Crash Prediction Method for Freeway Facilities with High Occupancy Vehicle (HOV) and High Occupancy Toll (HOT) Lanes

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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

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This study developed methods for estimating the expected crash frequency of urban freeway segments with HOV or HOT lanes. The safety impacts of the type of separation between the managed lanes and general purpose lanes were examined. Separate models were estimated for fatal and injury (FI) crashes and all crashes. The models for facilities with HOV lanes were estimated using five years' of data from California, Washington, and Florida. All these facilities have one HOV in each direction (included in the count of total number of lanes). The effect of separation type on crash rates is found to be statistically significant only in the models for ten-lane facilities. The models for freeways with HOT lanes were estimated using four years' of data from 27 miles (48 segments) of freeways from the states of California, Texas, and Florida. All these facilities have two HOT lanes in each direction. Facilities with a 1-foot separation are estimated to have more crashes than those that have a 3-foot separation which in turn have more crashes than facilities with a 20-foot separation. All the estimated models have been implemented in a spreadsheet program which will enable analysts to apply these equations for crash prediction. Overall, this study provides procedures that will help FDOT consider safety in decisions about planning and designing freeways with HOV or HOT lanes.</td></tr>
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EXECUTIVE SUMMARY

This study developed methods for estimating the expected crash frequency of urban freeway facilities with HOV or HOT lanes. The scope of the research is limited to freeway segments (crashes on ramps and interchanges are excluded). The safety impacts of the type of separation between the managed lanes and general purpose lanes are examined. Separate models are estimated for fatal and injury (FI) crashes and all crashes. Crashes with the injury severity levels of "K", "A', "B", and "C" are classified as FI crashes. "All" crashes include FI crashes and crashes with "property damage only" (injury severity level of "O").

The models for facilities with HOV lanes were estimated using five years' of data from California, Washington, and Florida. Separate equations were developed depending on the total number of lanes in the freeway facility leading to models for six-, eight-, ten-, and twelve- lane facilities. All these facilities have one HOV in each direction (included in the count of total number of lanes).

The models for FI crashes (N_{FI}) for six-, eight-, ten-, and twelve- lane freeways are:

$$N_{FI}(6) = 0.2 * \exp(-16.174 + \ln(L) + 1.760Ln(AADT) - 0.039Ln(LSW))$$
$$N_{FI}(8) = 0.2 * \exp(-4.41 + \ln(L) + 0.757Ln(AADT) - 0.051Ln(LSW) + 0.382(FL))$$
$$N_{FI}(10) = 0.2 * \exp(-8.861 + \ln(L) + 1.12Ln(AADT) - 0.055Ln(LSW) + 0.522(FL) + 0.310(WA) - 0.141(BW23))$$
$$N_{FI}(12) = 0.2 * \exp(-7.109 + \ln(L) + 0.972Ln(AADT))$$

The models for all crashes (N_{all}) for six-, eight-, ten-, and twelve- lane freeways are:

$$N_{all}(6) = 0.2 * \exp(-14.07 + \ln(L) + 1.648Ln(AADT) - 0.074Ln(LSW) + 0.537(CA))$$
$$N_{all}(8) = 0.2 * \exp(-3.31 + \ln(L) + 0.759Ln(AADT) - 0.026Ln(LSW))$$
$$N_{all}(10) = 0.2 * \exp(-9.555 + \ln(L) + 1.277Ln(AADT) - 0.084Ln(LSW) + 0.126(PS))$$
$$N_{all}(12) = 0.2 * \exp(-4.409 + \ln(L) + 0.860Ln(AADT))$$

In the above equations, AADT is the annual average traffic volume (veh/day), L represents the segment length (in miles) and LSW is the left-shoulder-width (in foot). There are four levels of separation between the managed lanes and the general purpose lanes: Painted stripe, Buffer width 0-1 foot, Buffer width 1-2 foot, and Buffer width 2-3 Foot (represented by binary variables PS, BW01, BW12, and BW23 respectively). CA is a binary (0 or 1) variable that indicates whether the segment is from California or not. FL is a binary (0 or 1) variable that indicates whether the segment is from Florida or not. Similarly WA is a binary variable that indicates whether the segment is from Washington tor not. The prediction from the regression equation is scaled by 0.2 to obtain a yearly crash prediction (note that 5-years of data were used in model estimation).

The effect of separation type is on crash rates is found to be statistically significant only in the models for ten-lane facilities. A painted stripe separation is correlated with more total (all) crashes on 10-lane freeways (compared to buffer separation). Wider buffer separation (2-3 foot) is correlated with fewer fatal and injury crashes. The effect of separation type was not statistically significant in the case of six-, eight-, and twelve- lane facilities.

Consistent with other HSM models, the equations for freeways with HOV lanes indicate that the crashes increase with increase in traffic volume (AADT) and segment length (measured in miles). Increased width of the left shoulder (measured in feet) is associated with a decrease in the number of crashes in all models except the ones for twelve-lane facilities. Systematic statistical differences in the crash rates (after controlling for traffic volumes, lengths, left shoulder width, and separation type) among the three states were also observed in some of the models.

The models for freeways with HOT lanes were estimated using four years' of data from 27 miles (48 segments) of freeways from the states of California, Texas, and Florida. All these facilities have two HOT lanes in each direction. The models for FI crashes (N_{FI}) and all crashes (N_{all}) for urban freeways with HOT lanes are:

$$N_{FI} = 0.25 * \exp(-3.583 + \ln(L) + 0.577Ln(AADT) + 0.077(NL) + 1.39(S1) + 0.527(S3))$$

$$N_{all} = 0.25 * \exp(-2.899 + \ln(L) + 0.594Ln(AADT) + 0.086(NL) + 1.247(S1) + 0.839(S3))$$

In the above equations, AADT is the annual average traffic volume (veh/day), L represents the segment length (in miles) and NL is the number of lanes. There are three levels of separation between the managed lanes and the general purpose lanes: 1 feet, 3 feet, and 20 feet (represented by binary variables S1, S3, and S20 respectively). The prediction from the regression equation is scaled by 0.25 to obtain a yearly crash prediction (note that 4-years of data were used in model estimation).

Facilities with a 1-foot separation are estimated to have more crashes than those that have a 3-foot separation which in turn have more crashes than facilities with a 20-foot separation. This result is presented with the implicit assumption that there are no other systematic differences in the safety of freeway facilities across the three states as each type of separation is unique to a state. With the availability of data from additional HOT lane facilities, especially those that have become operational recently, the models for HOT-lane facilities can be updated to improve their statistical robustness.

All the estimated models have been implemented in a spreadsheet program which will enable analysts to apply these equations for crash prediction. Overall, this study provides procedures that will help FDOT consider safety in decisions about planning and designing freeways with HOV or HOT lanes. Future efforts should seek to enhance the models developed in this study using data from more states and from recent years. Such an effort poses important data challenges as data content, formats, and completeness vary across the states.

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LIST OF ACRONYMS/ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CDF	Cumulative Density Function
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
EB	Empirical Bayes
ETL	Express Toll Lanes
FI	Fatal and Injury
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GP	General-purpose
HOT	High-Occupancy Toll
HOV	High-Occupancy Vehicle
HSM	Highway Safety Manual
NB	Negative Binomial
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
SOV	Single Occupancy Vehicle
SPF	Safety Performance Functions
U.S.	United States

CHAPTER 1:
INTRODUCTION

Managed lane strategies are "the evolution of traditional lane management strategies, with the primary difference being the idea of active management over the life of the facility" (Federal Highway Administration, 2008). Kuhn et al. (2005) identified the following as the different types of managed-lanes operational strategies: High Occupancy Vehicle (HOV) lanes, High Occupancy /Toll (HOT) lanes, exclusive lanes, mixed-flow separation/bypass lanes, lane restrictions, and dual facilities. HOV lanes are reserved for vehicles with a driver and one or more passengers. In some cases, other vehicles such as motorcycles, transit buses, and emergency vehicles are permitted in the HOV lanes. When single occupancy vehicles (SOVs) are permitted to use the HOV lanes with a toll, the facilities are known as high-occupancy toll (HOT) lanes (Chang et al., 2008).

Since their inception in late 1960s, HOV lanes have been increasingly implemented across the United States. Several FDOT projects using managed lanes are currently under consideration in various Districts, including SR-826 in Miami, I-4 in Orlando and the Pensacola Bay Bridge. In addition to encouraging carpooling and increasing person throughput, the HOV facilities help alleviate congestion, improve travel time reliability, and benefit air quality (Stockon et al., 1999; Skowronek et al., 2002; Fuhs and Obenberger, 2002; Chang et al., 2008; GDOT, 2010). At the same time design elements of HOV/HOT facilities such as orientation (i.e., contra-flow or concurrent flow), lane access type (i.e., continuous or limited), and lateral separation from general purpose lanes (i.e., buffer or barrier) can also impact the safety of the facility.

The Highway Safety Manual (HSM) provides the transportation industry with a methodology to predict crashes and quantify the safety benefits of various design features on various highway types excluding freeway facilities. The recently completed NCHRP Project 17-45, "Enhanced Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges" produced a set of safety prediction methods for basic freeway facilities. Neither of these studies address freeway facilities with managed lanes.

Given the increase in the number of managed lane facilities and the lack of systematic methods to analyze their safety, this study aims to develop methods to estimate the expected crash frequency of freeway facilities with HOV or HOT lanes. The scope of the research will be limited to urban freeways, where most of such facilities are situated. In consideration of the data availability issues, this study examines only freeway segments and not ramps or interchange areas. Among the design elements, the focus is on the type of separation between the managed and general purpose lanes. Overall, this research provides procedures that will help FDOT consider safety in decisions about planning and designing freeways with HOV or HOT lanes.

The rest of this report is organized as follows. Chapter 2 presents a review of literature on the safety of freeways with managed lanes. Chapter 3 presents a detailed overview of the data assembled and the procedures involved. Chapter 4 presents the safety performance functions estimated. Chapter 5 presents an overall summary of this effort and identifies the major conclusions and areas for future work. Along with this report, spreadsheet implementations of the models presented in Chapter 4 are also available. These may be used by analysts to apply the developed equations for crash frequency estimation of freeway segments with HOV or HOT lanes.

CHAPTER 2:
LITERATURE REVIEW

This chapter presents a brief synthesis of the literature on the topic of safety of managed lane facilities. Section 2.1 focuses on before-and-after studies on safety of facilities with managed lanes. Section 2.2 examines the impacts of the geometry of managed lane facilities on safety. Specifically the impacts of the type of separation between the managed lanes and general purpose lanes, the nature of access to the managed lanes, and the width of the lanes are discussed. A tabular summary of all the articles reviewed is included in Appendix A.

2.1 BEFORE AND AFTER STUDIES

Several of the earliest before- and after- studies on the safety of managed lane (HOV) facilities are from the state of California. Golob et al. (1989) evaluated the safety performance of HOV lanes that are not physically separated from adjacent general-purpose lanes. Crash frequencies from 14 months after the construction of HOV lanes were compared to the six-year data prior to HOV lane construction on SR-91 in Los Angeles. The authors report that the proportion of total crashes within the HOV section and downstream were not statistically different. The case study indicated no adverse effect on safety conditions that could logically be attributed to the HOV operation. The authors further concluded that the safety effect of HOV lanes were too subtle to be identified in aggregate crash frequencies. However, the authors observed a migration in crash locations due to traffic bottlenecks at the end of the HOV lane sections. The authors concluded that "while the HOV lane on SR-91 has not degraded safety, it has also not alleviated conditions." Golob et al. (1990) examined the freeway-median HOV lanes in SR 55 in California using before- and after- data and reported a 2% increase in crashes because of the additional HOV lane.

Urbanik and Bonilla (1987) compared the before- and after- crash data on twelve freeway segments in California, and found that removing an inside shoulder to accommodate HOV lanes resulted in either no change or a significant reduction in overall crashes in eleven segments. Reductions on property-damage-only crashes were statistically significant; however, reductions in fatal and injury crashes were not. The reduction was attributed in part to the reduction on congestion levels on these facilities. Hockaday et al. (1992) evaluated the effects of HOV lanes on the safety of selected California freeways. They suggested that the observed crash patterns resulted from differences in traffic flow and congestion rather than geometric and operational characteristics of HOV lanes. Further, they also report that the crash "hot spots" during peak periods on freeways with and without HOV lanes were a result of localized congestion. Case (1997) analyzed nine facilities with 0-2 foot buffer between the HOV and general-purpose lanes. For six of the nine facilities, crash rates after the construction of HOV lanes exceeded the pre-HOV crash rates. Further, the crash rates were found to increase with the increase in the speed differentials between the HOV and the general-purpose lanes.

Bauer et al. (2004) evaluated the safety of adding an additional travel lane on urban freeways in California by narrowing existing lanes and converting a part of existing shoulder into a travel lane. In a majority of the study locations, the additional lane was a buffer-separated HOV lane. The authors found a statistically-significant increase in crash frequencies when four lane facilities were converted to five lane facilities. This increase was partly attributed to the increased speed differentials between HOV lanes and the general-purpose lanes. The same study also reports that conversion of five lane facilities to six lane facilities did not result in a statistically significant change in crashes.

Other researchers have also examined the safety of HOV facilities in Texas using before- and after- studies. Skowronek et al. (2002) conducted a before-and-after analysis to evaluate the safety performance of buffer-separated and barrier-separated HOV facilities in Texas. The relatively high crash rates on barrier-separated HOV lanes were found to be the result of construction projects along the study corridors, and were not directly attributed to the HOV facility. Crash rates increased after the implementation of buffer-separated concurrent flow HOV lanes, and a more pronounced increase was found during peak periods. The increase, although documented on the entire corridor (i.e., with and without buffer-separated HOV lanes), could be partially attributed to violations and illegal weaving maneuvers. Cothron et al. (2004b) conducted a before-and-after crash analysis to evaluate the safety performance of one barrier-separated HOV lane corridor and two buffer-separated HOV lane corridors in Texas. The two corridors with buffer-separated HOV facilities showed a 56% and 41% increase in corridor injury crash rates in the "after" period relative to the "before" period. Also, crash rates were higher during peak periods in the after-period. The speed differential between the HOV lane and the adjacent general-purpose lane was found to contribute to the increased crash occurrence. Cothron et al. (2004b) also concluded that construction of buffer-separated HOV lanes resulted in an increase in the crash occurrences on the inside general-purpose lane (i.e., on the general-purpose lane closest to the buffer-separated HOV lanes). The reduction in lane and shoulder width to accommodate the HOV lane was cited as a possible cause for the crash rate increase in the after-period.

More recently, some researchers have also evaluated the safety benefits of other managed lane strategies. For example, Sullivan and Burris (2006) conducted a benefit-cost analysis of variable pricing project along SR-91 Express Lanes in California. The express lanes were 10 miles long constituting of two lanes in each direction, separated from general-purpose lanes by a painted buffer with plastic pylons. The authors monitored the trends in crashes and found no significant difference between the express lanes and the general-purpose lanes. Lee et al. (2007) evaluated the safety of a freeway operations strategy that restricted the inside left lanes to HOV vehicles and allocated right shoulders as general-purpose lanes during peak hours. The authors developed negative binomial (NB) regression models for different lane groups (i.e., all lanes combined, inside left lanes that were used as HOV lanes, general-purpose lanes excluding inside left lanes, and right shoulders that were used as general-purpose lanes). The study concluded that the operational strategy did not significantly affect crash frequency in the study area (Washington and Northern Virginia).

Cao et al. (2011) explored the benefits and costs associated with converting I-394 HOV lanes to HOT lanes in Minnesota. The authors applied empirical Bayes (EB) method to estimate the safety benefits of the conversion. The authors found a 5.3% reduction in the number of crashes after the conversion. Additionally, the study results were published in the Crash Modification Factors (CMF) Clearinghouse. Table 2.1 lists the CMFs and crash reduction Factors (CRFs) for converting HOV lanes to HOT lanes from Cao et al (2011) as published in the clearinghouse website.

Table 2.1 CMFs and CRFs to Convert HOV Lanes to HOT Lanes (Source: Cao et al., 2011)

Crash Severity	CMF	CRF
All	0.95[1]	5%[1]
Fatal (K)	0.00[2]	100%[2]
Serious Injury (A)	0.39[2]	61%[2]
Minor Injury (B)	1.06[1]	-6%[1]
Possible Injury (C)	0.96[1]	4%[1]
Property Damage Only (O)	0.89[1]	11%[1]

[1] Based on the study design, sample size, standard error, potential bias, and data source, the CMF Clearinghouse has given a star quality rating of three.

[2] Based on the study design, sample size, standard error, potential bias, and data source, the CMF Clearinghouse has given a star quality rating of two.

2.2 FACILITY DESIGN CONSIDERATIONS

Some of the key parameters that affect safety of managed lanes include the overall design of the facility, inclusion of roadside safety features, frequency and location of ingress/egress points, adequate pavement shoulder widths and transition areas, and the presence of law enforcement (GDOT, 2010). Eiseley et al. (2006) determined that safety of managed-lane facilities have a strong interaction with the cross-section of the facility, type of lane separation (i.e., buffer-separation versus barrier-separation), and the access design of the facility. Section 2.2.1 presents a synthesis of the literature on the safety effects of separation between the general purpose lanes and the managed lanes. Section 2.2.2 focuses on the impacts of access to the managed lanes. Section 2.2.3 examines the safety impacts of the width of the facility.

2.2.1 Separation between the Managed Lanes and General Purpose Lanes

One of the important aspects impacting the safety of facilities with managed lanes the separation of the managed lanes from the general purpose lanes. This has been recognized as early as 1979 when Miller et al. (1979) reported that the lack of physical separation between the HOV lane and the general-purpose lanes can create several operational and safety problems.

In a study more than two decades later, Perez and Sciara (2003) argued that physical separation, such as posts or concrete barriers, is preferred to pavement marking because physical separation provides access control, reduce violations, and maintain improved service and safety. Furthermore, it restricts driver from swerving into the juxtaposed lane, in which the traffic may be moving at a different speed. On comparing posts and concrete barriers, the researchers note that posts are cheaper to install, require less right-of-way, and unlike concrete barriers, posts “allow emergency and maintenance vehicles to drive over them to take advantage of the higher travel speeds in the HOT lane”.

Skowronek et al., (2002) also argue that barrier-separated HOT lanes should offer better safety compared to buffer-separated HOV lanes primarily because of restricted access in the former facilities. In contrast, buffer-separated HOV lanes provide the possibility for illegal maneuvers by road users when the HOV facilities are underutilized and when there is a large speed differential between the HOV lanes and the general-purpose lanes.

Fitzpatrick et al. (2008) recorded vehicle maneuvers at five HOV and HOT locations in

Dallas, Houston, and Minneapolis, and found that 9% of vehicles moving into the HOV lane and 8% of vehicles moving out of the HOV lane crossed the solid white lane markings (i.e., not in compliance with the pavement markings). They also found that the percentage of non-compliance increased to about 15% when the average speed was < 40 mph or > 60 mph. From the data presented in Newman et al. (1988), Bonneson et al. (2012) inferred that a 25 mph speed differential was associated with 130% increase in crash rate. This is because, the greater a vehicle deviates from the average speed on the roadway, the greater its chances of involving in a crash (American Association of State Highway and Transportation Officials, 2011). These empirical study clearly reinforces the necessity to consider the impacts of illegal maneuvers and speed differentials (between the managed lanes and the general purpose lanes) on safety of managed lane facilities.

Cothron et al. (2004a) conducted a survey to document road users' opinions on the safety of buffer-separated and barrier-separated HOV lanes. For buffer-separated HOV lanes, the survey respondents identified the following as potential safety issues: ingress/egress difficulty, vehicles that cross the buffer illegally, speed differential between the HOV and general-purpose lanes, and presence of reduced inside shoulder. For barrier-separated HOV lanes, excessive speeds in the HOV lanes and at ingress/egress locations; inadequate sight distance at access points and horizontal curves; and insufficient signing and illumination were identified as potential safety concerns.

Hlavacek et al. (2007) assembled an expert panel to gather a collective knowledge of factors involved in the choice of separation between managed lanes and general-purpose lanes. The following are some specific observations and recommendations of the expert panel:

- Generalizations about choosing the best form of delineation are very difficult to make because each distinct situation presents a vast, tangled web of different emphases, limitations, and demands.
- Either buffer-separation or pylons are preferable to barriers in cases of restricted right-of-way. Concrete barriers should not be considered for single-lane facilities unless a barrier-to-barrier clear width of at least 18 ft can be provided.
- Concrete barriers provide the best means of controlling access and are therefore the best means of guaranteeing toll collection from all users.
- Buffer-type delineators are the least costly in terms of both initial and maintenance costs.
- Post type delineators can significantly reduce illegal crossing of the delineation zone, compared to buffer only installations, but represent large continuous maintenance costs.
- The expert panel generally found posts to be the least favorable type of delineation. However, they agreed that posts could be used successfully to ease drivers into the idea of having a separated, managed facility that can only be entered at specific locations. Once the managed lane is established, the posts could be removed to leave just the buffer.

The panel also strongly discouraged the use of concrete barriers without grade-separated, fly-over connections as weaving sections introduce the possibility of drivers striking the end of the barrier at high speeds. An overall synthesis of the safety issues of the different types of lane separation are presented in Table 2.2 (GDOT, 2010).

Table 2.2 Potential Safety Issues of Different Lane Separation Types(GDOT, 2010)

Potential Safety Issue	Barrier-Separation	Buffer-Separation	Striping
Excessive Speeding	✓		
Crash frequency at ingress/egress locations	✓	✓	✓
Crash severity at ingress/egress locations	✓		
Illegal lane-weaving		✓	✓
Speed differential crashes			✓
Incident management accessibility	✓		
Debris collection on buffer area		✓	
Inclement weather (snow, flooding, etc.)	✓	✓	

✓ areas of potential concern for the reviewed separation technique.

2.2.2 Access to Managed Lanes

A design issue closely related to the separation between the managed lanes and the general purpose lanes is that of access. There are two major types of HOV configurations: continuous access and limited access (Figure 2.1). Continuous access allows vehicles to enter or exit the facility at any location; in other words, lane changing maneuvers are not concentrated at specific locations. Limited access HOV facilities permit entering and exiting maneuvers at specific ingress and egress locations. Kononov et al. (2008) stated that it is critical to ensure that the ingress/egress locations of HOV lanes are carefully designed to minimize turbulence both in the HOV lanes and the general-purpose lanes.

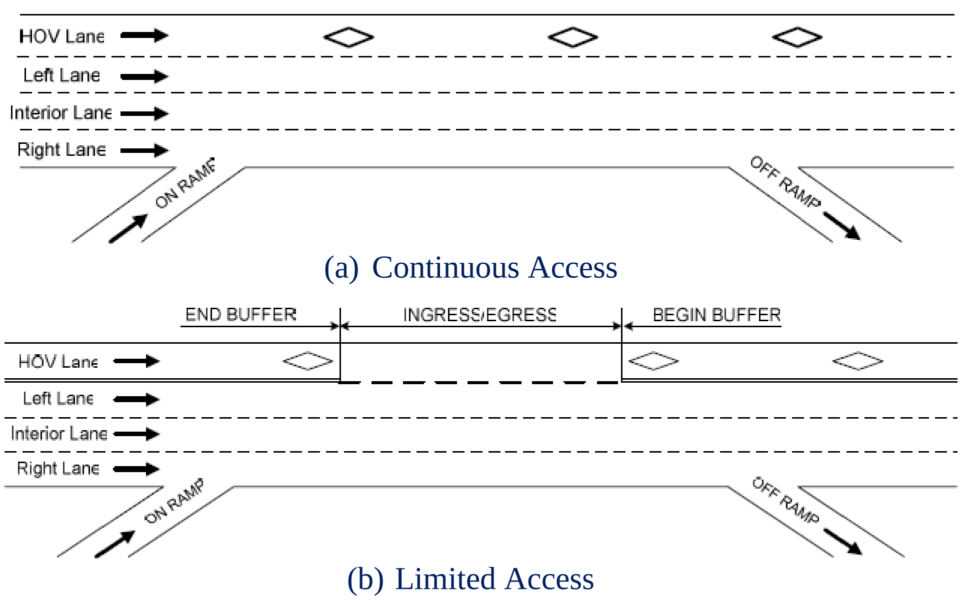

Figure 2.1 HOV Lane Access Configurations (Source: Jang et al., 2009)

Newman et al. (1988) compared the safety performance of continuous- and limited- access HOV facilities in California. The crash rates of the following three access types were compared: 15 segments with continuous access and no buffer, 13 segments with limited access and a 2-ft buffer, and 6 segments with limited access and a 13-ft buffer. The authors concluded that there was no difference in crash rate between the continuous access facilities and the limited access facilities with a 2-ft buffer. As expected, the segments with a 13-ft buffer had a lower crash rate compared to the other two types.

In contrast to the work of Newman et al (1988) later studies report statistical differences based on access type. Chung et al. (2007) calculated crash rates using data from 2001-2003 on HOV facilities in California, and found that rear-end and sideswipe crashes accounted for approximately 75-90% of total crashes. They found that a greater percentage of crashes occurred on the inside general-purpose lane along the corridors with limited access than along continuous access corridors.

Jang et al. (2009) also analyzed crash data during peak hours from 1999-2003 along 824 miles of freeways with HOV facilities in California. The increased weaving opportunities on continuous access HOV lanes resulted in greater proportion of sideswipe crashes. Crashes at HOV lanes with limited access were predominantly rear-end since weaving is prohibited except at ingress/egress locations. The authors concluded that the HOV facilities with limited access offered no safety advantages over the facilities with continuous access. Moreover, the combined crash rates of the HOV facility and its adjacent lanes were higher for the facility with limited access. The authors also compared the crash rates of four freeway segments with continuous access (40.7 mi) and four segments with limited access with a 1-5 ft buffer in California. Facilities with continuous HOV access were found to have 16% fewer fatal and injury crashes than the facilities with limited HOV access. Additionally, the study results were published in the CMF Clearinghouse. Table 2-3 lists the CMFs and CRFs for converting continuous access HOV lanes to limited access HOV lanes. Note that these CMFs and CRFs take into account crashes in HOV and inside general-purpose lanes only.

Table 2.3 CMFs and CRFs to Convert Continuous Access HOV Lanes to Limited Access HOV Lanes (HOV and Left-lane Crashes Only)

Crash Type	Crash Severity	CMF	CRF
All	All	1.54	-54.1%
All	Fatal and Serious Injury	1.20	-19.6%

Note: Based on the study design, sample size, standard error, potential bias, and data source, the CMF Clearinghouse has given a star quality rating of two.

Jang and Chan (2009) used several statistical tests including empirical cumulative density function (CDF), Kolmogorov-Smirnov tests, and comparison of means based on Poisson distributed samples, and historical crash data, and concluded that limited access HOV lanes appears to “have a safety performance disadvantage when measured by crash distribution or crash rates for the HOV lanes alone and for the HOV and inside general-purpose lanes combined”.

2.2.3 Width of the Facility

The total width of the HOV facility includes median shoulder, HOV lane, and buffer zone (Jang et al., 2013). When the right-of-way recommended by the design guidelines such as

AASHTO Green Book (2011) are unavailable, trade-offs in one or more of the widths are inevitable. Cooner and Ranft (2006) analyzed police reports of crashes that occurred on buffer-separated HOV facilities in Texas and found that greater width of the facility was associated with improved safety. Jang et al. (2009) concluded that HOV facilities with shoulder width greater than 8 ft displayed significantly lower crash rates regardless of access type. Also, they indicated that crash rates diminished with an increase in shoulder width on the HOV lane facilities with both limited and continuous access.

CHAPTER 3:
DATA

This chapter presents a detailed description about the acquisition and assembly of data to support the development of the crash prediction models for freeway facilities with HOV and HOT lanes. Data for HOV lanes are described in Section 3.1 and the data for HOT lanes are described in Section 3.2.

3.1 DATA FOR MODELING FACILTIES WITH HOV LANES

Data from the states of California, Washington, and Florida were used to develop models for facilities with HOV lanes. The assembly of data from each state is described in separate sections (3.1.1 – 3.1.3) below. Section 3.1.4 presents a comprehensive summary of data from all three states.

3.1.1 California

Data for California are available from the Highway Safety Information System (HSIS) and were requested and obtained through the online HSIS data-request process. Data were available for years 2006 through 2010 representing a total of 5 years of data. Table 3.1 lists the variables of potential interest from HSIS describing the roadway characteristics. The roadway variables extracted include functional classification, number of lanes (including the HOV lanes), lane geometry, median geometry, shoulder geometry, and the Annual Average Daily Traffic (AADT). The variables "feat_lf" and "feat_rf" (Table 3.1) identify whether the segment of the freeway has HOV lanes. Only those segments that have one HOV lane in each direction are included in the database. It is useful to acknowledge that the definitions of variables do differ across the states. Section 3.1.4 presents the definitions of variables as used in the final analysis after ensuring consistency in definition across the data from the three states.

Consistency checks were performed to remove segments with missing data. Only those segments that had clean data for all the five years were retained. Homogeneity of roadway design features (based on variables listed in Table 3.1) was ensured for each segment. If there were adjoining roadway segments that were identical interns of the roadway design features listed in Table 3.1, these were merged to form larger homogenous segments.

Segments shorter than 0.01 miles were removed. The threshold of 0.01 miles for minimum length of urban freeway segments was also employed in the NCHRP 17-45 study (Bonneson et al., 2012) for data from California and Washington. However, after accounting for exposure criteria, the data from California used in their final models had segments lengths greater than 0.1 miles (Segments shorter than 0.1 miles still existed in data from Washington used in the final model development). The exposure criteria is more relevant in the NCHRP 17-45 study given its focus on both rural- and urban- segments. The current study is focused on facilities with managed lanes and are, therefore, expected to have high traffic volumes. The models presented in the HSM for urban segments use a minimum segment length of 0.04 miles while the models for rural segments use a minimum segment length of 0.1 miles (See Srinivasan et al., 2011). While there is no consistency in the choice of a threshold for this minimum segment length, there is also a general caution against using "very short" segments. This is motivated by the fact that crash locations may not be very precisely recorded and geo-coded and that short segments can bias the results (Hauer,

2001) of negative binomial models with constant over-dispersion parameters (the type of models used in the HSM). Overall, exploring the development of new models (with potentially additional data) with a larger threshold on minimum segment length and/or additional statistical corrections is identified as an area of future work.

Table 3.1 Roadway Data Variables Extracted for Limited Access Facilities in California

Variable	Description
cntyrte	Road County Route
district	District
rte_nbr	Roadway Route Number
begmp	Begin Milepost
endmp	End Milepost
seg_lng	Segment Length
no_lanes	Total Number of Lanes
no_lane1	Number of Lanes in Direction 1
no_lane2	Number of Lanes in Direction 2
lanewid	Lane Width
func_cls	Functional Class
rodwycls	Roadway Classification
terrain	Terrain
desg_spd	Design Speed
toll	Toll and Forest Roads
med_type	Median Type
medbarty	Median Barrier Type
medwid	Median Width
feat_lf	Left RDBD Special Feature
feat_rg	Right RDBD Special Feature
aadt	AADT for the years 2006-2010
trktot	Total Truck AADT for the years 2006-2010
rshldwid	Right Shoulder Width in Direction 1 for the years 2006-2010
lshldwid	Left Shoulder Width in Direction 1 for the years 2006-2010
rshl_wd2	Right Shoulder Width in Direction 2 for the years 2006-2010
lshl_wd2	Left Shoulder Width in Direction 2 for the years 2006-2010

The two types of separation that are prevalent on HOV sections in California are defined as buffer and painted stripe. Buffer separation is characterized by a yellow left-edgeline marking for the standard travel lanes and a white right-edgeline marking for the HOV lane(s), with a gap between the two markings that ranges from none to a few feet. Satellite images from Google Earth of each HOV section were examined in order to determine the approximate size of the buffer. Buffer distances were divided into three categories, less than one foot, one to two feet, and two to three feet. Figures 3.1- 3.4 show examples of buffer separation in California. Painted stripe separation in California consists of a standard dashed white line, identical to the separation between standard travel lanes. Examples of painted-stripe separation in California are shown in

Figure 3.5-3.6

Figure 3.1 California Buffer Separation on I-605 (Buffer of less than 1 foot)

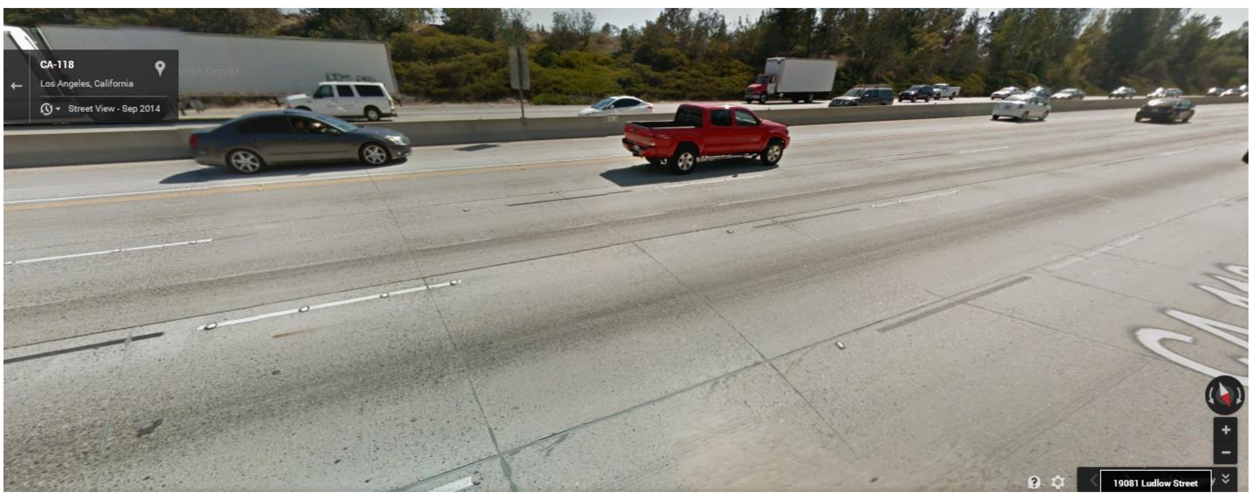

Figure 3.2 California Buffer Separation on SR-118 (Buffer of 1-2 feet)

Figure 3.3 California Buffer Separation on SR-57 (Buffer of 2-3 feet)

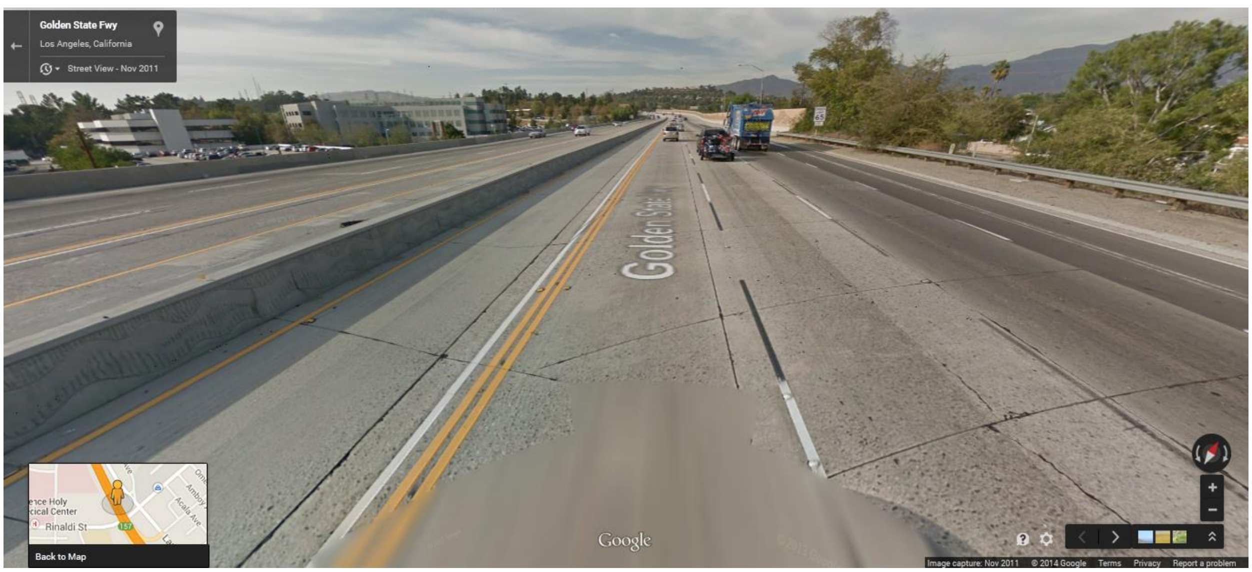

Figure 3.4 California Buffer Separation on I-5 (Buffer of 1-2 feet)

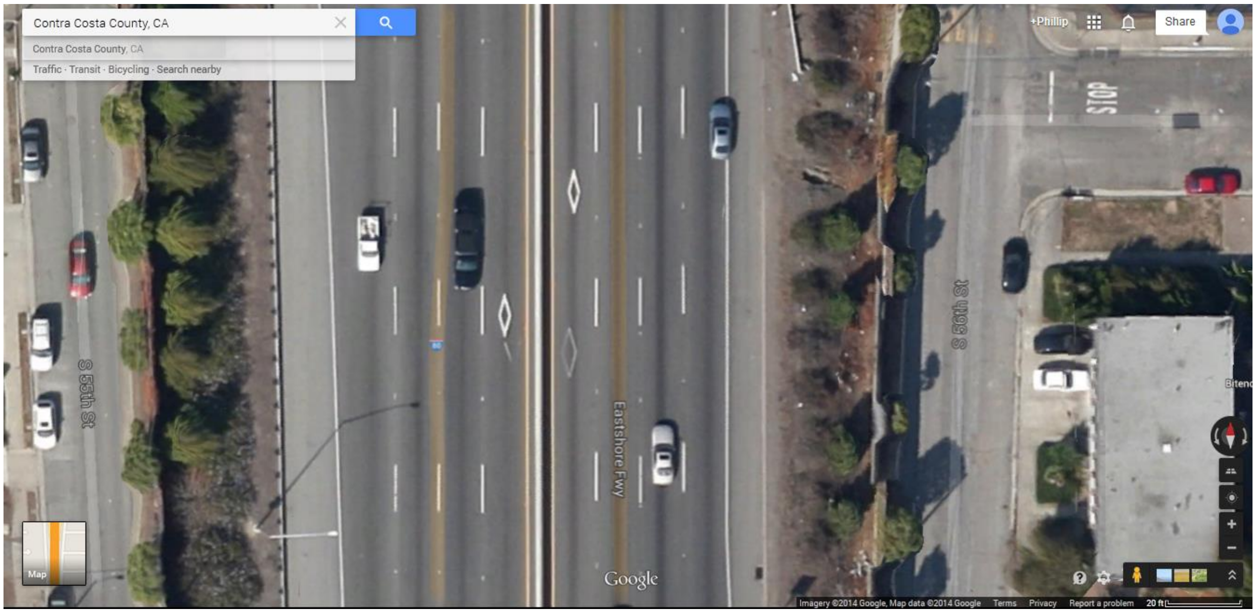

Figure 3.5 California Painted Stripe Separation on I-80

Figure 3.6 California Painted Stripe Separation on SR-237

Table 3.2 lists the variables of potential interest from HSIS describing the crash characteristics for California. The crash characteristics extracted include the location, date, time, weather conditions, lighting conditions, number of vehicles involved, and the severity for each crash. The crashes were mapped to roadway segments based on the crash location data (route number and mile post). Crashes happening exactly in-between two segments were assigned to the "upstream" segment based on the mile post. It is useful to emphasize that the data files include crashes on the main line of the entire facility, i.e, crashes on both the managed lanes the general purpose lanes. Crashes on ramps were excluded from the analysis. The crash files merged with roadway characteristics files provide the number of crashes by each severity type (fatal and Injury crashes versus Property Damage Only crashes) on each segment and for the years 2006-2010.

Table 3.2 Crash Data Variables Extracted for Limited Access Facilities in California

Variable	Description
cnty_rte	Road County Route
rte_nbr	Roadway Route Number
milepost	Milepost
caseno	Unique Crash Case Number
acctype	Type of Collision
tot_kill	Occupants Killed
tot_inj	Occupants Injured
hour	Time of Accident
weather1	Weather
int_rmp	Intersection/Ramp Accident Location
sde_hwy	Side of Highway
severity	Collision Severity
light	Light Condition
acc_date	Date of Accident
numvehs	Total Number of Vehicles

Tables 3.3 and 3.4 present an overview of the California data. Statistics on number of segments, total length and separation type by the number of lanes in reported in Table 3.3. The data assembled for California include 1480 segments representing 365 miles of freeways with HOV lanes. Eight- and ten-lane freeways are most commonly represented in the data although the data does include freeways from six- to seventeen- lanes (the number of lanes include one HOV lane in each direction). The summary table also highlights that all four types of separation are present in California. With increasing number of lanes, the proportion of segments with painted stripes decreases with a corresponding increase in the proportion of segments with 2-3 foot buffer.

Statistics on number of crashes, traffic volume, and average segment lengths by the number of lanes in reported in Table 3.4. The five years of data includes a total of 39,970 Fatal and Injury (FI) crashes and 137,475 crashes in all. Crashes with the injury severity levels of “K”, “A’, “B”, and “C” are classified as FI crashes. “All” crashes include FI crashes and crashes with “property damage only” (injury severity level of “O”). As already discussed, the total includes crashes on both the managed lanes and the general purpose lanes and exclude crashes on ramps and interchanges. The crash rates (measured in crashes per 1000 units of AADT per mile per lane per year) are also presented. The trends indicate a decreasing crash rate with increasing number of lanes. The average length of segments from California is 0.25 miles.

Table 3.3 California Data: Number of Segments, Total Length and Separation Type

					Separation Type			
Number of Lanes	**Number of Segments**	**% of all Segments**	**Total Length of Segments (miles)**	**% of Total Length**	**Painted Stripe**	**Buffer < 1 Foot**	**Buffer 1-2 Foot**	**Buffer 2-3 Foot**
6	95	6.4%	25.312	6.9%	86.3%	1.1%		12.6%
7	76	5.1%	15.409	4.2%	46.1%	7.9%	15.8%	30.3%
8	340	23.0%	100.057	27.4%	67.9%	1.8%	9.4%	20.9%
9	157	10.6%	28.063	7.7%	45.9%	7.6%	19.1%	27.4%
10	411	27.8%	115.951	31.8%	13.9%	15.3%	40.9%	29.9%
11	143	9.7%	25.774	7.1%	7.7%	8.4%	51.7%	32.2%
12	138	9.3%	31.511	8.6%	6.5%	2.9%	60.1%	30.4%
13	44	3.0%	5.774	1.6%			38.6%	61.4%
14	57	3.9%	13.949	3.8%			15.8%	84.2%
15	13	.9%	1.991	.5%			23.1%	76.9%
16	5	.3%	.889	.2%			40.0%	60.0%
17	1	.1%	.299	.1%				100.0%
Total	1480	100.0%	364.979	100.0%	33.6%	7.0%	29.1%	30.3%

Table 3.4 California Data: Crashes, Traffic Volume, and Average Segment Length

Number of Lanes	**FI Crashes**	**FI Crash Rate[1]**	**All Crashes**	**All Crashes Rate[1]**	**Average AADT**	**Average Segment Length (miles)**
6	1700	.02343	5146	.07628	128,461.66	.26644
7	943	.01499	2987	.05103	151,027.31	.20275
8	8650	.01521	28547	.05021	174,637.34	.29429
9	3089	.01468	10255	.04997	196,631.22	.17875
10	14708	.01124	51990	.04010	235,819.96	.28212
11	3121	.00995	10992	.03559	247,919.47	.18024
12	4151	.00982	14590	.03588	258,559.92	.22834
13	903	.00947	3240	.03707	276,581.82	.13123
14	2162	.00788	7960	.02773	303,298.25	.24472
15	378	.00845	1239	.02808	309,846.15	.15315
16	148	.00745	447	.02193	311,160.00	.17780
17	25	.00294	82	.00965	334,400.00	.29900
Total	39978	.01301	137475	.04477	214,433.30	.24661

[1] Rate is calculated as crashes per 1000 units of AADT per lane per mile per year

3.1.2 Washington

Data for Washington for the years 2006-2010 were also obtained from the Highway Safety Information System (HSIS). Table 3.5 lists the variables of potential interest from HSIS describing the roadway characteristics and crashes. The overall data assembly procedure for Washington was largely similar to that for California with one exception. The managed lane identifiers were recorded in a separate file (the number of lanes as recorded in the roadway files exclude any "special" lanes like HOV lanes). Table 3.6 lists the variables in this additional file (i.e., data on special use lanes). The variables describing the HOV lanes were mapped to the roadway files and the data were re-segmented to create homogenous segments. Only those segments in which an HOV lane was present in each direction of travel were retained for further analysis.

Table 3.5 Roadway Data Variables Extracted for Limited Access Facilities in Washington

Variable	Description
rte_nbr	Route Number
road_inv	Route Type ID
begmp	Begin Milepost
endmp	End Milepost
seg_lng	Segment Length
func_cls	Functional Classification
rodwycls	Roadway Classification
no_lanes	Total Number of Lanes
no_lane1	Number of Lanes in Direction 1
no_lane2	Number of Lanes in Direction 2
lanewid	Lane Width
med_type	Median Type
medbarty	Median Barrier Type
medwid	Median Width
aadt	AADT for the years 2006-2010
lshldwid	Left Shoulder Width in Direction 1 for the years 2006-2010
lshl_ty2	Left Shoulder Type in Direction 2 for the years 2006-2010
lshl_typ	Left Shoulder Type in Direction 1 for the years 2006-2010
lshl_wd2	Left Shoulder Width in Direction 2 for the years 2006-2010
rshldwid	Right Shoulder Width in Direction 1 for the years 2006-2010
rshl_ty2	Right Shoulder Type in Direction 2 for the years 2006-2010
rshl_typ	Right Shoulder Type in Direction 1 for the years 2006-2010
rshl_wd2	Right Shoulder Width in Direction 2 for the years 2006-2010
spd_limt	Speed Limit
trkpcts	Truck Percentage

Table 3.6 Roadway Data Variables Extracted for Managed Lane Facilities in Washington

Variable	Description
road_inv	Route type ID
begmp	Begin Milepost
sln_rarm	Special Use Lanes RV Arm
sln_rtno	Special Lane Route Number
sln_rdty	Special Lane Related Route Type
sln_qual	Special Lane Related Road Quality
sln_abid	Special Lane AB Indicator
sln_side	Special Lane Left/Right Side Indicator
sln_type	Special Lane Type
sln_date	Special Lane Date
sln_wid	Special Lane Width
sln_sfty	Special Lane Surface Type

In Washington, all sections of freeways with managed lanes are separated by painted stripe (a single solid white line). Examples of painted stripe separation in Washington are shown in Figure 3.7 – 3.9.

Figure 3.7 Washington Painted Stripe Separation on I-5

Figure 3.8 Washington Painted Stripe Separation on I-90

Figure 3.9 Washington Painted Stripe Separation on I-405

Table 3.7 lists the variables of potential interest from HSIS describing the crash characteristics for Washington.

Table 3.7 Crash Data Variables Extracted for Limited Access Facilities in Washington

Variable	Description
rd_inv	Route Type ID
milepost	Milepost
rodwycls	Roadway Classification
caseno	Unique Crash Case Number
rte_nbr	Route Number
func_cls	Functional Classification
accyr	Accident Year
month	Accident Month
daymth	Accident Day of Month
weekday	Day of Week
acctype	Type of Accident
severity	Collision Severity
numvehs	Number of Vehicles
loc_type	Accident Location Type
light	Lighting Condition
coltype1	Accident Type 1
coltype2	Accident Type 2
weather	Weather

The crash files merged with roadway characteristics files provide the number of crashes by each severity type (Fatal and Injury crashes versus Property Damage Only crashes) on each segment and for the years 2006-2010.

Tables 3.8 and 3.9 present an overview of the Washington data. Statistics on number of segments and total length by the number of lanes in reported in Table 3.8. Overall data assembled for Washington include 524 segments representing 66 miles of freeways with HOV lanes. Eight- and ten-lane freeways are most commonly represented in the data although the data does include freeways from six- to eleven- lanes (the number of lanes include one HOV lane in each direction). As already indicated, all segments from Washington have a painted stripe separation between the managed lanes and the general purpose lanes.

Statistics on number of crashes, traffic volume, and average segment lengths by the number of lanes in reported in Table 3.9. The five years of data includes a total of 6678 Fatal and Injury (FI) crashes and 17,651 crashes in all. The crash rates (measured in crashes per 1000 units of AADT per mile per lane per year) are also presented. The trends indicate a decreasing crash rate with increasing number of lanes. The average length of segments from Washington is 0.12 miles.

Table 3.8 Washington Data: Number of Segments and Total Length

Number of Lanes	Number of Segments	% of all Segments	Total Length of Segments (miles)	% of Total Length
6	120	22.9%	18.270	27.6%
7	25	4.8%	2.460	3.7%
8	191	36.5%	20.320	30.7%
9	40	7.6%	5.040	7.6%
10	129	24.6%	17.690	26.8%
11	19	3.6%	2.310	3.5%
Total	524	100.0%	66.090	100.0%

Table 3.9 Washington Data: Crashes, Traffic Volume, and Average Segment Length

Number of Lanes	FI Crashes	FI Crash Rate[1]	All Crashes	All Crashes Rate[1]	Average AADT	Average Segment Length (miles)
6	1384	.02680	3410	.06835	113,989.50	.15225
7	421	.03134	1171	.09369	133,314.76	.09840
8	1822	.01987	4871	.05286	156,731.92	.10639
9	551	.01623	1536	.04405	178,601.04	.12600
10	2242	.01923	6008	.05310	194,549.34	.13713
11	258	.01027	655	.02542	215,989.58	.12158
Total	6678	.02122	17651	.05675	158,954.42	.12613
[1] Rate is calculated as crashes per 1000 units of AADT per lane per mile per year						

3.1.3 Florida

The Florida data were compiled from the Roadway Characteristics Inventory (RCI) and the Crash Analysis Reporting System (CARS) databases obtained from FDOT. Table 3.10 lists the roadway data variables extracted for the managed lane facilities in Florida. The managed lanes in Florida were identified based on roadway ID and mileposts.

Table 3.10 Roadway Data Variables Extracted for Managed Lane Facilities in Florida

Variable	Description
CnSecSub	County, Section, and Subsection Number
BMilePost	Begin Milepost
EMilePost	End Milepost
Seg Length	Segment Length
AVGDFACT	Directional Distribution Factor
AVGKFACT	30th Highest Hour Factor
HRZCANGL	Horizontal Curve Central Angle
HRZDGCRV	Horizontal Degree of Curve
FUNCLASS	Functional classification
INTERCHG	Type of Interchange
LANDUSE	Prevailing Type of Land Use
MAXSPEED	Maximum Speed Limit
MEDWIDTH	Median Width
NOLANES	Total Number of Lanes
RDACCESS	Access Control Type
RDMEDIAN	Type of Median
SECTADT	Section Average Daily Traffic
SHLDTYPE	Highway Shoulder Type
SLDWIDTH	Highway Shoulder Width
SURWIDTH	Highway Surface Width
URBSIZE	Urban Area Size
ISLDTYP2	Other Inside Shoulder Type
ISLDTYPE	Inside Shoulder Type
ISLDWDTH	Inside Shoulder Width
ISLDWTH2	Inside Shoulder Width
SHLDTYP2	Other Highway Shoulder Type
SHLDWTH2	Other Highway Shoulder Width
TOLLTYPE	Toll Type
HOVNUMLN	High Occupancy Vehicle Lanes – Number of Lanes
HOVTYPE	High Occupancy Vehicle Lane Type
HOVLanes	High Occupancy Vehicle Lanes

In Florida, all HOV facilities have a buffer separation between the managed lanes and general purpose lanes. Buffer separation in Florida consists of a double dashed white line with a gap of 2-3 foot between the two markings. Examples of buffer separation in Florida are shown in Figures 3.10 and 3.11.

Figure 3.10 Florida Buffer Separation on I-95

Figure 3.11 Florida Buffer Separation on I-95

The overall data assembly procedure for Florida was largely similar to that for California. The crash files (obtained from the CARS system) merged with roadway characteristics files provide the number of crashes by each severity type (fatal and Injury crashes versus Property Damage Only crashes) on each segment and for the years 2006-2010.

Tables 3.11 and 3.12 present an overview of the Florida data. Statistics on number of segments and total length by the number of lanes in reported in Table 3.11. Overall data assembled for Florida include 299 segments representing 61 miles of freeways with HOV lanes. Eight- and ten-lane freeways are most commonly (98%) represented in the data (the number of lanes include one HOV lane in each direction). As already indicated all segments in Florida have a 2-3 Foot buffer between the managed lanes and the general purpose lanes.

Statistics on number of crashes, traffic volume, and average segment lengths by the number of lanes in reported in Table 3.12. The five years of data includes a total of 8851 Fatal and Injury (FI) crashes and 18,617 crashes in all. The crash rates (measured in crashes per 1000 units of AADT per mile per lane per year) are also presented. The trends indicate a decreasing crash rate with increasing number of lanes. The average length of segments from Florida is 0.2 miles.

Table 3.11 Florida Data: Number of Segment and Total Length

Number of Lanes	Number of Segments	% of all Segments	Total Length of Segments (miles)	% of Total Length
6	5	1.7%	2.180	3.6%
8	115	38.5%	26.007	42.8%
10	179	59.9%	32.643	53.7%
Total	299	100.0%	60.830	100.0%

Table 3.12 Florida Data: Crashes, Traffic Volume, and Average Segment Length

Number of Lanes	FI Crashes	FI Crash Rate[1]	All Crashes	All Crashes Rate[1]	Average AADT	Average Segment Length (miles)
6	140	.01349	327	.03254	132,800.00	.43600
8	3893	.01996	8151	.04238	218,269.06	.22615
10	4818	.01598	10139	.03372	221,093.69	.18236
Total	8851	.01747	18617	.03703	218,530.81	.20344

[1] Rate is calculated as crashes per 1000 units of AADT per lane per mile per year

3.1.4 Data Combined from all Three States

Tables 3.13 and 3.14 present an overview of the data obtained from all the three states. Statistics on number of segments and total length by the number of lanes in reported in Table 3.13. The total data assembled from the three states comprise 2303 segments representing 491 miles. Ten-lane segments constitute 31% of the segments and 33.8% of the length. Eight lane segments comprise 28% of the segments and 30% by length. Six- and twelve- lane facilities comprise 9.6% and 6% of the segments (9.3% and 6.4% of length) respectively. Together these four facility types cover over 75% of all segments. These “balanced” segments (equal number of lanes in each direction) are used for further model building. The choice of developing separate models by number of lanes in the facility is also consistent with the approach adopted in the HSM and in NCHRP 17-45. Development of models for unbalanced segments (unequal number of lanes in both directions) is relegated as future work.

Table 3.13 All Data: Number of Segments and Total Length

Number of Lanes	Number of Segments	% of all Segments	Total Length of Segments (miles)	% of Total Length
6	**220**	**9.6%**	**45.762**	**9.3%**
7	101	4.4%	17.869	3.6%
8	**646**	**28.1%**	**146.384**	**29.8%**
9	197	8.6%	33.103	6.7%
10	**719**	**31.2%**	**166.284**	**33.8%**
11	162	7.0%	28.084	5.7%
12	**138**	**6.0%**	**31.511**	**6.4%**
13	44	1.9%	5.774	1.2%
14	57	2.5%	13.949	2.8%
15	13	.6%	1.991	.4%
16	5	.2%	.889	.2%
17	1	.0%	.299	.1%
Total	2303	100.0%	491.899	100.0%

Table 3.14 presents the distribution of separation type and the location of the segments. The data for six-, eight-, ten-, and twelve- lane freeways (segments of interest) are highlighted in bold font. The data indicates that segments with painted stripes are less likely with increasing number of lanes while buffer separation of more than 1 foot is more likely with the increasing number of lanes. The table also indicates that data for eight- and ten- lane facilities are available from all three states while data for six-lane facilities are mostly from California and Washington and data for twelve- lane facilities are entirely from California.

Table 3.14 All Data: Separation Type of Location of Segment (State)

	Separation Type				State		
Number of Lanes	**Painted Stripe**	**Buffer < 1 Foot**	**Buffer 1-2 Foot**	**Buffer 2-3 Foot**	**California**	**Florida**	**Washington**
6	**91.8%**	**.5%**		**7.7%**	**43.2%**	**2.3%**	**54.5%**
7	59.4%	5.9%	11.9%	22.8%	75.2%		24.8%
8	**65.3%**	**.9%**	**5.0%**	**28.8%**	**52.6%**	**17.8%**	**29.6%**
9	56.9%	6.1%	15.2%	21.8%	79.7%		20.3%
10	**25.9%**	**8.8%**	**23.4%**	**42.0%**	**57.2%**	**24.9%**	**17.9%**
11	18.5%	7.4%	45.7%	28.4%	88.3%		11.7%
12	**6.5%**	**2.9%**	**60.1%**	**30.4%**	**100.0%**		
13			38.6%	61.4%	100.0%		
14			15.8%	84.2%	100.0%		
15			23.1%	76.9%	100.0%		
16			40.0%	60.0%	100.0%		
17				100.0%	100.0%		
Total	44.3%	4.5%	18.7%	32.5%	64.3%	13.0%	22.8%

3.2 DATA FOR MODELING FACILITIES WITH HOT LANES

Unlike freeway facilities with HOV lanes, facilities with HOT lanes are much fewer and more recent (See Table 3.15). Data from the states of California, Florida, and Texas were used to develop crash prediction models for facilities with HOT lanes. The assembly of these data are described in this section.

Table 3.15 HOT Lane Facilities in the U.S.

Facility	**City**	**Operational since**	**Segment**	**Length (miles)**	**No. of HOT Lanes**	**Separation Type**
SR 91	Orange County, CA	January 2003	SR 55 and SR 91 interchange to just west of SR 91 and SR 71 interchange in Orange and Riverside counties	10	4	Flexible Poles
I-15	San Diego, CA	September 2008	SR 163 to SR 78	20	4	Movable Barrier

I-680	Oakland, CA	September 2010	Highway 84 in Alameda County to Highway 237 in Santa Clara County	14	2	Double White Line
I-25	Denver, CO	June 2006	20th St to E 70th Ave	4.5	2 (reversible)	Concrete Barrier
I-394	Minneapoli s MN	May 2005	Wayzata Boulevard to Highway 100	6	2	Double White Line
I-394	Minneapoli s MN	May 2005	Highway 100 to just east of Park Palace/Xenia Avenue	3	2 (reversible)	Concrete Barrier
I-35W	Minneapoli s MN	September 2009	Highway 13 in Burnsville to I-494 and from I-494 to downtown Minneapolis	14	2	Double White Line
I-10	Houston, TX	April 2009	Between SR 6 and I-610	12	4	Flexible Poles
I-95	Miami, FL	December 2008	The Golden Glades interchange to downtown Miami	7	4	Flexible Poles
I-15	Salt Lake City, UT	September 2006	U.S. 6 in Spanish Fork to 2300 North in Salt Lake City and from Parrish Lane in Centerville to Layton Parkway	62	2	Double White Line
SR 167	Seattle, WA	May 2008	Auburn to Renton Counties	9	2	Double White Line

The California data are from SR-91 in Orange and Riverside Counties. The data for SR91 were obtained from HSIS and processed using the same procedure as in the context of the California facilities with HOV lanes. Four years of data are used for the analysis. Google Earth images were used to view the entirety of the roadway section in order to confirm the recorded cross-sectional data and to add separation type and separation width variables to the data set. SR-91 uses flexible pole separation with a separation distance of 3 feet between the HOT lanes and the general purpose lanes. While the total number of lanes varies, there are 4 HOT lanes (2 in each direction) throughout the section. Figure 3.12 and 3.13 provide images of the SR-91 cross-section and the separation used.

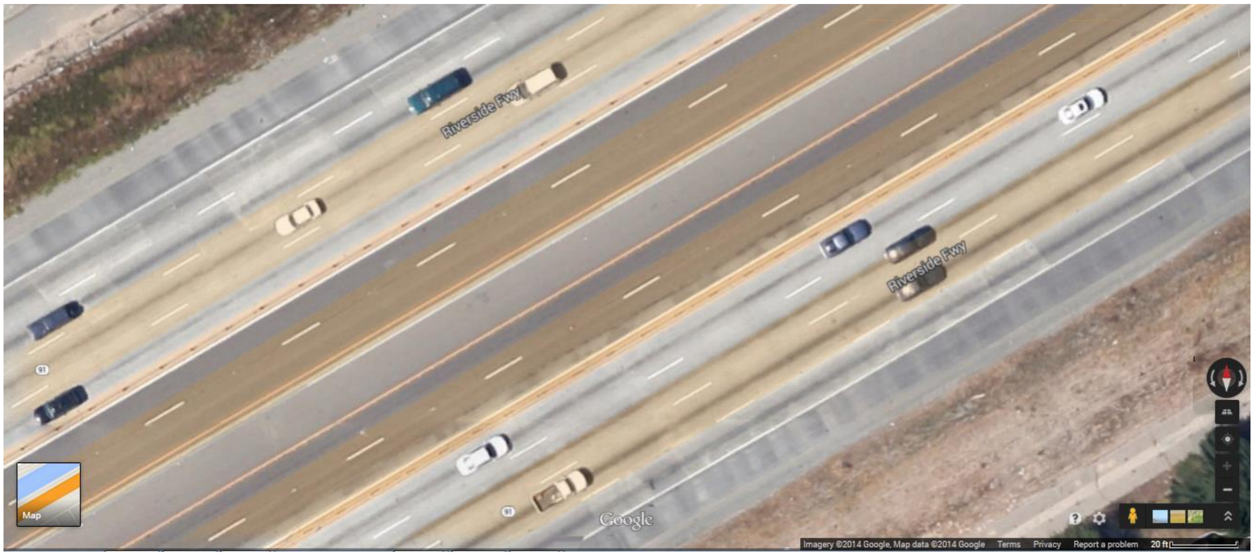

Figure 3.12 HOT Lane Cross-Section on California SR-91

Figure 3.13 HOT Lane Separation on California SR-91

The only HOT lane facility in Florida is on I-95. The data assembly procedure follows what was described in Section 3.1.3 for HOV lanes. The Florida data (2009-2012) were compiled from the Florida Roadway Characteristics Inventory and the Florida Crash Analysis Reporting System, provided by FDOT. Google Earth images were used to view the entirety of the roadway section in order to confirm the recorded cross-sectional data and to add separation type and separation width variables to the data set. This section of I-95 uses flexible pole separation with a separation distance of 1 foot between the HOT lanes and the general purpose lanes. While the total number of lanes varies, there are 4 HOT lanes (2 in each direction) throughout the section. Figure 3.14 provides an image of the I-95 cross-section and the separation used.

Figure 3.14 HOT Lanes on I-95 in Florida

Texas data were obtained from the section of I-10 near Houston. The data was assembled from crash data and roadway inventory data provided by the Texas Department of Transportation. Table 3.16 lists the roadway data variables extracted for the managed lane facilities in Texas. Segments with managed lanes were first identified using the data variable "HWY_DES2"; code "A" is used to identify sections with HOV/HOT lanes.

Table 3.16 Roadway Data Variables Extracted for Limited Access Facilities in Texas

Variable	Description
DI	District ID
CO	County Number
CITY	City Number
HWY	Signed Highway (Highway System + Number + Suffix)
HSYS	Highway System
HNUM	Highway Number
FUN_SYS	Functional Classification
Len_Sec	Length of Section (To DFO – From DFO)
RU	Rural Urban code
HWY_DES2	Highway Design = A (With HOV Lanes)
ADT_CUR	ADT for year 2013
HY1	ADT for 2012
HY2	ADT for 2011
HY3	ADT for 2010
HY4	ADT for 2009
HY5	ADT for 2008
HP_SWL	HP-Shoulder-Left (Width of inside shoulder on divided sections,

	or width of left shoulder traveling in descending marker direction)
HP_SWR	HP-Shoulder-Right (Width of outside shoulder on divided sections, or width of right shoulder traveling in ascending marker direction)
HP_MED_W	HP-Median-Width (Median width + both inside shoulders)
TRK_AADT	Truck AADT Percent
SPD_MAX	Maximum Speed Limit
SPD_MIN	Minimum Speed Limit
NUM_LANES	Number of lanes (Does not include turning or climbing lanes)
SUR_W	Surface Width (Does not include Shoulder Widths)
RB_WID	Roadbed Width (Includes Shoulder Width and Surface Width)
DIR_TRAV	Cardinal Direction
S_TYPE_I	Shoulder Type Inside
S_WID_I	Shoulder Width Inside
S_USE_I	Shoulder Use Inside
S_TYPE_O	Shoulder Type Outside
S_WID_ O	Shoulder Width Outside
S_USE_ O	Shoulder Use Outside
MED_TYPE	Median Type
MED_WID	Median Width
FRM_DFO	From Distance From Origin (DFO)
TO_DFO	To DFO
BMP	Begin Milepost
EMP	End Milepost
HOV_TYP	HOV Lanes
SPEC_LANE_TYPE	Type of Special Lanes
SPEC_LANE_NUM_LANES	Number of Lanes of Special Lanes

The crash data were requested through the *TxDOT's Crash Records Information System* (CRIS). The crash data files have crash location information, including the highway number and the DFO (Distance From Origin) at which the crash occurred. This information was used to assign crashes to segments. Only the crashes that occurred on main/proper lanes (code ROAD_PART_ID = ‘1 – Main/Proper Lane’) and on segments (code INTRSCT_RELAT_ID = ‘4 – Non Intersection’), and which were reportable (code Texas_Reportable_Fl = ‘Y – Yes’) were queried. The queried crash files were merged with final roadway characteristics dataset to obtain the number of crashes on each segment for each severity type.

Google Earth images were used to view the entirety of the roadway section in order to confirm the recorded cross-sectional data and to add separation type and separation width variables to the data set. This section of I-10 uses flexible pole separation with a separation distance of 20 feet between the HOT lanes and the general purpose lanes. As opposed to the layout seen in California and Florida, this section of I-10 in Texas has both a left shoulder for the main travel lanes and a right shoulder for the HOT lanes, resulting in a much wider separation width. While the total number of lanes varies, there are 4 HOT lanes (2 in each direction) throughout the section. Figure 3.15 and 3.16 provide images of the I-10 cross-section and the separation used.

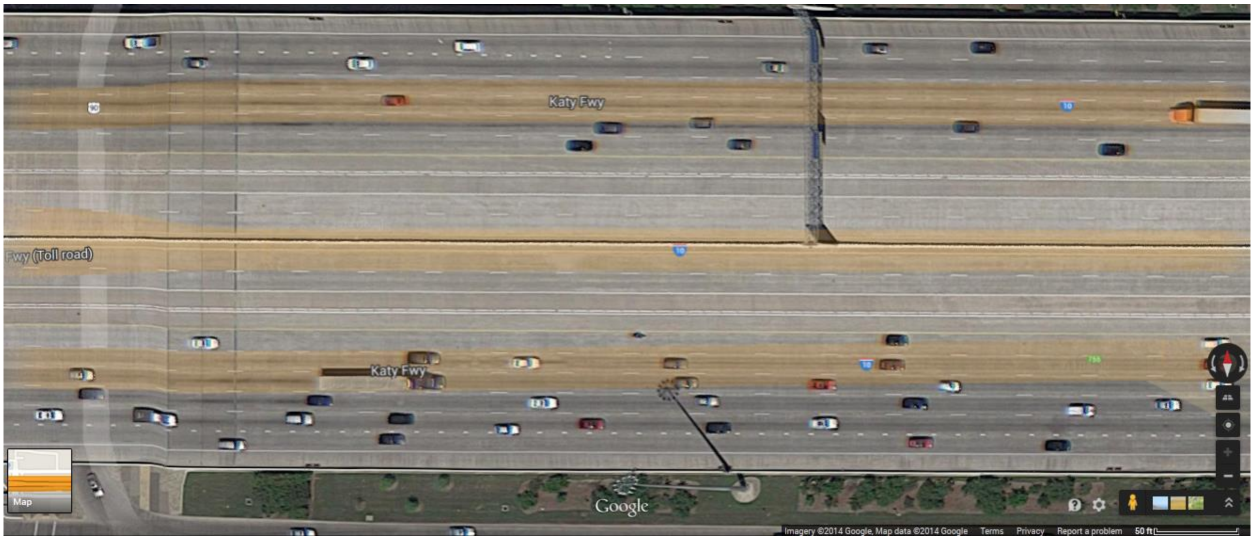

Figure 3.15 HOT Lane Cross-Section on Texas I-10

Figure 3.16 HOT Lane Separation on Texas I-10

The overall dataset comprises 13 segments (9 miles) from Texas, 17 segments (9.06 miles) from California and 18 segments (9.27 miles) from Florida (Table 3.17). The number of crashes (total for 4 years) is also higher for Florida compared to the other two states (for both FI crashes and All cashes). The average AADT of California and Florida facilities are much higher. Most of the segments from Florida are 12 lane facilities while California and Texas data primarily include eight- and ten-lane facilities (Table 3.18). All freeway segments in the dataset have 2 HOT lanes in each direction.

Table 3.17 Summary of Data Assembled for Modeling Freeways with HOT lanes.

	Texas	**California**	**Florida**
# Segments	13	17	18
Length	9.00	9.06	9.27
FI Crashes	584	834	2622
All Crashes	1591	2934	5941
AADT (Min)	188,408.25	125,500.00	181,000.00
AADT (Max)	276,374.00	318,000.00	258,500.00
AADT (average)	198,075.50	236,823.53	230,305.56

Table 3.18 Data for HOT Facilities: Number of Lanes by State

	Texas		**California**		**Florida**	
Number of Lanes	**No. Segments**	**%**	**No. Segments**	**%**	**No. Segments**	**%**
6	3	23.1	2	11.8	2	11.1
8	4	30.8	9	52.9		
10	6	46.2	5	29.4	3	16.7
12			1	5.9	13	72.2
Total	13	100.0	17	100.0	18	100.0

CHAPTER 4:
CRASH PREDICTION MODELS

This chapter presents the models estimated for freeway facilities with HOV or HOT lanes using the data described in the previous chapter. Section 4.1 presents an analysis framework describing the general structure of the models. The models developed for freeway facilities with HOV lanes are discussed in Section 4.2 and the models developed for freeway facilities with HOT lanes are discussed in Section 4.3.

4.1 ANALYSIS FRAMEWORK

Crash Prediction Models are also referred to as Safety Performance Function (SPFs) or Safety Prediction Models (SPMs). Safety performance functions (SPFs) are negative-binomial regression equations that "estimate expected average crash frequency as a function of traffic volume and roadway characteristics (e.g., number of lanes, median type, intersection control, number of approach legs)[1]". Sometimes, safety performance functions (SPFs) for roadway segments are used to describe equations that estimate expected average crash frequency as a function of *only* traffic volume and length assuming "base" conditions for other geometry and operational variables. Crash Modification Factors (CMFs) are used to adjust the predictions for site-specific deviations in roadway characteristics from the base conditions. Additionally a calibration factor may also be used to further adjust for systematic differences between the location/time where the model was estimated and the location/time where the model is being applied. The term "Safety Prediction Model" (SPM) is used to describe the full equation comprising of the SPF (which includes only length and AADT as predictors), the CMFs, and the calibration factors. This is the terminology adopted in the NCHRP 17-45 study. Other studies have labeled "Safety Performance Models" as "Full SPFs" to distinguish them from SPFs that consider only exposure variables.

The models developed in this study include factors other than length and AADT as predictor variables. Therefore, these may be labeled as "Safety Prediction Models" (consistent with the NCHRP 17-45) or "Safety Performance Functions" as defined in the introduction to the HSM.

The models for roadway segments may be represented as:

$$N = \exp(\alpha + LN(L) + \beta LN(AADT) + \beta_1 V_1 + \beta_2 V_2 + \beta_3 V_3 + \ldots + \beta_K V_K) \qquad \text{Eq. 4-1}$$

Where

N = Expected number of crashes (predicted)

AADT = Annual Average Daily Traffic (vehicles per day)

L = Length of the segment (miles)

$V_1 \ldots V_K$ = Roadway and operational characteristics of interest. In the current study, the separation between the managed lanes and general purpose lanes is an important characteristic of interest to be included in equation 4-1. An alternate approach would be to estimate separate equations for

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[1]Page 4 of http://www.highwaysafetymanual.org/Documents/HSMP-1.pdf

each separation type; however data availability limits our ability to develop such models. Other variables such as shoulder width are also considered. Sometimes logarithms of the variables describing the roadway characteristic are used instead of the variables themselves (see discussion in section 4.2.1 in the context of left shoulder width). When data from multiple states are pooled for estimation, indicator or "dummy" variables for each state may also be included to capture systematic differences across the states.

$\alpha,\beta,\beta_1,\ldots,\beta_K$ = Regression coefficients or parameters. Note that the coefficient on the segment length variable is fixed to 1 (customary in the HSM models). Broadly, this assumption reflects that a segment that is twice as long will have twice as many crashes if all else about the segments are the same.

The negative binomial regression model is estimated (using the SPSS IBM Statistics software in this study) assuming that the over-dispersion parameter (ratio of the variance to the mean) is a constant. This is consistent with the current HSM approach. However, researchers (see for example, Hauer, 2001) have argued that models estimated with constant over dispersion parameter and using data that have short segments can bias the model results because of the limited exposure of the shorter segments. The issue of the choice of a threshold for minimum segment length for this study was discussed in Chapter 3. The exploration of advanced statistical methods that relax the assumption of constant over dispersion parameters and its implication for model improvement is identified as an area of future work.

Separate models of the type (4-1) are estimated for crashes by level of severity. In this study, separate equations are estimated for fatal- and injury- (FI) crashes and for all crashes (as in the case of other HSM models[2]). Therefore, estimates of PDO crashes may be obtained by subtracting out the estimated FI crashes from the estimated all crashes. Further, in the case of facilities with HOV lanes, for each level of severity, separate equations are estimated depending on the total number of lanes (6, 8, 10, and 12) in the freeway (as already described, the total number of lanes include one HOV lane in each direction and represent equal number of lanes in each direction). Thus a total of eight equations are developed for facilities with HOV lanes. In the case of facilities with HOT lanes, such a stratification was not possible because of data limitations. Therefore, there are only 2 models for freeway facilities for HOT lanes (one for fatal and injury crashes and one for all crashes). All the estimated equations are implemented in a spreadsheet.

4.2 MODELS FOR FREEWAY FACILITIES WITH HOV LANES

The models developed for freeway facilities with HOV lanes are discussed in this section. Models for six-, eight-, ten- and twelve- lane freeways are presented in Sections 4.2.1 through 4.2.4 respectively. Each section has separate equations for fatal and injury (FI) crashes and for all crashes. Crashes with the injury severity levels of "K", "A', "B", and "C" are classified as FI crashes. "All" crashes include FI crashes and crashes with "property damage only" (injury severity level of "O"). As already discussed, the crashes on the entire facility (including both managed lanes and general purpose lanes) are modeled and crashes on ramps and interchanges are excluded. Five years' of data are used in model estimations. All facilities have one HOV lane in each

[2] NCHRP 17-45 presents separate equations for FI crashes and PDO crashes.

direction and the total number of lanes in each direction are equal.

4.2.1 Models for 6-lane freeways with HOV lanes

The equations for 6-lane freeways were estimated using 45 miles (220 segments) of data. 43.2% of all segments are from California, 54.5% from Washington and the rest (2.3%) from Florida. 92% of the segments have a painted stripe separation between the managed lanes and the general purpose lanes. About 8% have a 2-3 foot buffer separation.

The estimated models for FI crashes and all crashes are presented in Table 4.1. The table also presents the 90% confidence interval for the estimated coefficients. If this interval is entirely positive, this means that we are at least 90% sure that the estimated effect is positive (i.e. an increase in this variable is correlated with an increase in the number of crashes). Alternatively, if the interval is entirely negative, this means that we are at least 90% sure that the estimated effect is negative (i.e. an increase in this variable is correlated with a decrease in the number of crashes). Only effects that are statistically significant at 90% confidence level are presented in the table. Statistically insignificant effects are, however, discussed later in this section.

Table 4.1 Models for 6-lane Freeways with HOV lanes

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	**Coeff.**	**Std. Error**	**90% Confidence Interval**		**Coeff.**	**Std. Error**	**90% Confidence Interval**	
			Lower	**Upper**			**Lower**	**Upper**
Constant	-16.17	3.116	-21.29	-11.04	-14.07	2.924	-18.87	-9.260
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT in veh/day)	1.760	0.267	1.322	2.199	1.648	0.251	1.234	2.061
ln (left shoulder width in feet)	-0.039	0.019	-0.069	-0.008	-0.074	0.028	-0.121	-0.027
California (0 or 1)	-	-	-	-	0.537	0.193	0.219	0.855
Over Dispersion Parameter	0.571	0.073	0.462	0.704	0.589	0.064	0.493	0.704

The statistical outputs can also be represented as the following equations (following the format presented in Equation 4-1):

$$N_{FI} = 0.2 * \exp(-16.174 + \ln(L) + 1.760Ln(AADT) - 0.039Ln(LSW)) \qquad \text{Eq. 4-2}$$
$$N_{all} = 0.2 * \exp(-14.07 + \ln(L) + 1.648Ln(AADT) - 0.074Ln(LSW) + 0.537(CA)) \quad \text{Eq. 4-3}$$

In the above equations, N_{FI} represents the number of fatal and injury crashes per year and N_{all} represents the number of all crashes per year. L represents the segment length (in miles), LSW is the left-shoulder-width (in feet) and CA is a binary (0 or 1) variable that indicates whether the segment is from California (1) or not (0). The prediction from the regression equation is scaled by 0.2 to obtain a yearly crash prediction (note that 5-years of data were used in model estimation).

Separation type does not feature in the above equations as it was estimated to be statistically insignificant. This is likely because of the limited variability in separation type across 6-lane freeway segments (92% of the 6-lane freeway segments have a painted stripe separation between the managed lanes and the general purpose lanes).

Increased width of the left shoulder (measured in feet) is associated with a decrease in the number of crashes. The logarithm of the left shoulder width is included in the model reflecting the decreasing marginal benefits of increasing the left shoulder width. That is, the effect of increasing the left shoulder width by 2 feet from 8 to 10 feet has greater proportional safety benefits than increasing the left shoulder width by 2 feet from 10 to 12 feet (assuming all other factors remain unchanged).

California is estimated to have more total crashes on its 6-lane freeways than Washington or Florida. However, such a difference is not observed between among the three states in the case of fatal and injury crashes (at a statistical significance level of 90%).

The dispersion parameter is significant in both models reflecting that the crash data are over dispersed (variance in the crashes is greater than the average number of crashes). This value will be used if the Empirical Bayes (EB) method were employed in a before-and –after analysis (as outlined in the HSM) or to estimate the expected crash frequency of a segment.

Figure 4.1 shows the relationship between predicted FI crashes (per year) and AADT over the range of AADTs (56,200 – 273,991 veh/day) observed in the sample for 6-lane freeways. The graph was developed for a ½-mile segment with 8-foot left shoulder located in Florida (i.e., CA = 0). Figure 4.2 shows the relationship between predicted All crashes (per year) and AADT.

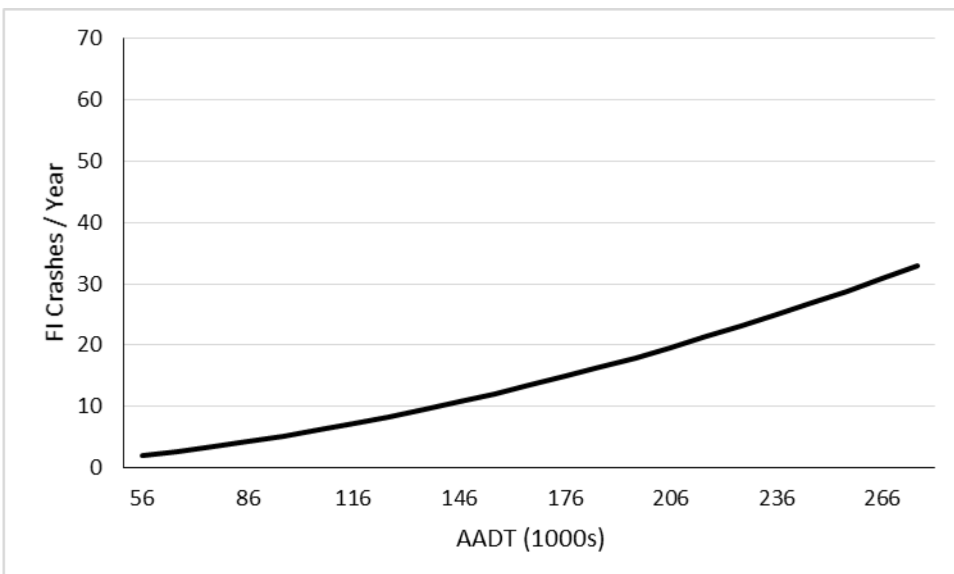

Figure 4.1 Variation of FI Crashes with AADT for 6-lane freeways with HOV lanes

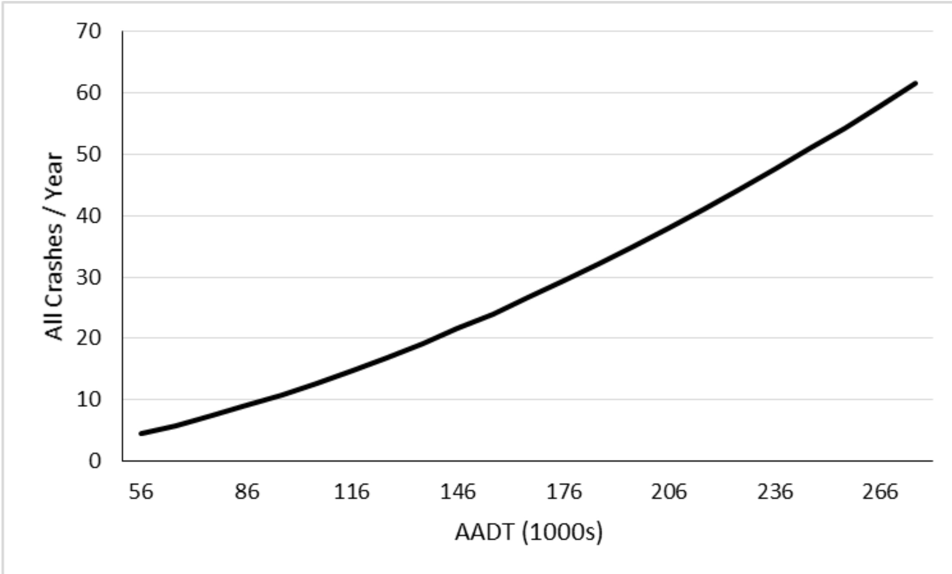

Figure 4.2 Variation of All Crashes with AADT for 6-lane freeways with HOV lanes

4.2.2 Models for 8-lane freeways with HOV lanes

The equations for 8-lane freeways were estimated using 146 miles (646 segments) of freeways from the states of California (52.5% of the segments), Washington (29.6% of the segments), and Florida (17.8% of the segments). 65% of the segments have a painted stripe separation between the managed lanes and the general purpose lanes. About 29% of the segments have a 2-3 foot buffer separation; 5% have a separation of 1-2 foot and about 1% have a separation of < 1 foot.

The estimated models for FI crashes and all crashes are presented in Table 4.2. The overall structure of this table is similar to the one presented in the context of 6-lane freeways

Table 4.2 Models for 8-lane Freeways with HOV lanes

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	Coeff.	Std. Error	90% Confidence Interval		Coeff.	Std. Error	90% Confidence Interval	
			Lower	Upper			Lower	Upper
Constant	-4.41	1.533	-6.93	-1.88	-3.31	1.37	-5.56	-1.05
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT in veh/day)	0.757	0.128	0.547	0.966	0.759	0.114	0.572	0.947
ln (left shoulder width in feet)	-0.05	0.01	-0.07	-0.02	-0.03	0.015	-0.060	-0.01
Florida (0 or 1)	0.382	0.088	0.238	0.527				
Over Dispersion Parameter	0.480	0.035	0.426	0.542	0.547	0.034	0.494	0.605

The statistical outputs can also be represented as the following equations:

$$N_{FI} = 0.2 * \exp(-4.41 + \ln(L) + 0.757Ln(AADT) - 0.051Ln(LSW) + 0.382(FL)) \quad \text{Eq. 4-4}$$
$$N_{all} = 0.2 * \exp(-3.31 + \ln(L) + 0.759Ln(AADT) - 0.026Ln(LSW)) \quad \text{Eq. 4-5}$$

In the above equations, FL is a binary (0 or 1) variable that indicates whether the segment is from Florida (1) or not (0). All other terms have already been defined in the context of the equations for 6-lane freeways.

Although there is variability in separation type in the data, the statistical analysis shows that the effect of separation type on crashes is not statistically significant (at 90% confidence level).

It also useful to note that among the 646 segments, 115 are from Florida and all of these have a buffer separation of 2-3 foot. All the 191 segments from Washington have a painted stripe separation. Only the segments from California have variability in separation type. Therefore, there is a potential confounding between the effects of the separation type and the location of the segment. In order to examine whether the statistical insignificance of the separation type is possibly because of this confounding, additional models for 8-lane facilities were estimated using only California data (see Table B1 in Appendix B). However, these models also indicate that the separation type is statistically insignificant. Overall, our analysis indicates that separation type is not a statistically significant predictor of crashes in the case of 8-lane facilities with HOV lanes.

Increased width of the left shoulder (measured in feet) is associated with a decrease in the number of crashes. Florida is estimated to have more fatal and injury crashes on its 8-lane freeways than California or Washington. However, such a difference is not observed (at a statistical significance level of 90%) among the three states in the case of total crashes.

Figure 4.3 shows the relationship between predicted FI crashes (per year) and AADT over the range of AADTs (63,200 – 288,400 veh/day) observed in the sample for 8-lane freeways. The graph was developed for a ½-mile segment with 8-foot left shoulder located in Florida (i.e., FL = 1). Figure 4.4 shows the relationship between predicted All crashes (per year) and AADT.

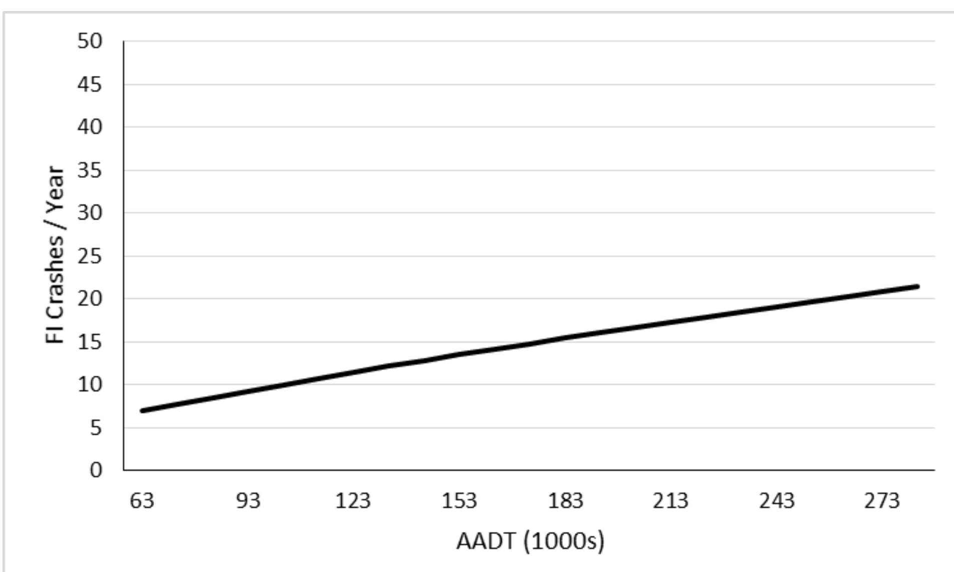

Figure 4.3 Variation of FI Crashes with AADT for 8-lane freeways with HOV lanes

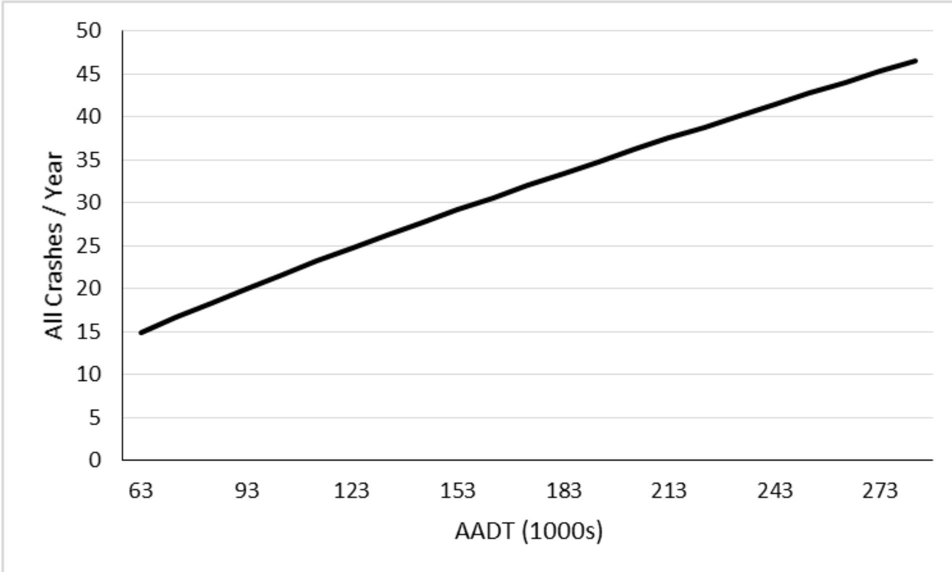

Figure 4.4 Variation of All Crashes with AADT for 8-lane freeways with HOV lanes

4.2.3 Models for 10-lane freeways with HOV lanes

The models for 10-lane freeways are estimated using 166 miles (719 segments) of freeways from the states of California (57% of the segments), Washington (18% of the segments), and Florida (25% of the segments). The estimated models for FI crashes and all crashes are presented in Table 4.3.

Table 4.3 Models for 10-lane Freeways with HOV lanes

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	**Coeff.**	**Std. Error**	**90% Confidence Interval**		**Coeff.**	**Std. Error**	**90% Confidence Interval**	
			Lower	**Upper**			**Lower**	**Upper**
Constant	-9.441	2.144	-12.96	-5.914	-13.59	2.163	-17.14	-10.03
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT in veh/day)	1.171	0.172	0.887	1.454	1.610	0.174	1.324	1.895
Painted Stripe (0 or 1)					0.180	0.103	0.010	0.350
Buffer 2-3 Foot (0 or 1)	-0.124	0.075	-0.247	0.000				
ln (left shoulder width in feet)	-0.093	0.049	-0.175	-0.012	-0.150	0.052	-0.236	-0.064
Over Dispersion Parameter	0.304	0.029	0.260	0.355	0.401	0.031	0.353	0.455

The statistical outputs can also be represented as the following equations:

$$N_{FI} = 0.2 * \exp(-8.861 + \ln(L) + 1.12Ln(AADT) - 0.055Ln(LSW) + 0.522(FL) + 0.310(WA) - 0.141(BW23)) \quad \text{Eq. 4-6}$$

$$N_{all} = 0.2 * \exp(-9.555 + \ln(L) + 1.277Ln(AADT) - 0.084Ln(LSW) + 0.126(PS)) \quad \text{Eq. 4-7}$$

In the above equations, L represents the segment length (in miles), LSW is the left-shoulder-width (in feet). FL is a binary (0 or 1) variable that indicates whether the segment is from Florida or not. Similarly WA is a binary variable that indicates whether the segment is from Washington or not. There are four levels of separation between the managed lanes and the general purpose lanes: Painted stripe, Buffer width 0-1 foot, Buffer width 1-2 foot, and Buffer width 2-3 Foot (represented by binary variables PS, BW01, BW12, and BW23 respectively). 26% of the segments have a painted stripe; 9% have a buffer width of 0-1 foot, 23% have a buffer width of 1-2 foot and the rest (42%) have 2-3 foot buffer as the separation.

Increased width of the left shoulder (measured in feet) is associated with a decrease in the number of crashes. In the case of the model for fatal and injury crashes, Florida and Washington are estimated to have, in general, more crashes on its 10-lane freeways than California. However, such a difference is not observed among the three states in the case of total crashes (at a statistical significance level of 90%).

Facilities with a buffer separation of 2-3 foot are estimated to have fewer fatal and injury crashes than facilities in which the buffer width between the managed and general purpose lanes is shorter (including a simple painted stripe separation). There is no difference (statistically) in fatal and injury crashes between facilities that have a painted stripe and those that have a buffer separation of 0-2 foot. Facilities with a painted stripe separation are estimated to have more "all" crashes compared to those in which managed and general purpose panes are separated with a buffer. At the same time, there is no statistical difference in all crashes between a buffer of 0-2 foot compared to a buffer of 2-3 foot. Overall, the results indicate that the separation type does impact the number of crashes. Using a buffer instead of a painted stripe will lead to fewer total crashes on 10-lane freeways. However, increasing the width of the buffer will not reduce total crashes. At the same time, the benefit of a wider buffer (2-3 feet) is that it leads to fewer fatal and injury crashes.

It also useful to note that among the 719 segments, 179 are from Florida and all of these have a buffer separation of 2-3 feet. All the 129 segments from Washington have a painted stripe separation. Only the segments from California really have variability in separation type. Therefore, there is a potential confounding between the effects of the separation type and the location of the segment. In order to examine whether the statistical significance of the separation type will hold even after removing the confounding factor, additional models for 10-lane facilities were also estimated using only California data (see Table B2 in Appendix B). The results from these models are consistent with the findings from the models estimated using data from all three states.

Figure 4.4 shows the relationship between predicted FI crashes (per year) and AADT over the range of AADTs (90,800 – 386,400 veh/day) observed in the sample for 10-lane freeways. The graph was developed for a ½-mile segment with 8-foot left shoulder located in Florida (i.e., FL = 1). Separate graphs are presented for facilities with a 2-3 Foot buffer and the rest of the facilities (i.e., those that have a painted stripe or a buffer of less than 2 foot). The profiles indicate that at any level of AADT, facilities with a 2-3 foot buffer have 87% (=exp(-0.124)) of the crashes on an identical facility with a painted stripe of a buffer of < 2 foot. Figure 4.5 shows the relationship between predicted All crashes (per year) and AADT. Separate graphs are presented for facilities with a painted stripe and the rest of the facilities (i.e, those with a buffer width of 0-3 feet). The profiles indicate that at any level of AADT, facilities with a painted stripe have 113% (=exp(0.18)) of the crashes on an identical facility with a buffer separation.

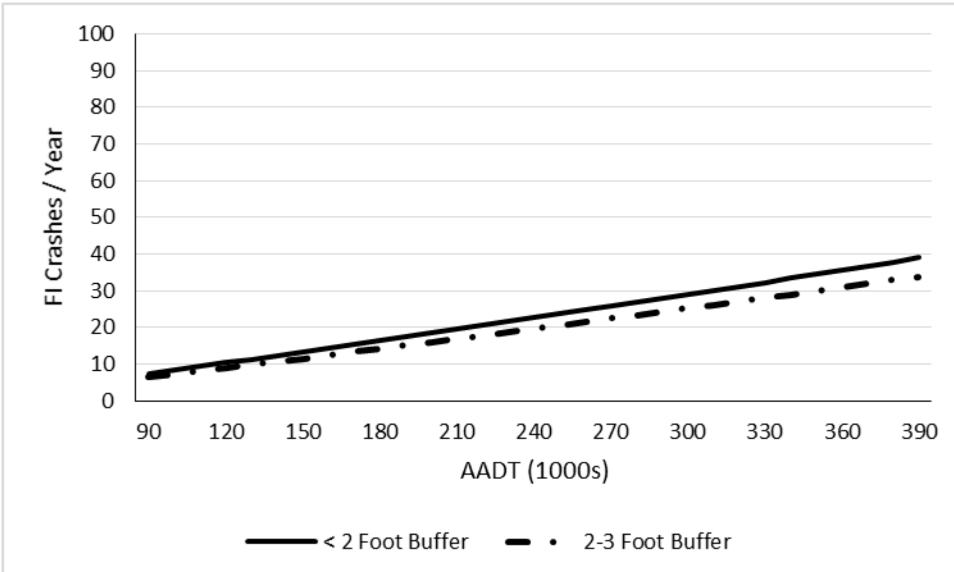

Figure 4.5 Variation of FI Crashes with AADT for 10-lane freeways with HOV lanes

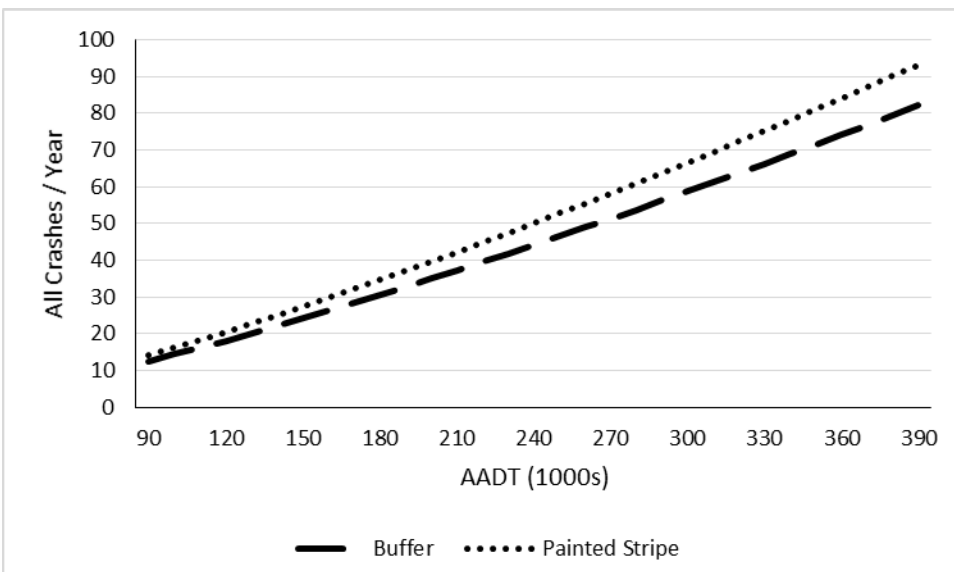

Figure 4.6 Variation of All Crashes with AADT for 10-lane freeways with HOV lanes

4.2.4 Models for 12-lane freeways with HOV lanes

The models for 12-lane freeways are estimated using 31 miles (138 segments) of freeways from the state of California. The estimated models for FI crashes and all crashes are presented in Table 4.4.

Table 4.4 Models for 12-lane Freeways with HOV lanes

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	**Coeff.**	**Std. Error**	**90% Confidence Interval**		**Coeff.**	**Std. Error**	**90% Confidence Interval**	
			Lower	**Upper**			**Lower**	**Upper**
Constant	-7.109	5.016	-15.360	1.142	-4.409	4.912	-12.488	3.669
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT in veh/day)	0.972	0.403	0.310	1.634	0.860	0.394	0.212	1.509
Over Dispersion Parameter	0.438	0.066	0.342	0.561	0.500	0.063	0.406	0.616

The statistical outputs can also be represented as the following equations:

$N_{FI} = 0.2 * \exp(-7.109 + \ln(L) + 0.972Ln(AADT))$ Eq. 4-8

$N_{all} = 0.2 * \exp(-4.409 + \ln(L) + 0.860Ln(AADT)\,)$ Eq. 4-9

Separation type was found to be statistically insignificant in the models for 12-lane freeways with HOV lanes. 6.5% of the segments have a painted strip separation, 2.9% have a buffer of 0-1 foot, 60% have a 1-2 foot buffer and 30% have a 2-3 foot buffer.

Figure 4.7 shows the relationship between predicted FI crashes (per year) and AADT over the range of AADTs (191,200 – 386,400 veh/day) observed in the sample for 12-lane freeways. Figure 4.8 shows the relationship between predicted all crashes (per year) and AADT.

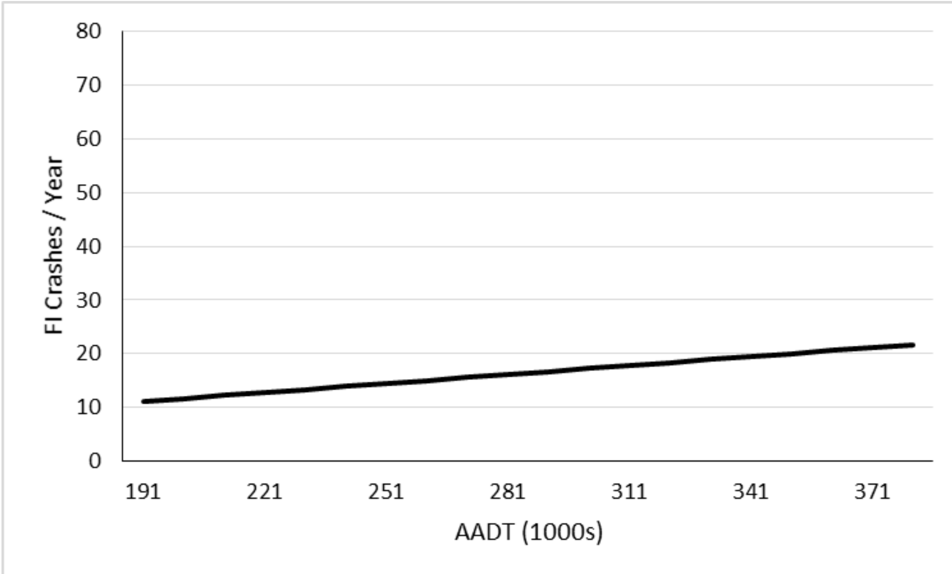

Figure 4.7 Variation of FI Crashes with AADT for 12-lane freeways with HOV lanes

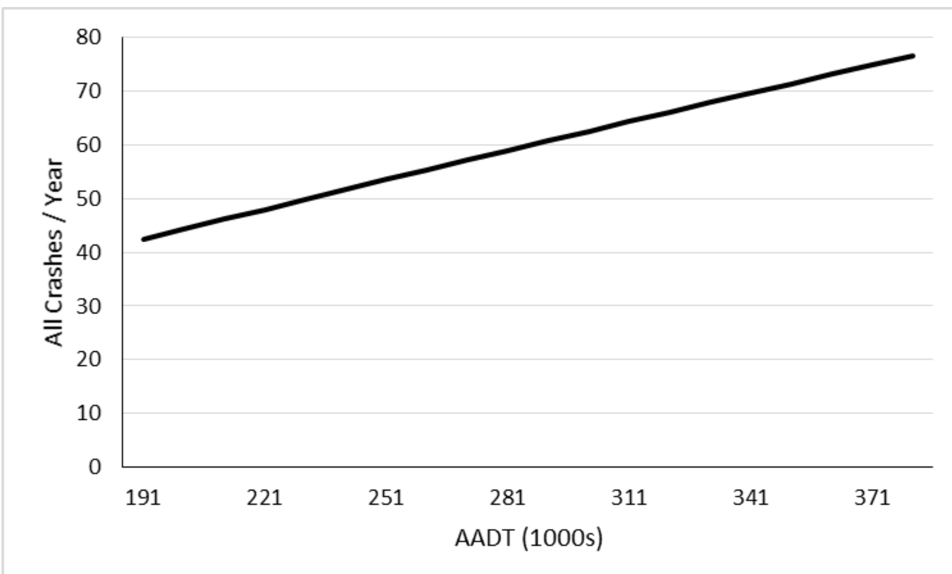

Figure 4.8 Variation of All Crashes with AADT for 12-lane freeways with HOV lanes

4.3 MODELS FOR FREEWAY FACILITIES WITH HOT LANES

The models for freeways with HOT lanes are estimated using 27 miles (48 segments) of freeways from the states of California, Texas, and Florida (Table 4.5).

Table 4.5 Models for Freeways with HOT Lanes

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	**Coeff.**	**Std. Error**	**90% Confidence Interval**		**Coeff.**	**Std. Error**	**90% Confidence Interval**	
			Lower	**Upper**			**Lower**	**Upper**
Constant	-3.583	4.276	-10.61	3.450	-2.899	4.729	-10.67	4.879
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT)	0.577	0.352	-0.002	1.155	0.594	0.389	-0.045	1.234
Number of Lanes	0.077	0.046	0.001	0.152	0.086	0.051	0.002	0.169
Separation = 1 Foot (0 or 1)	1.390	0.236	1.001	1.778	1.247	0.258	0.823	1.672
Separation = 3 Feet (0 or 1)	0.527	0.203	0.193	0.861	0.839	0.218	0.481	1.197
Over Dispersion Parameter	0.203	0.050	0.135	0.304	0.261	0.059	0.180	0.380

The statistical outputs can also be represented as the following equations:

$$N_{FI} = 0.25 * \exp(-3.583 + \ln(L) + 0.577Ln(AADT) + 0.077(NL) + 1.39(S1) + 0.527(S3)) \qquad \text{Eq. 4-10}$$

$$N_{all} = 0.25 * \exp(-2.899 + \ln(L) + 0.594Ln(AADT) + 0.086(NL) + 1.247(S1) + 0.839(S3)) \qquad \text{Eq. 4-11}$$

In the above equations, L represents the segment length (in miles) and NL is the number of lanes. There are three levels of separation between the managed lanes and the general purpose lanes: 1 feet, 3 feet, and 20 feet (represented by binary variables S1, S3, and S20 respectively). A separation of 20 feet (S20) is taken as the reference category and the effects of the other two separation types are estimated relative to this category. The prediction from the regression equation is scaled by 0.25 to obtain a yearly crash prediction (note that 4-years of data were used in model estimation).

The results indicate that the crashes increase with increase in traffic volume (AADT). The effect of AADT on total and injury crashes is significant at 89% confidence whereas the effect of AADT on total crashes is significant at 88% confidence. The variability of AADT along these three freeway facilities are relatively limited leading to the reduced level of significance of the effect of AADT. The coefficient on the length variable is fixed to one as already discussed in the case of models for HOV facilities. A positive correlation is estimated between number of lanes and crashes. This is not to be interpreted as a causal effect; rather, the variable is included to control for differences in number of lanes in the data samples from the three states (Florida predominantly has 12 lanes whereas data from California and Texas are 8-10 lanes). In the future, with the availability of more data, it is anticipated that separate models will be developed for segments with different number of lanes as in the case of the models for HOV facilities.

Facilities with a 1-foot separation are estimated to have more crashes than those that have a 3-foot separation which in turn have more crashes than facilities with a 20 foot separation. This result is presented with the *implicit assumption that there are no other systematic differences in the safety of freeway facilities across the three states as each type of separation is unique to a state*. The section of I-95 in Florida uses flexible pole separation with a separation distance of 1 foot between the HOT lanes and the general purpose lanes. SR-91 in California uses flexible pole separation with a separation distance of 3 feet between the HOT lanes and the general purpose lanes. The section of I-10 in Texas uses flexible pole separation with a separation distance of 20 feet between the HOT lanes and the general purpose lanes. As opposed to the layout seen in California and Florida, this section of I-10 in Texas has both a left shoulder for the general purpose lanes and a right shoulder for the HOT lanes, resulting in a much wider separation width.

Figure 4.9 shows the relationship between predicted FI crashes (per year) and AADT over the range of AADTs (188,408 – 318,000 veh/day) observed in the sample for freeways with HOT lanes. The graph was developed for a ½-mile segment with 10 lanes. Separate graphs are presented for the three levels of separation (1 Foot, 3 Foot, and 20-Foot buffers). The profiles indicate that at any level of AADT, facilities with a 3 Foot buffer have 170% (=exp (0.527)) of the crashes on an identical facility with a 1 Foot buffer. And facilities with a 20 foot buffer have 400% (=exp (1.39)) of the crashes on an identical facility with a 1 Foot buffer.

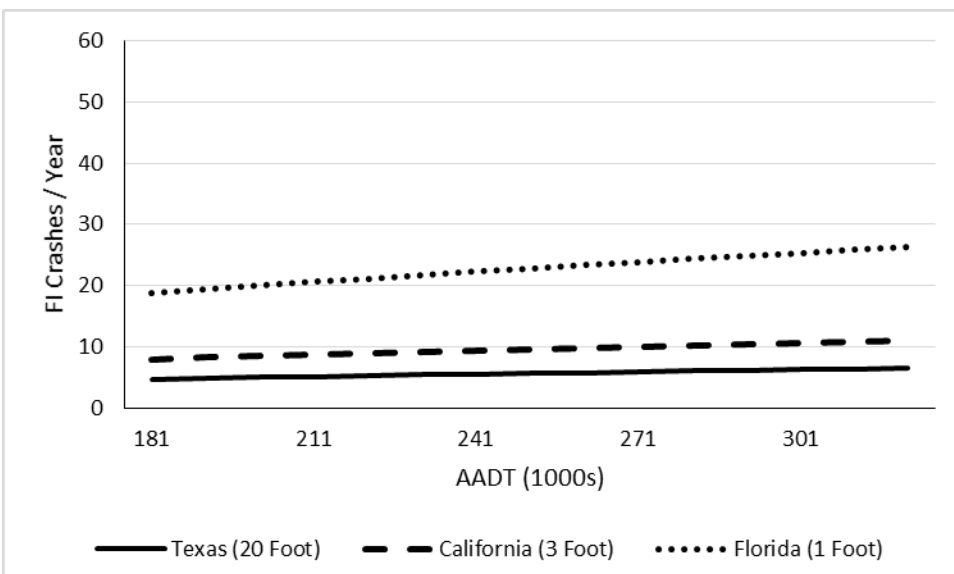

Figure 4.9 Variation of FI Crashes with AADT for 10-lane freeways with HOT lanes

Figure 4.10 shows the relationship between all crashes and AADT. The profiles indicate that at any level of AADT, facilities with a 3 Foot buffer have 231% (=exp (0.839)) of the crashes on an identical facility with a 1 Foot buffer. And facilities with a 20 foot buffer have 349% (=exp (1.247)) of the crashes on an identical facility with a 1 Foot buffer.

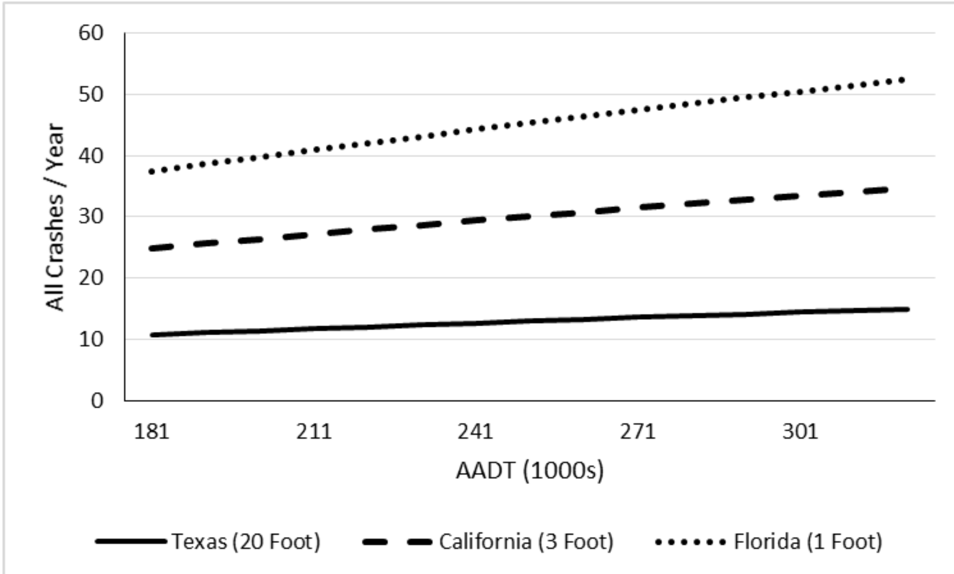

Figure 4.10 Variation of All Crashes with AADT for 10-lane freeways with HOT lanes

CHAPTER 5:
SUMMARY AND CONCLUSIONS

HOV and HOT lanes are increasingly being adopted as lane-management strategies in urban freeways for alleviating congestion, improving travel-time reliability, and for benefitting air quality. At the same time, design elements of HOV/HOT facilities such as orientation (i.e., contra-flow or concurrent flow), lane access type (i.e., continuous or limited), and lateral separation from general purpose lanes (i.e., buffer or barrier) can also impact the safety of the facility.

The Highway Safety Manual has provided the transportation industry with a methodology to predict crashes and quantify the safety benefits of various design features on various highway types excluding freeway facilities. The recently completed NCHRP Project 17-45, "Enhanced Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges" produced a set of safety prediction methods for basic freeway facilities. These methods, however, do not address freeway facilities with managed lanes.

Given the increase in the number of managed-lane facilities and the lack of systematic methods to analyze their safety, this study presents methods to estimate the expected crash frequency of freeway facilities with HOV or HOT lanes. The scope of the research is limited to urban freeways, where most of such facilities are situated. In consideration of the data availability issues, this study examines only freeway segments and not ramps or interchange areas (correspondingly, crashes on ramps and interchanges were excluded during the data preparation stage). Among the design elements, the focus is on the type of separation between the managed lanes and general purpose lanes. Separate models are estimated for fatal and injury (FI) crashes and all crashes. Crashes with the injury severity levels of "K", "A', "B", and "C" are classified as FI crashes. "All" crashes include FI crashes and crashes with "property damage only" (injury severity level of "O").

All the estimated models have been implemented in a spreadsheet program which will enable analysts to apply these equations for crash prediction purposes.

5.1 MODELS FOR FREEWAYS WITH HOV LANES

The models for facilities with HOV lanes were estimated using five years' of data from California, Washington, and Florida. Separate equations were developed depending on the total number of lanes in the freeway facility leading to models for six, eight, ten, and twelve lane facilities. All these facilities have one HOV in each direction (included in the count of total number of lanes).

The models for FI crashes (N_{FI}) for six-, eight-, ten-, and twelve- lane freeways are:

$$N_{FI}(6) = 0.2 * \exp(-16.174 + \ln(L) + 1.760Ln(AADT) - 0.039Ln(LSW))$$
$$N_{FI}(8) = 0.2 * \exp(-4.41 + \ln(L) + 0.757Ln(AADT) - 0.051Ln(LSW) + 0.382(FL))$$
$$N_{FI}(10) = 0.2 * \exp(-8.861 + \ln(L) + 1.12Ln(AADT) - 0.055Ln(LSW) + 0.522(FL) + 0.310(WA) - 0.141(BW23))$$
$$N_{FI}(12) = 0.2 * \exp(-7.109 + \ln(L) + 0.972Ln(AADT))$$

The models for all crashes (N_{all}) for six-, eight-, ten-, and twelve- lane freeways are:

$$N_{all}(6) = 0.2 * \exp(-14.07 + \ln(L) + 1.648Ln(AADT) - 0.074Ln(LSW) + 0.537(CA))$$

$N_{all}(8) = 0.2 * \exp(-3.31 + \ln(L) + 0.759Ln(AADT) - 0.026Ln(LSW))$
$N_{all}(10) = 0.2 * \exp(-9.555 + \ln(L) + 1.277Ln(AADT) - 0.084Ln(LSW) + 0.126(PS))$
$N_{all}(12) = 0.2 * \exp(-4.409 + \ln(L) + 0.860Ln(AADT))$

In the above equations, AADT is the annual average traffic volume (veh/day), L represents the segment length (in miles) and LSW is the left-shoulder-width (in foot). There are four levels of separation between the managed lanes and the general purpose lanes: Painted stripe, Buffer width 0-1 foot, Buffer width 1-2 foot, and Buffer width 2-3 Foot (represented by binary variables PS, BW01, BW12, and BW23 respectively). CA is a binary (0 or 1) variable that indicates whether the segment is from California or not. FL is a binary (0 or 1) variable that indicates whether the segment is from Florida or not. Similarly WA is a binary variable that indicates whether the segment is from Washington tor not. The prediction from the regression equation is scaled by 0.2 to obtain a yearly crash prediction (note that 5-years of data were used in model estimation).

The effect of separation type is on crash rates is found to be statistically significant only in the models for ten-lane facilities. Ten lane facilities with a buffer separation of 2-3 foot are estimated to have fewer fatal and injury crashes than facilities in which the buffer width between the managed and general purpose lanes are shorter (including a simple painted stripe separation). There is no difference (statistically) in fatal and injury crashes between facilities that have a painted stripe and those that have a buffer separation of 0-2 foot. Facilities with a painted stripe separation are estimated to have greater total crashes compared to those in which managed and general purpose panes are separated with a buffer. At the same time, there is no statistical difference in total crashes between a buffer of 0-2 foot compared to a buffer of 2-3 foot. Overall, the results indicate that the separation type does impact the number of crashes on ten-lane facilities. Using a buffer instead of a painted stripe will lead to fewer total crashes on 10-lane freeways. However, increasing the width of the buffer will not reduce total crashes. At the same time, the benefit of a wider buffer (2-3 feet) is that it leads to fewer fatal and injury crashes.

The effect of separation type was not statistically significant in the case of six, eight, and twelve lane facilities. Almost all the six-lane segments (92% by number of segments and 89% by length) in this sample have a painted stripe separation between the managed- and general-purpose lanes. The total volume of twelve-lane facilities are limited and most of these have a buffer separation (1+ feet). Therefore, it is not surprising that the effect of separation turned out to be statistically significant in these facilities. Although there is variability in separation type in the data for eight-lane facilities, the analysis shows that the effect of separation type on crashes is not statistically significant (at 90% confidence level).

Consistent with other HSM models, the equations for freeways with HOV lanes indicate that the crashes increase with increase in traffic volume (AADT) and segment length (measured in miles). The coefficient associated with segment length is fixed to 1 which is customary and consistent with other HSM models. Increased width of the left shoulder (measured in feet) is associated with a decrease in the number of crashes in all models except the ones for twelve-lane facilities. Systematic statistical differences in the crash rates (after controlling for traffic volumes, lengths, left shoulder width, and separation type) among the three states were also observed in some of the models.

5.2 MODELS FOR FREEWAYS WITH HOT LANES

The models for freeways with HOT lanes are estimated using four years' of data from 27 miles (48 segments) of freeways from the states of California, Texas, and Florida. All these facilities have two HOT lanes in each direction.

The models for FI crashes (N_{FI}) and all crashes (N_{all}) for urban freeways with HOT lanes are:

$$N_{FI} = 0.25 * \exp(-3.583 + \ln(L) + 0.577Ln(AADT) + 0.077(NL) + 1.39(S1) + 0.527(S3))$$

$$N_{all} = 0.25 * \exp(-2.899 + \ln(L) + 0.594Ln(AADT) + 0.086(NL) + 1.247(S1) + 0.839(S3))$$

In the above equations, AADT is the annual average traffic volume (veh/day), L represents the segment length (in miles) and NL is the number of lanes. There are three levels of separation between the managed lanes and the general purpose lanes: 1 feet, 3 feet, and 20 feet (represented by binary variables S1, S3, and S20 respectively). The prediction from the regression equation is scaled by 0.25 to obtain a yearly crash prediction (note that 4-years of data were used in model estimation).

Facilities with a 1-foot separation are estimated to have more crashes than those that have a 3-foot separation which in turn have more crashes than facilities with a 20 foot separation. This result is presented with the *implicit assumption that there are no other systematic differences in the safety of freeway facilities across the three states as each type of separation is unique to a state*. The section of I-95 in Florida uses flexible pole separation with a separation distance of 1 foot between the HOT lanes and the general purpose lanes. SR-91 in California uses flexible pole separation with a separation distance of 3-feet between the HOT lanes and the general purpose lanes. The section of I-10 in Texas uses flexible pole separation with a separation distance of 20 feet between the HOT lanes and the general purpose lanes. As opposed to the layout seen in California and Florida, this section of I-10 in Texas has both a left shoulder for the general purpose lanes and a right shoulder for the HOT lanes, resulting in a much wider separation width.

The results also indicate that the crashes increase with increase in traffic volume (AADT). However, these effects were statistically significant at about 88% confidence (all other results are reported with a 90% confidence are higher). This marginally-lower level of confidence is because of the limited variability in traffic volumes across the different segments from the same facilities. A positive correlation is estimated between number of lanes and crashes. This is not to be interpreted as a causal effect; rather, the variable is included to control for differences in number of lanes in the data samples from the three states (Florida predominantly has 12 lanes whereas data from California and Texas are 8-10 lanes).

5.3 AVENUES FOR FUTURE WORK

The safety analysis of facilities with HOV/HOT lanes pose certain challenges that are different when compared to the analysis of other types of facilities already covered by the HSM. Specifically, the number of facilities with HOT lanes are fewer and they are localized in certain geographical locations. Further, certain design features of managed-lane facilities (both HOV and HOT) also appear to be systematically different from state to state. Thus, a comprehensive understanding of the safety of facilities with managed lanes requires data from several states. Such an effort poses important data challenges as data content, formats, and completeness vary across the states. Therefore, enhancements to the models developed in this study using data from additional states and from more recent years is identified as an important avenue for future effort. In particular, with the availability of data from additional HOT lane facilities, especially those that have become operational recently, the models for HOT-lane facilities can be updated to improve their statistical robustness.

The substantive focus of this study has been on freeway segments (not ramps or interchanges) with the specific emphasis on the examination of the safety effects of the separation between the managed lanes and general purpose lanes. Future efforts can extend this study to develop equations specifically for ramps, access points to the managed lanes, and interchange areas. Additional studies are also needed to consider the effects of other geometry/design elements of interest.

Finally, this study developed separate models for FI crashes and all crashes. The study does not distinguish between crash types such as rear-end and side-swipes. As discussed in the literature review, different types of separation and access can differentially affect the various types of crashes. Therefore, development of separate models by crash type is another avenue for future work.

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APPENDIX A

Table A1 Summary of Literature on the Safety Performance of HOV Lanes

No.	Title and Reference	Study Locations	Sample Size	Analysis Years	Analysis Type	Conclusions
1	Cross-Section Designs for the Safety Performance of Buffer-Separated High-Occupancy Vehicle Lanes (Jang et al., 2013)	California	153 miles	2005-2007	Crash prediction models using NB regression	• Proposed a quantitative method to select cross-sectional design for HOV facilities based on crash and geometric data.
2	HOV Lane Configurations and Safety Performance of California Freeways – An Investigation of Differential Distributions and Statistical Analysis (Jang and Chan, 2009)	California	continuous access HOV corridors: 393 segments; limited access HOV corridors: 418 segments	2003-2005	Empirical cumulative density function (CDF), Kolmogorov-Smirnov tests, and comparison of means based on Poisson distributed samples	• Continuous-access HOV lanes performed better than limited-access lanes by several safety metrics. • The historical data for the HOV segments and the GP lanes also revealed similar observations with the same conclusion. • Ingress/egress locations appeared to have a strong correlation with crash rates of freeway segments for both HOV and GP lanes.
3	Safety Performance of High-Occupancy Vehicle (HOV) Facilities: Evaluation of HOV Lane Configurations in California (Jang et al., 2009)	California	continuous access HOV corridors: 279 miles; limited access HOV corridors: 545 miles	1999-2003	Comparison of crash freq. and crash rates from limited and continuous access HOV facilities.	• The HOV facility with limited access offered no safety advantage over the one with continuous access; combined crash rates of the HOV and its adjacent lanes were higher for the HOV facility with limited access. • HOV facilities with shoulder width > 8 ft displayed significantly lower crash rates regardless of access type.
4	Intermediate Access to Buffer-Separated Managed Lanes (Fitzpatrick et al., 2008)	Texas and Minnesota	2 sites in Dallas, TX; 2 sites in Houston, TX; 1 site in Minneapolis, MN	Traffic operations data and spot speed data were collected for two days.	Simple percentages: number of maneuvers by site and access opening length, percent of compliance, vehicle positioning, etc.	• The percent of maneuvers in compliance with pavement markings varied by the intermediate access opening length. • As the HOV lane volume increased, the proportion of passing maneuvers initiated from GP lanes decreased.
5	HOV Lane Configurations and Collision Distribution on Freeway Lanes: Investigation of Historical Collision Data in California (Chung et al., 2007)	California	77 miles categorized by access type	Ten year crash data from 1994-2003	Crash rates and proportions by crash type, access type, and peak hr operation	• Limited access HOV lanes might experience a greater proportion of crashes near the HOV lanes. • Crash frequency during peak hours was higher compared to non-peak hours.

No.	Title and Reference	Study Locations	Sample Size	Analysis Years	Analysis Type	Conclusions
6	Safety Evaluation of Buffer-Separated High-Occupancy Vehicle Lanes in Texas (Cooner and Ranft, 2006)	Texas	I-35 East and I-635	1990-1994 in the before period; 1997-2000 in the after period	Before-and-after crash injury rates, frequency trends, and manually reviewing police reports	• Both corridors had an increase in crash rates after implementation of HOV lanes. • The increase in crashes was primarily focused on the HOV lane and inside GP lane. • The increase in crashes was attributed to speed differential between HOV and inside GP lanes.
7	Crash Analysis of Selected High-Occupancy Vehicle Facilities in Texas: Methodology, Findings, and Recommendations (Cothron et al., 2004a)	Texas	IH 30 (5.6 miles); IH 35E (6 miles), and IH 635 (8 miles)	generally, 5 year before and 4 year after data	Before-and-after crash injury rates, and reviewing crash rates	• Barrier-separated HOV lanes did not have an effect on injury crash rates. • Crash rates on buffer-separated HOV lanes increased compared to the before-period. Also, the increase was specific to HOV lane and the inside GP lane.
8	An Evaluation of Dallas Area HOV Lanes, Year 2002 (Skowronek et al., 2002)	Texas	IH 30 (5.6 miles); IH 35E (6 miles), and IH 635 (8 miles)	IH 30 - 1990-1999; IH 35E: 1990-1994 and 1997-1999; IH 635: 1990-1994 and 1997-1999.	Before-and-after comparison of crash rates at each corridor; critical crash rates	• Yearly crash rates for Dallas area freeways with a buffer-separated HOV lane increased in the years after the HOV lane was implemented. Also, there was a more pronounced crash rate increase during the peak travel periods. • At least a portion of the crash rate increase can be attributed to conflicts at intermediate access locations and lane changes by illegal users of the HOV lane as they approach enforcement areas.
9	The Safety of Concurrent-Lane HOV Projects (Case, 1997)	HOV projects from several states	9 locations with 0-2 ft buffer between HOV and GP lanes	Only the projects with at least 6 months of after data are included.	Simple before-and-after analysis	• Building new HOV lanes with 0'-2' buffer resulted in crash rates significantly higher than they would have been had GP lanes been constructed.

No.	Title and Reference	Study Locations	Sample Size	Analysis Years	Analysis Type	Conclusions
10	Safety of Freeway Median High Occupancy Vehicle Lanes: A Comparison of Aggregate and Disaggregate Analyses (Golob et al., 1990)	California	SR 55 (10 miles)	6 years of before data and 9 months of after data.	Time series analysis of crash frequency. and crash type, crash rates based on estimated AADT, location distribution of crashes	• The HOV lane had contributed to an increase in crashes on that route of 2% over and above the expected frequency from mixed-flow operation. • Congestion played a major role in the changes over time in the crash occurrence on SR 55.
11	Safety of High-Occupancy Vehicle Lanes Without Physical Separation (Golob et al., 1989)	California	SR 91 (24 miles)	6 years of before data and 14 months of after data.	Comparing crash freq. and crash characteristics associated with HOV lane to those associated with temporal and spatial control groups	• Significant migration of crash locations were found due to combination of relief of congestion in the project area and a corresponding creation of more severe bottlenecks downstream. • No adverse effects on safety conditions could logically be attributed to the HOV operation; all the changes in patterns can be explained by changes in the location and timing of traffic congestion.
12	Operational and Safety Experience with Freeway HOV Facilities in California (Newman et al., 1988)	California	5 facilities (LA 10, LA 91, Ora 55, Mrn 101, and SF 280)	14 months	Crash frequency. and crash rates	• No difference in crash rate was observed between continuous access facilities and limited access facilities with a 2-ft buffer. • Segments with a 13-ft buffer had a lower crash rate compared to the facilities with 2-ft buffer and no buffer.

Table A2 Summary of Literature on the Performance of Several Managed-lane Strategies

No.	Title and Reference	Study Locations	Sample Size	Analysis Years	Analysis Type	Conclusions
1	Safety Benefits of Converting HOV Lanes to HOT Lanes: Case Study of I-394 MNPass (Cao et al., 2011)	Minnesota	239 segments	4 years of before and 2 years of after data	EB before-and-after analysis to convert HOV to HOT	• Conversion from HOV to HOT lanes reduced crash frequency by 5.3%.
2	Relationships Between Safety and Both Congestion and Number of Lanes on Urban Freeways (Kononov et al., 2008)	Colorado, California, and Texas	Not available from the source	five years	SPFs using neural networks	• Comparison of SPFs of multilane freeways suggested that adding lanes may initially result in a temporary safety improvement that disappears as congestion increases. • Safety was found to deteriorate with the degradation in the quality of service expressed through the LOS.
3	Safety Impacts of a Freeway Managed Lane Strategy: Inside Lane for HOV Use and Right-Shoulder Lane as a Travel Lane during Peak Periods (Lee et al., 2007)	Washington, DC, and northern Virginia	I-66 (6.5 miles)	2002-2004	NB regression models	• The managed-lane strategy did not appear to be significant to the crash frequency in the inner-left lanes for HOV, GP lanes, or right shoulders. • High AADT volume, and a natural causal factor, light conditions, especially combined with motorists' aggressive lane change behaviors in merging and diverging areas, were presumably major factors influencing crashes in the study area.
4	Safety Effects of Narrow Lanes and Shoulder-Use Lanes to Increase Capacity of Urban Freeways (Bauer et al., 2004)	California - Urban freeways	247.6 miles	2 years of before and 7 years of after data	Observational before-and-after with EB	• 4-5 lane conversion resulted in statistically significant 10%-11% increase in crash frequency. • 5-6 lane conversion resulted in statistically insignificant 3%-7% increase in crash frequency.
5	California Experience with Inside Shoulder Removals (Urbanik and Bonilla, 1987)	California	12 segments	1974-1984	Before-and-after crash rates	• Removal of inside shoulders resulted in either no significant change or a significant reduction in overall crashes at 11 of 12 freeway segments studied in California. • Reduced crashes appeared to be related to lower congestion levels. • Crash severity was not affected; only the reduction in PDO crashes was found to be significant.

Table A3 Summary of Literature on the Design Considerations and Performance of Freeways and Managed Lanes

No.	Title and Reference	Content
1	NCHRP Project 17-45: Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges (Bonneson et al., 2012)	• An overall framework for safety prediction methods for freeways and interchanges. • Analytical models and procedures within the overall framework.
2	HOT Lane Buffer and Mid-point Access Design Review Report (Burgess et al., 2006)	• Recommendations on the preferred buffer widths, HOV facility widths, and access location openings.
3	A Review of HOV Lane Performance and Policy Options in the US (Chang et al., 2008)	• Assessment of performance of existing HOV lane facilities in the U.S. • Effects related to the conversion from HOV lanes to HOT lanes.
4	Guidance for Planning, Operating, and Designing Managed Lane Facilities in Texas (Eisele et al, 2001)	• Geometric guidance for designing managed-lane facilities. • Critical design elements of managed-lane facilities including geometric design criteria; link between operations, design, and enforcement; and ingress/egress treatments.
5	Evaluating Criteria for Adapting HOV Lanes to HOT Lanes: Development and Application of HOT START Software Tool (Eisele et al., 2006)	• A decision-support tool to aid in evaluating key issues related to converting a HOV lane to a HOT lane.
6	Development of High-Occupancy Vehicle Facilities: Review of National Trends (Fuhs and Obenberger, 2002)	• A summary of recent experiences, growth, type, and changes that have occurred with HOV lane operational policies. • Trends in future HOV lane development based on the current roadway improvement plans of various states.
7	I 85 HOV to HOT Conversion Project: Environmental Assessment-Finding of No Significant Impact (GDOT, 2010)	• Design alternatives for implementing managed lanes on I-85.
8	Managed Lanes Handbook (Kuhn et al., 2005)	• Review of research on managed lanes. • An overview of managed lanes, and discussion on critical issues and key resources in planning, design, operations, evaluations, and several other aspects.
9	A Guide for HOT Lane Development (Perez and Sciara, 2003)	• An overview of HOT lanes; planning and implementation process; technical and operational issues; current experience; and lessons learned.
10	Investigating the General Feasibility of High-Occupancy/Toll Lanes in Texas (Stockton et al., 2000)	• Factors that assist in deciding the implementation of HOT lanes. • Critical issues and other aspects such as design requirements and operational limitations.
11	The ABC's of HOV– The Texas Experience (Stockton et al., 1999)	• An overview of HOV lanes and performance measures.

APPENDIX B

Table B1 Models for 8-lane Freeways with HOV lanes (California Data Only)

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	**Coeff.**	**Std. Error**	**90% Confidence Interval**		**Coeff.**	**Std. Error**	**90% Confidence Interval**	
			Lower	**Upper**			**Lower**	**Upper**
Constant	-11.62	1.892	-14.73	-8.51	-8.43	1.878	-11.52	-5.34
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT in veh/day)	1.345	0.157	1.087	1.603	1.182	0.156	0.926	1.438
Over Dispersion Parameter	0.400	0.042	0.335	0.476	0.537	0.047	0.466	0.620

Table B2 Models for 10-lane Freeways with HOV lanes (California Data Only)

	Fatal and Injury Crashes (FI)				All Crashes (All)			
Variable	**Coeff.**	**Std. Error**	**90% Confidence Interval**		**Coeff.**	**Std. Error**	**90% Confidence Interval**	
			Lower	**Upper**			**Lower**	**Upper**
Constant	-9.44	2.144	-12.96	-5.91	-13.5	2.16	-17.14	-10.03
ln (length in miles)	1.000	Fixed			1.000	Fixed		
ln (AADT in veh/day)	1.171	0.172	0.887	1.454	1.610	0.174	1.324	1.895
Painted Stripe (0 or 1)					0.180	0.103	0.010	0.350
Buffer 2-3 Foot (0 or 1)	-0.12	0.075	-0.247	0.000				
ln (left shoulder width in feet)	-0.09	0.049	-0.175	-0.01	-0.15	0.052	-0.236	-0.06
Over Dispersion Parameter	0.304	0.029	0.260	0.355	0.401	0.031	0.353	0.455