and average speeds (mi/h) under incident and incident-free conditions, respectively. l_j is the length (mi) of the segment j. The total incident delay D for a particular incident site is

$$D = \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} d_{ijm}$$

Note that it is not straightforward to determine the traffic speed under incident-free conditions primarily because traffic demand may vary dramatically. In this study, we used the free-flow speed as the reference speed, which can be derived from traffic speed and flow data. In the remaining part of this section, we will examine each of those five selected incidents in detail.

Incident 1(ID Number: 316748)

Incident 1 occurred on a HOV segment at 5:55:48 PM, 1/12/2012. Its location is shown in FIGURE 3.2. The incident was caused by a crash and blocked two right lanes of four GP lanes for 41 minutes. By plotting the speed profiles of the detectors upstream from the incident, FIGURE 3.3 shows that the incident impacted a stretch of freeway 6.49 miles long and involved 14 detectors (see FIGURE 3.2). The shock wave caused by the incident can be clearly observed propagating upstream in FIGURE 3.3. FIGURE 3.4 and FIGURE 3.5 show the speed profiles of three selected detectors that are located at the beginning, middle and end of the impacted HOV and GP segments, respectively. We also constructed speed-flow curves for all impacted detector locations using one-week traffic data aggregated at 15-minute intervals. Free-flow speeds for incident delay calculation were obtained from these speed-flow curves. As an example, FIGURE 3.6 shows the speed-flow curve of the detector that is immediately upstream of the incident location. TABLE 3.6 summarizes the incident delay for each segment as well as total incident delay. We further introduced a delay index to describe the relative impact of an incident on traffic operations as follows:

$$\text{Delay Index} = \frac{(\text{Incident Travel Time} - \text{Free Flow Travel Time})}{\text{Incident Travel Time}}$$

It is noted in TABLE 3.6 that the delay indexes of HOV and GP lanes have similar values, implying that incident 1 has almost identical influence on both HOV and GP lanes.
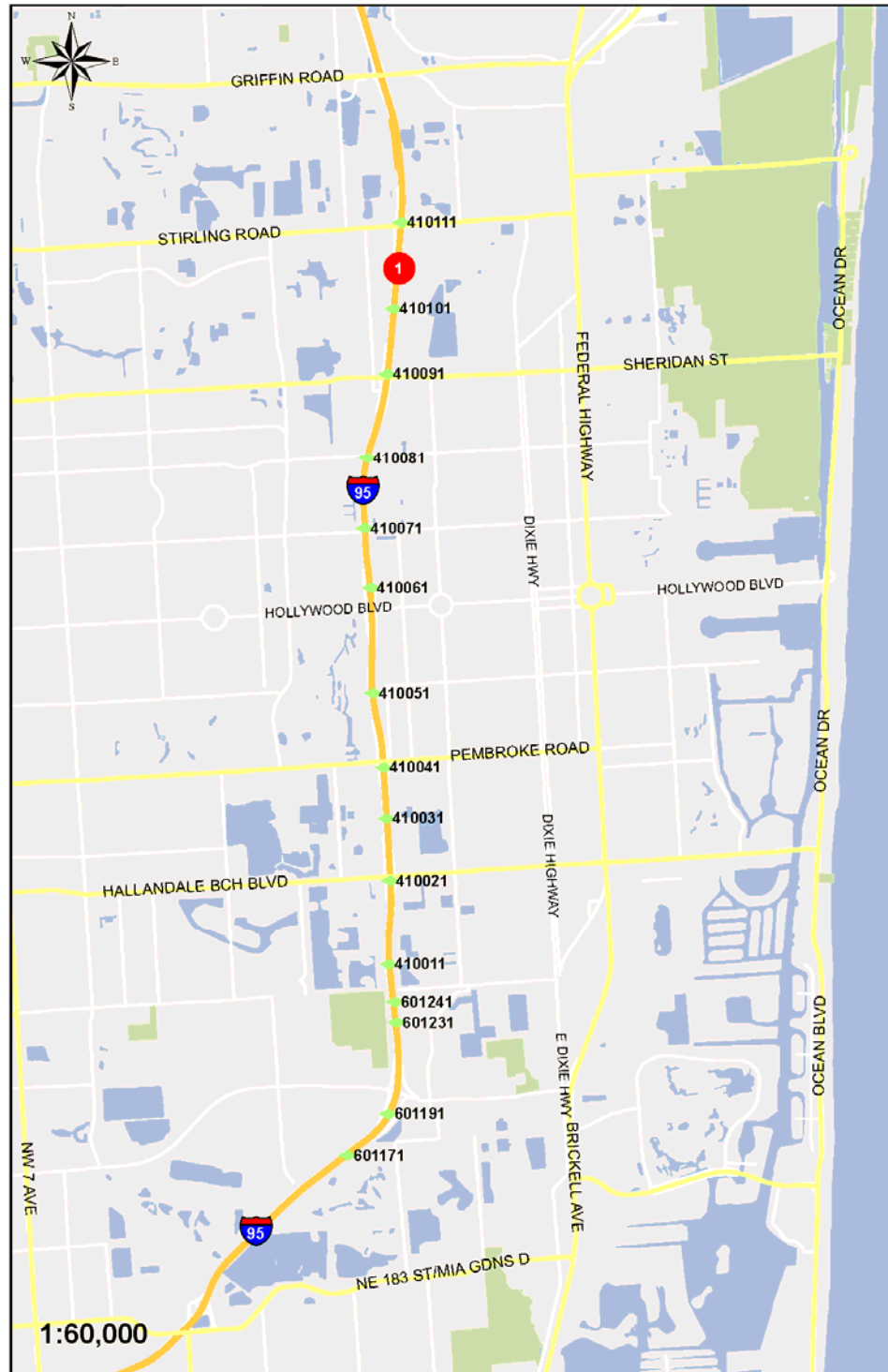
FIGURE 3.2 Incident 1 Site and Influenced Detectors
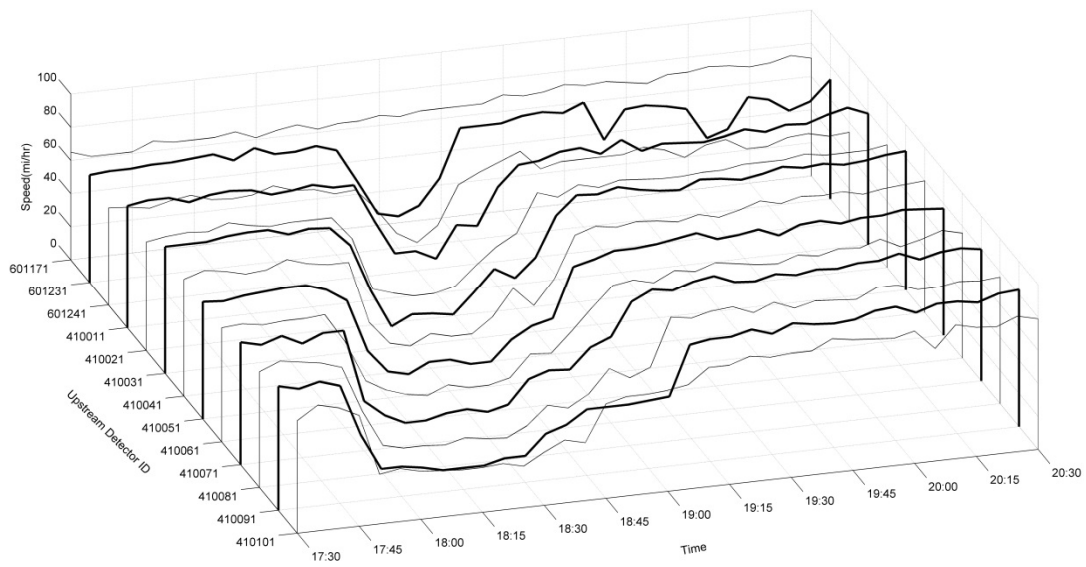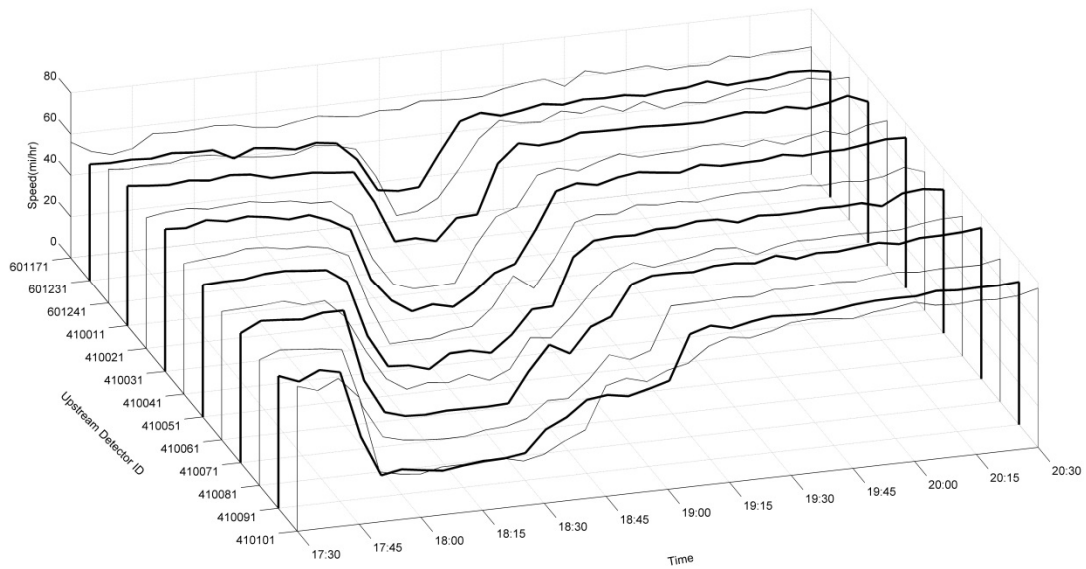
a) HOV Lane Segments

b) GP Lane Segments

FIGURE 3.3 Speed Profiles of Upstream Detectors for Incident 1
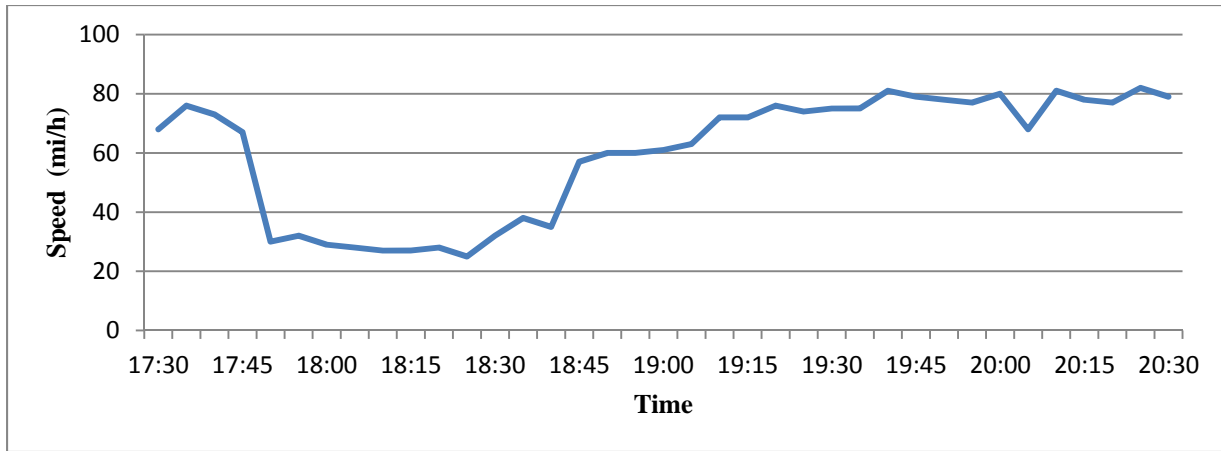
a) Detector 410101 HOV Lane Speed Profile
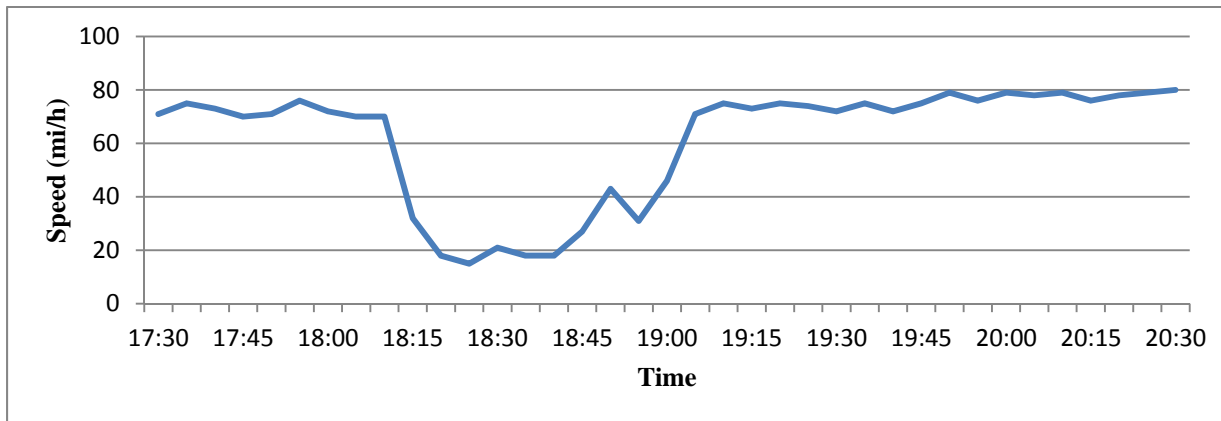
b) Detector 410041 HOV Lane Speed Profile
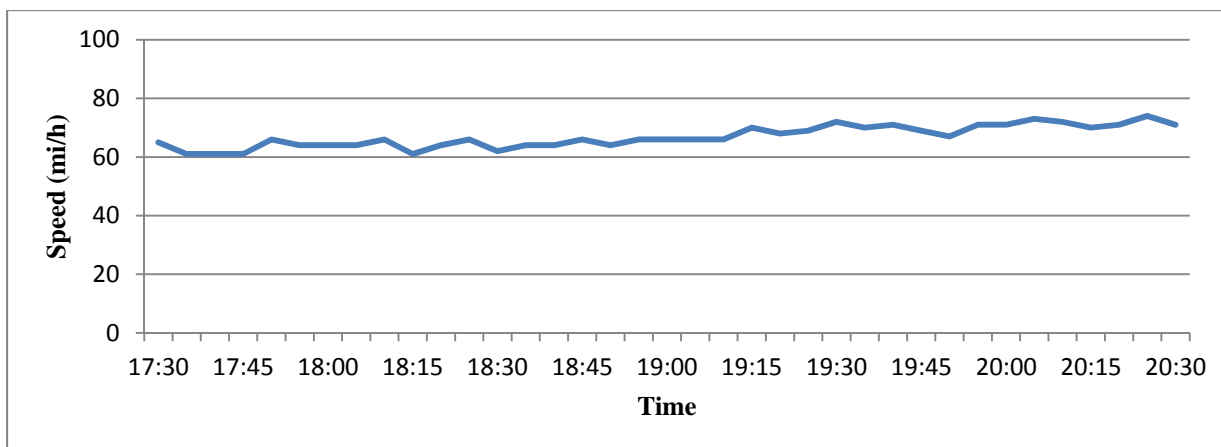
c) Detector 601171 HOV Lane Speed Profile

FIGURE 3.4 Selected HOV Lane Speed Profiles for Incident 1

a) Detector 410101 GP Lanes Speed Profile

b) Detector 410041 GP Lanes Speed Profile

c) Detector 410101 GP Lanes Speed Profile

FIGURE 3.5 Selected GP Lane Speed Profiles for Incident 1
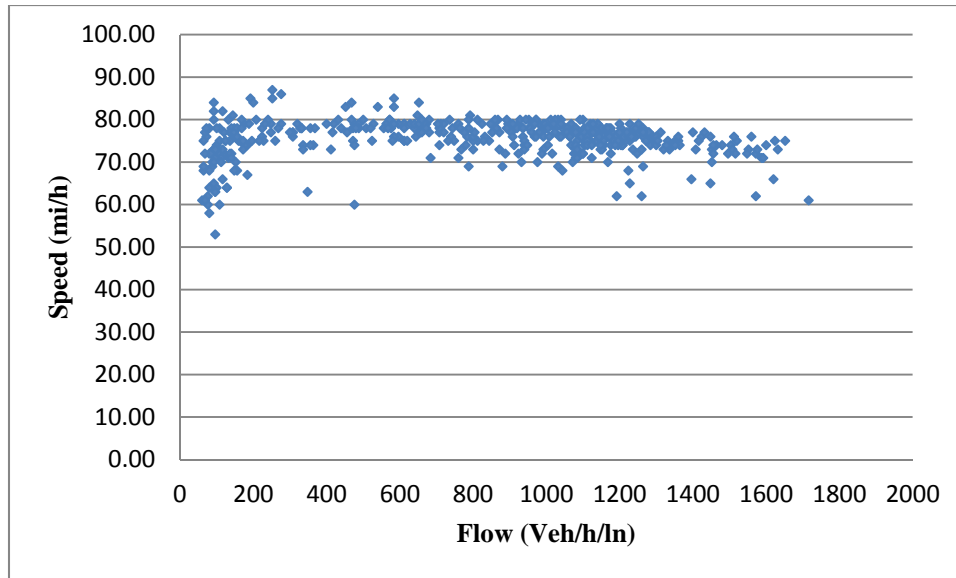
a) Speed-Flow Curve for Detector 410101 HOV Lane
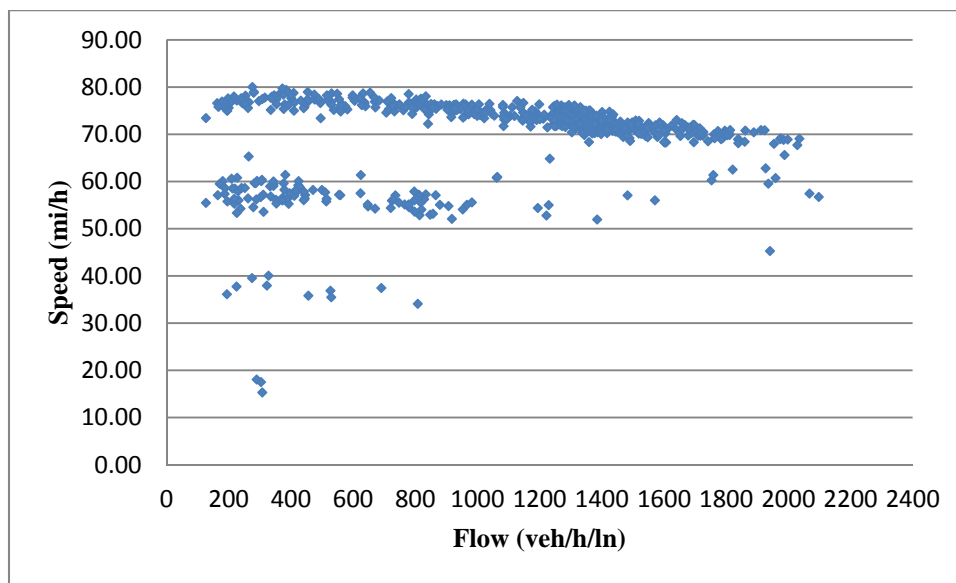
b) Speed-Flow Curve for Detector 410101 GP Lanes

FIGURE 3.6 Speed-Flow Curves for Detector 410101

TABLE 3.6 Incident Impact on HOV and GP Lanes (Incident 1)

Detector Station	Length (mi)	HOV Lane				GP Lanes			
		Incident Travel Time (h)	Free-flow Travel Time (h)	Delay (veh-h)	Delay Index (%)	Incident Travel Time (h)	Free-flow Travel Time(h)	Delay (veh-h)	Delay Index (%)
410111	0.30	15.90	13.89	2.02	12.64	75.44	67.55	7.89	10.46
410101	0.55	44.90	27.76	17.42	38.19	199.08	118.20	81.03	40.63
410091	0.55	57.52	24.31	33.24	57.74	276.94	122.74	154.21	55.68
410081	0.50	51.01	23.39	27.73	54.15	220.76	110.89	109.88	49.77
410071	0.50	48.52	24.95	24.04	48.59	208.27	116.58	92.16	44.03
410061	0.55	47.86	26.93	20.99	43.74	220.83	128.68	92.16	41.73
410051	0.50	42.79	21.67	21.12	49.36	177.30	107.49	69.87	39.38
410041	0.45	35.21	21.13	14.23	39.99	168.97	101.71	67.28	39.80
410031	0.40	30.13	18.17	12.04	39.71	135.28	85.06	50.22	37.13
410021	0.50	10.51	6.39	4.13	39.25	37.84	24.79	13.05	34.49
410011	0.41	25.02	18.40	6.64	26.47	121.10	94.84	26.32	21.68
601241	0.18	13.45	11.90	1.90	11.56	50.12	41.08	9.05	18.04
601231	0.59	47.87	41.76	9.45	12.76	201.45	173.05	29.19	14.10
601171	0.52	36.16	34.16	2.14	5.52	122.58	124.24	2.48	0
Total	6.49	506.86	314.79	197.08		2215.99	1416.89	804.79	
Delay Index (%)		37.89				36.06			
		36.40							

Incident 2 (ID Number: 324919)

Incident 2 occurred on a HOV segment at 4:24:00 PM, 3/13/2012. It was caused by a crash and blocked two right lanes of four GP lanes for 19 minutes. FIGURE 3.7 shows the incident location and the impacted stretch of freeway that is 8.49 miles long and involves 18 detectors. FIGURE 3.8 illustrates the speed profiles of upstream detectors for incident 2. Three selected detectors that are located at the beginning, middle and end of the impacted section of HOV and GP lanes are shown in FIGURE 3.9 and FIGURE 3.10, respectively. Speed-flow curves were constructed for all impacted detector locations using one-week traffic data aggregated at 15-minute intervals. Free-flow speeds were estimated from these speed-flow curves. As an example, FIGURE 3.11 shows the speed-flow curve of the detector that is immediately upstream of the incident location. TABLE 3.7 summarizes the incident delay for each segment as well as total incident delay. It shows that HOV lanes have a slightly higher delay index than GP lanes, which suggests that the incident has more severe impact on HOV lanes than GP lanes, even though the difference is not significant.
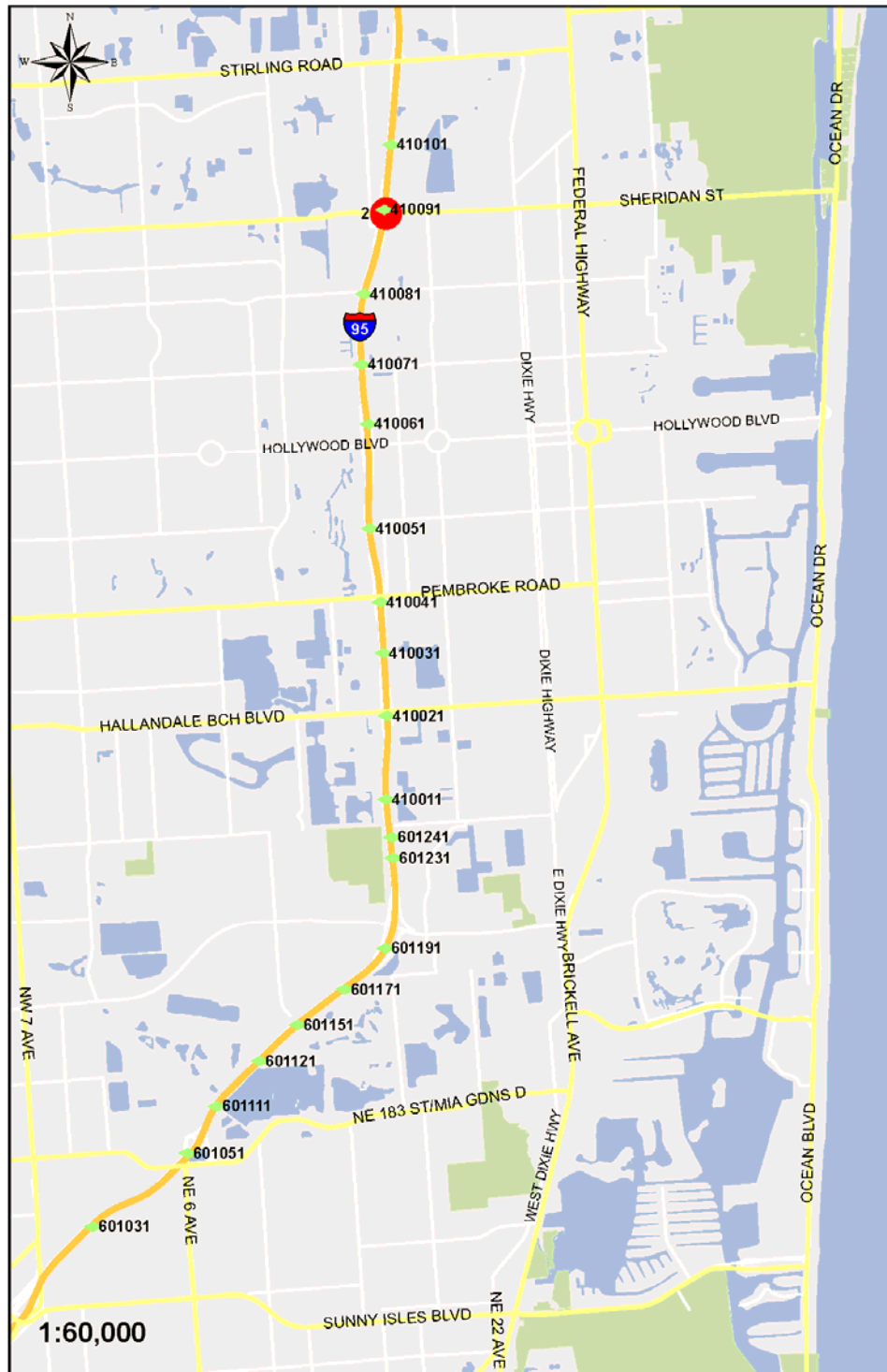
FIGURE 3.7 Incident 2 Site and Influenced Detectors
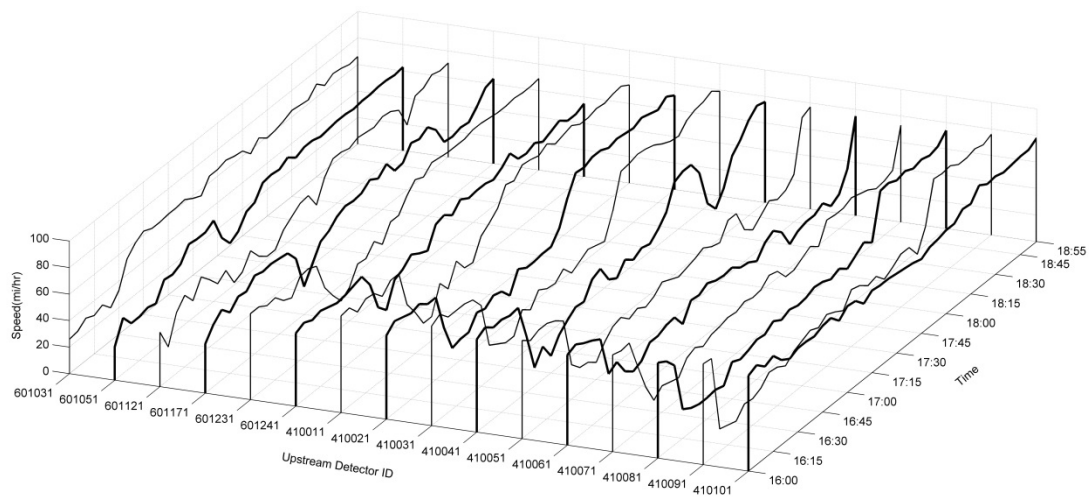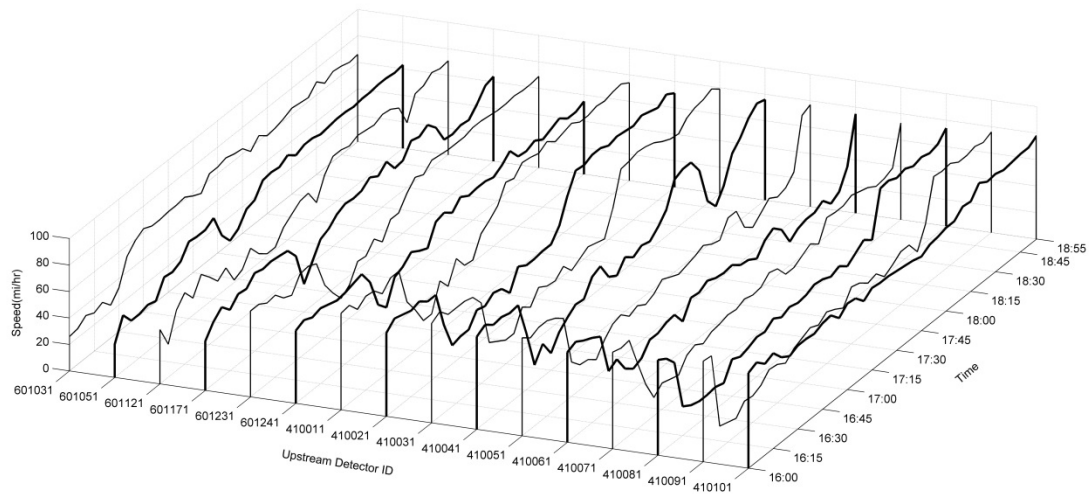
a) HOV Lane Segments


b) GP Lane Segments

FIGURE 3.8 Speed Profiles of Upstream Detectors for Incident 2
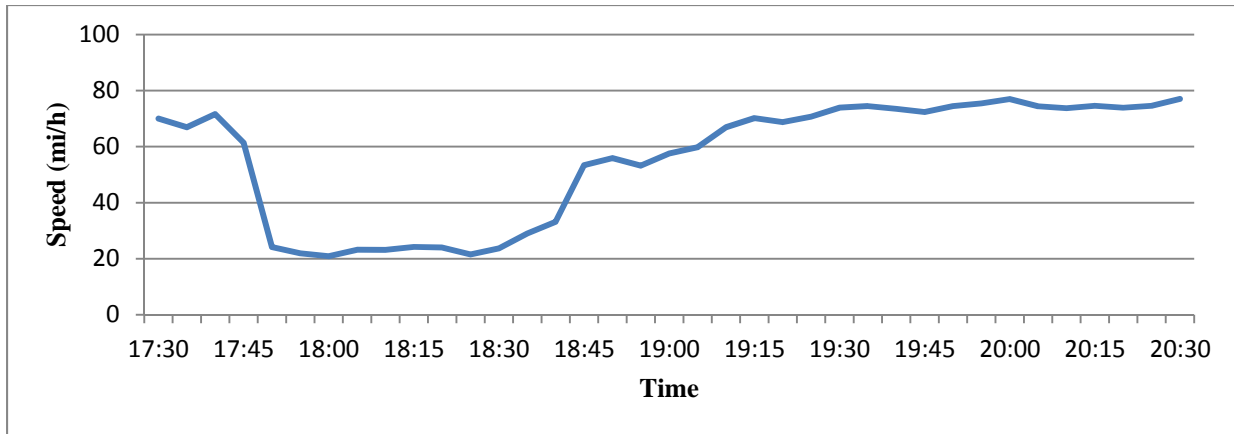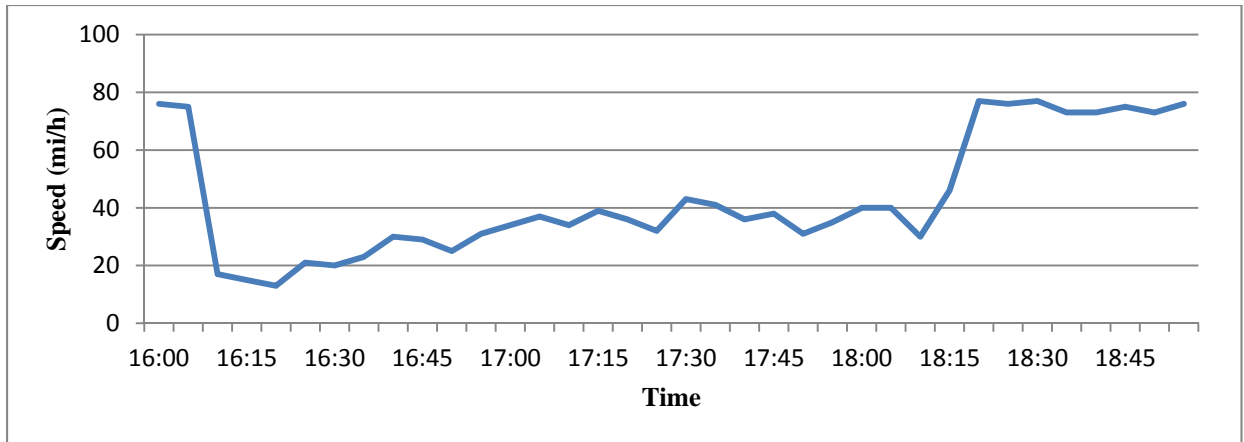
a) Detector 410091 HOV Lane Speed Profile
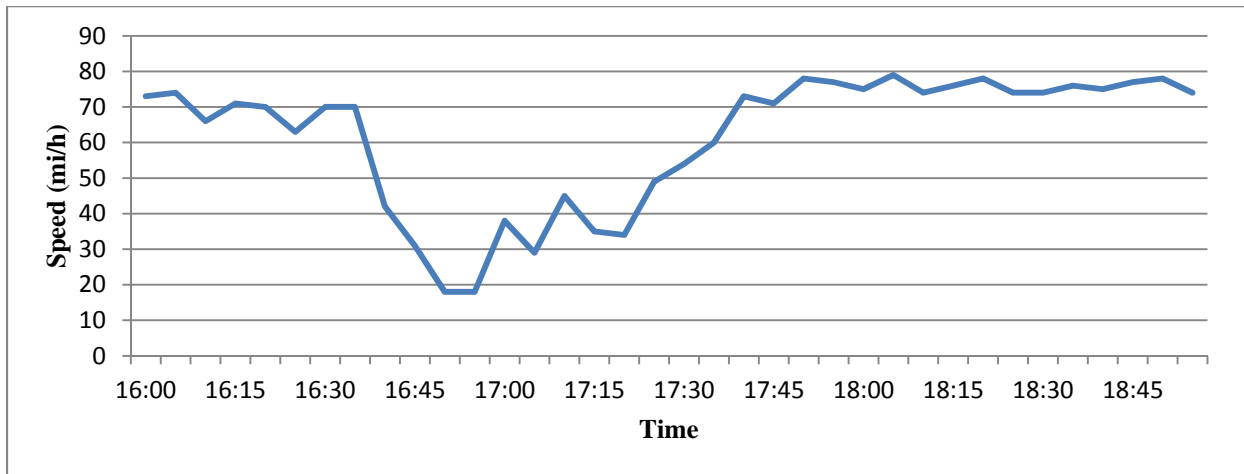
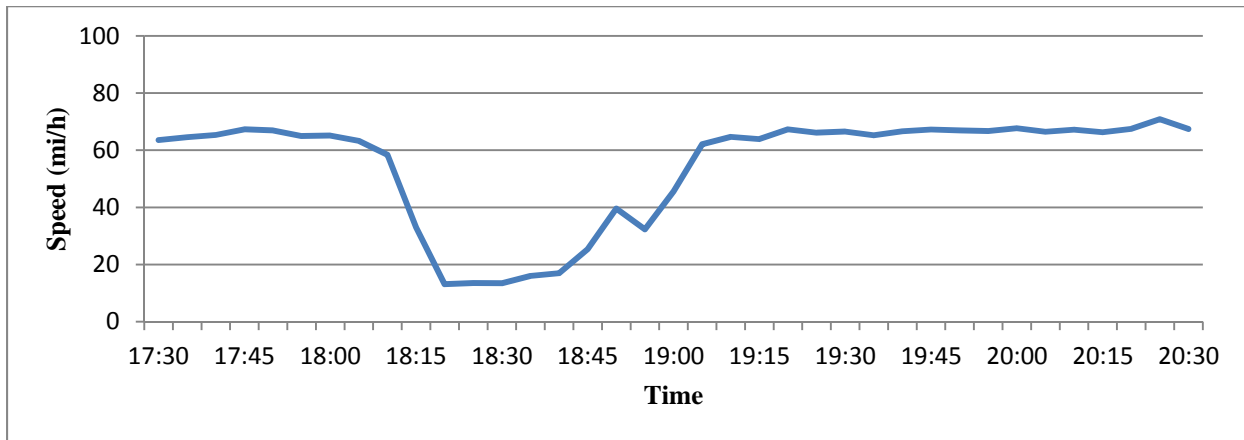b) Detector 410011 HOV Lane Speed Profile
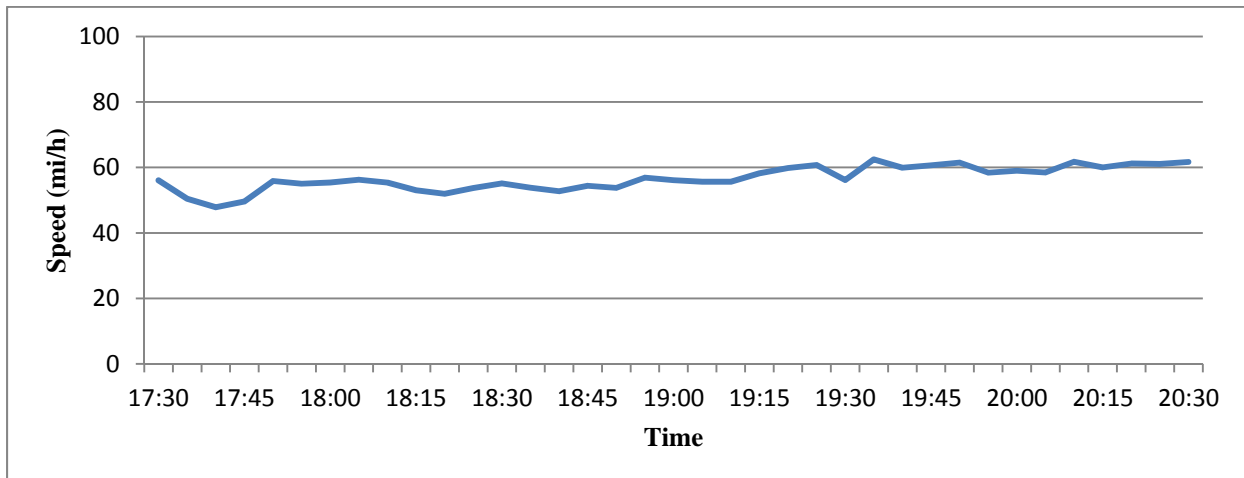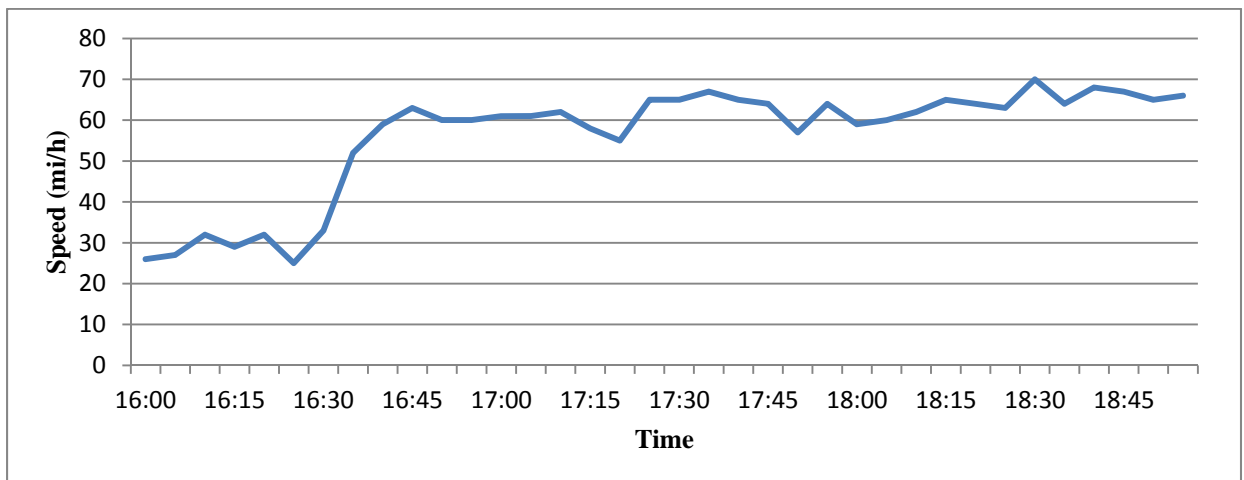

Detector 610031 HOV Lane Speed Profile

FIGURE 3.9 Selected HOV Lane Speed Profiles for Incident 2

a) Detector 410091 GP Lanes Speed Profile


b) Detector 410011 GP Lanes Speed Profile

c) Detector 610031 GP Lanes Speed Profile

FIGURE 3.10 Selected GP Lanes Speed Profiles for Incident 2
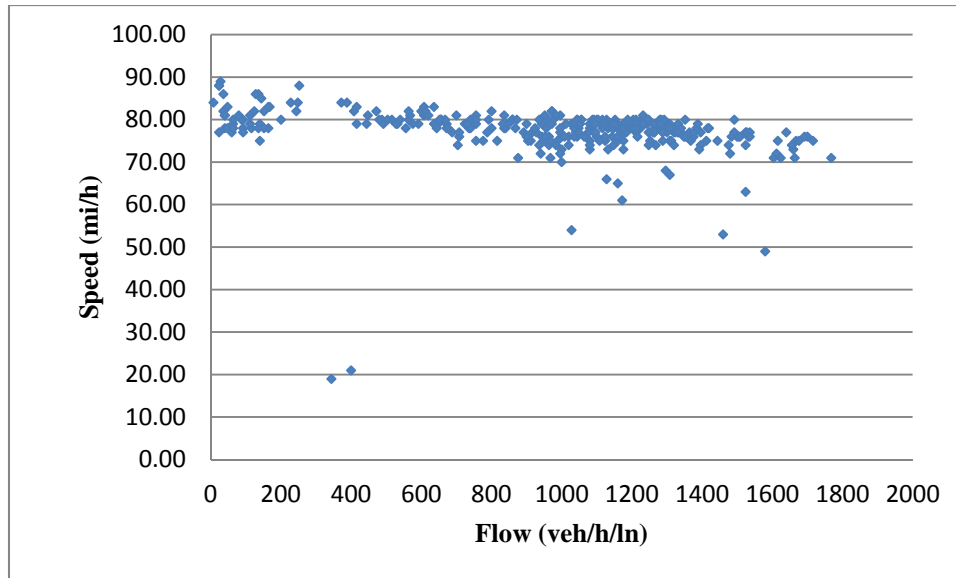
a) Speed-Flow Curve for Detector 410091 HOV Lane
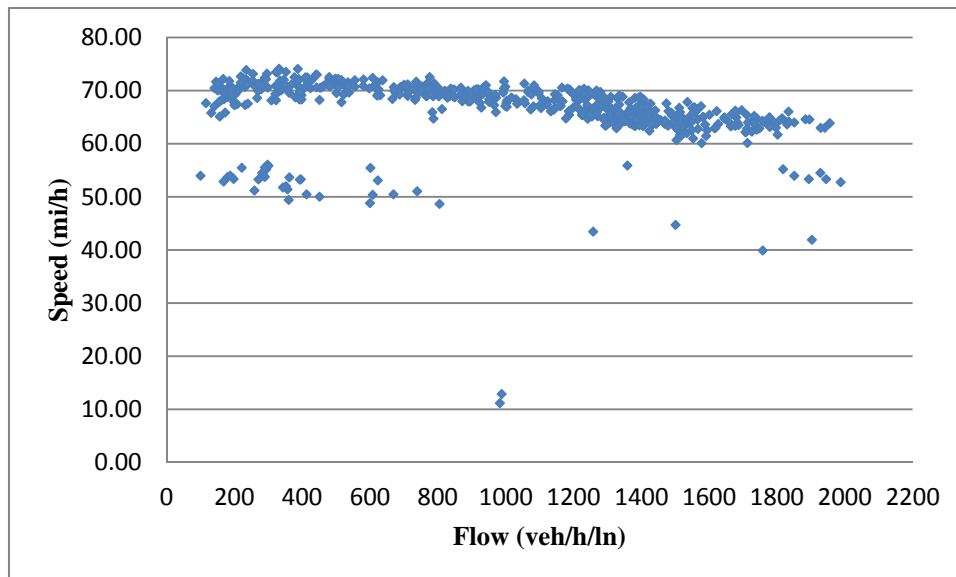
b) Speed-Flow Curve for Detector 410091 GP Lanes

**FIGURE 3.11 Speed-Flow Curves for Detector 410091**

TABLE 3.7 Incident Impacts on HOV and GP Lanes (Incident 2)

Detector Station	Length (mi)	HOV Lane				GP Lanes			
		Incident Travel Time (h)	Free-flow Travel Time (h)	Delay (veh-h)	Delay Index (%)	Incident Travel Time (h)	Free-flow Travel Time(h)	Delay (veh-h)	Delay Index (%)
410101	0.25	16.22	14.36	2.27	11.45	69.39	61.58	7.82	11.27
410091	0.55	105.21	31.30	38.36	70.25	357.09	128.09	229.01	64.13
410081	0.50	85.83	29.67	35.24	65.44	301.07	114.20	186.87	62.07
410071	0.50	84.59	31.47	39.01	62.80	294.71	122.66	172.06	58.38
410061	0.55	89.54	33.36	46.43	62.75	334.85	135.65	199.20	59.49
410051	0.50	85.33	25.97	40.93	69.57	293.06	110.41	182.64	62.32
410041	0.45	51.31	24.28	20.78	52.68	208.22	110.04	98.18	47.15
410031	0.40	48.16	20.98	16.27	56.44	183.37	91.19	92.18	50.27
410021	0.50	14.35	6.87	6.28	52.11	50.58	27.00	23.62	46.62
410011	0.52	42.32	25.13	12.78	40.62	198.17	133.05	65.15	32.86
601241	0.20	16.35	12.78	4.39	21.83	71.74	60.26	14.77	15.99
601231	0.59	58.07	43.80	8.79	24.58	252.16	191.03	61.26	24.24
601171	0.91	114.94	66.13	25.28	42.47	359.50	263.90	96.11	26.59
601121	0.79	95.30	53.86	21.31	43.48	270.73	178.57	92.83	34.04
601051	0.84	90.54	56.51	17.90	37.58	300.69	207.86	92.83	30.87
601031	0.45	43.78	36.59	5.83	16.44	100.27	75.55	24.73	24.66
Total	8.49	1041.84	513.05	341.84		3645.60	2011.04	1639.23	
Delay Index (%)		50.76				44.84			
		46.15							

Incident 3 (ID Number: 316748)

Incident 3 occurred on a HOV segment at 7:28:11 AM, 11/16/2011. The incident was caused by disabled vehicles and blocked two right lanes of four GP lanes for 7 minutes. By plotting the speed profiles of upstream detectors in FIGURE 3.13, we observed that the incident impacted a stretch of freeway that is 7.92 miles long and involves 16 detectors (see FIGURE 3.12). The shock wave caused by the incident can be clearly observed in FIGURE 3.13. FIGURE 3.14 and FIGURE 3.15 show three selected detectors that are located at the beginning, middle and end of the impacted HOV and GP segments respectively. Speed-flow curves were constructed for all impacted detector locations using one-week traffic data aggregated at 15-minute intervals. Free-flow speeds were obtained from these speed-flow curves. FIGURE 3.16 shows the speed-flow curve of the detector that is immediately upstream of the incident location. TABLE 3.8 summarizes the incident delay for each segment as well as total incident delay. It can be observed that GP lanes have a higher delay index than HOV lanes, which suggests that the incident imposed more severe impacts on GP lane operations than HOV lanes. Once again, the difference is relatively insignificant.
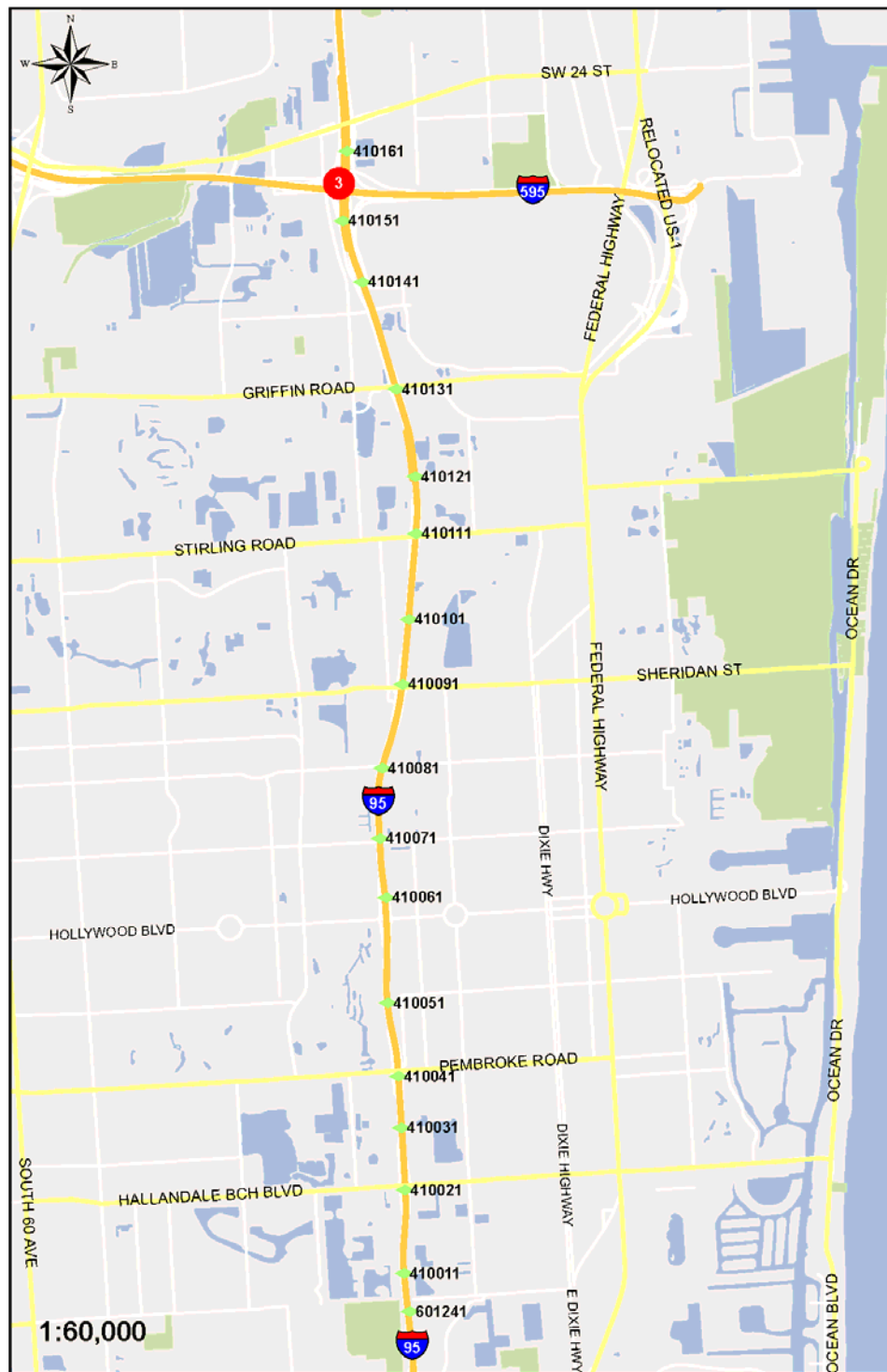
**FIGURE 3.12 Incident 3 Site and Influenced Detectors**
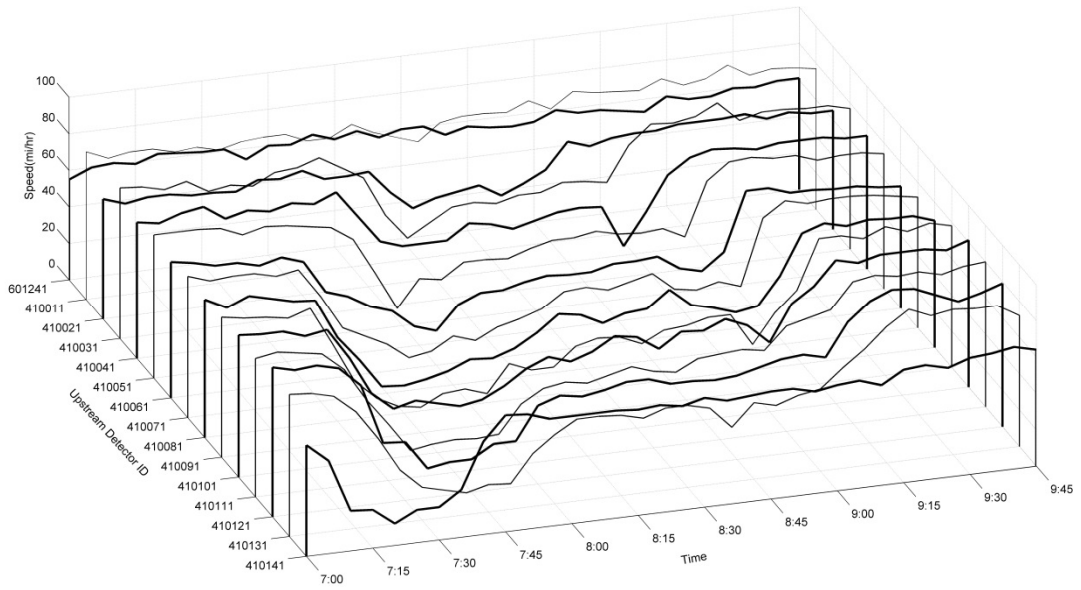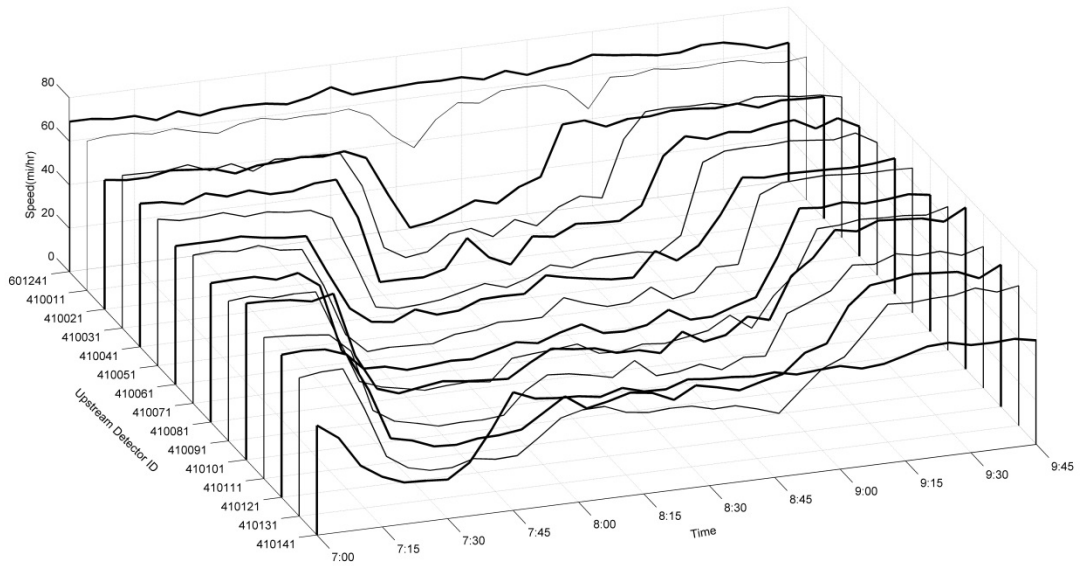
a) HOV Lane Segments

b) GP Lane Segments

FIGURE 3.13 Speed Profiles of Upstream Detectors for Incident 3
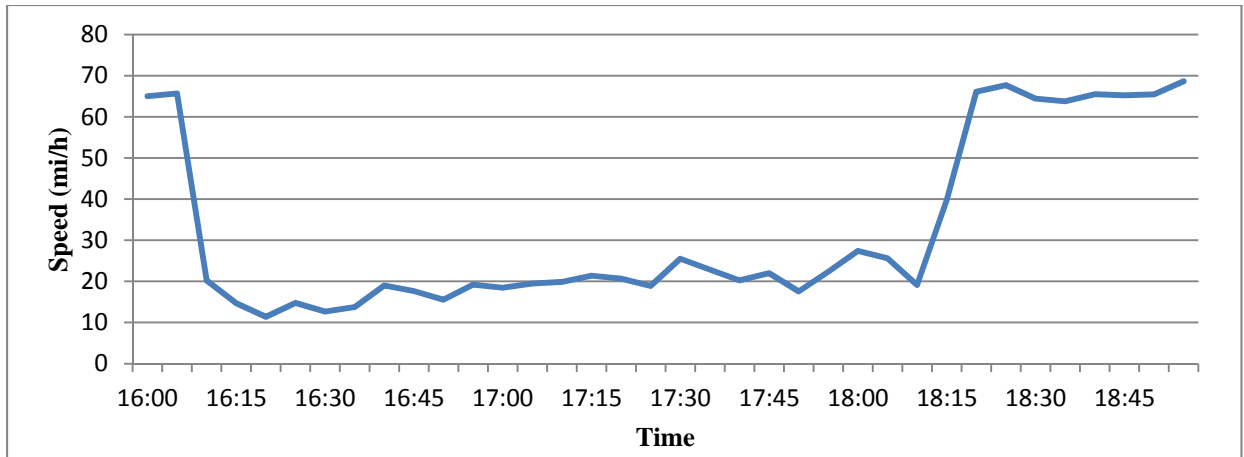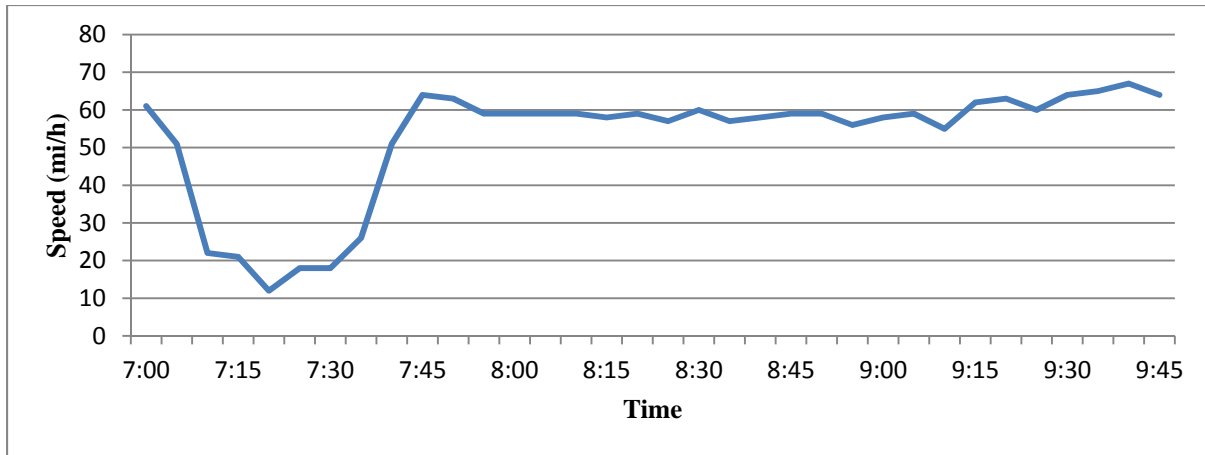
a) Detector 410141 HOV Lane Speed Profile
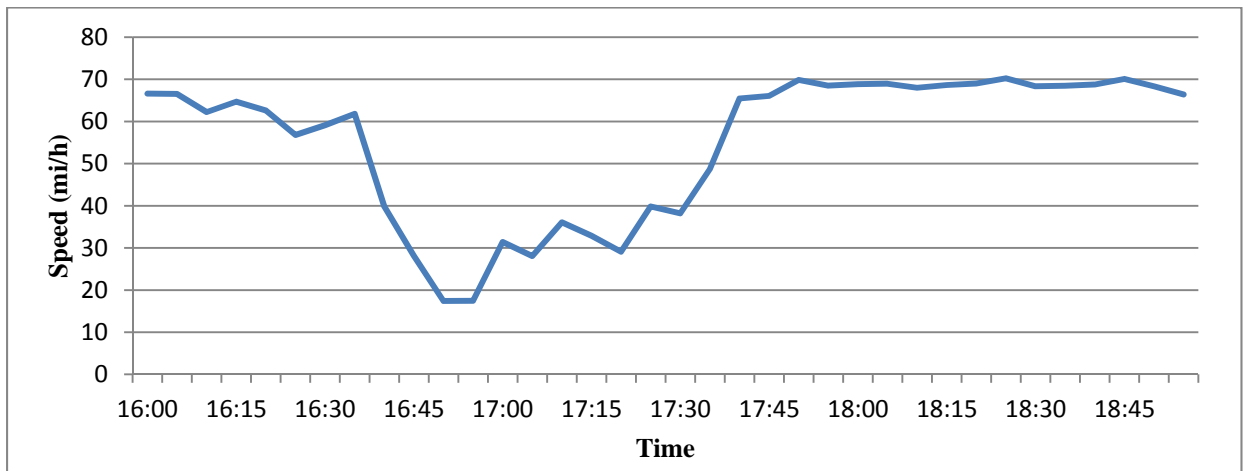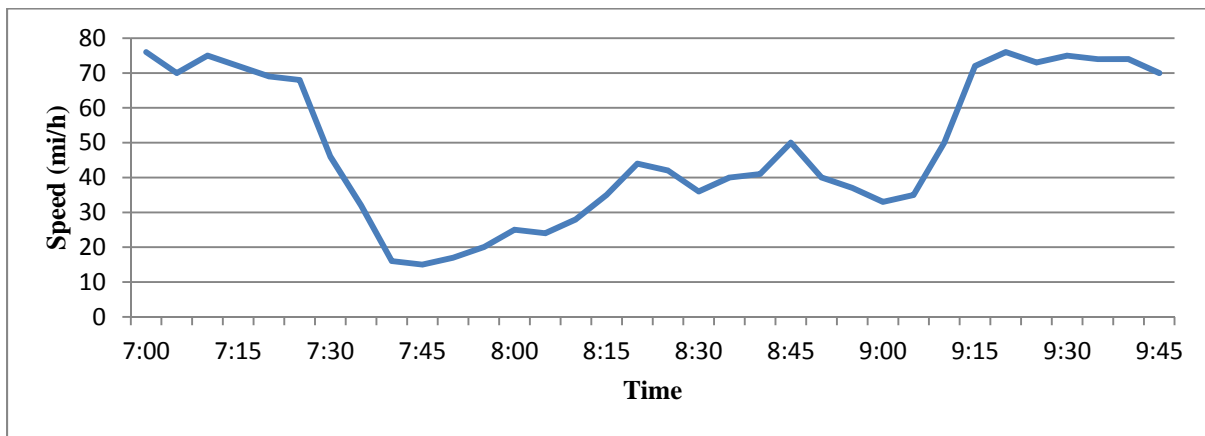

b) Detector 410081 HOV Lane Speed Profile
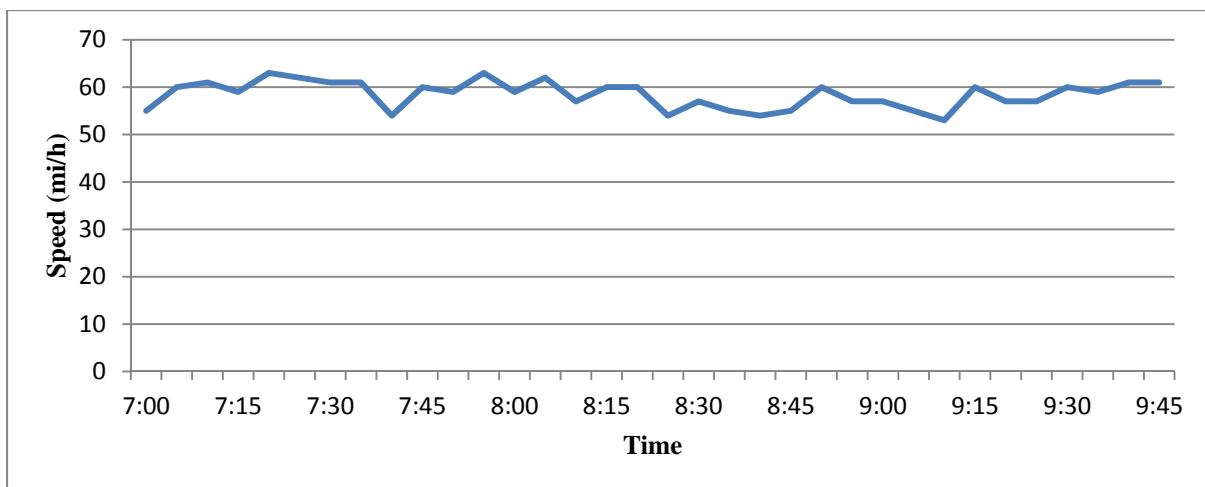
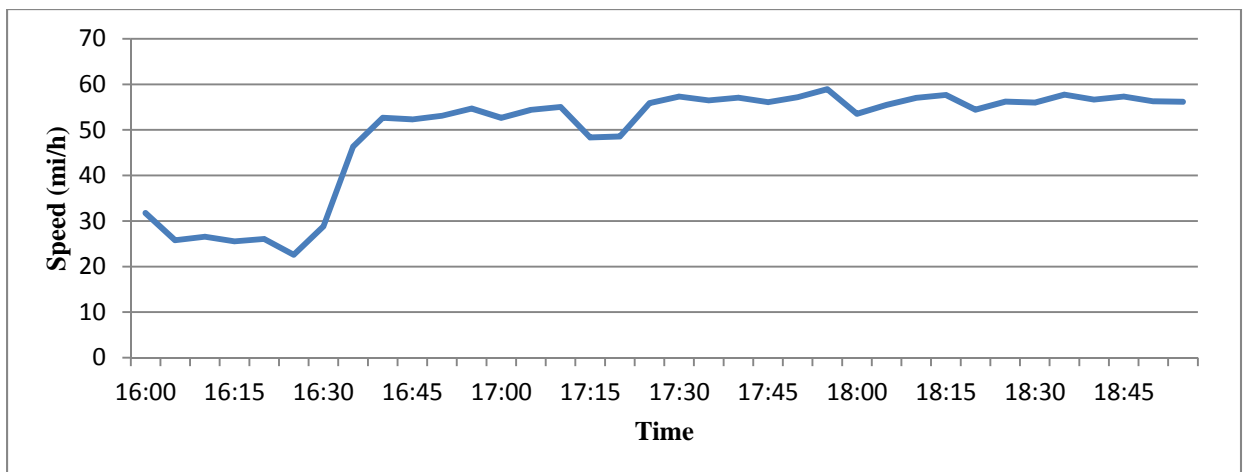
c) Detector 601241 HOV Lane Speed Profile

FIGURE 3.14 Selected HOV Lane Speed Profiles for Incident 3
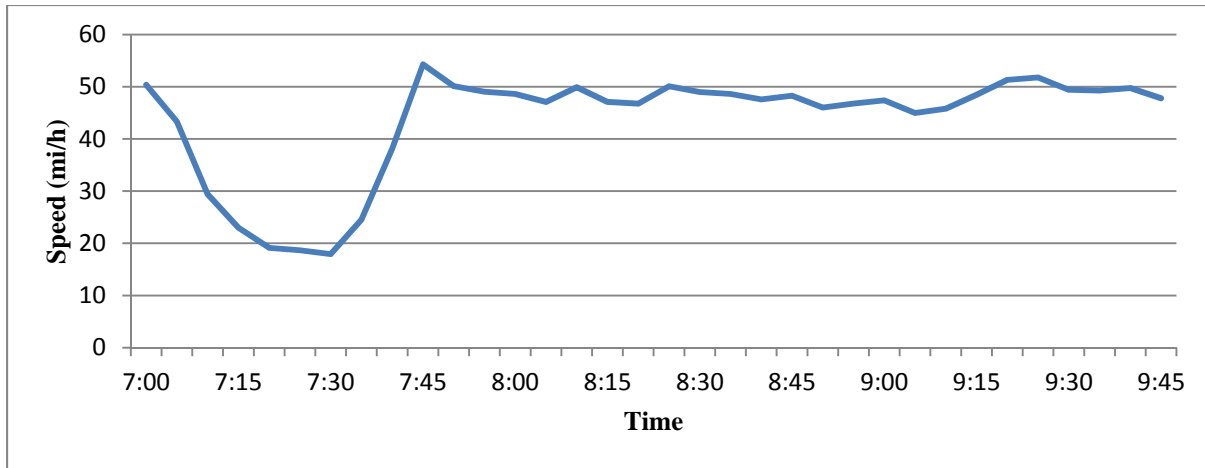
a) Detector 410141 GP Lanes Speed Profile
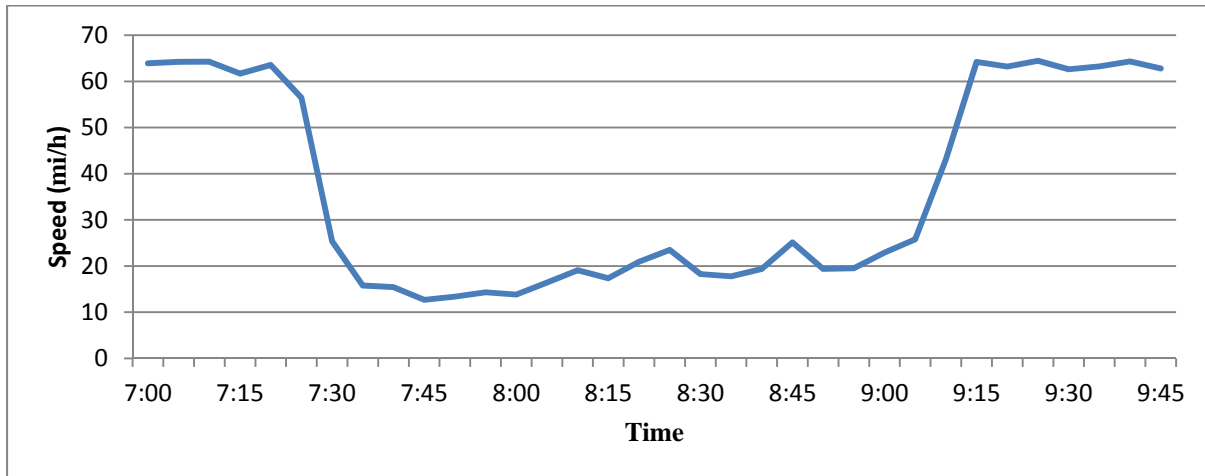

b) Detector 410081 GP Lanes Speed Profile
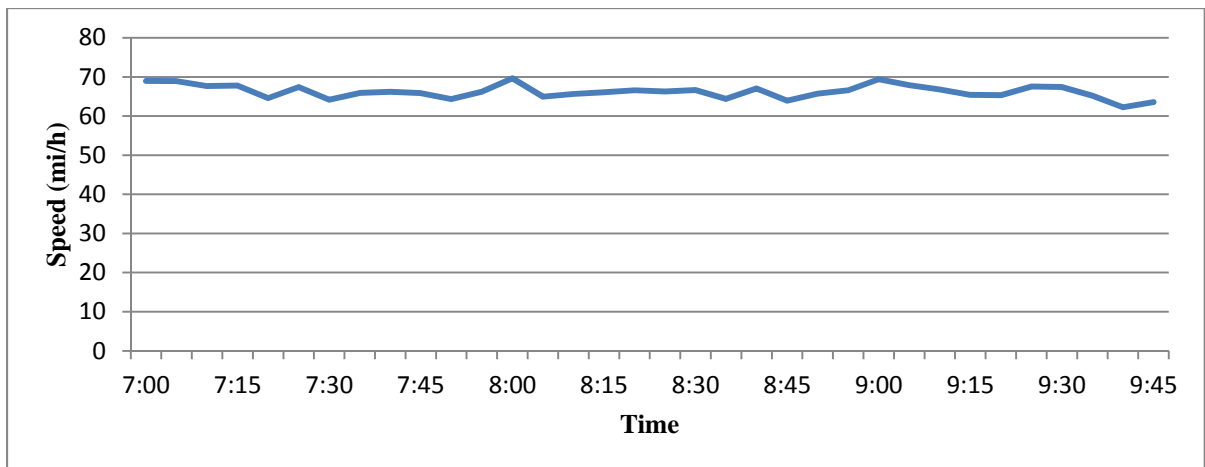
c) Detector 601241 GP Lanes Speed Profile

FIGURE 3.15 Selected GP Lane Speed Profiles for Incident 3
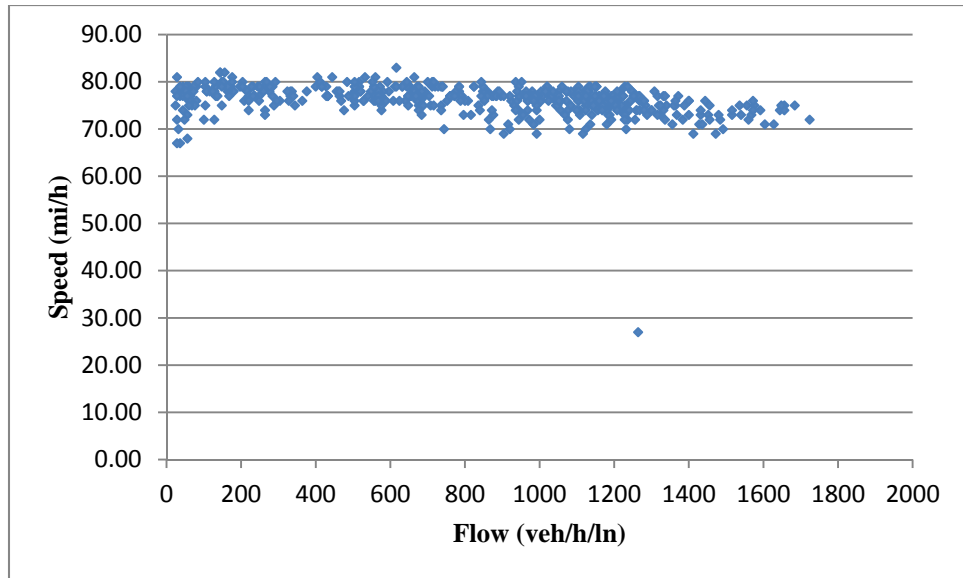
a) Speed-Flow Curve for Detector 410141 HOV Lane
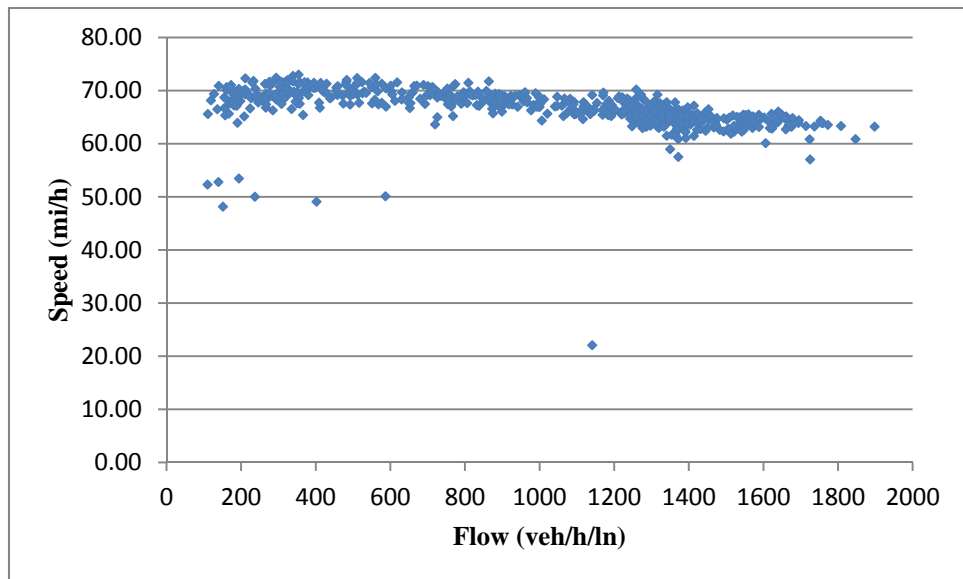

b) Speed-Flow Curve for Detector 410141 GP Lanes

FIGURE 3.16 Speed-Flow Curves for Detector 410141

TABLE 3.8 Incident Impact on HOV and GP Lanes (Incident 3)

Detector Station	Length (mi)	HOV Lane				GP Lanes			
		Incident Travel Time (h)	Free-flow Travel Time (h)	Delay (veh-h)	Delay Index (%)	Incident Travel Time (h)	Free-flow Travel Time(h)	Delay (veh-h)	Delay Index (%)
41016131	0.25	10.05	9.40	0.65	6.42	45.72	42.96	2.80	6.05
41015131	0.45	18.67	16.36	2.31	12.39	84.28	73.78	10.50	12.46
41014131	0.60	50.93	35.70	15.25	29.89	130.99	99.17	31.82	24.29
41013131	0.70	67.43	32.60	34.86	51.65	409.27	174.62	234.65	57.33
41012131	0.45	39.35	20.23	19.13	48.60	240.03	104.18	135.85	56.60
41011131	0.45	45.13	22.89	22.23	49.27	249.14	112.39	136.75	54.89
41010131	0.55	43.77	27.04	16.99	38.23	241.74	121.91	119.83	49.57
41009131	0.55	59.04	26.31	32.75	55.43	322.27	124.83	197.44	61.26
41008131	0.50	51.53	25.26	26.29	50.98	280.15	107.76	172.39	61.54
41007131	0.50	49.95	27.09	22.98	45.77	263.38	114.48	148.90	56.53
41006131	0.55	54.56	32.35	22.21	40.70	263.75	128.71	135.04	51.20
41005131	0.50	29.49	19.43	10.06	34.10	221.13	106.22	114.90	51.96
41004131	0.45	22.97	17.68	5.34	23.03	188.09	103.38	84.71	45.04
41003131	0.40	18.23	14.78	3.62	18.97	150.29	86.74	63.55	42.29
41002131	0.50	4.79	3.82	0.97	20.22	31.65	20.17	11.48	36.26
41001131	0.41	11.35	10.85	0.54	4.37	101.86	94.47	7.39	7.25
60124131	0.11	4.56	4.84	0.01	0	28.02	26.48	1.54	5.49
Total	7.92	581.79	346.64	236.18		3251.74	1642.25	1609.53	
Delay Index (%)		40.42				49.50			
		48.12							

40

Incident 4 (ID Number: 04026)

This incident occurred at 8:48 AM on 9/30/2011 on GP lanes in the segment of 95 Express. It blocked the two left lanes of four GP lanes for 59 minutes. The evaluation of traffic data obtained from upstream detectors showed that six detectors were affected by this incident. FIGURE 3.19 depicts the speed profiles of three detectors in GP lanes around the incident time, which are the first, middle and last affected detectors, respectively. It is clear that after the occurrence of the incident, the first upstream detector was affected immediately. The shock wave propagated upstream, and other detectors were also affected. FIGURE 3.20 also depicts the speed profiles corresponding to the upstream detectors located in HOT lanes. For all affected detectors, the speed-flow patterns are constructed using one-week traffic data, which are aggregated at 15-minutes intervals. Two examples of these flow-speed patterns are shown in FIGURE 3.21. TABLE 3.9 presents the detailed calculation of incident delay and delay index.
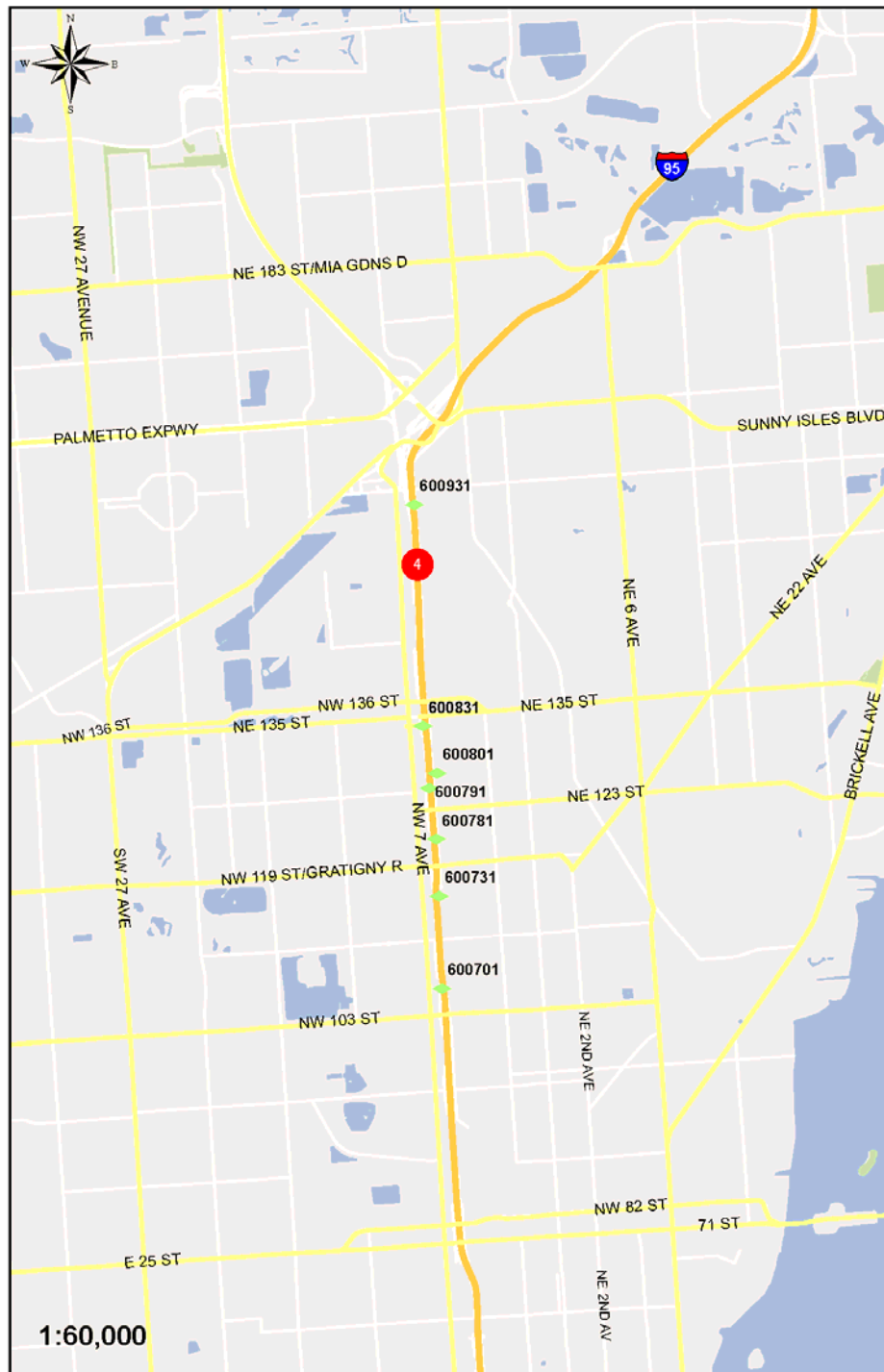
FIGURE 3.17 Incident 4 Site and Influenced Detectors
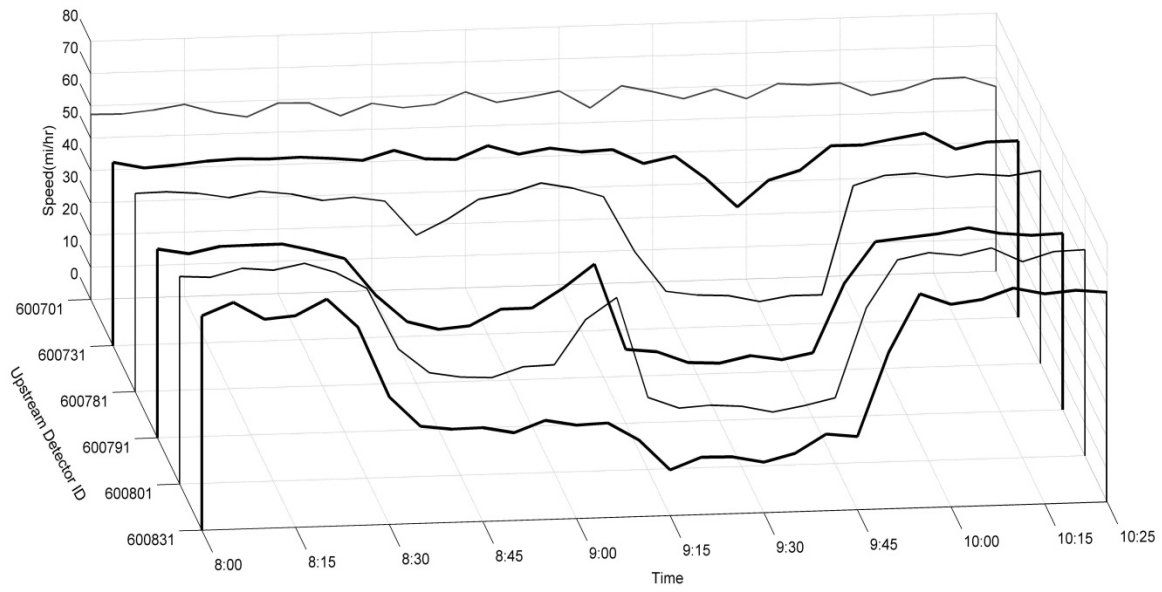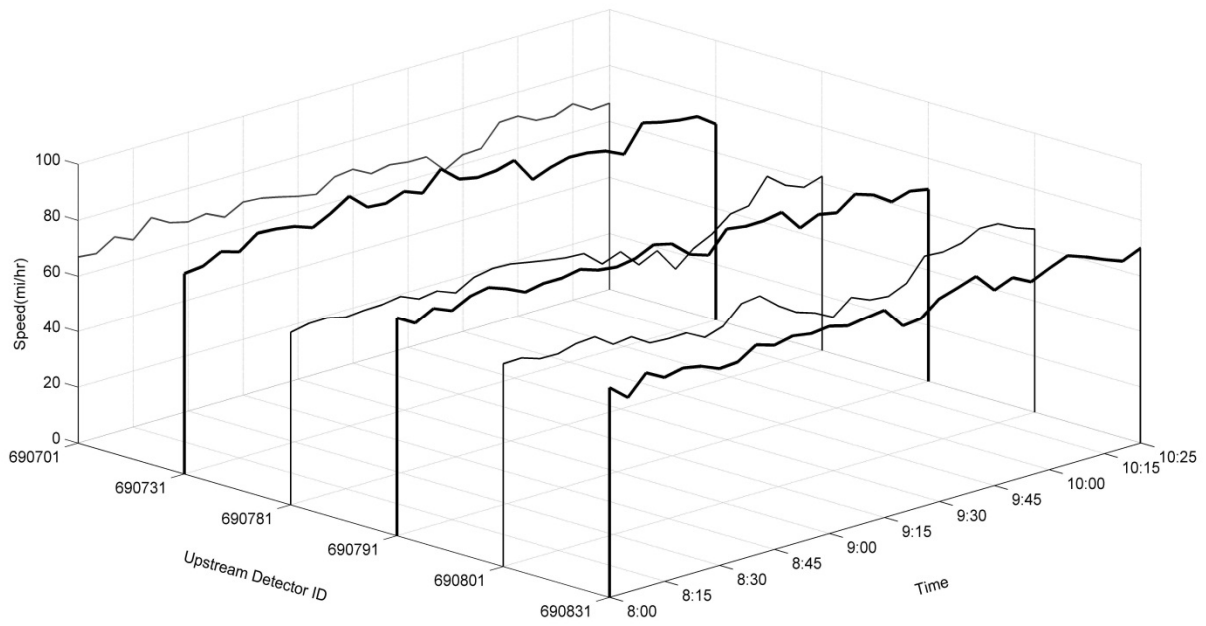
a) GP Lane segments

b) HOT Lane segments

FIGURE 3.18 Speed Profile of Upstream Detectors for Incident 4
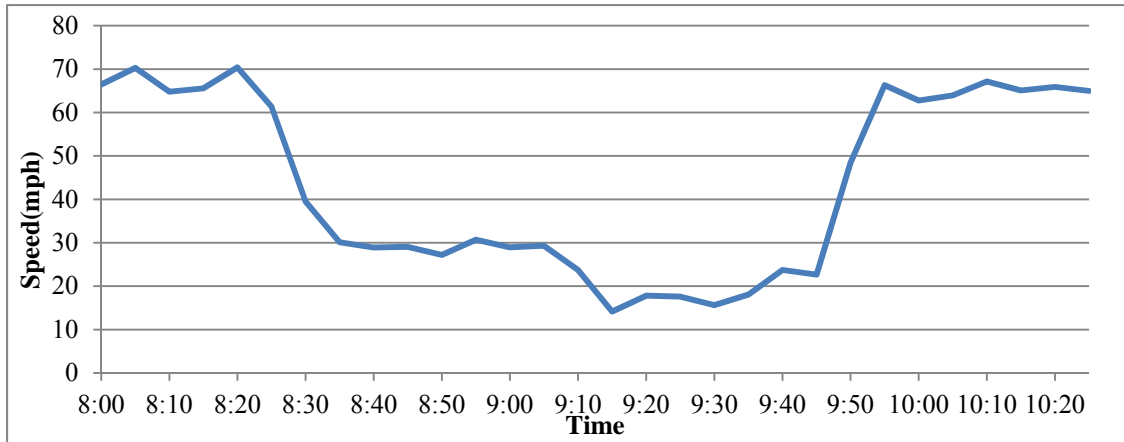
a) Detector 600831 GP Lanes Speed Profile
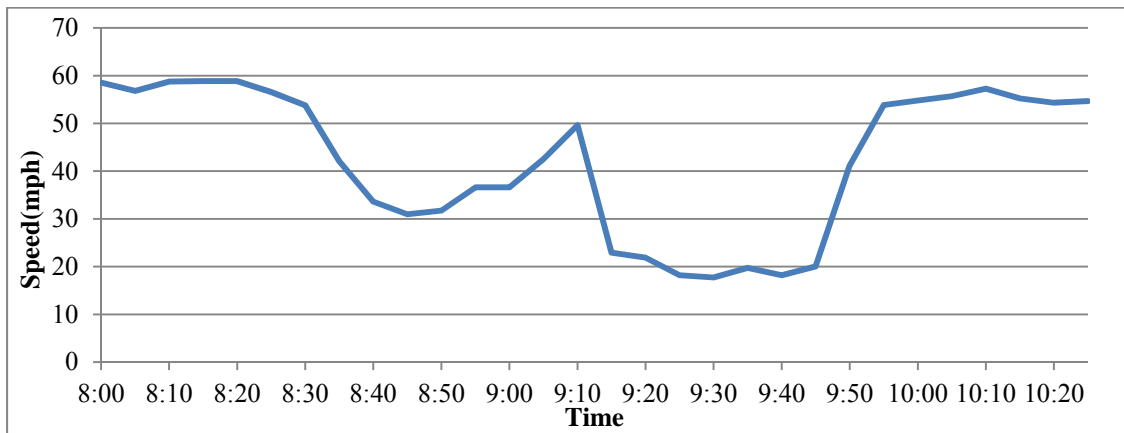
b) Detector 600791 GP Lanes Speed Profile
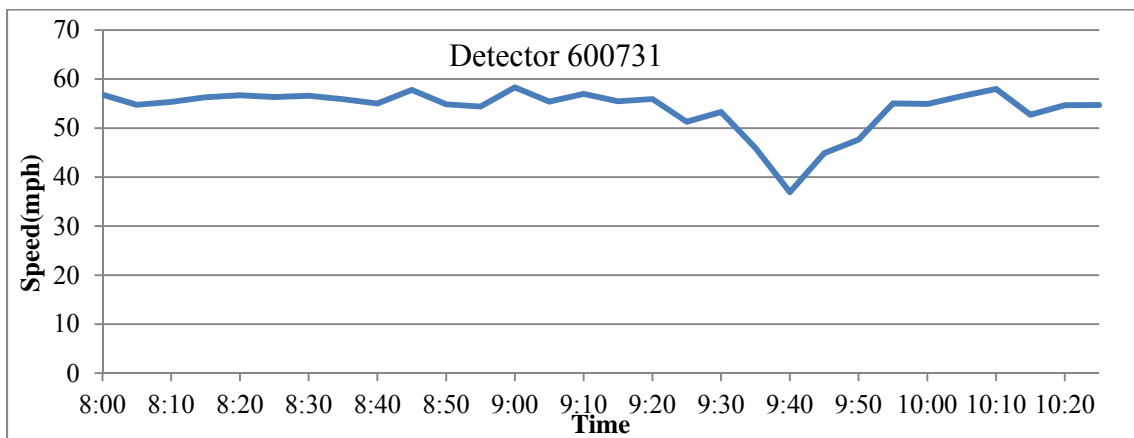
c) Detector 600731 GP Lanes Speed Profile

FIGURE 3.19 Selected GP Lanes Speed Profiles for Incident 4
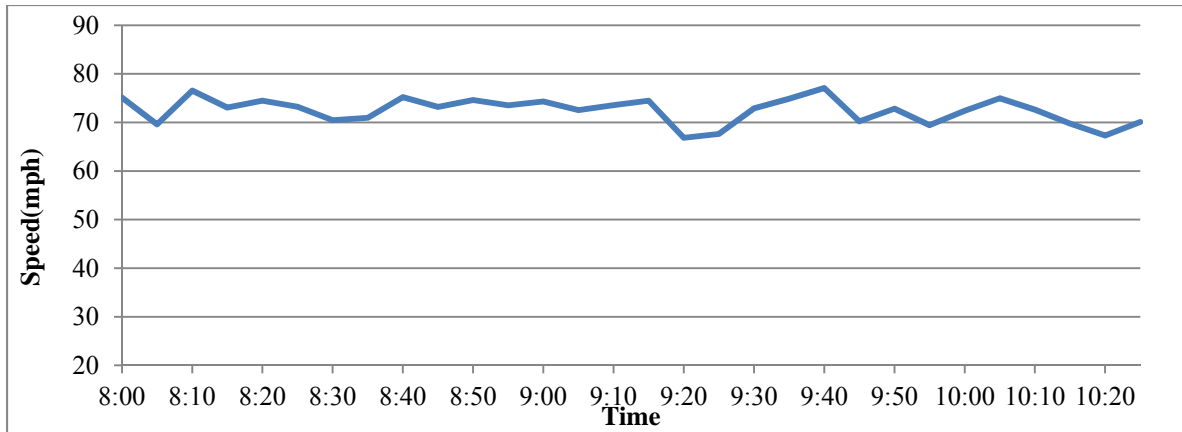
a) Detector 600831 HOT Lanes Speed Profile
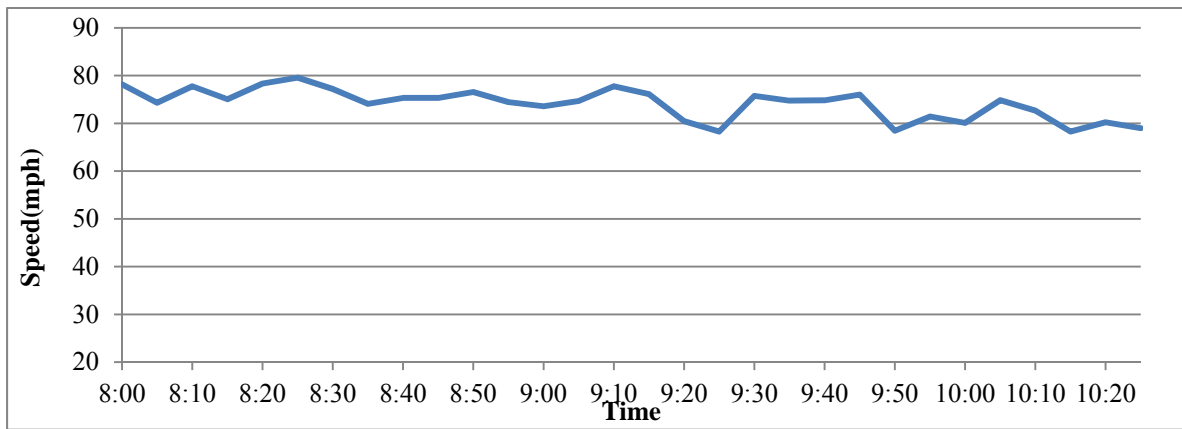
b) Detector 600791 HOT Lanes Speed Profile
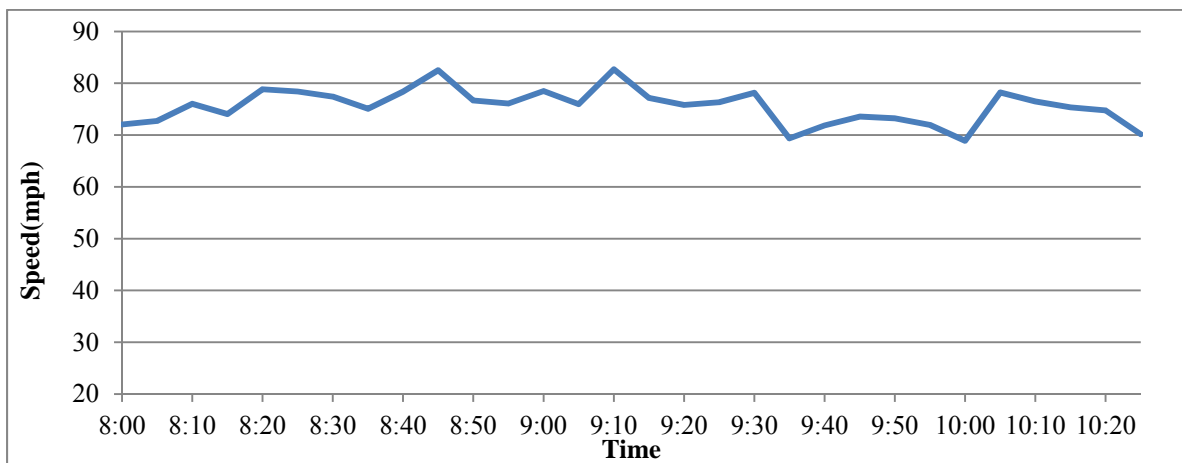
c) Detector 600731 HOT Lanes Speed Profile

FIGURE 3.20 Selected HOT Lanes Speed Profiles for Incident 4
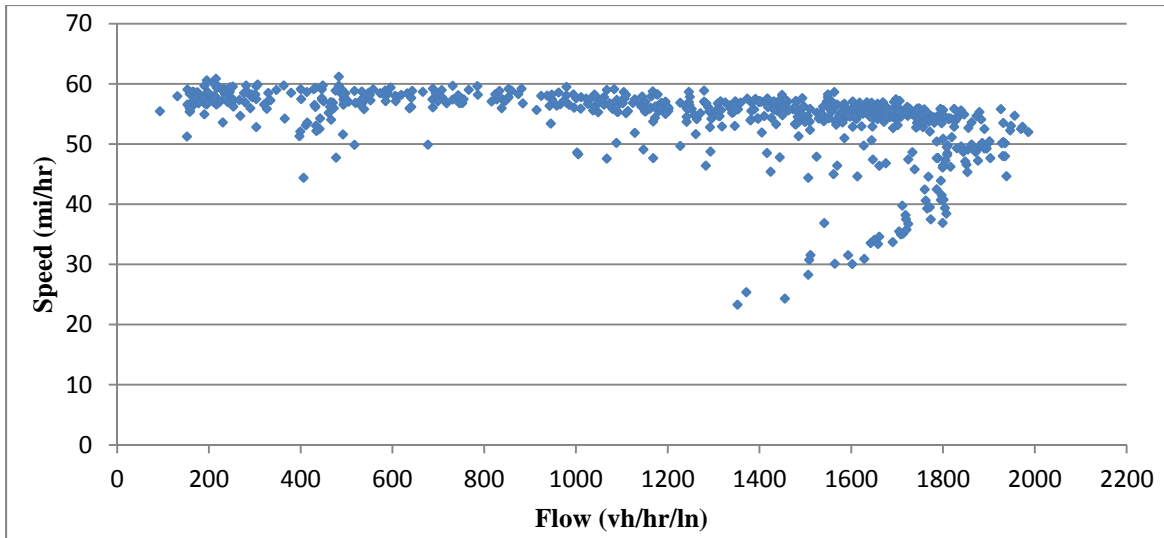
a) Speed-Flow Curve for Detector 600731 GP Lanes
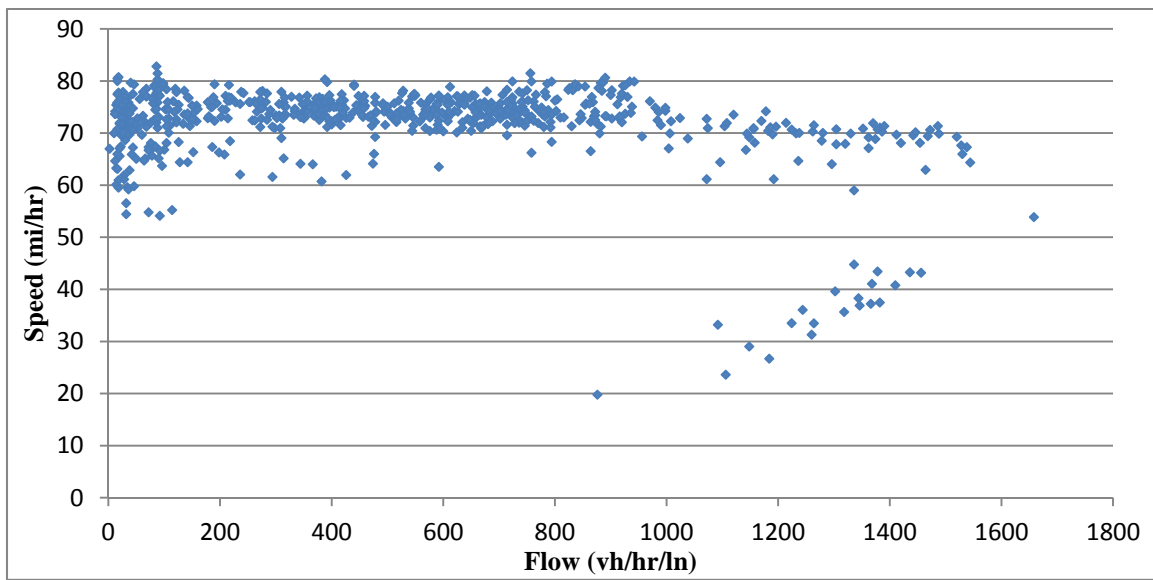
b) Speed-Flow Curve for Detector 600731 HOT Lanes

FIGURE 3.21 Speed-Flow Curves for Detector 600731

**TABLE 3.9 Incident Impacts on HOT and GP Lanes (Incident 4)**

Detector Station	GP Length (mi)	HOT Length (mi)	HOT Lanes				GP Lanes			
			Incident Travel Time (h)	Free-flow Travel Time (h)	Delay (veh-h)	Delay Index (%)	Incident Travel Time (h)	Free-flow Travel Time(h)	Delay (veh-h)	Delay Index (%)
600831	0.35	0.30	17.78	17.16	0.62	3.49	98.42	50.23	48.19	48.96
600801	0.26	0.55	17.44	16.21	1.23	7.05	87.63	55.84	31.79	36.28
600791	0.22	0.55	9.98	9.87	0.11	1.10	77.62	51.79	25.83	33.28
600781	0.35	0.50	27.07	24.46	2.61	9.64	98.1	74.64	23.49	23.91
600731	0.5	0.50	24.78	24.45	0.33	1.33	142.11	131.39	10.72	7.54
600701	0.3	0.55	17.79	16.03	1.76	9.89	67.06	64.61	2.45	3.65
Total	1.98	1,98	114.84	108.18	6.66		570	428.5	142.44	
Delay Index (%)			5.80				24.95			
			21.77							

47

Incident 5(ID Number: 310107)

This incident occurred at 7:01 AM, 11/17/2011 on the GP lanes of the segment of 95 Express and blocked three left lanes of four GP lanes for 37 minutes. The evaluation of traffic data obtained from upstream detectors shows that 14 GP lane detectors and 13 HOT lane detectors were affected by this incident. FIGURE 3.24 depicts the speed profiles around the incident time of three detectors in GP lanes, which are representing the first, middle and last affected detectors, respectively. FIGURE 3.25 also shows three detectors located in HOT lanes. Similar to other incidents, the segment-specific, overall delay and delay index are presented in TABLE 3.10.
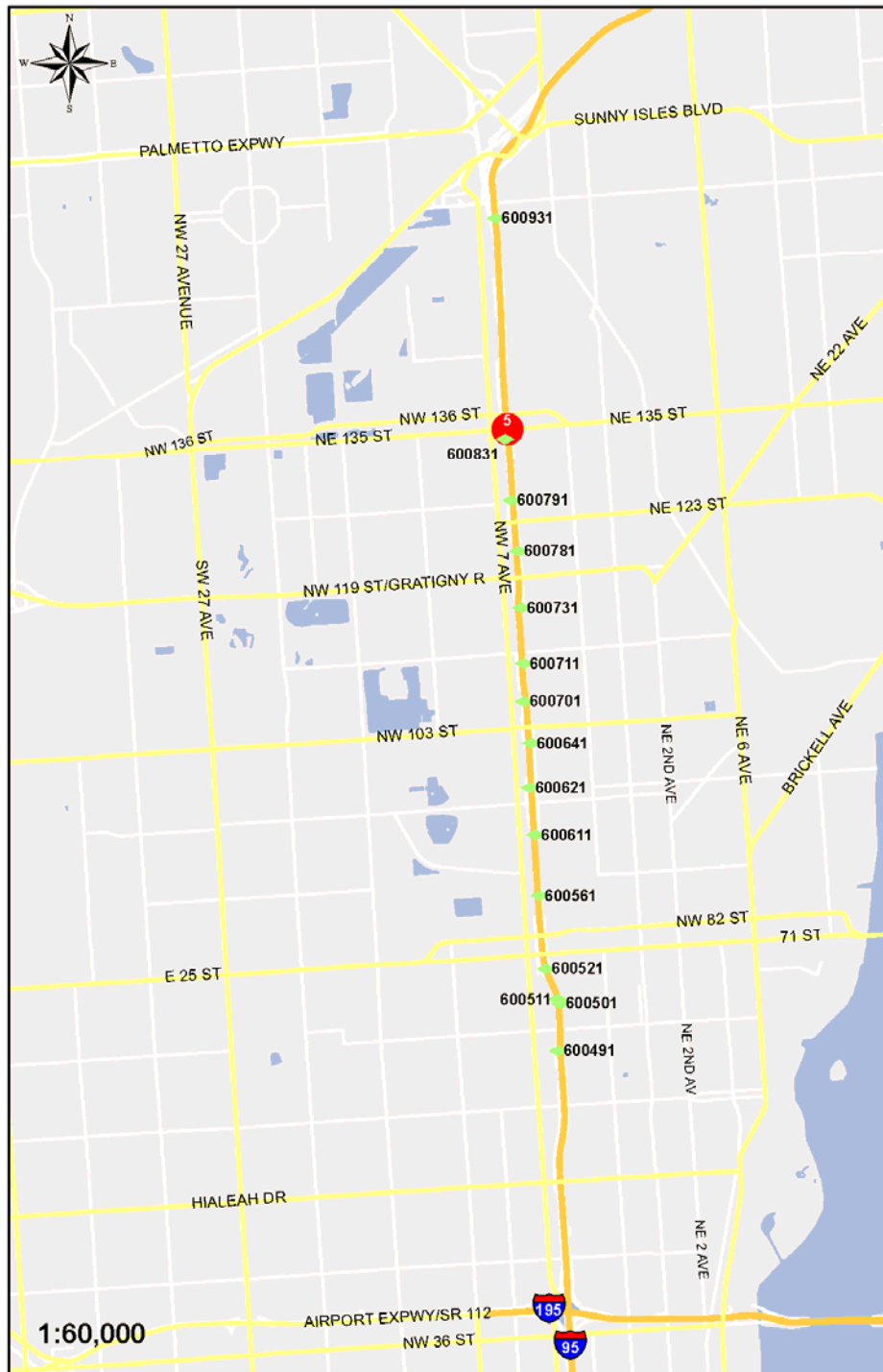
FIGURE 3.22 Incident 5 Site and Influenced Detectors
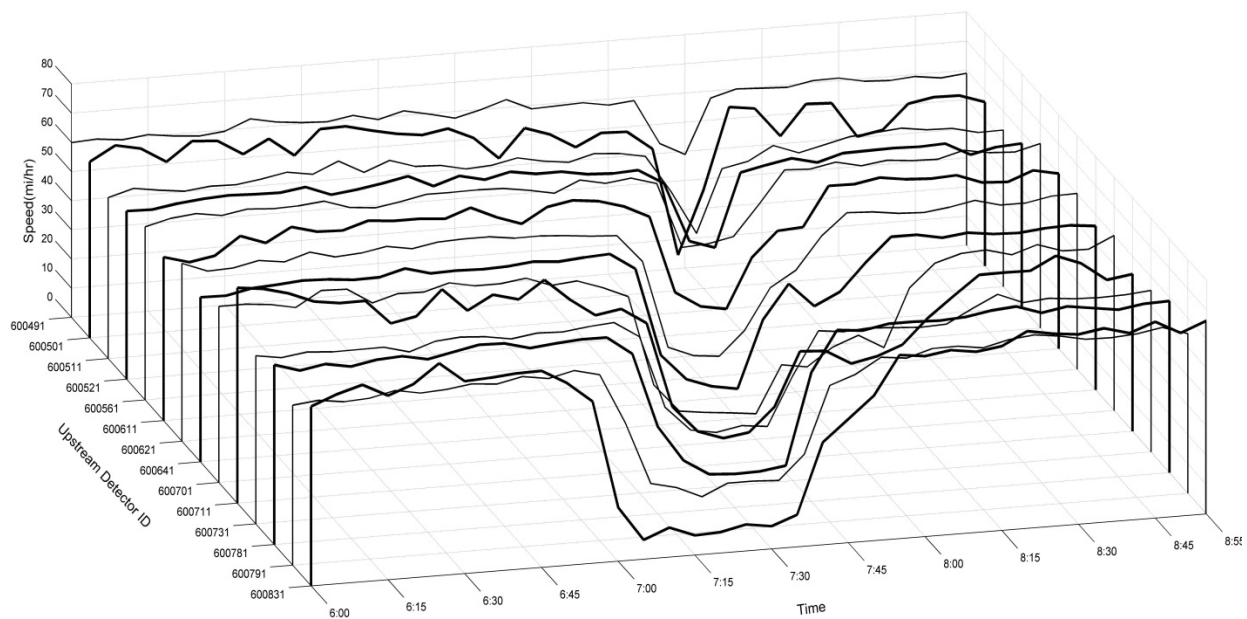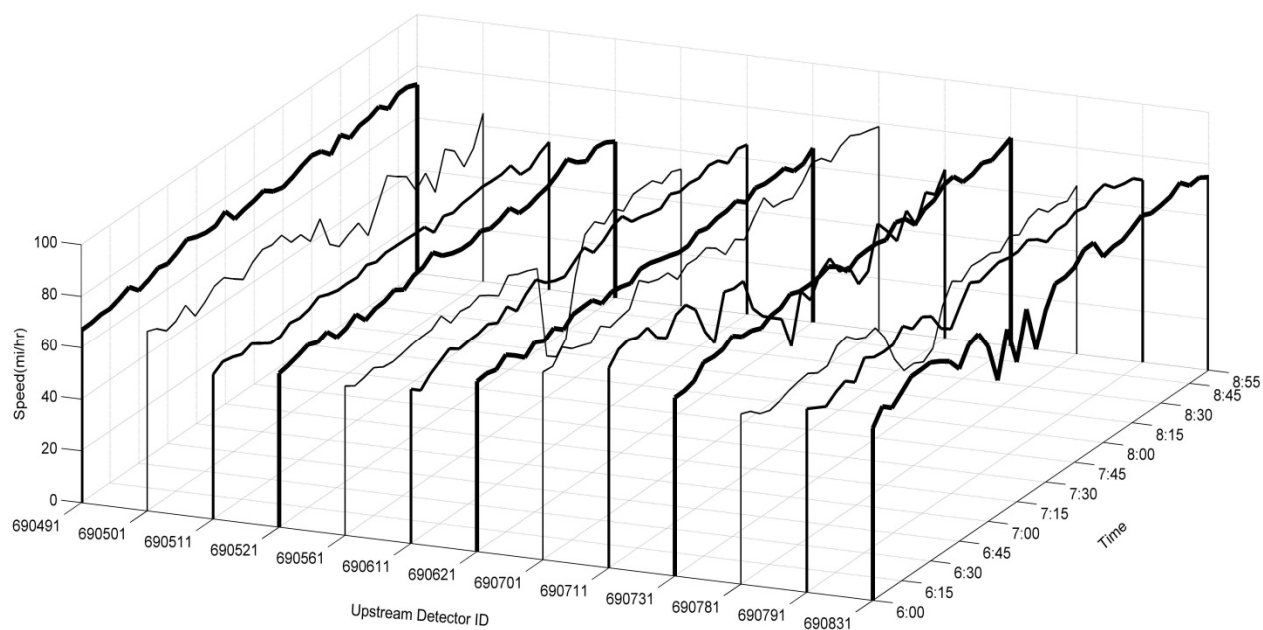
a) GP Lane segments

b) HOT Lane segments

FIGURE 3.23 Speed Profile of Upstream Detectors for Incident 5
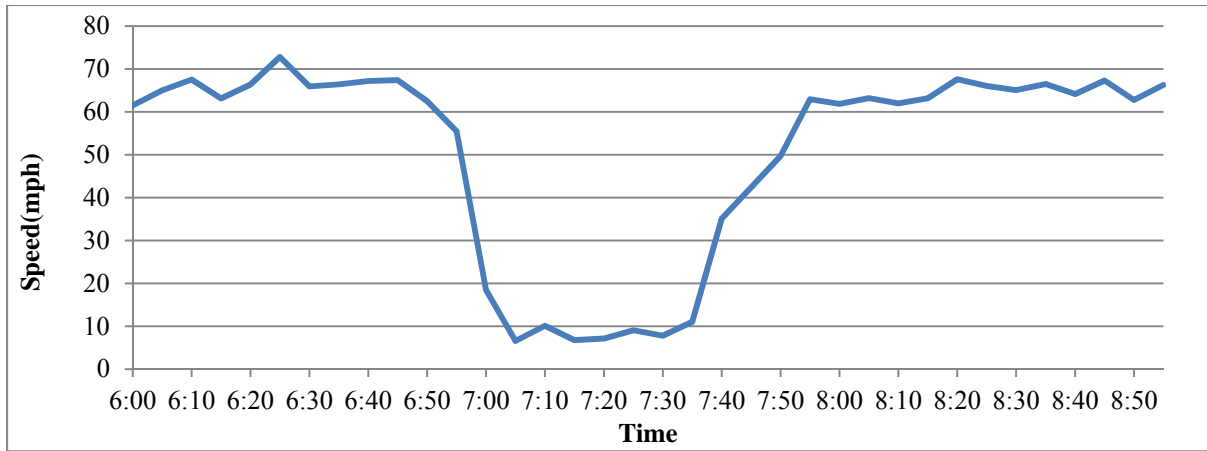
a) Detector 690831 GP Lanes Speed Profile
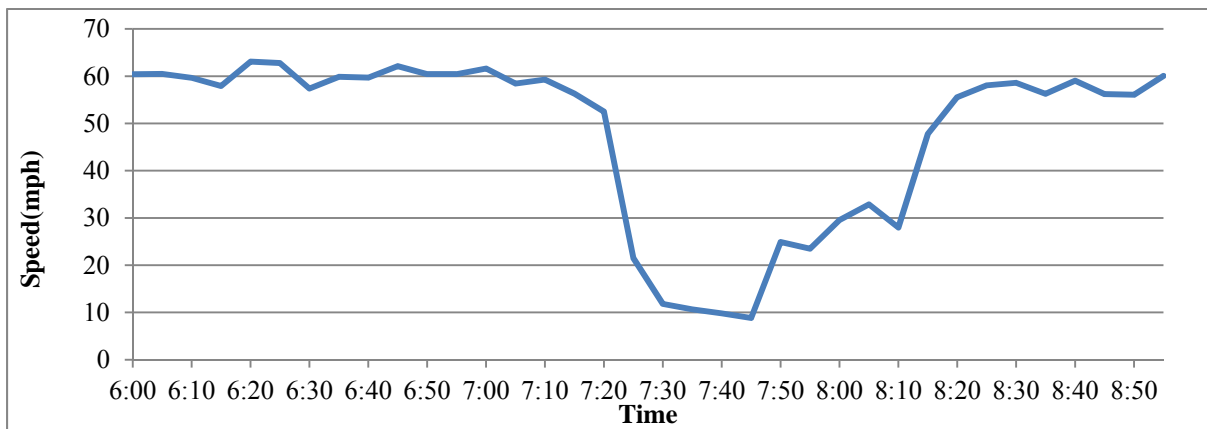
b) Detector 690701 GP Lanes Speed Profile
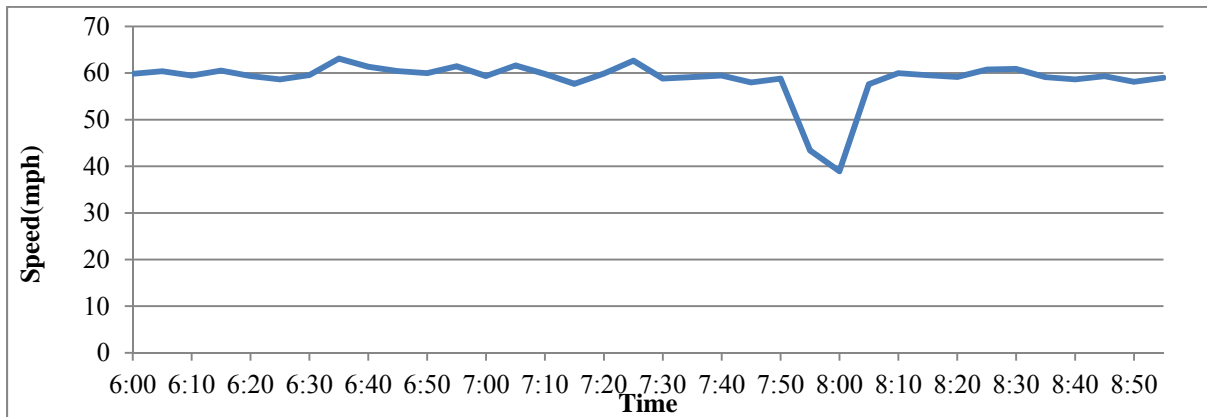
c) Detector 690491 GP Lanes Speed Profile

FIGURE 3.24 Selected GP Lanes Speed Profiles for Incident 5
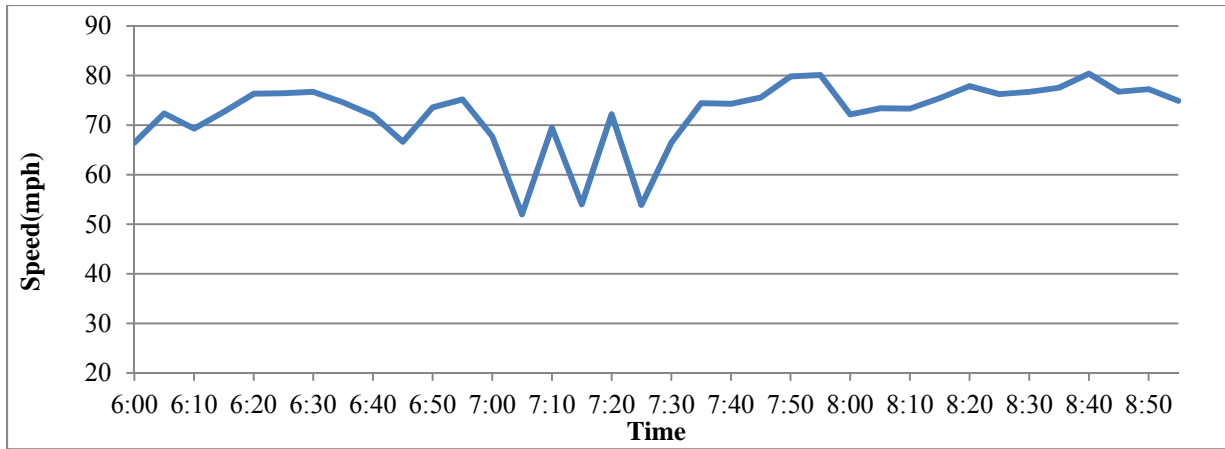
a)   Detector 690931 HOT Lanes Speed Profile
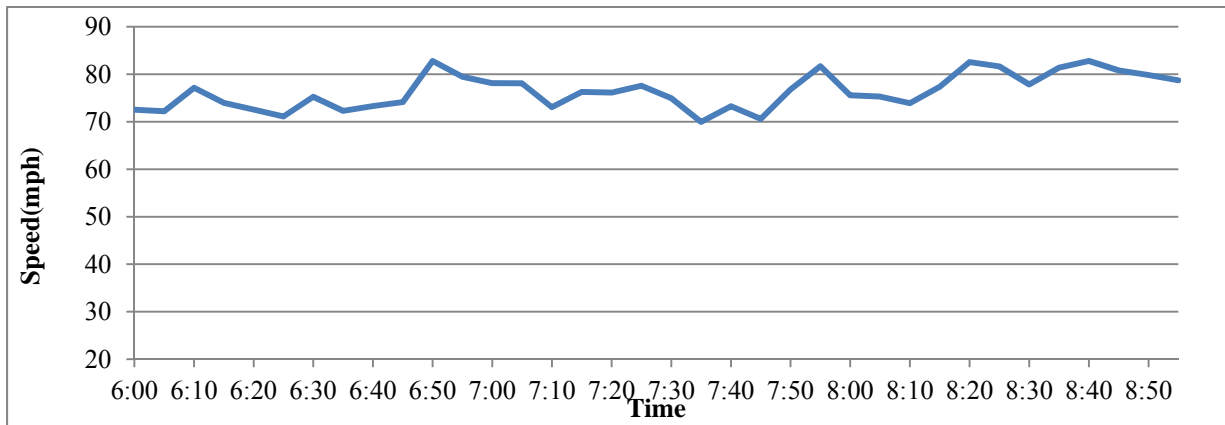

b)   Detector 690701 HOT Lanes Speed Profile
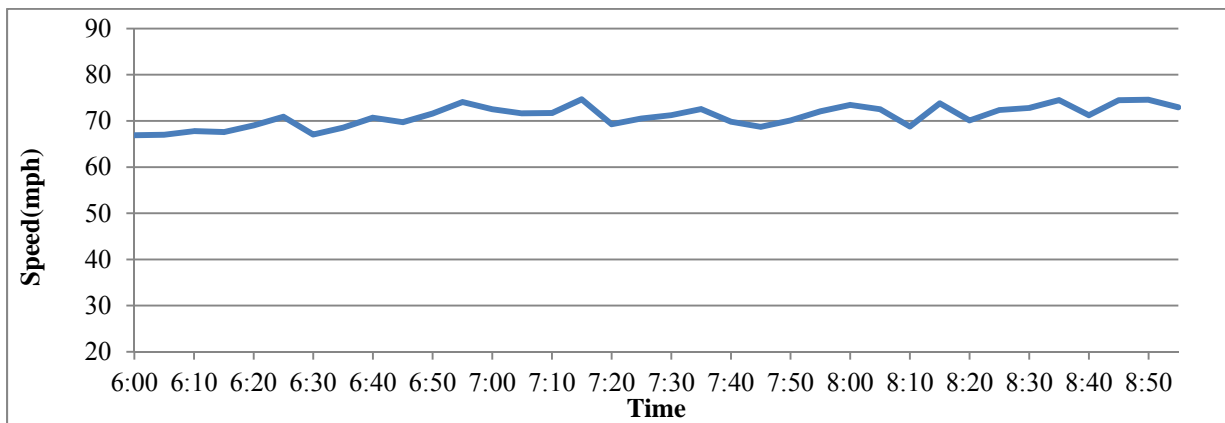
c)   Detector 690491 HOT Lanes Speed Profile

FIGURE 3.25 Selected HOT Lanes Speed Profiles for Incident 5
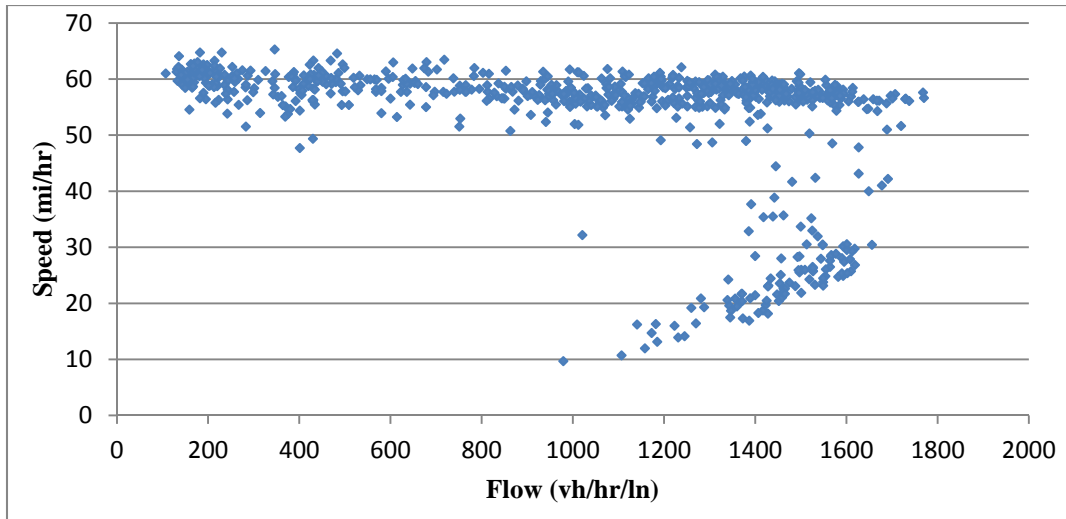
a) Speed-Flow Curve for Detector 600701 GP Lanes
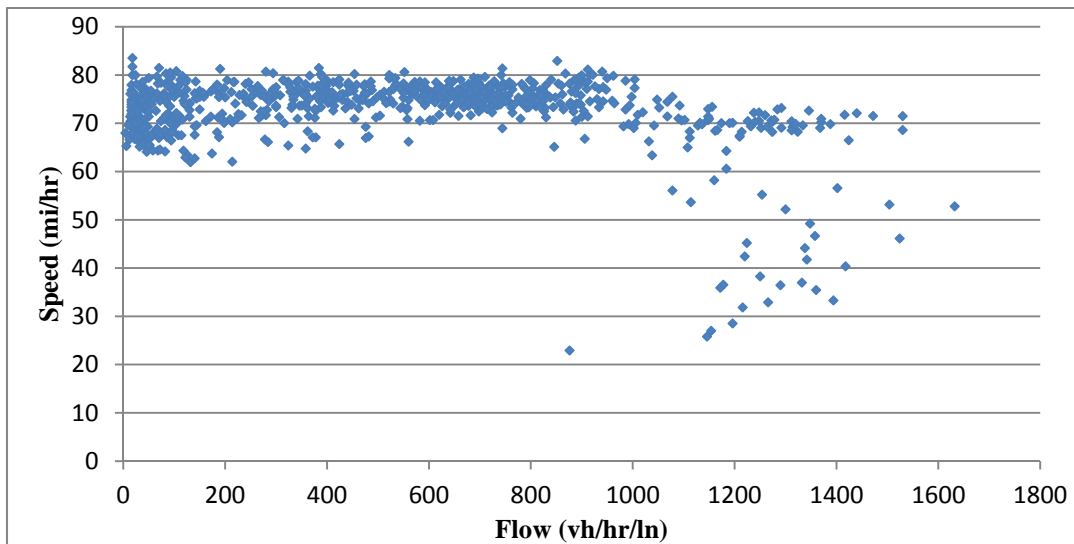
b) Speed-Flow Curve for Detector 600701 HOT Lanes

FIGURE 3.26 Speed-Flow Curves for Detector 600701

**TABLE 3.10 Incident Impact on HOT and GP Lanes (Incident 5)**

Detector Station	GP Length (mi)	HOT Length (mi)	HOT Lanes				GP Lanes			
			Incident Travel Time (h)	Free-flow Travel Time (h)	Delay (veh-h)	Delay Index (%)	Incident Travel Time (h)	Free-flow Travel Time(h)	Delay (veh-h)	Delay Index (%)
600831	0.26	0.26	15.66	14.77	0.89	5.68	72.99	41.27	31.72	43.46
600791	0.43	0.43	22.47	22.35	0.12	0.53	143.33	111.48	31.85	22.12
600781	0.35	0.35	29.27	25.05	4.22	14.42	106.95	83.99	22.96	21.47
600731	0.37	0.37	19.23	19.12	0.11	0.57	136.96	108.08	28.88	21.09
600711	0.31	0.31	27.38	20.87	6.51	23.78	129.89	70.69	59.2	45.58
600701	0.27	0.41	21.10	20.88	0.22	1.04	105.89	63.82	42.07	39.73
600641	0.28	-	-	-	-	-	96.38	72.29	24.09	24.99
600621	0.31	0.45	29.02	28.73	0.29	1.00	96.88	74.75	22.13	22.84
600611	0.36	0.36	21.91	21.86	0.05	0.23	107.28	92.95	14.33	13.36
600561	0.44	0.44	47.27	31.76	15.51	32.81	119.97	113.95	6.02	5.02
600521	0.35	0.35	25.73	25.58	0.15	0.58	85.36	80.07	5.29	6.20
600511	0.13	0.13	10.60	10.52	0.08	0.75	37.44	36.88	0.56	1.50
600501	0.16	0.16	12.28	11.12	1.16	9.45	50.27	40.6	9.67	19.24
600491	0.16	0.16	9.39	9.39	0	0.00	40.64	39.52	1.12	2.76
Total	4.18	4.18	291.31	262	29.31		1330.23	1030.34	299.89	
Delay Index (%)			10.06				22.54			
			20.30							

3.4 Summary

This chapter has examined how incidents on GP lanes and the responses to the incidents affected the operations of HOV/HOT lanes in District 4 and 6. Incident delays on HOV and HOT lanes were estimated based on the travel time difference under incident and incident-free conditions for five representative incidents using a large amount of archived data along I-95. The results are summarized in TABLE 3.11.

Based on the incident analyses, we have the following major observations:

- The results confirmed that the number of blocked lanes and the duration of lane blockage are not directly correlated to the magnitude of the impact of an incident on travel time. For example, for those three incidents on HOV segments, all have two right lanes blocked while incident 1 has the longest lane blockage duration. However, incident 1 turned out to impose the least amount of overall incident delay. Indeed, incident delay essentially depends on the demand-capacity ratios during the occurrence and recovery period of the incident. We thus should use cautions to use either the number of blocked

lanes or the duration of the lane blockage as the only criterion to decide whether the restrictions to HOV or HOT lanes should be lifted during incidents.

TABLE 3.11 Summary of Incident Impact on Managed Lanes

Incident ID	Lane Blockage	Lane Reopen Time (min)	Incident Type	Managed Lane Type	Impacted Area		Delay Index (%)		
					Number of Detectors	Length (mi)	Managed Lane	GP Lanes	Total
316748	2 Right Lanes (of 4 GP Lanes) Blocked	41	Crash	HOV	14	6.49	37.89	36.06	36.40
324919	2 Right Lanes (of 4 GP Lanes) Blocked	19	Crash	HOV	18	8.49	50.76	44.84	46.15
309947	2 Right Lanes (of 4 GP Lanes) Blocked	7	Disabled Vehicle	HOV	16	7.92	40.42	49.50	48.12
304026	2 Left Lanes (of 4 GP Lanes) Blocked	59	Disabled Vehicle	HOT	7	1.98	5.80	24.95	21.77
310107	3 Left Lanes (of 4 GP Lanes) Blocked	37	Crash	HOT	12	4.18	10.06	22.54	20.30

- Incidents on GP lanes of HOV segments have comparable impacts on both GP and HOV operations while incidents on GP lanes of HOT segments have considerably less impacts on HOT lanes than GP lanes. This can be primarily explained by different lane separation configurations. HOV lanes in District 4 are separated from GP lanes by double broken lines with no physical barrier. When major incidents happen on GP lanes, it is tempting for motorists on GP lanes to use HOV lane as a passing lane to bypass the incident location even though they are not supposed to do so. Such lane changing behaviors may trigger congestion on the HOV lanes. In contrast, HOT lanes in District 6, i.e., 95 Express, are segregated from GP lanes by plastic delineators and motorists can only access the lanes at the entrances. HOT lane users may still be influenced by an incident on GP lanes due to rubbernecking, but its impact is limited. Moreover, the

pricing algorithm of 95 Express prices the lanes solely based on their conditions without taking into the consideration the traffic conditions on GP lanes. Consequently, an incident on GP lanes has mild impacts on the HOT lanes, as observed in TABLE 3.11.

- For major incidents on GP lanes, it may be beneficial to temporally lift the restrictions of HOV or HOT lanes. Compared to the status quo, the benefit of opening HOV lanes may be limited, because, it appears that motorists on GP lanes have voluntarily utilized the HOV lanes as a passing lane during major incidents. Another possibility is that despite no written policy for opening HOV lanes to all traffic during a major incident, police officers on site may have adopted the practice of directing vehicles into the HOV lane to bypass the incident site.

4 DEVELOPMENT OF A FRAMEWORK TO DECIDE APPROPRIATENESS OF OPENING HOV/HOT LANES TO GP TRAFFIC

4.1 Introduction

Traffic incidents may severely reduce the operational capacity of freeway facilities. When the remaining capacity cannot serve the incoming flow, a freeway bottleneck is activated and travelers incur additional delays as a result of queuing. If a traffic incident occurs on GP lanes, it may be beneficial to allow the GP traffic into HOV/HOT lanes, which temporarily increases the bottleneck capacity. However, the opening of HOV/HOT lanes will adversely impact the operations of HOV/HOT lanes, thereby reducing the incentives for people to carpool or use public transit, which could potentially compromise the success of HOV/HOT lanes. It is thus critical to develop a framework to determine the appropriateness of diverting GP traffic to HOV/HOT lanes under different scenarios.

The traditional way of evaluating the effectiveness of a specific incident management scheme is to compare the incident-induced vehicle delays before and after the implementation of the scheme. In this study, however, the opening of HOV/HOT lanes involves two distinct types of freeway lanes, i.e., GP and HOV/HOT lanes, which generally operate at different average vehicle-occupancy rates. Therefore, the incident-induced passenger delay should also be considered as an equally relevant performance measure when it comes to the decision of whether to divert GP traffic to HOV/HOT lanes or not.

As discussed in the previous chapter, the methods used in the literature to estimate incident delays can be broadly classified into three categories, namely deterministic queuing, shock wave analysis and travel time difference approach. The travel time difference approach is adopted in Chapter 3 to estimate the incident delay primarily because the method can fully exploit the specific data set. That being said, the objective of this chapter is to develop a decision support tool that helps practitioners decide the appropriateness of opening HOV/HOT lanes, and the travel time difference approach would be too resource-intensive to be useful on a daily basis. The widely-used deterministic queuing analysis, on the other hand, requires far fewer inputs for delay estimation. We thus adopt the deterministic queuing analysis to estimate the incident-induced delay in this chapter. The remainder of this chapter is organized as follows: Section 4.2 presents the literature review. Section 4.3 derives closed-form incident delay formulas for both vehicle and passenger delays. Section 4.4 demonstrates the proposed methodology and provides recommendations on whether the opening of HOV/HOT lanes to GP traffic is warranted in five selected incidents. Section 4.5 summarizes this chapter.

4.2 Literature Review

The deterministic queuing analysis utilizes a queuing diagram as shown in FIGURE 4.1. The incoming demand is assumed to be constant and is represented by the upstream flow rate λ_1. μ_1 and μ_2 denote the bottleneck departure rates before and after the incident clearance, respectively, and their values are governed by the capacity, or the maximum discharge rate of the bottleneck. The magnitude of the incident delay is represented by the area inside the difference between the cumulative arrival and cumulative departure curves, i.e., the shaded area in FIGURE 4.1. The incident duration, time interval AB, is from the time the incident occurs to the time it is cleared, which is the sum of incident detection time, response time and clearance time (Morales, 1987).

The influence of the incident is over and the queue dissipates at time C. The time interval BC is the incident recovery duration.
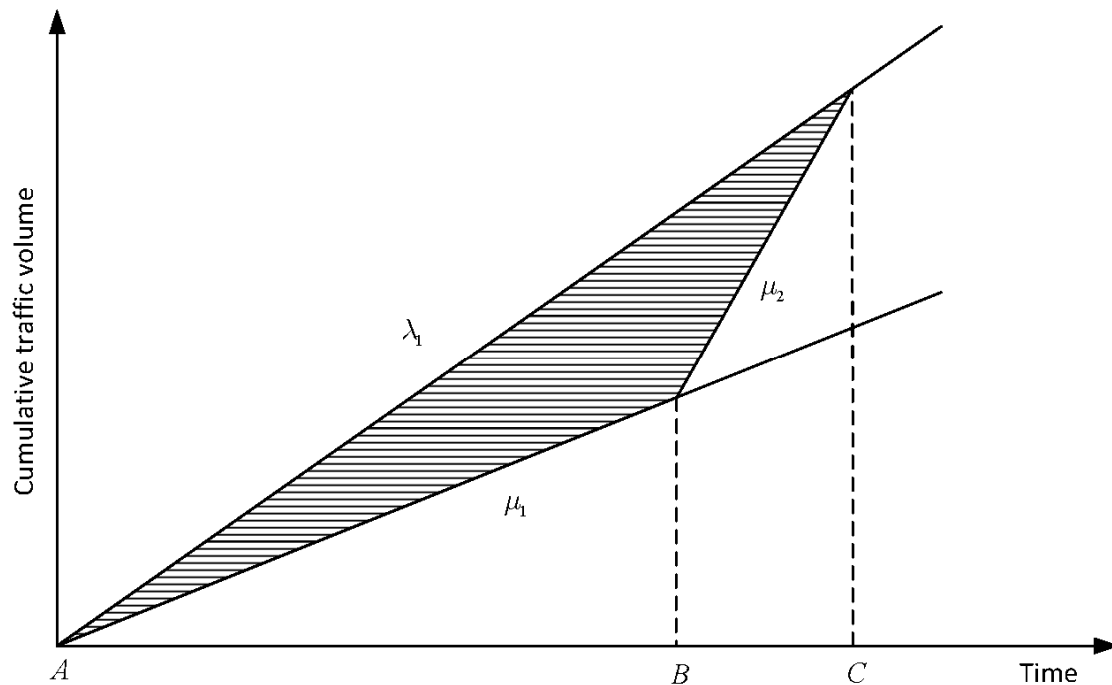
FIGURE 4.1 Cumulative Arrival and Departure Curves

Apart from the incident-related data, a number of parameters need to be pre-specified in order to properly quantify the incident delay. The following sections conduct a literature review on empirical studies of three parameters involved in the incident delay calculation.

4.2.1   Capacity reduction

The general wisdom that the impact of incidents is not proportional to the number of blocked lanes has been verified by Goolsby (1971). Goolsby investigated 27 incidents using detailed incident reports and video surveillance data of a three-lane segment along the Gulf Freeway in Houston, Texas. It is estimated that an incident blocking one lane of three lanes results in an average capacity reduction of 50% even though the physical reduction is only 33%. Goolsby further concluded that an incident blocking two lanes of three lanes reduces the capacity by an average of 79%. An incident that blocks the shoulder lane was found to reduce the capacity by an average of 33%. The disproportionate reduction in capacity is primarily caused by the inquisitive behavior (rubbernecking) of travelers.

TABLE 4.1 presents a widely-used lookup table showing the remaining capacity ratios under various incident conditions developed by Lindley (1986). The study used flow rates passing one-lane and shoulder incidents for typical four, six and eight lane freeways and estimated values for other situations since flow rates during all incident scenarios were not readily available. The lookup table developed provides rules of thumb in estimating the capacity reduction, and was

adopted by several most referred-to handbooks and manuals, such as Highway Capacity Manual (TRB, 2000) and Traffic Incident Management Handbook (FHWA, 2000).

TABLE 4.1 Portion of Freeway Capacity Available under Incident Conditions

Number of freeway lanes in each direction	Shoulder disablement	Shoulder accident	Lane blocked		
			One	Two	Three
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.25
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

Source: Lindley (1986)

Smith et al. (2003) suggested that capacity reduction should be modeled as a random variable. They measured the incident capacity reduction for over 200 incidents that occurred on urban freeways in the Hampton Roads region of Virginia. Their results also confirmed that traffic incidents reduce road capacity well beyond the physical blockage of lanes. An incident blocking one of three freeway lanes results in a mean capacity reduction of 63%, while an incident blocking two of three freeway lanes results in a mean capacity reduction of 77%.

4.2.2 *HOV/HOT lane capacity*

Previous studies show that HOV lanes provide less vehicular capacity than adjacent GP lanes. The HOV System Manual (TRB, 1998) recommends that the operating capacity of concurrent flow (buffer-separated/non-separated) HOV lanes is 1,200–1,500 vehicles per hour per lane (vphpl) and 1,500–1,800 vphpl for exclusive (barrier-separated) HOV lanes. Kwon and Varaiya (2008) estimated a reduction of 20% in capacity values of HOV lanes from 2,000 vphpl to 1,600 vphpl after the activation of HOV lanes. Guin et al. (2008) observed that the effective capacity values of buffer-separated HOV lanes are in the range of 1,400–1,700 vphpl while 2,400–2,600 vphpl for GP lanes. Burris and Lipnicky (2009) reported that the capacity of a barrier-separated HOV lane is approximately 1,600 vphpl, whereas the capacities of GP lanes are closer to 2,200 vphpl and 2,000 vphpl in two directions, respectively. Manda et al. (2011) investigated a stretch of HOV lane on I-95 in the District 4 of Florida Department of Transportation (FDOT) and concluded that the reduction in capacity of HOV lane is in the range of 10% to 25% compared with the adjacent GP lanes. Liu et al. (2011) estimated that the HOT lane capacity at the SR-91 Express Lane system in Orange County, California is between 1,650 and 1,800 vphpl. In this study, we will estimate the capacity values of GP and HOV/HOT lanes based on the speed-flow curves developed in the previous chapter.

4.2.3 *Average vehicle occupancy*

The incident delay analysis in this study involves multiple types of lanes, and vehicle occupancy varies depending on location, time and trip purpose. Therefore, it is critical to have the corresponding average vehicle occupancy of each facility when estimating the incident-induced

passenger delay. Based on the nationwide statistics, the average vehicle occupancy for home-to-work trips has declined from 1.3 in 1977 to about 1.14 in 1995 (LAO, 2000). LACMTA (2002) conducted a HOV performance evaluation study in Caltrans District 7, and they concluded that the average vehicle occupancy for HOV 2+ lanes varies between 2.0 to 2.3. Nee et al. (2004) investigated 11 sites of five HOV corridors in the Puget Sound region, and they found that the average vehicle occupancy on GP lanes is in the range of 1.0 to 1.3 while the average vehicle occupancy on HOV lanes ranges from 2.1 to 3.4 at most sites except one site, which has the average vehicle occupancy of 9.2 due to the heavy use of transit buses. ConnDOT (2010) reported that the average vehicle occupancy values on two HOV facilities have been ranging from 2.1 to 2.2 since the state lowered its HOV occupancy requirement from three to two persons in 1993.

It can be observed that the respective values of average vehicle occupancy on GP and HOV lanes are relatively consistent in the literature. Nevertheless, the average vehicle occupancy on HOT lanes varies significantly from facility to facility. Shoup and Brown (2001) reported that 80 percent of vehicles traveling on the SR-91 HOT lanes pay tolls, and only 20 percent of the travelers are HOV with three or more persons, who are exempted from tolling. As a result of the high patronage of single occupancy vehicles (SOVs), the average vehicle occupancy on the HOT lanes is 1.65. Transit Cooperative Research Program (TCRP) Report 95 (TRB, 2006) mentioned much higher average vehicle occupancy on HOT lanes. The average vehicle occupancy values reported on GP and HOT lanes of the I-394 MnPASS Express Lanes are 1.01 and 2.88, respectively.

4.3   Closed-Form Incident Delay Derivation

The methodology we propose to determine the appropriateness of lifting HOV/HOT restrictions is to compare the incident delays. This section focuses on the derivation of closed-form expressions for incident delays under the status quo condition as well as in the situation when HOV/HOT lanes are open to GP traffic after an incident. The derivation follows the deterministic queuing analysis approach and calculates the area between the cumulative arrival and departure curves. For both situations in this study, the potential demand variation that might occur due to the incident is not considered. It is also noted that the queuing diagram only provides incident-induced vehicle delays. The passenger delay can be obtained by multiplying the vehicle delay by the corresponding average vehicle occupancy values.

For the status quo case, the shaded triangle in FIGURE 4.1 illustrates the vehicle delay, which is relatively straightforward to calculate. When HOV/HOT lanes are open to GP traffic in an incident, both arrival and departure rates change due to the opening. Furthermore, two possible scenarios may happen, and the closed-form delay formulas for these two scenarios need to be derived separately. One possible scenario is that the additional capacity brought by the opening of HOV/HOT lanes speeds up the queue dissipation process quickly enough that the queue is cleared before the incident on GP lanes is fully removed from the freeway. The other possible outcome is that the bottleneck queue dissipates only after the incident is fully cleared. The Sections 4.3.1 and 4.3.2 present the derivation of closed-form incident delay expressions for these two scenarios. To facilitate the discussion, a list of notations is provided as follows:

t_0: Incident start time.
t_1: Time to lift the occupancy restriction of HOV/HOT lanes.

t_2: Queue clearance time when the occupancy restriction is lifted.

t_3: Incident clearance time.

t_4: Queue clearance time under the status quo condition.

Q_1: Incident-induced vehicle delay under the status quo condition.

Q_2: Incident-induced vehicle delay when the occupancy restriction is lifted.

Q_3: Homogenous user queuing delay.

Q_4: Heterogeneous user queuing delay.

x_1: Recovery duration when the occupancy restriction is lifted.

x_2: Recovery duration under the status quo condition.

P_1: Passenger incident delay under the status quo condition.

P_2: Passenger incident delay when the occupancy restriction is lifted.

O_G: Average vehicle occupancy for GP lane users.

O_H: Average vehicle occupancy for HOV/HOT lane users.

λ_1: Arrival flow rate under the status quo condition.

λ_2: Arrival flow rate when the occupancy restriction is lifted.

λ_G: GP lane demand.

λ_H: HOV/HOT lane demand.

μ_1: Departure flow rate after the incident occurs.

μ_2: Departure flow rate after the queue clearance.

μ_3: Departure flow rate after the occupancy restriction is lifted.

μ_4: Departure flow rate after the queue clearance when the occupancy restriction is lifted.

C_G: Full capacity of GP lanes.

C_H: Full capacity of HOV/HOT lanes

β_1: Remaining capacity ratio under the status quo condition.

β_2: Remaining capacity ratio when the occupancy restriction is lifted.

4.3.1 Scenario 1: $t_2 \leq t_3$

The arrival flow rate λ_1 is equal to the traffic flow rate on GP lanes before the incident occurs, i.e., λ_G. After the HOV/HOT lanes are open to GP traffic, the arrival rate of the bottleneck includes traffic flow on both GP and HOV/HOT lanes, i.e., $\lambda_2 = \lambda_G + \lambda_H$. The incident reduces the capacity of the bottleneck to μ_1, and $\mu_1 = \beta_1 C_G$. After the incident is fully cleared from the freeway, the bottleneck capacity recovers to the level before the incident occurs, i.e., $\mu_2 = C_G$. When the restriction of occupancy on HOV/HOT lanes is lifted, the capacity of the bottleneck is effectively increased to μ_3, and $\mu_3 = \beta_2(C_G + C_H)$, and travelers on GP lanes have the access to utilize the managed lanes to bypass the incident site. In this scenario, the queue dissipates before the incident on GP lanes is fully removed from the freeway as shown in FIGURE 4.2. Although the bottleneck capacity will be further increased when the incident is fully removed, it does not affect the incident delay calculation. It is noted that t_0, t_1 and t_3 can be extracted from archived incident reports, therefore, the closed-form incident delay expression should be a function of them and also bottleneck departure and arrival flow rates.

Since t_2 and t_4 are not readily available from incident reports, they can be calculated as $t_2 = t_1 + x_1$ and $t_4 = t_3 + x_2$, respectively.

$$x_1 = \frac{(\lambda_1 - \mu_1)t_1}{(\mu_3 - \lambda_2)}$$

$$x_2 = \frac{(\lambda_1 - \mu_1)t_3}{(\mu_2 - \lambda_1)}$$

The incident-induced vehicle delay under the status quo condition:
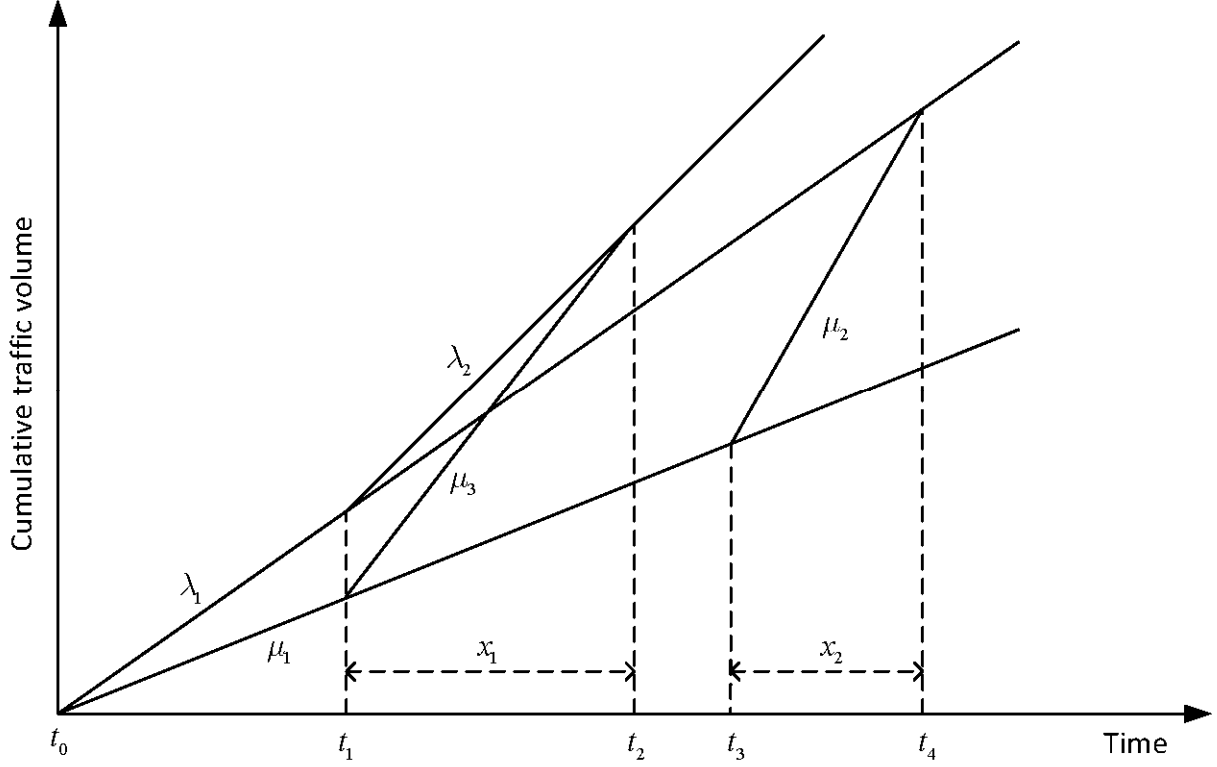
FIGURE 4.2 Queuing Diagram for Scenario 1

$$Q_1 = \frac{(\lambda_1 - \mu_1)t_3(t_3 + x_2)}{2}$$

$$= \frac{(\lambda_1 - \mu_1)t_3[t_3(\mu_2 - \lambda_1) + (\lambda_1 - \mu_1)t_3]}{2(\mu_2 - \lambda_1)}$$

$$= \frac{t_3{}^2(\lambda_1 - \mu_1)(\mu_2 - \mu_1)}{2(\mu_2 - \lambda_1)}$$

The incident-induced vehicle delay when the occupancy restriction is lifted can be derived as follows:

$$Q_2 = \frac{(\lambda_1 - \mu_1)t_1(t_1 + x_1)}{2}$$

$$= \frac{(\lambda_1 - \mu_1)t_1[t_1(\mu_3 - \lambda_2) + (\lambda_1 - \mu_1)t_1]}{2(\mu_3 - \lambda_2)}$$

$$= \frac{t_1{}^2(\lambda_1 - \mu_1)(\mu_3 - \lambda_2 + \lambda_1 - \mu_1)}{2(\mu_3 - \lambda_2)}$$

4.3.2   Scenario 2: $t_2 > t_3$

In this scenario, the bottleneck queue dissipates after the incident is fully cleared as shown in FIGURE 4.3. As a result, the bottleneck capacity is further improved from μ_3, and reaches the full capacity of all lanes, including both GP and HOV/HOT lanes, i.e., $\mu_4 = C_G + C_H$.
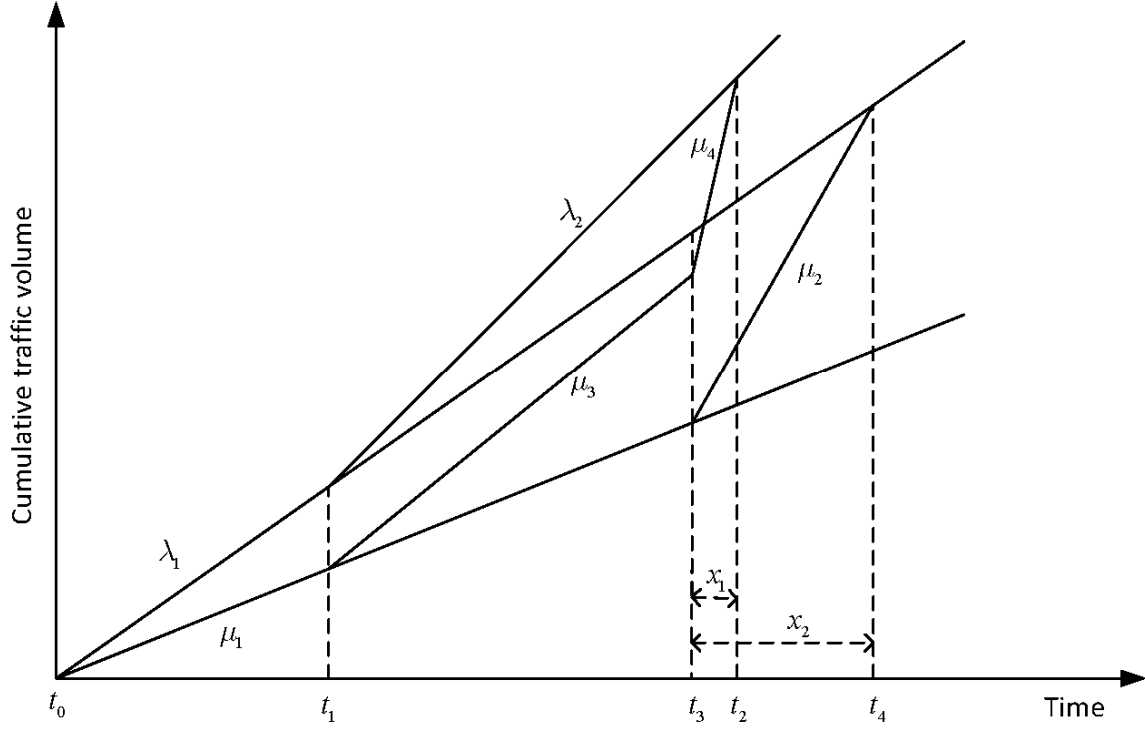
FIGURE 4.3 Queuing Diagram for Scenario 2

Similar to scenario 1, t_2 and t_4 need to be calculated by referring to t_3. They can be calculated as $t_2 = t_3 + x_1$ and $t_4 = t_3 + x_2$ respectively.

$$x_1 = \frac{[\lambda_1 t_1 + \lambda_2(t_3 - t_1)] - [\mu_1 t_1 + \mu_3(t_3 - t_1)]}{(\mu_4 - \lambda_2)}$$

$$= \frac{t_1(\lambda_1 - \lambda_2 - \mu_1 + \mu_3) + t_3(\lambda_2 - \mu_3)}{(\mu_4 - \lambda_2)}$$

$$x_2 = \frac{(\lambda_1 - \mu_1)t_3}{(\mu_2 - \lambda_1)}$$

The incident-induced vehicle delay under the status quo condition is exactly the same as Q_1 in scenario 1:

63

$$Q_1 = \frac{t_3{}^2(\lambda_1 - \mu_1)(\mu_2 - \mu_1)}{2(\mu_2 - \lambda_1)}$$

The incident-induced vehicle delay when the occupancy restriction is lifted can be derived as follows:

$$Q_2 = \frac{t_1{}^2(\lambda_1 - \mu_1)}{2} + \frac{[2(\lambda_1 - \mu_1)t_1 + (\lambda_2 - \mu_3)(t_3 - t_1)](t_3 - t_1)}{2} + \frac{(\mu_4 - \lambda_2)x_1{}^2}{2}$$

$$= \frac{(2t_3 - t_1)t_1(\lambda_1 - \lambda_2 - \mu_1 + \mu_3) + t_3{}^2(\lambda_2 - \mu_3)}{2} + \frac{[t_1(\lambda_1 - \lambda_2 - \mu_1 + \mu_3) + t_3(\lambda_2 - \mu_3)]^2}{2(\mu_4 - \lambda_2)}$$

4.4 Incident-Induced Passenger Delay

Under the status quo condition, the passenger delay can be obtained by simply multiplying the vehicle delay by the average vehicle occupancy of GP lane users.

$$P_1 = O_G Q_1$$

On the other hand, the incident-induced vehicle delay consists of two parts, namely homogenous user queuing delay, Q_3, and heterogeneous user queuing delay, Q_4.

$$Q_3 = \frac{t_1{}^2(\lambda_1 - \mu_1)}{2}$$

$$Q_4 = Q_2 - \frac{t_1{}^2(\lambda_1 - \mu_1)}{2}$$

From the time the incident occurs to the time of opening of HOV/HOT lanes, travelers queuing at the bottleneck are all GP lane users and hence the delay experienced during this period is the homogenous user queuing delay. The opening of HOV/HOT lanes makes users from two distinct types of lanes (i.e., GP and HOV/HOT lanes) join the same queue, and hence the incident delay experienced after the opening of HOV/HOT lanes is termed the heterogeneous user queuing delay. The passenger delay during this period can be obtained by multiplying the heterogeneous user queuing delay by the weighted mean of the vehicle occupancy values.

$$P_2 = Q_3 O_G + Q_4 \left[\frac{\lambda_G O_G + \lambda_H O_H}{\lambda_G + \lambda_H} \right]$$

$$= \frac{t_1{}^2(\lambda_1 - \mu_1)}{2} O_G + \left[Q_2 - \frac{t_1{}^2(\lambda_1 - \mu_1)}{2} \right] \left[\frac{\lambda_G O_G + \lambda_H O_H}{\lambda_G + \lambda_H} \right]$$

4.5 Numerical Examples

To illustrate the methodology developed in the above section, we will apply the closed-form incident delay formulas to calculate the incident-induced vehicle and passenger delays for the five incident cases we identified in the previous chapter. TABLE 4.2 shows the general description of the five selected incidents.

TABLE 4.2 General Description of Five Selected Incidents

Incident ID	Lane blockage	Lane reopen time (min)	Incident type	Managed lane type	Impacted area	
					Number of detectors	Length (mi)
316748	2 right lanes (of 4 GP lanes) blocked	41	Crash	HOV	14	6.49
324919	2 right lanes (of 4 GP lanes) blocked	19	Crash	HOV	18	8.49
309947	2 right lanes (of 4 GP lanes) blocked	7	Disabled Vehicle	HOV	16	7.92
304026	2 left lanes (of 4 GP lanes) blocked	59	Disabled Vehicle	HOT	7	1.98
310107	3 left lanes (of 4 GP lanes) blocked	37	Crash	HOT	12	4.18

For the capacity reduction ratios, TABLE 4.1 is adopted since it provides a widely-used guideline on the capacity reduction in incident situations. The capacity values of GP and HOV/HOT lanes are estimated from the speed-flow curves prepared in Chapter 3. When these field-measured data are not available, capacity values suggested by empirical studies in the literature can be used.

An important observation from Chapter 3 is that some motorists on GP lanes may voluntarily utilize the HOV lanes as a passing lane during major incidents and disturb the HOV lane operation. As a result, it is not appropriate to entirely ignore the incident-induced delay on HOV lanes in the status quo situation as assumed in Section 4.3. On the other hand, it is unclear how significant the impact of this voluntary behavior can be on the available capacity of HOV and GP lanes. By adding one more lane, the remaining capacity ratio should be higher according to TABLE 4.1. However, the HOV lane can only be treated as partially open and the remaining capacity should be less than that when the HOV lane is fully open to GP traffic. We propose a rule of thumb to tackle this problem without changing the closed-form incident delay formulas derived in Section 3.3. For all GP lane incidents occurring on HOV lane segments, the revised remaining capacity ratio $\bar{\beta}_1$ for the status quo situation should be obtained by interpolating between the corresponding two rows in TABLE 4.1 and a revised remaining capacity ratio lookup table under incident conditions is developed in TABLE 4.3. The arrival flow $\lambda_1 = \lambda_G + \lambda_H$ and departure rate $\mu_1 = \bar{\beta}_1(C_G + C_H)$. When the incident is fully cleared from the freeway, the discharging flow rate should be set at the full capacity across all lanes until the queue dissipates.

David et al. (1998) described a performance monitoring system for the I-95 HOV lanes in South Florida and mentioned that the average vehicle occupancy rates for GP and HOV lanes are in the ranges of $1.12 - 1.21$ and $1.80 - 2.27$, respectively. It is reported by the National TDM and Telework Clearinghouse (2010) that the average vehicle occupancy for work trips in Florida is 1.08 and the average carpool size is 2.2 based on the Census 2000 data. According to the latest 95 Express Annual Report (FDOT, 2013), the average vehicle occupancy rates for the

northbound GP and HOT lanes are 1.14 and 1.61 respectively in 2012. In this study, the average occupancy rates on GP, HOV and HOT lanes are assumed to be 1.1, 2.2 and 1.6, respectively.

TABLE 4.3 Revised Remaining Capacity Ratio for HOV Segment

Number of GP lanes in each direction (with one HOV lane)	Shoulder disablement	Shoulder accident	GP lanes blocked		
			One	Two	Three
2	0.97	0.82	0.42	0.09	N/A
3	0.99	0.84	0.54	0.21	0.07
4	0.99	0.86	0.62	0.33	0.17
5	0.99	0.88	0.68	0.45	0.23
6	0.99	0.90	0.73	0.54	0.31
7	0.99	0.92	0.77	0.60	0.39

From the incident reports, we can extract t_0, t_1 and t_3. t_0 is the time when an incident occurs. It is actually difficult to know exactly when an incident occurs based on an incident report due to the delay between the actual incident time and the time the traffic authority is informed. In this study, the entry "incident detected time" in the incident report is chosen to be t_0. To fully exploit the additional capacity brought by the opening of HOV/HOT lanes, traffic authorities may want to lift the occupancy restriction as soon as an incident is detected if the opening is warranted. However, traffic authorities still have to rely on first responders to assess the severity of the incident and also to help divert traffic into the HOV/HOT lanes if necessary. Therefore, practically speaking, the earliest time possible for traffic authorities to make the decision of whether to open the HOV/HOT lanes is the time that first responders arrive at the incident site. The entry "first responder arrival time" in the incident report is used to approximate t_1. t_3 is the incident clearance time and the entry "lane reopen time" can be used to approximate it. All inputs for the closed-form incident delay formulas are listed in TABLE 4.4. It is worth mentioning that the time points reported in incident reports should be treated with caution because sometimes they are estimates made by the first responders on the scene and may not necessarily reflect the actual time in the field. We assume a minimum of five minutes between the "incident occurrence time" and "first responder arrival time" and hence $t_1 \geq 5$ minutes.

The resulting vehicle and passenger delays using the closed-form incident formulas derived are both reported in TABLE 4.5. For each incident, the incident delays under two situations, i.e., the status quo and the opening of HOV/HOT lanes, are considered. In all five incidents, the queue dissipates after the incident is fully cleared, i.e., $t_2 > t_3$, the delay formulas in Section 3.2 apply here.

The results in TABLE 4.5 show that it would be beneficial to open the HOV/HOT lanes in the first, fourth and the last incident while not appropriate to open the HOV lanes in the second and third incident based on both vehicle and passenger delay criteria. Although evaluating both criteria provides consistent recommendations for all five incidents in this study, the two delay

66

indicators may suggest contradicting recommendations in other incident scenarios. For example, FIGURE 4.4 depicts the change of the passenger delay with respect to the average vehicle occupancy on HOT lanes for the fourth incident. It can be observed that the passenger delay in the opening HOT lanes situation surpasses that in the status quo situation if the average vehicle occupancy on HOT lanes exceeds 5.35. It would not be beneficial in terms of passenger delay to lift the occupancy restriction on HOT lanes while the vehicle delay criterion suggests the opposite. When these two criteria suggest contradicting recommendations, the traffic authority needs to make a trade-off between different performance measures based on their operational objectives.

TABLE 4.4 Inputs for the Closed-Form Incident Delay Formulas

Model input	Incident ID				
	316748	324919	309947	304026	310107
λ_1(veh/h)	6808	5652	4416	4192	4944
λ_2(veh/h)	6808	5652	4416	5844	6012
μ_1(veh/h)	3366	3086	3234	1900	884
μ_2(veh/h)	10200	9350	9800	7600	6800
μ_3(veh/h)	4080	3740	3920	5350	3564
μ_4(veh/h)	10200	9350	9800	10700	9900
t_1(min)	5	5	5	26	5
t_2(min)	41	19	7	59.3	36.9

TABLE 4.5 Incident Delay Calculation

Incident ID	Vehicle delay (veh-h)		Passenger delay (person-h)		Recommendation on lifting vehicle occupancy restriction
	Status quo	Opening HOV/HOT	Status quo	Opening HOV/HOT	
316748	1626.98	1226.34	1789.67	1482.40	Lift
324919	114.28	133.67	125.71	168.32	Do not lift
309947	0.79	1.17	0.87	1.50	Do not lift
304026	1872.26	1007.89	2059.49	1220.72	Lift
310107	2447.35	885.79	2692.09	1051.79	Lift
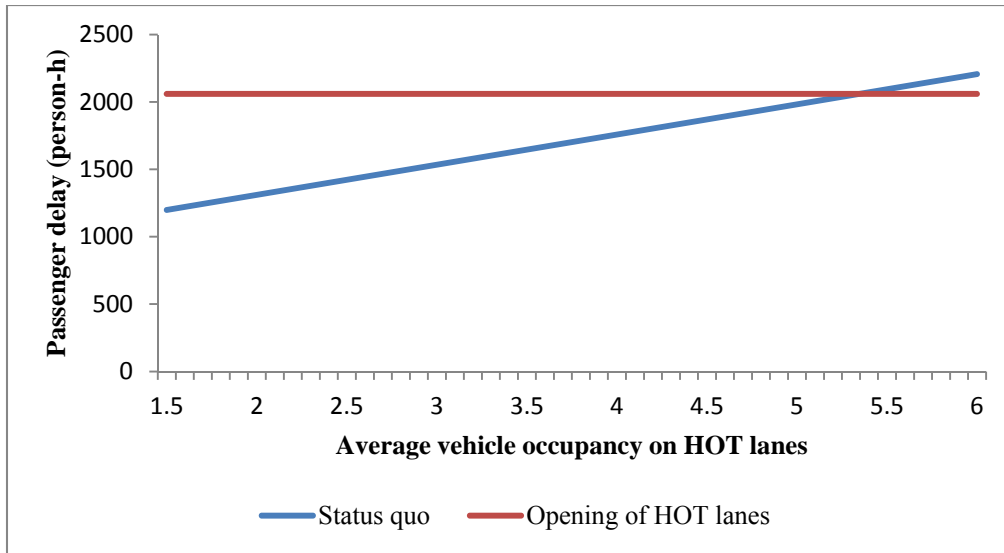
FIGURE 4.4 Impact of Average Vehicle Occupancy on Passenger Delay

4.6   Summary

This chapter has developed a framework to determine the appropriateness of diverting GP traffic to HOV/HOT lanes under different scenarios. By employing the deterministic queuing analysis, closed-form incident delay formulas were derived. The methodology was applied to five selected incidents and recommendations regarding the appropriateness of diverting GP traffic to HOV/HOT lanes are given. The procedure proposed requires a limited number of inputs from the field officers and hence it is relatively easy to implement by practitioners. It can serve as a decision support tool to traffic authorities when it comes to the decision whether HOV/HOT lanes should be open to GP traffic in incident situations.

5 REVIEW OF LEGAL ASPECTS OF OPENING HOV/HOT LANES AND ENFORCEMENT OF FHP

5.1 Introduction

Effective operations and management of modern highway transportation systems require coordination between transportation and public safety agencies. The operation of managed lane facilities heightens the need for collaboration, given the role of enforcement agencies in enforcing lane usage requirements like vehicle occupancy, vehicle type, or tolling. Enforcement promotes compliance with lane usage and consequently the perception of equity among users. The promise of travel time savings is maximized when compliance is optimized (Cothron et al., 2003). The coordinated effort between the disciplines extends to other, related operational aspects, like traffic incident management (TIM).

FHP and FDOT have a long history of interagency cooperation that extends from executive offices in Tallahassee, to district/regional command, and ultimately to the practitioners working in the field. Co-location of FHP dispatch with FDOT Traffic Management Centers (TMC), work zone safety hireback programs, and participation in TIM teams around the state are just a few examples of the coordinated effort between the agencies in traffic operations.

A strong foundation of cooperation sets the stage for successful implementation of policies related to the operation of managed lane facilities, particularly HOV and HOT lanes in south Florida. With the goal of reviewing the legal aspects of opening HOV/HOT lanes and FHP enforcement, the methodology requires a review of laws, informal survey of other states, and meetings with South Florida stakeholders. A review of relevant Florida Statutes preceded meetings with FDOT and FHP managers in Miami-Dade and Broward Counties. Personal contact with these individuals provides valuable insight into operations that allows the research team to develop the framework for the task. Similarly, contact with transportation and state police agencies in several other states serves to reinforce the state of the practice and recommendations herein.

The following sections evaluate the legal and operational parameters of lifting HOV and/or HOT lane restrictions where a traffic incident is impacting adjacent general purpose travel lanes. Legal considerations center on statutory authority, while operational concerns review the activities associated with communicating changes to officers in the field.

5.2 Legal Parameters of Opening HOV/HOT

Visible enforcement demonstrates that the managed lane operator is serious about the integrity of use by qualified vehicles (Sas et al., 2007). As with all roadway networks, efficiency is created by the orderly conduct of drivers, which improves both safety and capacity. "Order is created by a consistent set of roadway rules accompanied by a perceived risk of sanction if they are not followed" (Carrick and Washburn, 2012).

There is likely a delicate balance that must be struck between visible enforcement that deters HOV/HOT violations and that which adversely affect operations. It has been noted that heightened enforcement activities on HOV lanes has the potential to contribute to slow downs and "rubbernecking" (Wikander et al., 2006). Carrick and Washburn (2013) found that the advent of state move over laws have changed the roadside enforcement stop from a potential driver distraction to a theoretical lane blocking event with a quantifiable impact on capacity.

They conclude that manual traffic enforcement, particularly during periods of high flow rates, requires prudence on the part of enforcement personnel to minimize operational impacts.

South Florida HOV lanes were implemented in the 1970's and the FHP has been the lead agency for enforcement from the onset. For many years, HOV violators were simply cited under the Florida statute "Violation of Traffic Control Device", a moving violation, but no points were assessed against the driving record of the violator. Since then, a specific statute has been created to accommodate the HOV violation, Florida Statute 316.0741. With a specific statute, Department of Highway Safety and Motor Vehicles (DHSMV) uniform traffic citation records can be readily searched for enforcement trends.

TABLE 5.1 shows HOV citations issued for Broward and Palm Beach Counties during 2011 and 2012. FHP was responsible for 81 percent of all HOV citations, including 74 percent of those in Palm Beach and 94 percent in Broward. Sheriff's offices (SO), police departments (PD) and other types of law enforcement agencies (Other) account for the remaining citations.

TABLE 5.1 HOV Citations Issued for Broward and Palm Beach Counties

Year	Law enforcement agency	Palm Beach	Broward
2011	FHP	5757	4671
	PD	119	23
	SO	1897	219
	Other	313	3
	Total	8086	4916
2012	FHP	5585	3761
	PD	108	28
	SO	1252	299
	Other	388	0
	Total	7333	4088

Source: Department of Highway Safety and Motor Vehicles

Traditional HOV enforcement in Miami-Dade County has waned with the implementation of HOT lanes, known as the 95 Express Lanes. There are tolling exemptions for HOV3 as well as hybrid and electric vehicles. Exempt vehicles must be registered with South Florida Commuter Services (SFCS) and display a decal. Like traditional HOV enforcement, officer observation and manual enforcement are required for occupancy violations. With the Express Lanes, officers would be additionally required to call SFCS to verify the registration.

FDOT provides overtime funding for "hireback" of FHP troopers to work the Miami-Dade 95 Express Lanes. The overtime hireback program allows troopers to staff the lanes from 6 am to 10 pm on weekdays. On the Miami-Dade HOT lanes, narrow shoulders complicate enforcement,

so troopers exercise great judgment in enforcement. A visible law enforcement presence and enforcement for a variety of traffic infractions serves to communicate the FDOT/FHP commitment to compliance with Express Lane use, even though citations for the HOV violation are few. The needed deterrence is achieved through general enforcement presence.

The legal requirements for HOV facilities originate in federal law, Title 23 USC § 166 - HOV Facilities. Federal law establishes guidelines for states operating HOV and HOT facilities with emphasis on general guidance; exceptions; requirements applicable to tolls; HOV facility management, operation, monitoring, and enforcement; certification of low emission vehicles; and definitions.

Florida implements the requirements of Title 23 USC § 166 in several different statutes. Florida law follows the guidance of federal law by describing HOV facilities and the occupancy exceptions in Florida Statute 316.0741, High-occupancy vehicle lanes. Definitions of HOV, hybrid vehicles, and inherently low-emission vehicles are followed with agency guidance for issuance of a decal for vehicles meeting emissions requirements. Most importantly, the law directs compliance by drivers and establishes an enforcement mechanism: "Except as provided in subsection (4), a vehicle may not be driven in an HOV lane if the vehicle is occupied by fewer than the number of occupants indicated by a traffic control device. A driver who violates this section shall be cited for a moving violations, punishable as provided in chapter 318(Fla Stat. 316.0741(3))."

HOT lanes are established in Florida Statute 338.166, which authorizes the FDOT to request the issuance of bonds and use funds collected for the maintenance of the facility and/or other state roads. The critical part of Florida Statute 338.166(4) is "The department may implement variable rate tolls on high-occupancy toll lanes or express lanes (Fla Stat. 338.166(4))." Variable rate tolls would include a zero rate and thus serve to lift tolls under incident conditions, a foundational question posed in this report.

While use of variable tolls on HOT lanes or express lanes answers part of the research question, Florida law does not specify when HOV restrictions might be lifted. This is not uncommon, since only one state has any such language in law. Virginia is the only state with specific statutory language concerning lifting HOV restrictions. The Virginia code, enacted in 2001, allows the HOV restrictions in the Hampton Roads area to be lifted when a lane blocking event is expected to last more than 10 minutes (VA statutes). According to Hampton Roads officials, lifting restrictions is fairly common and likely a legitimate means to offset underutilization of the HOV lanes.

HOV and, more recently, HOT lanes in northern Virginia are not covered by the exception in the Virginia code. According to Virginia Department of Transportation (VDOT) and Virginia State Police officials, lifting HOV/HOT restrictions in northern Virginia had been rare. When restrictions have been lifted due to a major incident or crime scene, it has generally a collaborative decision between the two agencies through the traffic management center.

As part of this research, state DOTs with HOV and/or HOT lanes were surveyed by email with the assistance of the American Association of State Highway Transportation Officials (AASHTO). Other than the narrowly constructed language in the Virginia code, most other states simply rely on broader language authorizing agencies to manage and operate transportation

systems. Florida Statute 316.006(1) establishes jurisdiction to control traffic on state roads to the FDOT.

> *"STATE.—The Department of Transportation shall have all original jurisdiction over all state roads throughout this state, including those within the grounds of all state institutions and the boundaries of all dedicated state parks, and may place and maintain such traffic control devices which conform to its manual and specifications upon all such highways as it shall deem necessary to indicate and to carry out the provisions of this chapter or to regulate, warn, or guide traffic." (FS 316.00(1))*

Florida Statute 321.05(1) provides FHP with similar authority, "To patrol the state highways and regulate, control, and direct the movement of traffic thereon." (Fla Stat. 321.05(1), 2012) Given these two statutes, the powers and authority of both the FDOT and FHP appear to include actions associated with directing traffic into or out of managed lanes.

Beyond the statutory authority to lift HOV/HOT restrictions, one state has a written policy/procedure that outlines lifting HOV restrictions. Maryland has a written procedure that outlines lifting of HOV restrictions, "when a nonrecurring incident within the general purpose lanes occurs such that a lane of traffic is projected to be closed for one hour or longer…" (MSHA, 2012) The policy enumerates who makes the decision to lift restrictions, how information is communicated to law enforcement and to the public, and the duration of the changes. A copy of the Maryland HOV Policy for Lifting the HOV Restrictions on the I-270 and US 50 HOV Lanes is attached in the appendix to this report.

The only written guidance found for lifting HOT lane restrictions comes from the Florida Department of Transportation District VI Standard Operating Guidelines. Section 6.7.5 contains procedures for Express Lane (EL) event management and per the guidelines, tolls are set to $0.00 for any lane blocking event within the Express Lanes. Additionally, for other events, "Only upon FHP request and/or FDOT approval will traffic be diverted into the EL." (FDOT, 2012) The guide amplifies the responsibilities of TMC Operation Staff in the direction of field resources.

Most jurisdictions with HOV/HOT lanes have neither laws nor written procedures concerning lifting restrictions under incident conditions. The Massachusetts DOT indicated they comply if the Massachusetts State Police requests lifting HOV restrictions, which were noted as rare. California DOT (Caltrans) and the California Highway Patrol (CHP) jointly make similar decisions. The New Jersey Turnpike Authority confirmed that HOV restrictions have been lifted for incidents or severe weather. Similarly, the Louisiana DOT has an HOV facility on the Mississippi River Bridge in New Orleans, and HOV restrictions have been lifted for hurricane evacuations but not incidents. Minnesota does not have a written protocol for lifting HOV/HOT restrictions, but the DOT uses a facility performance metric for lifting tolls.

It is likely that dozens of other HOV/HOT facilities operate in similar informal arrangements between the DOT and public safety agencies. Most of these events are managed under the umbrella of agency enabling legislation and broad statutory authority granted to agencies in fulfilling their purpose. Like in Florida, such an arrangement appears sufficient.

Florida Statute 316.006(1) authorizes the FDOT to manage state roadways, 316.0741 authorizes the agency to regulate HOV lanes by rule, and 338.166 charges the Department with establishing variable tolling rates on HOT lanes. The legal authority and role of the Department of Transportation is fairly clear with respect to the operation of managed lane facilities. Under 321.05, the Florida Highway Patrol is authorized to regulate, control and direct traffic on roadways. Both the FDOT and FHP appear to have legal authority to effect changes to restricted lane use in the traffic incident management scenario. Their joint application of traffic changes and their collaboration in traffic incident management are legally valid extensions of their respective missions to promote a safe driving environment.

5.3   Operational Parameters of Opening HOV/HOT

The framework for traffic incident response is developed through national guidance and emerging responder training programs. "A traffic incident is an emergency road user occurrence, a natural disaster, or other unplanned event that affects or impedes the normal flow of traffic." (USDOT, 2009) Traffic incident management (TIM) is defined as, "A planned and coordinated multi-disciplinary process to detect, respond to, and clear traffic incidents so that traffic flow may be restored as safely and quickly as possible." (USDOT, 2012)

The Manual on Uniform Traffic Control Devices (MUTCD) provides guidance to traffic incident responders who are engaged in TIM activities. As a form of temporary traffic control zone, the traffic incident management area is recognized as an emergency scene and responders given wide latitude in handing traffic incidents.

The Second Strategic Highway Research Program (SHRP 2) created the National Traffic Incident Management Responder Training Course with the vision of standardizing response to traffic incidents. The Federal Highway Administration (FHWA) is implementing the product through a series of train-the-trainer workshops around the country, and South Florida was among the first regions to receive the training. Hundreds of area responders from police, fire, towing, and transportation disciplines have been trained since the 2012 program implementation.

When incidents occur on or adjacent to HOV/HOT lanes, responders are charged with managing those events toward the objectives of responder safety, reducing secondary crashes, and safe quick clearance. Ultimately, the goal of TIM is to restore the roadway to pre-incident operational efficiency. TIM involves many facets, but the question at hand centers on the decision to lift HOV/HOT restrictions and how those changes are communicated to others.

Decision making

The roles and responsibilities of agencies responding to traffic incidents are varied. Incidents may be as innocuous as a stalled vehicle on the shoulder requiring a single responder, or as elaborated as a multi-vehicle injury crash blocking travel lanes. There is no one-size-fits-all approach to response. Where HOV/HOT lanes are involved, "Decisions must be made on which entities are responsible for control of lanes in emergency and incident situations and protocols and interfaces must be established." (Sas et al., 2007) The MUTCD stipulates that agencies follow the National Incident Management System (NIMS) and promotes the concept of "unified command" for response. (USDOT, 2009) A collaborative approach to on-scene operations should precede recommendations and requests for TMC changes to HOV/HOT restrictions.

Units in the field and TMC operations must work together to ensure optimum response, safe quick clearance, and traveler information.

Joint operating agreements are an excellent way to plan for inevitable traffic incidents. Florida was among the first states to initiate a written, cooperative agreement between state transportation and public safety agencies. The "Open Roads Policy" establishes the joint commitment of both the FDOT and FHP in traffic incident management. The Open Roads Policy establishes the responsibilities of both agencies and institutes the goal of clearing roadway incidents within 90 minutes. Many areas of the state have replicated the statewide operating agreement to enlist the cooperation of scores of local agencies like public works, police departments, sheriff's offices, fire departments, and private towing companies.

The State of California uses "Joint Operational Policy Statements" or JOPS between Caltrans and CHP to specify how unplanned highway closures are handled. The JOPS is formatted as a signed MOU between the agency heads, and while it does not specifically address HOV/HOT lanes, it offers a framework for TIM and lane closings. A similar JOPS was implemented in Washington State in 1997. (Carson, 2010) An example of how it might be applied in the HOT scenario was provided by officials in California. Under the JOPS, the CHP officer on the scene is incident commander who works with CHP dispatch and the Caltrans TMC to communicate closures to Santa Clara Valley Transportation Authority (VTA) who adjust tolling in back office operations.

As is required by the MUTCD, the New Jersey Highway Incident Traffic Safety Guidelines for Emergency Responders embraces the concept of unified command and goes on to add, "The State Police have statutory authority over all incidents that occur on state highways and shall have final decision in all traffic control matters." (Office of the Attorney General, New Jersey, 2010)

In most cases, a collaborative process between law enforcement and transportation entities is applied in managing traffic, particularly on HOV/HOT lanes. Massachusetts, Virginia, Maryland, Minnesota, California, and Florida all indicate that the state law enforcement agency and state transportation agency work jointly to make decisions that affect lane usage.

Communicating operational changes

Communicating incident induced changes in HOV/HOT restrictions is an important part of traffic incident management. The national vision for TIM is a coordinated effort among on-scene responders. Likewise, coordination among entities like traffic management centers and public safety dispatch is equally essential. It is not only important for agencies to collaborate on decisions to lift HOV/HOT restrictions, such actions must filter down to the officers on the street. While most major incidents would occupy area enforcement responders for TIM, there is that slight chance that an unobligated enforcement officer might engage in HOV/HOT enforcement in conflict with an emergency lifting of restrictions. Communicating operational changes with enforcement personnel ensures fairness to drivers and deflects potential problems in the courts.

The frequency at which HOV lanes are opened under incident conditions appears to impact the methods of communicating with enforcement officers. In Hampton Roads, where HOV lanes are regularly opened by the DOT due to incidents, all communication is accomplished with DMS.

According to the State Police, troopers are expected to observe DMS messages concerning HOV enforcement. Conversely, in northern Virginia, troopers would be notified via police radio that restrictions were lifted according to State Police command. The difference being that such events have only occurred a handful of times over the last decade.

A number of agencies offered comment on how changes are communicated between transportation and law enforcement. The Massachusetts DOT complies with State Police requests and uses the DMS to communicate the changes to motorists. The New Jersey Turnpike Authority notifies the New Jersey State Police not to enforce the HOV lane restrictions via telephone and the public is informed via DMS and 511. The Minnesota DOT communicates HOV/HOT changes to the State Police so that enforcement changes can be made. What remained unclear was the subsequent communications with officers in the field.

Because the Maryland State Highway Administration has formalized their instructions, the communications between agencies is more specific. According to the policy, the TMC manager contacts the State Police and a joint decision is made to lift HOV restrictions. Subsequent actions have the highway department working with allied agencies for traffic control and motorist information and the State Police notifying local law enforcement. The only apparent deficiency in the policy is the notification of State Police personnel in the field.

To examine the law enforcement communication issue as it relates to South Florida HOV/HOT lanes, an examination of three operating scenarios might be beneficial. The HOV diversion scenario, HOT diversion scenario, and HOT lane incident scenario are described below.

HOV Diversion Scenario Communications

In the HOV diversion scenario, on-scene responders might be engaged in TIM on the adjacent general purpose lanes and perceive a need or benefit in moving traffic over to the HOV lanes to negotiate around the incident. Anecdotal information from FHP indicates that this is not an uncommon occurrence. Because the lanes are merely buffer separated, such a move is easily accomplished with minimal traffic control. Enforcement at the incident is not an issue because law enforcement responders are consumed with the tasks associated with TIM. There is no indication that downstream enforcement of HOV has ever been a problem in such a scenario, but it might be beneficial if field units were notified of changes. FHP command in Broward County indicated that law enforcement communications is improved with FHP notification to field units via radio and mobile data computer, as well as notification to local law enforcement dispatch. FIGURE 5.1 is a simple illustration of the communications that might be implemented to account for potential gaps.

HOT Diversion Scenario Communications
When a major incident occurs on general purpose lanes, the TMC might be required to make a decision to divert traffic onto HOT lanes as part of a TIM strategy. Such a scenario would be quite rare and has actually only occurred once in the first five years of 95 Express Lane operation. Operationally, the process requires removing delineators that divide the HOT lanes
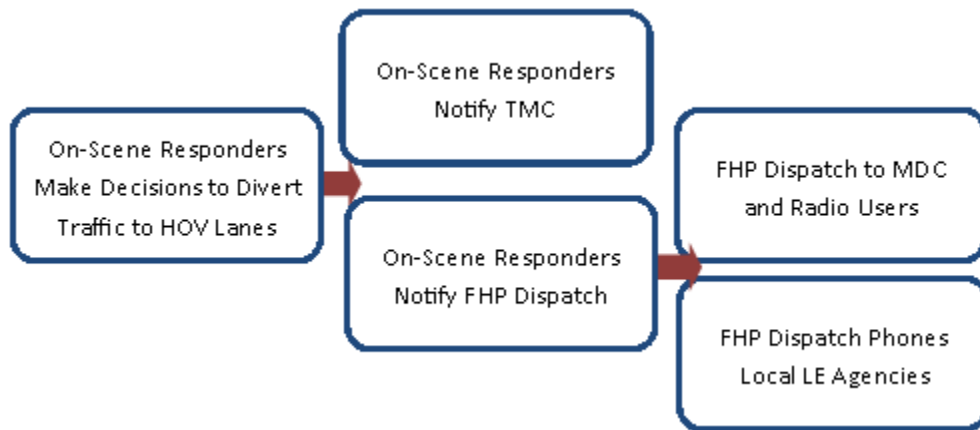
FIGURE 5.1 HOV Diversion - Communications Workflow

and general purpose lanes, establishing a transition, and communicating changes to drivers. The big difference in moving general purpose traffic to HOT lanes involves egress. According to District 6, it is essential that traffic be diverted back to the general purpose lanes downstream of the incident, since motorists would not be able to access exit ramps. The law enforcement communications workflow is similar to the HOV incident, with the important difference being the role of the TMC in making the decision. According to the District 6 operating guidelines, "Only upon FHP request and/or FDOT approval will traffic be diverted into the EL. TMC Operation Staff shall direct the Road Ranger, IRV, or Asset Maintenance to channelize the traffic in and out of the EL. It is critical to ensure traffic diverted into the EL must be immediately allowed to divert out of the EL once traffic passes the lane closure or event." (FDOT, 2012) Again, law enforcement communications is improved with FHP notification to field units via radio and mobile data computer, as well as notification to local law enforcement dispatch. FIGURE 5.2 is a diagram of the law enforcement communications involved with moving general purpose traffic to HOT lanes.
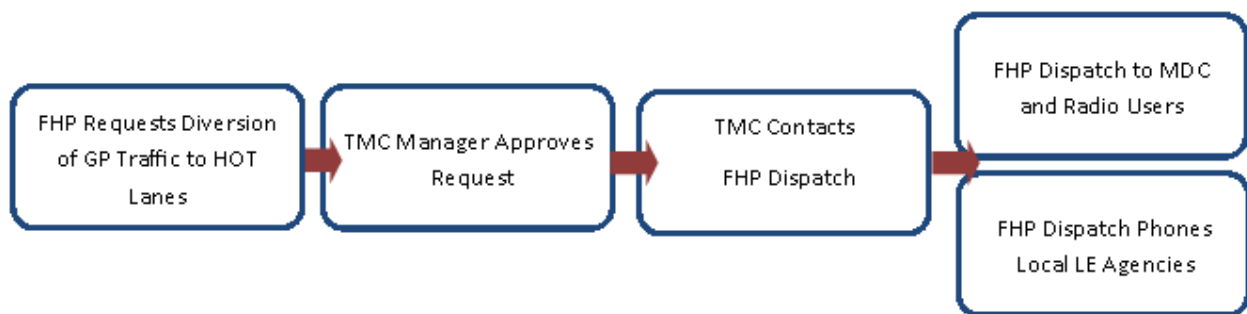
FIGURE 5.2 HOT Lane Diversion - Communications Workflow

HOT Lane Incident Scenario Communications
While the HOT lane incident is outside the scope of this project, it is beneficial to include a description of the scenario's communications for context. According to FDOT District 6, an incident within the HOT lanes is a weekly occurrence on the 95 Express Lanes. Between the dedicated FHP trooper(s), Road Rangers, Incident Response Vehicle, and asset management contractors, responders have become adept at implementing temporary traffic control to divert HOT lane users to general purpose lanes upstream of the incident. Similar to the HOT lane

diversion scenario, removing lane delineators and establishing a transition is required. A host of motorist notifications via DMS and tolling changes are also implemented by the TMC.

Under the current District 6 Standard Operating Guidelines, the TMC and FHP dispatch work together to manage the Express Lane incidents. Troopers in the field are advised over the police radio "in the blind" of the changes involving the HOT lanes, which means that a dispatch broadcast is made but field units are not required to acknowledge receipt of the message. Other agencies are generally not notified of changes, because in the Miami Express Lane scenario, local law enforcement does not typically engage in enforcement activities on the lanes. FIGURE 5.3 is an illustration of how a HOT lane incident might be communicated by law enforcement.
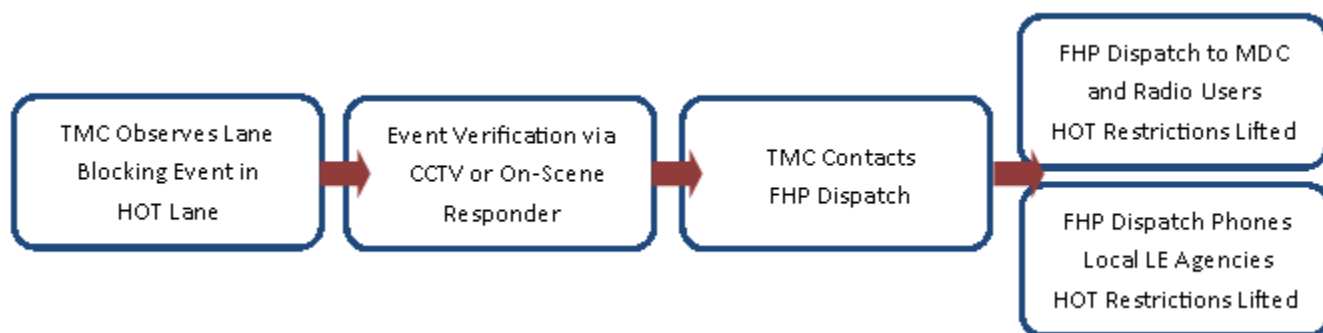
FIGURE 5.3 HOT Lane Incident - Communications Workflow

Operationally, TIM in HOV, HOT, and adjacent general purpose lanes all require similar coordination of effort and law enforcement communications. Communicating temporary changes to HOV/HOT enforcement is essential to operations. Law enforcement officers should be notified via mobile data computer and police radio. Given the lead role of the FHP, there should also be an agency to agency communication with local law enforcement, particularly in Broward and Palm Beach Counties.

5.4   Summary

The fundamental issues posed in this effort center on the legal authority to lift HOV/HOT restrictions, and how the traffic enforcement scenario that might be altered as a result of such a decision.

Florida Statute 316.006(1) authorizes the FDOT to manage state roadways, 316.0741 authorizes the agency to regulate HOV lanes by rule, and 338.166 charges the Department with establishing variable tolling rates on HOT lanes. The legal authority and role of the Department of Transportation is fairly clear with respect to the operation of managed lane facilities. Under 321.05, FHP is authorized to regulate, control and direct traffic on roadways. Both the FDOT and FHP appear to have legal authority to effect changes to restricted lane use in the traffic incident management scenario. Their joint application of traffic changes and their collaboration in traffic incident management are legally valid extensions of their respective missions to promote a safe driving environment.

The decision to formally lift HOV restrictions is likely rooted in a recommendation from FHP personnel on the scene. In the HOT lane scenario, a decision to divert traffic from GP lanes to HOT lanes would be a carefully orchestrated decision between FHP and FDOT personnel both in the field and in the TMC/dispatch center.

Though not legally necessary, a HOV/HOT policy or interagency operating agreement might be useful in ensuring that a coordinated TIM effort exists. The Maryland DOT policy might serve as a good example for the HOV scenario, and the FDOT District 6 Operating Guidelines a good starting point for the event affecting HOT lanes.

Communicating temporary changes to HOV/HOT enforcement is essential to operations. Law enforcement officers should be notified via mobile data computer and police radio. Given the lead role of the FHP, there should also be an agency to agency communication with local law enforcement.

6 DEVELOPMENT OF GUIDELINES TO IMPLEMENT A DIVERSION PLAN

6.1 Introduction

Standard operating guidelines to implement a diversion plan are critical to ensuring the consistency and success of lifting HOV/HOT lane eligibility restrictions for traffic incident management. However, only a few states have laws, policies or written procedures regarding the implementation of such a diversion plan. For example, Virginia employs specific statutory language concerning lifting HOV restrictions. The Virginia Code allows the HOV restrictions in the Hampton Roads area to be lifted when a lane-blocking event is expected to last more than 10 minutes (Virginia Code, 2001). Nevertheless, no guidelines are provided on how to implement a diversion plan if needed. Maryland State Highway Administration (MSHA) has a policy that outlines the procedure of lifting the HOV restrictions on the I-270 and US 50 HOV lanes (MSHA, 2012). The policy states that "the opening of HOV lanes to all traffic may be instated when a nonrecurring incident within the GP lanes occurs, such that a lane of traffic is projected to be closed for one hour or longer." The policy also provides specific procedures on decision making, information communication and dissemination. Two studies (Carson, 2005 and Fenno et al., 2006) funded by the Texas Department of Transportation (TxDOT) recognized that the potential benefit of diverting the GP traffic to HOV/HOT lanes may differ depending on the nature of the facility involved in the incident. Both studies adopted qualitative approaches to access the impacts of a diversion plan. A number of attributes, e.g., incident severity, lane blockage and time-of-day, were considered in developing look-up tables that enable field agents to make quick decisions on the diversion. Although qualitative approaches adopted by Virginia, Maryland and Texas are easy to follow and apply by field agents, the dynamic and uncertain nature of traffic conditions makes them almost impossible to account for various incident scenarios adequately. On the other hand, Chapter 3 of this report has proposed a quantitative approach to determine the appropriateness of diverting GP traffic to HOV/HOT lanes under different incident scenarios. The quantitative approach employs deterministic queuing analysis and develops closed-from incident delay formulas to quantify incident-induced vehicle and passenger delays. The method is theoretically sound, and can be easily implemented in any spreadsheet tools requiring only a few critical inputs. However, it may still be challenging for first responders in the field to utilize the quantitative approach to make diversion decisions in a timely manner.

Currently, no formal guidelines concerning lifting HOV/HOT restrictions are in place in Florida. From the review of legal aspects in Chapter 4 of this report, we understand that both FDOT and FHP have the legal authority to change the eligibility restrictions of HOV/HOT lanes under a traffic incident management scenario. Their joint application of changes in lane eligibility and collaboration in incident management are legal extensions of their respective missions to promote a safe driving environment. In fact, the FDOT District VI Standard Operating Guidelines (FDOT, 2012) specifically mentions that for incidents on GP lanes "only upon FHP request and/or FDOT approval will traffic be diverted into the Express Lane." Joint operations between FDOT and FHP on the diversion plan are likely to be the most effective way to ensure optimal incident response and clearance. Furthermore, Florida was among the first states to initiate a formal cooperative agreement between state transportation and public safety agencies. The "Open Roads Policy" establishes the joint commitment of both FDOT and FHP in pursuing

the goal of clearing roadway incidents within 90 minutes of the arrival of the first responding officer (FDOT, 2005).

6.2   Development of a Two-Stage Decision-Making Procedure

The objective of this chapter is to develop a practical and technically-sound procedure to implement a diversion plan. For first responders, it is imperative to have an easy-to-follow guideline that can be implemented quickly on the scene. A qualitative approach would serve this purpose well. However, the drawback of making a diversion decision solely on qualitative criteria is also apparent. The attributes and thresholds involved are usually based on engineering judgments, and there is no theoretical guarantee that the decision will alleviate the negative impacts of an incident. Moreover, since a qualitative approach is not able to quantify the impacts of an incident, it leaves little flexibility for transportation agencies to evaluate alternative options and tailor their decision to suit each facility. In contrast, a quantitative approach aims to quantify an incident's impact in terms of vehicle and passenger delays. It provides transportation agencies a decision-making tool that can handle a variety of incident scenarios and yield more accurate assessments. Although it requires more resources to reach a diversion decision, engineers at TMC are expected to implement the approach efficiently with the help of a spreadsheet tool. Given the strong partnership between FDOT and FHP on incident management and to be in compliance with the existing operating guidelines adopted by FDOT District VI, a two-stage diversion decision-making procedure is thus proposed to fully take advantage of the benefit of joint operations. The first-stage decision on the diversion is made by FHP officers on the scene based on qualitative decision criteria. If diversion is deemed to be necessary, FHP officers will make a request to FDOT to open the HOV/HOT lanes to the GP traffic. FDOT engineers at TMC may then perform a more in-depth quantitative analysis using inputs provided by FHP officers or their own data to make a second-stage decision. As such, the final diversion decision is jointly reached by both FHP and FDOT. The benefits of such a two-stage decision-making procedure are twofold. First, it ensures a quick decision on diversion for most incident cases. FHP officers can use a simple qualitative approach to rule out a large proportion of incidents that are not qualified for diversion. Second, the quantitative analysis performed by FDOT engineers enhances the chance of successful implementation and thus ensures the integrity and credibility of the diversion policy.

The remainder of this section focuses on two critical issues in developing the two-stage decision making procedure: diversion criteria and interagency collaboration and communications.

6.2.1   Diversion criteria

Since Chapter 4 has provided a very detailed description of quantitative-based diversion criteria that can be readily used by FDOT engineers at TMC, this section aims to develop qualitative diversion criteria for first responders in the field to use. Below we discuss three crucial aspects of qualitative diversion criteria similar to those identified in Carson (2005).

Incident Severity, Lane Blockage and Anticipated Incident Duration

Incident severity and lane blockage are directly related to negative impacts of an incident. Severe incidents blocking multiple lanes generally result in larger incident-induced delays. The major motivation of lifting HOV/HOT lane eligibility restrictions is to reduce traffic congestion

caused by incidents on GP lanes. It also provides additional safety benefits by enhancing the accessibility of the incident scene to first responders.

Carson (2005) investigated four types of events and prioritized them based on the nature of these events. Emergencies and evacuation that generally pose life-threatening conditions have the highest priority when it comes to opening managed lane facilities to all traffic. A diversion to managed lane facilities is also recommended for major incidents affecting multiple GP lanes. For construction or maintenance activities and special events, diversion is not recommended due to the planned nature of these events. Opening HOV/HOT lanes during these events may undermine the intended operating structure and lead to abuse of managed lane facilities.

Fenno et al. (2006) identified 16 potential incident scenarios based on HOV demand, GP demand, incident severity and lane blockage and classified these incident scenarios into three categories of diversion decisions: positive benefit, no significant benefit, or detrimental effect. They concluded that only four scenarios may lead to a positive benefit. Three of them involve high incident severity. The only scenario that has low incident severity involves high lane blockage on GP lanes, which may cause severe congestion for an extended period of time even though the incident can be cleared relatively quickly.

The anticipated duration of an incident is closely related to incident severity and lane blockage. Although the incident duration may also be influenced by other factors, such as the response time of towing companies, incident severity and lane blockage are more decisive factors in estimating the incident duration. FHP officers on the scene may also determine the anticipated incident duration based on similar incidents happened in the past.

Time-of-Day

Traffic conditions may vary significantly across different times of day, even during the course of an incident. The congestion relief impact of the diversion policy depends on the congestion level of GP lanes and the spare capacity of HOV/HOT lanes available to accommodate the GP traffic. If GP lanes are not congested, e.g., during a late-night incident, there is no need to consider opening HOV/HOT lanes to GP traffic in the first place. Conversely, when HOV/HOT lanes are already congested during peak hours, opening them to the GP traffic would yield minimal congestion relief benefit. On top of that, it may jeopardize the normal operations of managed lanes. It is also important to take into account future traffic demands during the period impacted by the incident. If an incident occurs at the beginning of peak hours, even though managed lanes have enough spare capacity, opening them to the GP traffic may not be beneficial due to the potential demand surge on managed lanes. On the other hand, the future demand is generally not an issue if incidents happen in off-peak hours or in the later stage of peak hours.

Alternative Routes and Strategies

Opening HOV/HOT lanes to all traffic will negatively affect managed lane users in the short term. If the diversion policy is used too often, it might discourage the utilization of managed lane facilities in the long run. Travel time reliability and higher level of service are often marketed as major selling points of managed lane facilities. Therefore, many transportation agencies treat lifting HOV/HOT eligibility restrictions as their last resort (Carson, 2005). They often prefer to divert traffic to alternative routes or apply other strategies.

The availability of alternative routes depends greatly on the specific incident location. FHP officers can decide whether alternative routes are available with the support of FDOT engineers. Opening the shoulder to the general traffic can also potentially be adopted as an alternative incident management strategy. Chapter 7 of this report is dedicated to investigating its feasibility in conjunction with other freeway management strategies, such as variable speed limits and ramp metering.

6.2.2 Inter-agency collaboration and communication

The proposed two-stage decision-making procedure highlights the importance of inter-agency collaboration and communication between FDOT and FHP. It is also equally essential to communicate the changes in HOV/HOT lane restrictions to road users and other relevant entities such as local law enforcement agencies and traffic engineers.

A diversion plan should specify the functions and responsibilities of agencies involved and include a communication strategy that keeps all parties informed and organized. Maryland has formalized the procedure (MSHA, 2012). Based on the policy, the supervisor at TMC will contact the state police and jointly decide to lift the HOV restrictions. Once the decision has been made, DOT personnel are responsible for informing travelers through appropriate media outlets and the state police will contact local law enforcement agencies.

"The Open Road Policy" is an inter-agency coordination agreement on incident management signed by FDOT and FHP. It provides an excellent framework for developing a formal diversion policy in Florida. According to the policy, FHP officers at the scene are responsible for deciding when to reopen closed lanes, coordinating with FDOT representatives to set up appropriate traffic control, and requesting authorized tow operators to clear the roadway. FDOT is committed to providing timely traffic control and deploying personnel and equipment for traffic control, roadway clearance, and debris clean up. The policy does not specify how to inform the diversion decision to law enforcement officers and the general public. For FHP officers, they are expected to receive the information via police radio. FDOT is responsible for informing the general public about the HOV/HOT restriction change via dynamic message signs (DMS) and the 511 travel information system. If the incident is expected to cause a large influx of traffic to local arterial system, FHP and FDOT also need to inform corresponding local agencies proactively such that they may increase manpower and change signal timing plans in response to the increase in travel demand.
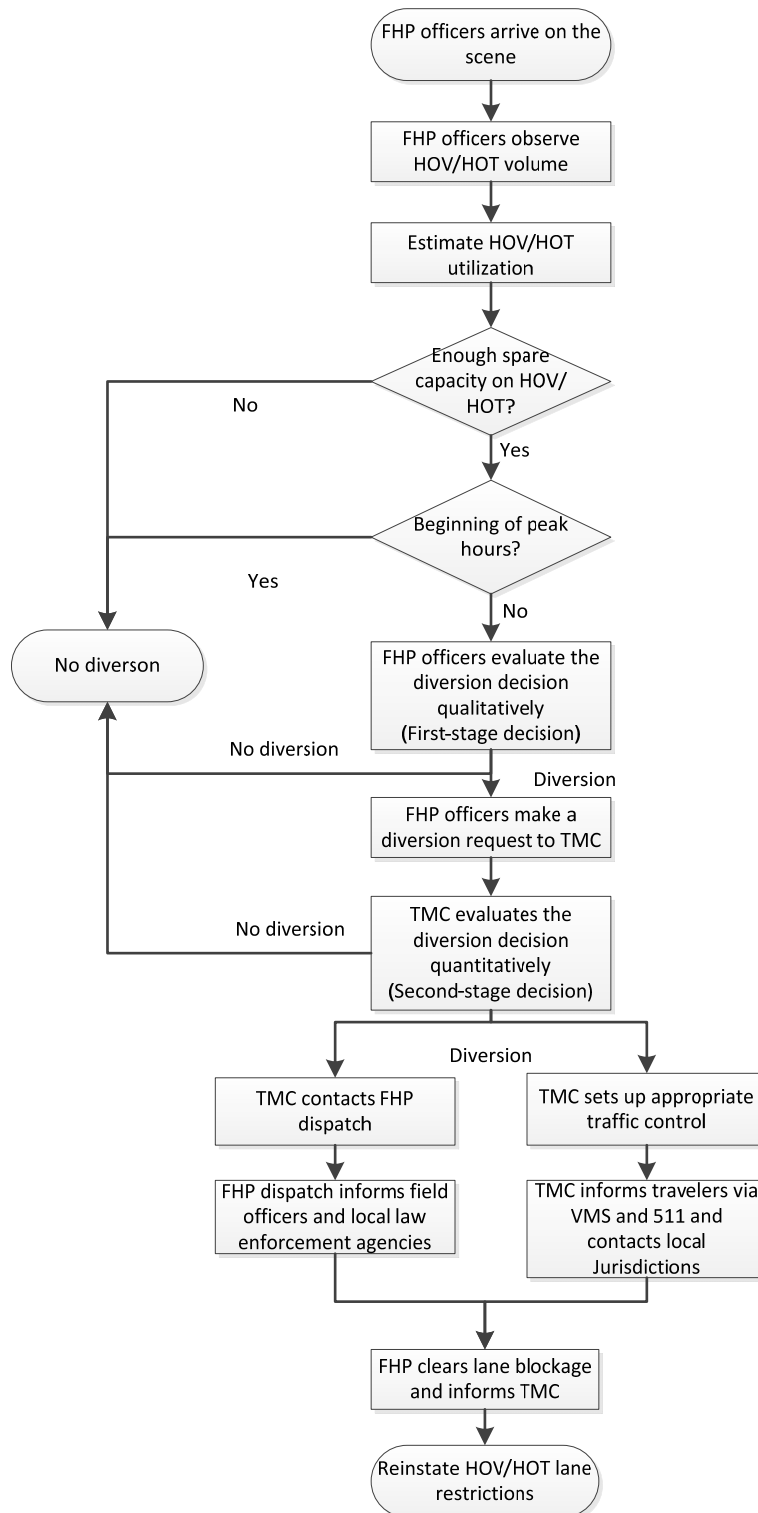
FIGURE 6.1 A Two-Stage Diversion Decision-Making Procedure

6.3 Recommended Implementation Procedure

This section recommends a practical procedure to implement a two-stage diversion plan. FIGURE 6.1 illustrates the flowchart of the recommended procedure. The flowchart is mostly self-explanatory. There are a couple of notes for the first-stage qualitative decision making procedure. To estimate the utilization rate of HOV/HOT lanes, it is necessary for field officers to know traffic volume and capacity, which, however, may not be readily available. A simplified method proposed in Fenno et al. (2006) is recommended here. Officers in the field can count vehicles on HOV/HOT lanes for one minute and use a capacity value of 25 vehicles per minute per lane (corresponding to a capacity of 1,500 vehicles per hour per lane). The utilization rate can thus be calculated as the observed one-minute volume divided by 25. If the utilization rate is higher than 80%, the HOV/HOT lane facility does not have enough spare capacity to accommodate the GP traffic, as suggested in Carson (2005). Furthermore, if an incident happens at the beginning of peak hours on GP lanes, the HOV/HOT lanes will most likely go beyond the measured utilization rate and thus may not have enough spare capacity to serve the diverted GP traffic. In these two scenarios, we thus do not recommend to open the HOV/HOT lanes to the GP traffic. TABLE 6.1 is a diversion decision look-up table adapted from Fenno et al. (2006). FHP officers may apply the table to make the first-stage diversion decision quickly.

TABLE 6.1 Look-Up Table for First-Stage Diversion Decision

			Level of traffic on GP lanes						
			Heavy			Moderate			Light
			Estimated incident clearance time						
	Blocked lanes	GP lanes	Less than 30 minutes	30 to 60 minutes	More than 60 minutes	Less than 30 minutes	30 to 60 minutes	More than 60 minutes	
Number of GP lanes blocked by incident	1	2	N	Y	Y	N	N	Y	N
	1	3	N	N	N	N	N	N	N
	1	4+	N	N	N	N	N	N	N
	2	2	N	Y	Y	N	N	Y	N
	2	3	N	Y	Y	N	N	Y	N
	2	4+	N	Y	Y	N	N	Y	N
	3	3	N	Y	Y	N	Y	Y	N
	3	4+	N	Y	Y	N	N	Y	N

6.4 Summary

This chapter has proposed a two-stage decision-making procedure to implement a diversion plan. At the first stage, FHP officers can use rules-of-thumb to make a quick but accountable decision on whether it is appropriate to lift HOV/HOT lane eligibility restrictions after major incidents on GP lanes. If lifting the resections is deemed to be necessary, FHP officers will make a request to FDOT. Engineers at TMC can then apply the quantitative approach developed in chapter 4 of this report to conduct a more thorough analysis and approve or disapprove the request

accordingly. We believe that such a two-stage procedure takes advantage of the existing partnership between FDOT and FHP on incident management. It allows quick decision making and ensures the integrity and credibility of the diversion policy.

7 FEASIBILITY OF SHOULDER USE BY GENERAL TRAFFIC

7.1 Introduction

This chapter provides our findings related to the shoulder lane use as well as simultaneous use of other freeway management techniques such as VSL and ramp metering. These findings are based on a thorough review of the international literature and related studies. Section 7.2 describes and discusses existing deployment of the shoulder lane use internationally and in the US, as well as research efforts to deploy shoulder lane use in conjunction with Active Traffic Management Strategies. Section 7.3 addresses specific concerns and issues that have been raised regarding their operation: safety issues, incident response, enforcement, liability concerns, public outreach and education, liability, personnel training, installation cost and maintenance concerns. Finally Section 7.4 provides an overview of the findings along with conclusions and recommendations.

7.2 Past Experience on the Deployment of the Shoulder Lane Use

Shoulder lane use (also referred to as hard shoulder running) has been implemented in Europe and the US as a means for increasing capacity. Often, the deployment of the shoulder lane use is accompanied by speed harmonization strategies, and is part of a broader active traffic management strategy. Both left and right shoulder lanes have been deployed in the past by agencies. Some agencies provide special access on the shoulder lanes for specific vehicle types, such as buses. A summary on the deployment of shoulder lanes is presented in the following sections.

7.2.1 European experience of shoulder lane use

The shoulder lane use in Europe is related to a broader implementation of advanced traffic demand management strategies. The Netherland, Germany, France and Great Britain have been developing and implementing strategies for the shoulder lane use in Europe, typically as part of active traffic management strategies such as speed harmonization or ramp metering, to address capacity limitations issues.

The Netherlands:

Temporary shoulder use was first implemented in the Netherlands in 2003. Along with the shoulder use, the technologies implemented in the facility (Kuhn, 2010) include overhead lane signs and full matrix signs, emergency refuge areas with automatic vehicle detection, variable route signs at junctions, advanced incident detection, CCTV surveillance, incident management, and public lighting.

Shoulder use in the Netherlands is only deployed concurrently with speed harmonization. Advanced technologies related to continuous freeway monitoring and traveler information systems are implemented along with the temporary shoulder use. The Dutch speed harmonization utilizes an advanced queue warning system instrumented with flashing lights and variable speed limit signs to inform drivers about congestion ahead and lane closures. Speed harmonization has also been implemented to address safety issues as a result of adverse weather, but also for reducing polluting elements at environmentally sensitive areas. Apart from the shoulder lane use, the use of a dynamic lane on the median (left) side is also implemented in the Netherlands, also referred to as plus lane. This typically occurs when traffic volume levels

approach congested conditions. FIGURE 7.1 shows an example of temporary shoulder lane and plus lane use in the Netherlands.

a)

b)

FIGURE 7.1 a) Temporary Shoulder Lane Use and b) Plus Lane Use in the Netherlands (source: Kuhn, 2010)

When the Dutch motor control and signaling system (MCSS) detects large speed drops within a certain area, it informs the drivers approaching that segment about the imminent speed drop and decreases the speed limit shown on the Variable Speed Limit signs incrementally (FIGURE 7.2) The speed limit at Dutch freeways is 120 km/h (75 mi/h) but may be reduced to 90 km/h (55 mi/h), 70 km/h (44 km/h) or even 50 km/h (31 mi/h) due to the speed harmonization system.

FIGURE 7.2 Speed Harmonization in the Netherlands

(source: Kuhn, 2010)

Based on analysis of the highway system performance, the benefits of right shoulder use in the Netherlands include increased overall capacity 7 to 22 percent (depending on usage levels) due to the decrease of travel times from 1 to 3 minutes and increase of traffic demand up to 7 percent during congested periods (Taale, 2006). In addition, a reduction of incidents has also been reported. Other benefits reported include fewer queues and shockwaves, lower travel speeds with harmonization, better monitoring, and faster incident response (Kuhn, 2010).

Germany:

The shoulder lane use has been in effect in Germany during the peak periods since the 1990s. As in the Netherlands, the shoulder use is implemented simultaneously with speed harmonization, to increase capacity at the freeway bottlenecks during congested conditions. The shoulder lane use and the speed harmonization (also known as line control) are two strategies used by traffic management centers in Germany as part of a comprehensive effort to provide proactive traffic management (Kuhn, 2010).

When travel speeds on the freeway are reduced, there are signs in place that guide for the temporary use of the shoulder lane. These signs and the overhead lane messages are blank when the shoulder lane use is not permitted. FIGURE 7.3 shows various signs used to indicate the operations due to the shoulder lane use, when the overhead gantries are not in place.
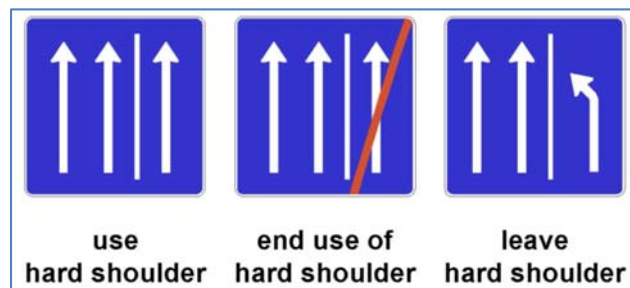
FIGURE 7.3 Temporary Shoulder Use Signs in Germany

(source: Kuhn, 2010)

Depending on the location of the bottlenecks and the characteristics of the corridor, the temporary shoulder use can either stop or continue through interchanges.

FIGURE 7.4 Termination of Hard Shoulder Use at an Interchange in Germany

(source: Kuhn, 2010)

The technologies that are installed with the required regulatory signs include overhead gantries, dynamic speed limit displays, dynamic message signs, roadway sensors, and CCTV cameras. CCTV cameras are also used by the freeway management authority to check for incidents and stalled vehicles before they activate the system.

Based on analysis of the freeway system performance it was concluded that the shoulder lane use in conjunction with the speed harmonization resulted in overall travel time reductions of up to 20 percent, temporary capacity increase of up to 25 percent and high acceptance of variable message signs when the speed limits selected for speed harmonization are considered reasonable. The addition of the shoulder lane slightly decreases the speeds and initially reduces the volumes on the freeway, but eventually delays the freeway flow breakdown and increases the overall throughput (FIGURE 7.5).
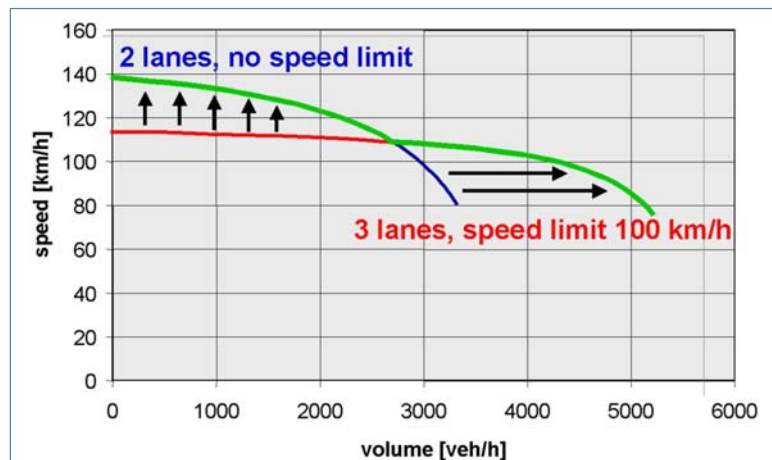
FIGURE 7.5 Speed-Volume Relationship of Temporary Shoulder use in Germany

(source: Sparmann, 2006)

Junction control (managing traffic onto or entering from one road to another) is also implemented in Germany. Junction control may include ramp metering to manage incoming traffic from the on-ramps, in conjunction with freeway lane control and it is used to prohibit vehicles from using the right-most lane of the freeway upstream of the merge, so that the ramp vehicles merge unencumbered onto the freeway. Lane control signals are installed upstream of both approaches of the merge (FIGURE 7.6) to dynamically provide priority to the movement with the highest demand (Berman et al., 2006). It is preferred to use junction control at ramp merge areas where the mainline has spare capacity (and accommodate the high merge volume).

(a)   (b)

FIGURE 7.6 Junction Control at a) On-Ramp in Germany and b) Off-Ramp with Shoulder Lane Use in the Netherlands (source: Kuhn, 2010)

Junction control can also be used at off-ramps when the shoulder lane is used, to dynamically create a two lane off-ramp; however, the exit ramp needs to have the available width to accommodate the exit lane (Fuhs, 2010).

Great Britain:

In 2001 the Ministry of Transport initiated an Advanced Traffic Management pilot project along M42 Motorway, which combines speed harmonization with shoulder lane use. The temporary shoulder lane use in the UK has been deployed only in conjunction with variable speed limit strategies, and it is activated in the field only after the speed limit has been reduced (first threshold is at 50 mi/h). Overhead gantries and dynamic message signs provide travelers with information on reduced speed limits and the availability of the shoulder lane for travel. Emergency refuge areas are located every 1640 ft along the shoulder (to the left of the freeway) to ensure safe operations of the shoulder lane use (FIGURE 7.7). The entrance taper is approximately 100 ft and the exit taper is 200 ft.

FIGURE 7.7 Emergency Refuge Area on Facility with ATM

(source: Kuhn, 2010)

The technologies that are installed on the M42 include lightweight gantries, lane control signals, dynamic speed limit signals, dynamic message signs, digital enforcement technologies, CCTVs, enhanced lighting, roadway sensors, emergency telephones, and emergency refuge areas.

The reported overall benefits from this ATM pilot project include increased capacity; enhanced trip reliability; reduced traveler stress, number and severity of crashes, traffic noise, fuel consumption and emissions (Kuhn, 2010). More specifically, travel time variability was reduced by 27 percent, and capacity was increased by 7 to 9 percent when the temporary shoulder lane use was in effect. The speed harmonization strategy resulted in an improvement of travel times by 24 percent and 9 percent for the northbound and southbound directions, respectively. Lastly, the ATM improved the distribution of flow across the travel lanes and did not have a negative impact on the traffic of the surrounding areas. Monthly crash rates were reduced from 5.08 to 1.83 (Kuhn, 2010).

France:

In Paris, France, an experiment was undertaken to utilize the shoulder lane along the A3-A86 junction. Dynamic equipment such as emergency call boxes, variable message signs and automatic incident detection were installed as well to manage safety-induced concerns. A before-and-after study at the area revealed significant capacity increases by 7% and 16% for each direction of travel after opening the shoulder lane to traffic (Cohen, 2004).

7.2.2   Shoulder lane use in the U.S.

Several states have successfully adopted the use of dedicated shoulder lanes to expand their existing capacity. Typically, agencies deploy the right shoulder lane, although in some cases, the left shoulder lane may also be available to the users. The following sections provide brief descriptions of field implementations of shoulder use treatments in the U.S.

In Virginia, the right shoulder lane use is implemented along I-66 (from US 50 to I-495) and it operates during the weekday peak periods on both directions. VDOT is responsible for this implementation, which was a result of the conversion of the freeway left-most lane to an HOV lane to maintain three general purpose lanes (FIGURE 7.8). This system operates since 1992. As it is shown in this figure, an overhead sign showing a downward green arrow informs the drivers when the shoulder lane use is allowed. Four emergency refuge areas in the eastbound and five refuge areas in the westbound approach are also in place along the 6.5 mile stretch of the corridor to provide accommodation for breakdown and enforcement when the shoulder lanes are in operation. The spacing between the emergency refuge areas ranges from 0.50 mi to 2.5 mi. The entrance and exit taper is 300 ft.

FIGURE 7.8 I-66 Shoulder Lane Use during Peak Periods

(source: Kuhn, 2010)

The shoulder lane is 11-ft wide and the maximum allowable speed is 55 mi/h. Analysis of the performance of the facility showed that the morning v/c ratios fell between 0.9 and 1.0 in the eastbound approach and between 0.83 and 1.01 for the westbound approach. A safety evaluation study of the shoulder lane use did not find sufficient evidence that the HOV/ shoulder lane strategy had a statistically significant effect on the crash frequency (Lee et al., 2007). Incident clearance time on this corridor is within 90 minutes 90 percent of the time, which is typical for the region (Kuhn, 2010).

Minnesota:

Minnesota DOT deploys priced dynamic shoulder lanes (PDSL) since 2009 along 1-35W (total length of installation is 2.5 mi). In this system the leftmost shoulder is used as MnPASS Express Lane during specific times when traffic along the general purpose lanes becomes congested. PDSLs are used at no charge by transit vehicles and high-occupancy vehicles, whereas, single-occupancy vehicles are required to pay a specific fee for access to the PDSL. The tolls are collected electronically. The PDSLs operate in conjunction with variable speed limits along the GP lanes (FIGURE 7.9). Regulatory signs over the PDSL provide information on the hours of operation and the MnPASS restrictions and toll rates.

FIGURE 7.9 PDSL on I-35W in Minnesota

(source: Kuhn, 2010)

The PDSL system deployed by MnDOT is part of a larger congestion mitigation program along I-35W (Kuhn, 2010), which includes the installation of park-and-ride lots, electronic signs that provide real-time traveler information, cameras and loop detection, sign gantries across the entire facility, variable speed limit panels, lane control signals, and dynamic message sign panels for toll display. Emergency refuge areas were also installed to assist in incident management and vehicle breakdowns; however the spacing of these refuge areas is not known.

Apart from the PDSL installation, the right-most freeway shoulder lane along I-94 is open to traffic since 2007, in response to the bridge collapse on I-35W. The goal of the utilization of the 12-ft wide shoulder lane was to alleviate congestion and provide additional capacity at all times. Before this conversion, the shoulder lane was operating as a bus-on-shoulder (BOS) lane. This deployment lead to improved traffic conditions and reduced travel times for all vehicles, but the transit performance deteriorated due to the presence of vehicles on the bus-on-shoulder (BOS) lane (Kuhn, 2012).

Massachusetts

Shoulder lane use is deployed at four facilities in the Boston area (two along I-93, one on I-95 and one on SR 3). The total length of the deployment is 45 miles. The rightmost shoulder lane is allowed for use by the general traffic during weekday am and pm peak periods; however heavy trucks are prohibited from using the shoulder lane. MassDOT treated the deployment of the shoulder lane as a typical widening project, i.e., drainage features were moved to the new edge of the pavement, guardrails and fixed objects were moved as well. Emergency refuge areas were installed every 0.5 mile to facilitate incident management and emergency response. FIGURE 7.10 shows the start of the shoulder lane use along I-93.

The shoulder lane use along I-95 is temporary and is projected to terminate with the widening of the roadway and the construction of an additional general purpose lane. Provisions for constructing an additional lane along SR-3 and terminating the use of the shoulder lane are also in place.

The technologies installed at these facilities include sensors, cameras, and overhead dynamic message signs; however most of this equipment was in place before the deployment of the shoulder lane.

FIGURE 7.10 Shoulder Lane Use on I-93 in Massachusetts

(source: Kuhn, 2010)

MassDOT has not performed any specific operational and safety performance evaluation along these four facilities. Kuhn (2010) reports that "In general, there has been a definite improvement in travel speeds along these corridors, though specific improvements are difficult to track because of the lack of complete deployment of devices in the field for data collection purposes". In addition, MassDOT does not report a significant difference in crash frequency as a result of the deployment of the shoulder lanes, but this could be due to the fact that the crash location information is not generally available.

Washington:

The rightmost shoulder lane use is deployed along a 1.55 mile stretch of US 2 Trestle Bridge in the Washington – Seattle region. The shoulder lane is open to traffic during the evening peak period and the maximum allowable speeds are 60 mi/h. The purpose of this project which started in 2009, was to alleviate congestion at this facility, improve travel times, and reduce the impacts of the bottleneck in its vicinity. WSDOT restriped the corridor to allow adequate space for the shoulder lane use (shoulder lane width restriped to 14 feet instead of 10 feet). The intention is for the shoulder use to be a permanent measure for the near future (Kuhn, 2010). A view of the facility is shown in FIGURE 7.11.

The facility does not deploy ITS technologies specific to the shoulder lane use. Regulatory signs are located either on the shoulder or the barrier, and these are manual flip signs operated by WSDOT personnel. The signs typically read "SHOULDER OPEN TO TRAFFIC" or "SHOULDER CLOSED". The dynamic message signs located along I-5 can be used to inform drivers that are destined for the US 2 trestle.

FIGURE 7.11 Shoulder Lane Use on US 2 Trestle in Washington State

(source: FHWA, 2010)

Reported analysis of the system performance showed that delays in the area were reduced from 8-10 minutes to 1-2 minutes per vehicle. In addition, travel times are more reliable, and the access ramp throughput has increased. The combination of the shoulder use along US 2 and ramp metering along I-5 resulted in an increase of average speeds from 10 mi/h to 37 mi/h, which is close to the maximum feasible speed due to road curvature. Concerning safety impacts, according to WSDOT personnel, collisions at the conflict location where roads merge at the trestle are reduced although actual numbers are not provided (Kuhn, 2010).

WSDOT deployed right shoulder lane use along a 4.5 mile stretch of the I-5 NB corridor (Marine View Drive to SR 528). The roadway surface was repaved to allow a 14ft wide shoulder lane, while the remaining three lanes were converted to 11 ft. wide. Dynamic signage for the shoulder lane, CCTV cameras and variable message signs were also installed. Among the reported benefits is significant traffic flow improvement, reduction of congestion-related incidents and benefit to cost ratio or 3:1, although detailed quantitative information is not available (Bandy and Trowbridge, 2012).

Florida:

Right shoulder lanes have been incorporated to the operation of the I-95 Express Lanes in the Miami area (Kuhn, 2010). The section between I-395 and I-595 was converted to a two HOT-lane facility by reducing the lane widths of the general purpose lanes and the HOT lanes to 11-ft and by narrowing the shoulder. Overhead electronic signs are available at the site to display the demand-varying toll rates. This installation was part of the Urban Partnership Agreement Project, where the objective was to provide free-flowing conditions on the managed-lane network.

Hawaii:

Temporary right-most shoulder use is in effect along H1 in Honolulu, Hawaii during the morning peak (Kuhn, 2010). The intention of the Hawaii DOT is to alleviate congestion during the morning peak period in the eastbound direction.

7.2.3 Bus-on-shoulders program

Bus on Shoulders (BOS) programs, are typically implemented to increase the transit service reliability on urban freeway and arterial networks. Several States operate BOS programs: Minnesota, Virginia, Maryland, Washington, New Jersey, Georgia, Delaware, Florida, Ohio and California. BOS programs are in effect also in Canada (Vancouver, Toronto and Ottawa), in New Zealand and in Ireland (Martin, 2006). Discussions on new BOS programs are underway in Illinois, Kansas, North Carolina, Montreal and Texas (Martin and Levinson, 2012). The length of BOS program applications ranges from 1,500 ft in Delaware to 230 miles in Minnesota. According to TCRP 151 Report (Martin et al., 2012) a 10-15 mph speed differential is suggested for the early operation of the BOS lanes, although this is subject to the drivers' discretion.

In California, transit vehicles use the shoulder lanes along I-805/SR52 (San Diego area), when the general purpose lanes become congested and speeds drop below 30 mi/h. The buses there cannot drive at speeds greater than 10 mi/h from the speed of the adjacent lanes. This system is in effect since 2005.

Buses are also allowed to use the shoulder lanes when the freeway is congested (when speeds drop at 25 mi/h) along a 9-mile segment extending from SR-874 (Don Shula Expressway) to SR-878 (Snapper Creek Expressway), in the Miami area. The buses' speed may not be greater than 35 mi/h. Similarly, in Georgia, buses are allowed to use the shoulder lanes on GA 400 whenever the speed of the facility drops below 35 mi/h, and cannot travel more than 15 mi/h faster than the general purpose lanes. In Minnesota, buses may use the shoulder lane when the speed of the remaining lanes drops below 35 mi/h, and may travel no more than 15 mi/h faster than the speed of the adjacent lanes. Buses must yield to vehicles exiting, entering or merging through the shoulder.

In New Jersey, buses are allowed to use the shoulder lane along Route 22 during congested conditions. In Washington, buses and three-plus carpools are allowed to use the shoulder lane along the westbound direction on SR 520 in the Seattle region. The stretch of the facility is approximately 2.7 miles and the system operates 24/7. Vehicles that use the shoulder must merge to the adjacent lanes at interchanges (FIGURE 7.12).

In Wilmington, Delaware, buses are allowed to use the arterial shoulder along US 202 as a way of a queue jump along a section of the facility that includes a traffic signal. This system operates 24/7. In Maryland, buses use the shoulder lane on a 4-mile arterial highway segment as a queue jump at several intersections along US 29 in Burtonsville. This system operates on weekdays during the am and the pm peak hours.

In Bethesda transit vehicles have shoulder queue jump to bypass congestion at the interchange of I-495 with I-270. This system also operates by time of day (peak periods). The maximum speed along the shoulder lane is 55 mi/h. Buses travelling along Route 267 (Dulles Access Highway) in Falls Church, Virginia, are provided with an eastbound queue jump. This treatment is available on weekdays during the pm peak hours. The maximum allowable speed on the shoulder lane is 25 mi/h.

FIGURE 7.12 SR 520 BOS On-Ramp Diamond Weave Markings in Washington State (source: Martin, 2006)

In summary, the BOS systems operate as expected, suggesting transit travel time savings and increased reliability (Martin and Levinson, 2012). The shoulder lane widths used for transit vehicles range from 10 ft to 14 ft. Typical pavement markings that indicate the exclusive use of the shoulder lanes by transit vehicles include "Watch for Buses on Shoulder", "Transit Lane Authorized Buses Only", "Buses May Use Shoulder", or diamond symbol.

7.2.4   Recent research on the deployment of the shoulder lane use

To date, limited research has been conducted to evaluate the feasibility of deploying hard shoulder lane use considering the simultaneous use of freeway/ramp management strategies such as VSL or ramp metering. Waller et al. (2009) used simulation to evaluate the potential for implementing two dynamic traffic management strategies, i.e., speed harmonization and peak period shoulder use at Texas freeways. The authors used a hybrid multi-resolution approach: they estimated the changes in route choice and identified congestion patterns through mesoscopic simulation. In addition, they assessed the impact of ATM strategies on driver behavior through microscopic simulation. For the mesoscopic simulation the authors used VISTA, and for the microsimulation portion of the experiment, they used VISSIM. The selected study area was in Austin, Texas. Waller et al. (2009) considered an offline and an online VSL algorithm to run in conjunction with the shoulder use. Their findings indicate that although there is no significant increase in the overall throughput, VSL and shoulder use result in traffic homogenization, as they reduce the number of lane changes and stops per vehicle. According to the authors, this combination of strategies also results in reduced speed variability and reduced density, thus smoother traffic flow conditions.

Waller et al. (2009) analyzed safety implications from the use of speed harmonization and shoulder lanes considering three crash precursors: coefficient of speed variation within and across lanes, and traffic density. They concluded that VSL reduces all three precursors and therefore, create safer driving conditions. The shoulder use reduces speed variation within the lane and traffic density, however, speed variation across lanes is increased due to increased lane changing maneuvers to and from the shoulder lane. These results are based on traffic simulation and assuming a strong correlation between the selected precursors of safety and observed crashes; thus it would be important to evaluate these findings in the field.

7.3 Overview of Issues Associated with Shoulder Lane Use

Several issues arise from the use and operation of shoulder lanes. These are safety issues, incident response, enforcement, public outreach and education, liability and legal issues, personnel training, installation cost and maintenance concerns. The following sections present a summary of past literature that pertains to these issues.

7.3.1 Safety issues

In general, the European experience records a significant reduction on crash frequency due to the implementation of the hard shoulder running in conjunction with other ATM strategies. In the US however data do not seem to be conclusive on the safety benefits of the shoulder lane use. Statistical analysis performed as part of the NCHRP Report 369 (Curren, 1995) examined accident severity, time of day, type of accident, and characteristics, and showed that there was not a significant difference in safety between sites that had been altered and non-altered. The report notes significant increase in crashes at a specific site, which was a combination of shoulder use and narrowed lanes for a stretch over one mile long. In addition, sideswipe, nighttime and truck-related crashes were also found to be increased. The author notes that "… the finding of greater variability in operating speeds for altered sections is intuitively consistent with findings that indicate higher accident rates in a majority of cases". However, the results of that study are now nearly 20 years old, plus there may have been interactions in the effects of lane width and use of shoulder lane for that site. In addition, the speed variability could be regarded a contributing factor for the increase in the accident frequency at the study sites.

Bauer et al. (2004) evaluated the safety effects of providing an additional lane by either narrowing lanes or making use of the shoulder lane at urban freeway segments in California with four or five lanes per direction. In the majority of the segments tested, the shoulder lane was converted to an HOV lane, and no additional measure (e.g., speed harmonization) was undertaken. The authors conducted a before-after study deploying the empirical Bayes method and their analysis revealed mixed results. Overall, accidents increased by 10% for all accident types at freeways converted from four to five lanes. Freeways converted to six lanes incurred an average increase between 3 and 4%, while the fatalities increased by 7%. The authors also note that for four to five lane conversions the sideswipe collisions increased and the rear-end collisions decreased, however, the opposite holds true for the five to six lane conversions. The authors postulate that the increased speed introduced by the vehicles driving on the shoulder-HOV lane and the speed differential might be a factor that contributed to the increased accident rates.

Research conducted by the Texas Transportation Institute (TTI) (as reported in Levecq et al., 2011) showed that reducing the lane width to accommodate for an extra lane had a positive impact in travel time, capacity, safety and operational quality. They further note that the increase in the number of crashes due to the lane narrowing is offset by the additional capacity. Levecq et al. (2011) recommended to have reduced lane widths only to short sections, in order to reduce truck-related crash rates that are high on those facilities.

A safety evaluation study of the shoulder lane use along I-66 in Virginia did not find sufficient evidence that the HOV/ shoulder lane strategy had a statistically significant effect on the crash frequency (Lee et al. 2007). The authors hypothesized that advanced incident identification and

clearance and enhanced dynamic message signs can be used to minimize the negative safety effect of the shoulder lane use.

A few studies investigated the safety effects of the inside (left) shoulder lane use. An early study by Urbanik and Bonilla, (1987) showed that the number of crashes decreased and remained low over time when inside shoulders were removed to increase capacity in Los Angeles, California.

Another safety concern is the reduction of the clear zone distance due to the shoulder lane use. According to Kuhn (2010) agencies may be able to move objects and obstacles to an acceptable distance; however, this is not always possible and agencies are required to seek design exemptions from FHWA.

In conclusion, although the European experience showed that safety significantly improved with the use of shoulder lanes, in the US, the results on safety impacts are not conclusive. The shoulder lane use has had positive safety results in some cases, but the negative safety impacts are associated with narrow lane widths and high speed differentials. It can be speculated that the use of variable speed limits will improve safety conditions since the average speed, and therefore the speed differentials, will decrease. This is also consistent with the European experience that employs variable speed limits in conjunction with the shoulder lane use.

7.3.2   Incident response

Traffic incidents are estimated to account for more than half of non-recurring congestion on our roadways. (Schrank and Lomax, 2003). Traffic Incident Management (TIM) is a planned and coordinated process among multiple disciplines to detect, respond to, and clear traffic incidents as quickly as possible. Effective TIM has proven effective in reducing incident duration and thereby restoring flow and improving safety.

Traffic incident management for uninterrupted flow facilities relies heavily on travel lane clearance strategies. One of the proposed national TIM performance measures is "time to clear travel lanes", and responders are trained to push, pull, or drag obstructions out of travel lanes as part of quick clearance strategies. The refuge of a shoulder on which to move lane blocking events benefits safe, quick clearance. Similarly, vehicle disablements and crash investigations generally occur on roadway shoulders and those activities are commonplace in urban freeway settings. If clearing lanes is paramount, clearing the potential distraction of vehicles on a roadway shoulder is close behind. Another TIM performance measure is "time to clear scene", wherein responders attempt to clear all vehicles from the facility as quickly as possible. Ultimately, the safety of persons involved in incidents, responders, and passing motorists are the focus of the third TIM performance measure "reduction of secondary crashes" (Owens et al., 2010).

From a traffic incident response perspective, incident responders often use roadway shoulders to reach traffic incidents, passing queues that generally ensue. If general purpose traffic occupies the shoulder lane, response, and ultimately clearance times, may suffer. Increased safety service patrols and the use of motorcycle law enforcement response are two ways in which shoulder access issues might be mitigated. In Virginia, the safety service patrol was increased during the shoulder lane operating hours (Kuhn, 2012). Incident clearance time on I-66 in Virginia is within 90 minutes 90 percent of the time, which is typical for the entire region.

The use of shoulder lanes by general purpose traffic means that the aforementioned incident management and response activities may need to be accommodated. In Great Britain and other parts of Europe, emergency refuge areas with emergency call boxes are installed every 1/3 mile to facilitate incident management and vehicle breakdowns. Similar applications in the US are spaced at ½ mile intervals. Emergency refuge areas were installed along I-35W in Minnesota to facilitate incident response when the PDSL system is in operation. Intelligent Transportation System (ITS) technologies are also in place to ensure swift incident response, and CCTV surveillance that check for incidents and stalled vehicles are located on the shoulder lane before the activation of the shoulder lane use. Improved incident detection, verification, and response may be a product of increased monitoring of shoulder use facilities. In the Netherlands, faster incident response was observed when shoulder lanes were utilized (Kuhn, 2010).

7.3.3   Enforcement issues

Shoulder lane use by general purpose traffic or buses requires consideration of traffic enforcement operations. Manual enforcement stops that are associated with routine police patrol and selective enforcement associated with shoulder lane use violations on roadways without sufficient shoulders is challenging. This has been observed along the 95 Express Lanes in Miami, where substandard width inside shoulders doesn't allow for violator and/or enforcement vehicles to safely stop adjacent to travel lanes. Designated enforcement areas with ingress/egress and a safe lateral buffer might be constructed as part of safety refuge areas or "accident investigation sites". Without a safe place to conduct enforcement stops, most routine enforcement would likely only occur downstream of the shoulder operations or at interchange locations in deference to public and officer safety.

The success of the shoulder lane use treatment, especially when it is deployed in conjunction with speed harmonization strategies, depends greatly on its enforcement. Automated speed enforcement, though used widely in Europe, is not provided in Florida. Florida law only allows the use of such technologies in tolling and red light enforcement. On the Minnesota BOS facilities, bus speed monitoring is typically done manually through officer observation using speed detection devices like RADAR or LASER. Speed enforcement is similarly based on visual observation in Washington and Massachusetts, where Kuhn (2010) noted no significant issues. Kuhn (2010) noted that in Virginia, enforcement during off-peak periods was found to be challenging due to the short interchange spacing.

The solution for Florida law enforcement agencies likely lies in Florida Statute 316.1905 "Electrical, mechanical, or other speed calculating devices; power of arrest; evidence". The law provides that,

> "Any police officer, upon receiving information relayed to him or her from a fellow officer stationed on the ground or in the air operating such a device that a driver of a vehicle has violated the speed laws of this state, may arrest the driver for violation of said laws where reasonable and proper identification of the vehicle and the speed of same has been communicated to the arresting officer."

The "fellow officer" enforcement arrangement would allow an officer to observe a violation from a position of safety, and communicate the information and description to another officer at a downstream point where there may be a shoulder, refuge, or ramp to accommodate a safe stop.

Conspicuous and highly visible traffic enforcement has a significant role in the orderly conduct of drivers on roadways. It is very important that implementation of hard shoulder running not eliminate the opportunity for traffic enforcement operations.

7.3.4 Public outreach and education

According to Kuhn (2010) Mn/DOT hosted occasionally media events after the deployment of the BOS, in an effort to demonstrate the travel time benefits from using the transit service. Kuhn (2010) also reported that typical outreach efforts were used in the Seattle area prior to the opening of the US 2 shoulder lane. Specifically for the BOS programs, the TCRP Report 151 (Martin et al., 2012) states that San Diego used a variety of outreach methods such as website, brochures, radio spots and print media to market their BOS program. They also made a special outreach effort for police, fire and emergency service agencies. Atlanta promoted their BOS program through a video displayed through their website. Miami and Ohio used variable message signs to inform drivers about the BOS program before its launching. Signage is also used as a means to public education for BOS projects.

Outreach efforts for the shoulder lane use project in Florida included web sites, public meetings, media campaigns, and the production of videos (Kuhn, 2012).

7.3.5 Personnel training

The Minneapolis-St. Paul transit operator (Metro Transit) uses training manuals and safety pamphlets for training its bus operators on the BOS operations. The manual includes training video and on-board training. Power point-based sessions were developed for training bus operators in Miami, Florida (Martin and Levinson, 2012). Specific personnel training efforts for shoulder lane use by general traffic have not been identified.

7.3.6 Liability issues

Kuhn (2010) reported that no liability issues were noted for the shoulder lane use in the US. A concern was expressed by the American Automobile Association (AAA) that the availability of shoulder for emergency refuge in the event of an incident would be further reduced due to the extension of operating hours along I-66 in Virginia. This issue was addressed by VDOT successfully, and no other concerns have appeared since.

7.3.7 Legal considerations

Florida Statute 316.006(1) establishes the jurisdiction of the FDOT to control traffic on state roads, and Florida Statute 316.091(5) specifically allows the Department and Expressway Authorities to use shoulder lanes on limited access facilities.

"The Department of Transportation and expressway authorities are authorized to designate use of shoulders of limited access facilities and interstate highways under their jurisdiction for such vehicular traffic determined to improve safety, reliability, and transportation system efficiency. Appropriate traffic signs or dynamic lane control signals shall be erected along those portions of the facility affected to give notice to the public of the action to be taken, clearly indicating when the shoulder is open to designated vehicular traffic. This section may not be deemed to authorize such designation in violation of any federal law or any covenant established in a resolution or trust indenture relating to the issuance of turnpike bonds, expressway authority bonds, or other bonds."

Lane direction control signals are provided in State Statute 316.0765 and, "When lane direction control signals are placed over the individual lanes of a street or highway, vehicular traffic may travel in any lane or lanes over which a green signal is shown, but shall not enter or travel in any lane or lanes over which a red signal is shown." This type of signal is specified in the Florida enabling statute and has accompanied shoulder running implementation in many jurisdictions, as was previously noted.

From a definition standpoint, Florida Statute 316.006(42) provides that a ROADWAY is "That portion of a highway improved, designed, or ordinarily used for vehicular travel, exclusive of the berm or shoulder." The DOT may need to consider the need for a legal opinion, or clarifying language since many laws governing the operation of motor vehicles include the term "roadway".

7.3.8 Installation cost

The installation of a temporary shoulder lane costs considerably less than the construction of new freeway lanes. For example, the upgrade of the lane control system along I-66 in Virginia is estimated to cost $7 million for a 6-mile segment, which is much less than constructing a 6-mile of new pavement in a congested urban area (Kuhn, 2010). The left shoulder lane use project scheduled to start in 2014 in Virginia is estimated to cost $20 million for rebuilding the existing shoulder along a 1.5 mile section of I-495 NB. The cost of the M42 project in Great Britain was £5.6 million per km (approximately $5.6 million per mile), while the cost of adding an extra lane would be between $18 and $25 million per mile.

In Minnesota, the PDSL project cost $13 million. This budget included resurfacing of the entire facility, including the shoulder lanes and emergency refuge areas. The average construction cost for upgrading the shoulder lanes for the Minnesota BOS program is estimated at $250,000 per mile on average. In Washington the redesign of a 4.5 mile long segment of I-5 that includes shoulder lane use, CCTVs, dynamic signing of the shoulder lanes, VMS, and ramp metering, is budgeted at $30 million, with an estimated benefit-to-cost ratio greater than 3:1 (Bandy and Trowbridge, 2012).

7.3.9 Maintenance concerns

Maintenance-related issues for shoulder lane use are identified in the NCHRP Report 369 (Curren, 1995). According to this report, highway appurtenances such as signage, barriers, drains, and lights were closer to traffic and were damaged more often and more severely when shoulder lane use was permitted. Also, during regular maintenance, additional personnel and equipment may be necessary to close lanes and provide adequate work area protection.

The report also suggests that clearance time for incidents doubles with shoulder lane use, given that in most cases it is required the shoulder lane to remain closed until the incident is cleared, or items are removed. Lastly, in several cases maintenance operations are responsible for removing debris from the shoulder lane before the start of operation.

7.4 Summary

In Europe, shoulder use deployment is typically part of a broader congestion management strategy and it operates in conjunction with traffic management strategies such as speed harmonization (variable speed limits), and junction control. The European paradigm shows that

the benefits from using shoulder lanes during peak periods are significant in terms of reducing travel times and increasing throughput. Additional benefits include improved travel time reliability and improved safety due to homogeneous speeds and headways.

The benefits provided from the European applications are part of a broader program of Advanced Traffic Management strategies, whereas, in the US shoulder lane use is usually not implemented in conjunction with other advanced management strategies, with the exception of the Minnesota deployment of the priced dynamic shoulder lanes (PDSL). Thus, the installed ITS equipment at any one site in the US is often limited. On the contrary, the installation equipment typically used in Europe includes overhead gantries, lane control signals, dynamic message signs, speed limit signals, as well as additional ITS equipment such as CCTVs, roadway sensors and incident detection.

To date, there is no concurrent deployment of shoulder lane use and ramp metering. Ramp metering is planned to be installed at the downstream boundary on-ramp of the I-5 NB project in Washington (Bandy and Trowbridge, 2012), however, it is not clear how this implementation will interact with the upstream shoulder lane use.

With respect to safety, although the shoulder lane use deployment in Europe is associated with significant safety improvements, this is not the case for the US. Negative safety impacts of shoulder lane use are associated with narrow lane widths and high speed differentials. It is possible that the use of variable speed limits would improve safety conditions since the average speed, and therefore the speed differentials, would decrease. Several simulation-based studies have reached this conclusion.

According to past experience, increased monitoring of shoulder lanes is associated with improved incident response times. Increased safety service patrols and motorcycle law enforcement response, as well as a comprehensive ITS and Traffic Management System will assist in mitigating shoulder access issues and providing acceptable incident response times. In addition, emergency refuge areas facilitate the incident response. Minimum spacing of emergency refuge areas is approximately 0.3 to 0.5 miles.

A few minor liability issues have been identified in the literature. From a legal perspective, in Florida, the term "roadway" may require clarifying language, since the shoulder is currently excluded from the definition of the term as defined in the Florida Statute.

Public outreach and education is typically done through media events, brochures, radio spots and public meetings. Training manuals and sessions are typically used for training transit operators of the BOS programs. Specific personnel training efforts for shoulder lane use by general traffic have not been identified.

 Overall, the shoulder lane use has been considered an inexpensive solution to increase capacity, and improve travel times, compared to adding an extra lane. However, there are several maintenance and enforcement concerns that pertain to the shoulder lane use. These issues are related to additional effort and time required occasionally from emergency vehicles to clear an incident or from maintenance personnel to provide adequate protection during regular maintenance works. Enforcement issues particularly related to the concurrent implementation of variable speed limits, have been identified in the past. Automated enforcement efforts such as

those reported in European installations would likely result in increased compliance and would enhance the performance of the strategy.

REFERENCES

Al-Deek, H. M., Garib, A., and Radwan, A. E. (1995) New Method for Estimating Freeway Incident Congestion *Transportation Research Record: Journal of the Transportation Research Board*, 1494, 30–39.

Ballard, A.J. (2004) Incident Management for Managed Lanes. Report 0-4160-17, Texas Transportation Institute, College Station, TX.

Bandy, M., Trowbridge, A. (2012) I-5/Northbound Marine View Drive to SR 528 Peak Use Shoulder Lane, Washington State DOT. http://www.psrc.org/assets/8180/19._WSDOT_-_I-5_NB_Marine_View_Dr_to_SR528_-_Peak_Use_Shoulder_Lane.pdf . Accessed August 2013.

Bauer, K. M., Harwood , D. W., Hughes, W. E., and Richard, K.R. (2004) Safety Effects of Narrow Lanes and Shoulder-Use Lanes to Increase Capacity of Urban Freeways. *Transportation Research Record: Journal of the Transportation Research Board*, 1897, 71–80.

Berman, W., Differt, D., Aufschneider, K., DeCorla-Souza, P., Flemer, A., Hoang, L., Hull, R., Schreffler, E., Zammit, G. (2006) *Managing Travel Demand: Applying European Perspectives to U.S. Practice*. Final Report No. FHWA-PL-06-015.

Blume, K. L. (1998) *Implementation of a Dynamic HOV Lane*. Department of Civil Engineering, Texas A&M University, College Station, TX.

Burris, M., and Lipnicky, K. (2009) HOV or General Purpose Lanes? *Public Works Management & Policy*, 14, 130–147.

California Department of Transportation (Caltrans). (2003) High-Occupancy Vehicle Guidelines for Planning, Design and Operations. http://www.dot.ca.gov/hq/traffops/systemops/hov/hov_sys/guidelines/. Accessed December 2012.

California Department of Transportation (Caltrans). (2012) HOV Inventory List. http://www.dot.ca.gov/hq/traffops/systemops/hov/reference.html. Accessed December 2012.

Carrick, G. and Washburn, S. (2012). The Move Over Law: Effect of Emergency Vehicle Lighting on Driver Compliance on Florida Freeways. *Transportation Research Record: Journal of the Transportation Research Board*, 2281, 1-7.

Carrick, G., and Washburn, S.S. (2013) Estimating the Impacts of Police Enforcement Stops on Freeway Operations and Capacity. *Transportation Research Record: Journal of the Transportation Research Board*, In Press.

Carson, J. L. (2005) *Strategies for Interim Use of Managed Lanes*. Report 0-4160-22, Texas Transportation Institute, Texas A&M University System, College Station, TX.

Carson, J. L. (2010) *Best Practices in Traffic Incident Management*. FHWA-HOP-10-050, Federal Highway Administration, Washington, DC.

Chang, M., Wiegmann, J., and Bilotto, C. (2008) *A Compendium of Existing HOV Lane Facilities in the United States*. FHWA-HOP-09-030, Federal Highway Administration, Washington, DC.

Chin, H. (1996) A Reexamination of the Analysis of Freeway Bottlenecks. *Journal of Transportation Engineering*, 66, 30–35.

Chou, C. and Miller-Hooks, E. (2011) Exploiting Capacity of Managed Lanes in Diverting Traffic around an Incident. *Transportation Research Record: Journal of the Transportation Research Board*, 2229, 75-84.

Cothron, A.S., Skowronek, D. A., and Kuhn, B.T. (2003) *Enforcement Issues on Managed Lanes*. FHWA/TX-03/4160-11. Texas Transportation Institute.

Cohen, S. (2004) Using the hard shoulder and narrowing lanes to reduce congestion. Some Lessons from an experience on the Paris motorway network. *In Proceedings of the 12th IEEE Conference on Road Transport Information and Control*, London, 149-153.

Connecticut Department of transportation. (ConnDOT). (2010) *High Occupancy Vehicle Lane Report 2010*. http://www.ct.gov/dot/lib/dot/documents/dpolicy/2010HovRpt.pdf. Accessed June 2013.

Curren, J. E. (1995) *Use of Shoulders and Narrow Lanes to Increase Freeway Capacity*. National Cooperative Highway Research Program Report 369, Transportation Research Board, Washington, D.C.

Daganzo, C. F., Laval, J. and Munoz, J. C. (2002) *Ten Strategies for Freeway Congestion Mitigation with Advanced Technologies*. UCB-ITS-PRR-2002-3, California PATH Program, Institute of Transportation Studies University of California, Berkeley, CA.

Dunn, W., Reiss, R., and Latoski, S. (1999) *NCHRP Synthesis of Highway Practice 279, Roadway Incident Diversion Practices*. Transportation Research Board, National Research Council, Washington, DC.

Federal Highway Administration (FHWA). (2000) *Traffic Incident Management Handbook. Office of Travel Management*, Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). (2004) *Managed Lanes: A Cross-Cutting Study*. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). (2005) *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation*. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). (2008a) *Managed Lanes: A Primer*. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). (2008b) Federal-Aid Highway Program Guidance on High Occupancy Vehicle (HOV) Lanes. www.ops.fhwa.dot.gov/freewaymgmt/hovguidance/hovguidance.pdf. Accessed December 2012.

Federal Highway Administration (FHWA). (2009). Manual on uniform traffic control devices: For streets and highways. http://mutcd.fhwa.dot.gov/htm/2009/part6/part6i.htm. Accessed May 2013.

Federal Highway Administration (FHWA). (2010) *Traffic Incident Management Handbook Update*. Office of Travel Management, Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). (2011) Managed Lane Chapter for the Freeway Management and Operations Handbook. http://ops.fhwa.dot.gov/freewaymgmt/publications/frwy_mgmt_handbook/revision/jan2011/mgdlaneschp8/sec8.htm. Accessed December 2012.

Federal Highway Administration (FHWA). (2012). Emergency Transportation Operations: Traffic Incident Management. http://www.ops.fhwa.dot.gov/eto_tim_pse/about/tim.htm. Accessed June 2013.

Fenno, D. W., Benz, R. J., Vickich, M. J., Theiss, L., Ranft, S. E., Ungemah, D. H., and Goodin, G. D. (2006) *Improved quantification of high-occupancy vehicle (HOV) lane delay savings: Year Two results*. Report FHWA/TX-06/0-4740-3, Texas Transportation Institute, Texas A&M University System, College Station, TX.

Florida Statute. (2012) § 316.0741 High-occupancy-vehicle lanes.

Florida Statute. (2012) § 338.166 High-occupancy toll lanes or express lanes.

Florida Statute. (2012) § 316.006 Jurisdiction.

Florida Statute. (2012) § 321.05 Duties, functions, and powers of patrol officers.

Florida Department of Transportation (FDOT). (2005) *Best Practices for Traffic Incident Management in Florida*. Florida Department of Transportation.

Florida Department of Transportation (FDOT). (2006) Florida Traffic Incident Management Strategic Plan. http://www.dot.state.fl.us/trafficoperations/Traf_Incident/pdf/PageSz-2006-AR-IM-CVO.pdf

Florida Department of Transportation (FDOT). (2012) *Florida Department of Transportation District VI Standard Operating Guidelines District VI*, Miami, Florida. Florida Department of Transportation.

Florida Department of Transportation (FDOT). (2013) *95 Express Annual Report*. Florida Department of Transportation, District Six, Miami, FL.

Florida's Turnpike Enterprise. (2012) Hurricane Evacuations and Toll Suspensions. http://www.floridasturnpike.com/sunpassages/archives/08.fall/index.html. Accessed December 2012.

Fu, L. (2004) A Fuzzy Queuing Model for Real-Time, Adaptive Prediction of Incident Delay for ATMS/ATIS. *Transportation Planning and Technology*, 27, 1–23.

Fuhs, C. (2010) *Synthesis of Active Traffic Management Experiences in Europe and the United States*. (Report No. FHWA-HOP-10-031).

Georgia State Road and Tollway Authority. (2012) Frequently Asked Questions. http://www.peachpass.com/faq. Accessed December 2012.

Goolsby, M. E. (1971) Influence of Incidents on Freeway Quality of Service. *Highway Research Record*, 349, 41–46.

Guin, A., Michael, H., and Randall, G. (2008) Analysis of Reduction in effective Capacities of High-Occupancy Vehicle Lanes Related to Traffic Behavior. *Transportation Research Record: Journal of the Transportation Research Board*, 2065, 47–53.

Henderson, D., Vandervalk, K. A., and Cromartie, K. (1998) I-95 HOV Performance Monitoring In South Florida. *The 68th Annual Meeting of the Institute of Transportation Engineers*. CDROM. Washington, DC.

Hoppers, K. P. (1999) *Opening HOV Lanes to General Traffic during Major Incidents and Severe Weather Conditions*. Department of Civil Engineering, Texas A&M University, College Station, TX.

Kraus, E., Quiroga, C., and Hamad, K. (2006) Estimating the Impact of Incident Delay Using Loop Detector Data. *ITE Annual Meeting and Exhibit Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, DC.

Kuhn, B. (2010) *Efficient Use of Highway Capacity Summary*. Report No. FHWA-HOP-10-023. College Station, TX, Texas Transportation Institute, Texas A&M University.

Kuhn, B. (2012) U.S. Experience with Safety Shoulder Use as Travel Lanes, *In Proceedings of the Transportation Research Board Annual Meeting*, Washington, D.C.

Kwon, J., and Varaiya, P. (2008) Effectiveness of California's High Occupancy Vehicle (HOV) System. *Transportation Research Part C*, 16, 98–115.

Lee, J.T., Dittberner, R., and Sripathi, H.(2007) "Safety Impacts of Freeway Managed-Lane Strategy - Inside Lane for High-Occupancy Vehicle Use and Right Shoulder Lane as Travel Lane During Peak Periods". *Transportation Research Record: Journal of the Transportation Research Board*, 2012, 113–120.

Legislative Analyst's Office (LAO). (2000) *HOV lanes in California: Are they achieving their goals?* www.lao.ca.gov/2000/010700 hov/010700 hov lanes.html. Accessed July 2013.

Levecq, C., Khun, B., and Jasek, D.(2011) *General Guidelines for Active Traffic Management Deployment – Best Practices and Outreach for Active Traffic Management*. UTMC Report No. 10-01-54-1, Texas Transportation Institute, College Station, TX.

Li, J., Lan, C. J., and Gu, X. (2006) Estimation on Incident Delay and Its Uncertainty on Freeway Networks. *Transportation Research Record: Journal of the Transportation Research Board*, 1959, 37–45.

Lighthill, M. J., and Whitham, G. B. (1955) On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 229, 317–345.

Lindley, J. A. (1986) *Quantification of Urban Freeway Congestion And Analysis of Remedial Measures*. Report No. FHWA/RD-87/052. Federal Highway Administration, Washington, DC.

Liu, S. and Murray-Tuite, P. (2008) *Evaluation of Strategies to Increase Transportation System Resilience to Congestion Caused by Incidents*. Report No. VPI-2006-03. Department of Civil and Environment Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Liu, X., Schroeder, B., Thomson, T., Wang, Y., Rouphail, N., and Yin, Y. (2011) Analysis of Operational Interactions between Freeway Managed Lanes and Parallel, General Purpose Lanes. *Transportation Research Record: Journal of the Transportation Research Board*, 2262, 62–73.

Los Angeles County Metropolitan Transportation Authority (LACMTA). (2002) *HOV Performance Program Evaluation report*. http://www.metro.net/projects_studies/hov/images/hov_final_evaluation_report.pdf. Accessed June 2012.

Lovell, D. J. and Windover, J. R. (1999) Discussion of "Analyzing Freeway Traffic under Congestion: Traffic Dynamics Approach" by D. H. Nam and Donald R. Drew, *ASCE Journal of Transportation Engineering*, 125 (4), 373-375.

Manda, H., Song, Z., Yin, Y., and Wang. Y. (2011) Comparison of Capacities of High-Occupancy-Vehicle and General Purpose Lanes. *TRB 89th Annual Meeting Compendium of Papers*. CD-ROM. Transportation Research Board of the National Academies, Washington DC.

Martin, P., Levinson, H.S. (2012) Texas Transportation Institute .*A Guide for Implementing Bus on Shoulder (BOS) Systems*. TCRP Report 151, Transportation Research Board, Washington, D.C.

Martin, P. (2006) *Bus Use of Shoulders*, TCRP Synthesis 64, Transportation Research Board, Washington, D.C.

Maryland State Highway Administration. (2012). *HOV Policy for Lifting the HOV Restrictions on the I-270 and US 50 HOV Lanes*. Maryland Department of Transportation.

Morales, M. J. (1987) Analytical Procedures for Estimating Freeway Congestion. *ITE Journal*, 57, 45–49.

Moskowitz, K., and Newman, L. (1963) Notes on Freeway Capacity. *Highway Research Record*, 27, 44–68.

National TDM and Telework Clearinghouse. (2010) *State Averages for Private Vehicle Occupancy, Carpool Size and Vehicles Per 100 Workers*. http://www.nctr.usf.edu/clearinghouse/censusavo.htm. Accessed July 2013.

Nee, J., Ishimaru, J. M., and Hallenbeck, M. E. (2004) *HOV Lane Performance Monitoring Report 2002: Volume 1*. WA-RD 584.2. Washington State Transportation Center (TRAC), Seattle, WA.

Office of the Attorney General, New Jersey. (2010) State of New Jersey Highway Traffic Safety Guidelines for Emergency Responders. Office of the Attorney General.

Owens, N. D., Armstrong , A.H., Mitchell, C., and Brewster , R.(2010) *Federal Highway Administration Focus States Initiative: Traffic Incident Management Performance Measures*. FHWA-HOP-10-010 Final Report, Federal Highway Administration, Washington, D.C.

Perez, B. G. and Sciara, G. C. (2003) *A Guide for HOT Lane Development*. FHWA-OP-03-009. Federal Highway Administration, Washington, DC.

PTV. (2005) VISSIM 4.10 User Manual. PTV Planung Transport Verkehr AG, Karlsruhe, Germany.

Quiroga, C. (2000) Performance Measures and Data Requirements for Congestion Management Systems. *Transportation Research Part C*, 287–306.

Rakha, H., and Zhang, W. (2005) Consistency of Shock-Wave and Queuing Theory Procedures for Analysis of Roadway Bottlenecks. *Proceedings CD-ROM for the 84th Annual Meeting of Transportation Research Board*, Washington, DC.

Richards, P. I. (1956) Shock Waves on the Highway. *Operations Research*, 4, 42–51.

Sas, M., Carlson, S, Kim, E., Quant, M. (2007) Considerations for High Occupancy Vehicle (HOV) to High Occupancy Toll (HOT) Lane Conversions Guidebook. FHWA-HOP-08-034. Federal Highway Administration.

Schrank, D. L., Lomax, T. J. (2003) The Urban Mobility Report. Texas Transportation Institute, the Texas A & M University System, College Station, TX.

Shoup, D. C., and Brown, J. (2001) *Pricing Our Way Out of Traffic Congestion: parking cash out and HOT lanes*. UCTC No. 509. University of California Transportation Center. Berkeley, CA.

Skabardonis, A., Petty, K., Noeimi, H., Rydzewski, D., and Varaiya, P. P. (1996) I-880 Field Experiment: Data-Base Development and Incident Delay Estimation Procedures. *Transportation Research Record: Journal of the Transportation Research Board*, 1554, 204–212.

Smith, B. L., Qin, L., and Venkatanarayana, R. (2003) Characterization of Freeway Capacity Reduction Resulting from Traffic Accidents. *Journal of Transportation Engineering*, 362 – 368.

Sparmann, J. (2006), Freeway Operation in Germany: Experiences in Hessen. In Proceedings of the 1st International Symposium on Freeway and Tollway Operations, Athens, Greece.

Taale, H. (2006) *Regional Traffic Management - Method and Tool*. AVV Transport Research Centre, Rotterdam, The Netherlands: Ministry of Transport, Public Works, and Water Management, Directorate-General of Public Works and Water Management.

Texas Transportation Institute (TTI). (2005) *Managed Lanes Handbook*. Report 0-4160-24, Texas Transportation Institute, Texas A&M University System, College Station, TX.

Title 23 USC(2012) § 166 - HOV Facilities.

The American Association of State Highway and Transportation Officials (AASHTO). (2004) *Guide for High-Occupancy Vehicle (HOV) Facilities, 3rd Edition*, Washington, DC.

Transportation Research Board (TRB). (1998) *NCHRP Report 414: HOV Systems Manual*. Transportation Research Board, National Research Council, Washington, DC.

Transportation Research Board (TRB). (2000) *Highway Capacity Manual*. Transportation Research Board, Washington, DC.

Transportation Research Board (TRB). (2006) *Transit Cooperative Research Program (TCRP) Report 95: Traveler Response to Transportation System Changes Handbook Chapter 2, HOV Facilities*. Transportation Research Board, Washington, DC.

Urbanik, T., Bonilla, C. (1987) *California Experience with Inside Shoulder Removals*. Transportation Research Record 1122. Transportation Research Board, Washington, DC, National Academy of Science.

U.S. Dept. of Transportation, Federal Highway Administration. (2007). *Intelligent Transportation Systems for Traffic Incident Management.* Retrieved December 18, 2012 from http://ntl.bts.gov/lib/jpodocs/brochure/14288_files/14288.pdf.

U.S. Dept. of Transportation, Federal Highway Administration. (2009). *Manual on uniform traffic control devices: For streets and highways*. Retrieved May 31, 2013 from http://mutcd.fhwa.dot.gov/htm/2009/part6/part6i.htm .

U.S. Dept. of Transportation, Federal Highway Administration. (2012). Emergency Transportation Operations: Traffic Incident Management. Retrieved June 1, 2013 from http://www.ops.fhwa.dot.gov/eto_tim_pse/about/tim.htm.

Virginia Department of Transportation (VDOT). (2012) High Occupancy Vehicle (HOV) Lanes - Rules and FAQs. http://www.virginiadot.org/travel/hov-rulesfaq.asp. Accessed December, 2012.

Virginia Code. (2012) § 33.1-46.2. Designation of high-occupancy vehicle lanes; use of such lanes; penalties.

Virginia Code. (2001) § 33.1-46.2. Designation of high-occupancy vehicle lanes; use of such lanes; penalties.

Waller, T., Ng, M.W., Ferguson, E., Nezamuddin, N., Sun, D.(2009) *Speed Harmonization and Peak-period Shoulder Use to Manage Urban Freeway Congestion*. Report No. FHWA/TX-10/0-5913-1. Kingsville, TX, Texas A&M University.

Wang, Y. Yu, R., Lao, Y., and Thomson, T. (2011) *Quantifying Incident-Induced Travel Delays on Freeways Using Traffic Sensor Data: Phase II*. WA-RD 758.1, Washington State Transportation Center (TRAC), University of Washington, Seattle, WA.

Washington State Transportation Center. (2007) *TRAC HOV Public Opinion Survey Results*. Washington State Transportation Center, University of Washington, Seattle, WA.

Washington State Department of Transportation (WSDOT). (2012) HOV Common Questions. http://www.wsdot.wa.gov/HOV/FAQ.htm. Accessed December 2012.

Wikander, J. and Goodin, G. (2006) *High-Occupancy Vehicle (HOV) Lane Enforcement Considerations Handbook*. Texas Transportation Institute, College Station, TX.

APPENDIX

HOV Policy for Lifting the HOV Restrictions on the I-270 and US 50 HOV Lanes

9/14/2012

Policy Statement: The temporary lifting of HOV restrictions and the opening of HOV lanes to all traffic may be instated when a nonrecurring incident within the general purpose lanes occurs, such that a lane of traffic is projected to be closed for one hour or longer, inclement weather conditions are projected to create extraordinary delays, or when the Snow Emergency Plan is in effect. The HOV lane restriction for the facility will be reinstated when the Traffic Operations Center (TOC) determines that the roadway is back to normal conditions.

Procedure:

1. The Field Supervisor/On-call Supervisor at the Traffic Operations Center (TOC) in College Park will contact the Barrack Commander or their designee at the appropriate Maryland State Police (MSP) Barrack (Rockville or College Park) to jointly decide to lift the HOV restrictions.

2. Once the decision has been made to lift the restrictions, the MSP Barrack Commander or their designee will contact the appropriate County Police.

3. The TOC supervisor will contact the Statewide Operations Center (SOC) and the appropriate County Department of Transportation (MCDOT or Prince George's DPW&T). The SOC, through their current notification process, will contact the on-call person at the Office of Customer Relations and Information.

4. The Office of Customer Relations and Information and the TOC will both contact the appropriate media outlets to alert commuters that the HOV lane restrictions will be lifted. CHART will activate the Dynamic Message Signs (DMS) and the Highway Advisory Radio (HAR). CHART will also send out a notification to the Executive Paging Group and the Regional and Intermodal Planning Division's HOV Coordinator.

5. The HOV lane restrictions for the facility will be reinstated when the TOC determines that traffic is back at normal conditions.

The lifting of the restriction begins once the pertinent agencies and personnel have been notified.

Approved:

_____
Melinda B. Peters, Administrator

9/20/12
_____
Date