Crash Prediction Method for Freeway Segments with High Occupancy Vehicle (HOV) Lanes

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Total words: 6300
5 Tables @ 250/table = 1250 words
Total effective words = 7550 words
This study developed methods for estimating the expected crash frequency on urban freeway segments with HOV 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 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). Models are presented for six-, eight-, ten-, and twelve-lane facilities. The effect of separation type on crash rates is found to be statistically significant only in the models for ten-lane facilities. 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.
INTRODUCTION
Since their inception in late 1960s, High Occupancy Vehicle (HOV) lanes have been increasingly implemented across the United States. In addition to encouraging carpooling and increasing person throughput, the HOV facilities help alleviate congestion, improve travel time reliability, and benefit air quality (1,2,3,4,5). At the same time, design elements of HOV 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 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 (6). 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 (7). 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 on freeway facilities with HOV 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. 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 states consider safety in decisions about planning and designing freeways with HOV lanes.

The rest of this paper is organized as follows. The next section provides an overview of the literature on the safety of HOV facilities. This is followed by a discussion about the data assembled for developing the crash-prediction models. The models developed for six-, eight-, ten-, and twelve- lane facilities are presented and discussed next. The paper ends with a summary, major conclusions, and directions for further research.

LITERATURE REVIEW
This section presents a brief synthesis of the literature on the topic of safety of managed lane facilities. The first sub-section focuses on before-and-after studies on safety of facilities with managed lanes. The second sub-section examines the impacts of the geometry of managed lane facilities on safety.

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. (8) 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 case study indicated no adverse effect on safety conditions that could logically be attributed to the HOV operation. Golob et al. (9) 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.

Other researchers have also examined the safety of HOV facilities in Texas using before- and after- studies. Skowronek et al. (2) 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. (10) 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.

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 (5). Eiseley et al. (11) 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. This section presents a synthesis of the literature on the safety effects of separation between the general purpose lanes and the managed lanes and the impacts of access to the managed lanes.

Separation between the Managed Lanes and General Purpose Lanes
One of the important aspects impacting the safety of facilities with managed lanes is the separation of the managed lanes from the general purpose lanes. This has been recognized as early as 1979 when Miller et al. (12) reported that the lack of physical separation between the HOV lane and the general-purpose lanes can create several operational and safety problems.

Skowronek et al., (2) also argue that barrier-separated lanes should offer better safety compared to buffer-separated 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. (13) 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 data presented by Newman et al. (14), Bonneson et al. (7) 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. 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. (15) 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 (15).

Hlavacek et al. (16) 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 panel concluded that generalizations about best forms of delineation are difficult to make because of differences in emphases, limitations, and demands across situations. At the same time, the panel discussed the impacts of various aspects such as access control, tolling, initial and maintenance costs, reduction of illegal maneuvers, and providing visual cues to drives on separation types.

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. 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. Newman et al. (14) 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, later studies report statistical differences based on access type. Jang et al. (17) observed increased weaving opportunities on continuous access HOV lanes that 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. Facilities with continuous HOV access were found to have 16% fewer fatal and injury crashes than the facilities with limited HOV access.

Jang and Chan (18) 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”.

Overall, the literature provides several qualitative and quantitative insights into the impacts of HOV facility design on safety. However, much of these past studies are focused on one/few facilities. In contrast, the objective of this effort is to pool data from several HOV facilities across multiple states to develop crash–prediction models of the type presented in the...
DATA

This section presents a detailed description about the acquisition and assembly of data from the states of California, Washington, and Florida to support the development of the crash prediction models for freeway facilities with HOV lanes.

Data for California and Washington are available from the Highway Safety Information System (HSIS). These data were requested and obtained through the online HSIS data request process. The Florida data set was compiled from the Florida Roadway Characteristics Inventory and the Florida Crash Analysis Reporting System, provided by FDOT. Data are available separately for each year from 2006 – 2010 representing a total of 5 years of data. The yearly data files were first combined creating two files, one for roadway data and another for crash data. The following are the broad categories of roadway variables extracted: functional classification, number of lanes, lane geometry, median geometry, shoulder geometry, and AADT. For the crash files, the extracted variables include date, time, weather conditions, lighting conditions, number of vehicles, and crash severity.

Consistency checks were performed to remove any segments with missing data. Further, only those segments that had clean data for all the five years were retained. It is useful to note that data were acquired from HSIS for all highways that had a managed lane somewhere along its length. Therefore, the next step was the extract out only those segments that had managed lanes. The roadway feature variable was used to identify managed lane facilities.

Once the required roadway data variables were extracted for all the managed lane facilities, the segments were merged into longer homogeneous segments. The segments in original raw data files obtained from the HSIS are relatively short as roadways are segmented whenever there is a slight change in any of the recorded data variables. Since fewer roadway variables are required to develop the models, only these data variables were used to generate longer homogeneous segments.

The crash data files have crash location information, including the route number and the milepost at which the crash occurred. This information was used to assign crashes to segments. Crashes that occurred on the point between two roadway segments were consistently assigned to the beginning segment. The crash files were then merged with roadway characteristics files to obtain the number of crashes on each segment for each severity type and for the years 2006-2010.

Facilities in California have roadway segments that were separated by either a buffer or 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. Painted stripe separation in California consists of a standard dashed white line, identical to the separation between standard travel lanes. In the Washington data, all sections have painted stripe separation consisting of a single solid white line. In the Florida data, all sections are defined as buffer separated. Buffer separation in Florida consists of a double dashed white line with a small gap of about two feet between the two markings. The final report by Srinivasan et al. (19) provides additional details on data assembly including images of different types of separation by state.
Table 1 presents an overview of the data from each state, including statistics on number of segments, segment length, separation type by the number of lanes, the number of crashes, traffic volume, and average segment lengths by the number of lanes. Crashes with the injury severity levels of “K”, “A”, “B”, and “C” are classified as Fatal and Injury (FI) crashes. Total crashes include FI crashes and crashes with property damage only. The crash counts include crashes on both the managed lanes and the general purpose lanes and exclude crashes on ramps and interchanges.

In California, eight- and ten-lane freeways are most commonly represented in the data although the data does include freeways from six- to seventeen- lanes (in all states, the number of lanes include one HOV lane in each direction). 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. In Washington, eight- and ten-lane freeways are most commonly represented, although the data does include freeways from six- to eleven- lanes. In Florida, eight- and ten-lane freeways are most commonly (98%) represented in the data. As already indicated only data from California include segments of all four separation types.

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. Development of models for unbalanced segments (unequal number of lanes in both directions) is relegated as future work.
**TABLE 1. Data Descriptives by State.**

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<th>State</th>
<th>Number of Lanes</th>
<th>Number of Segments</th>
<th>Painted Stripe</th>
<th>Separation Type Buffer</th>
<th>Total FI Crashes</th>
<th>Total Crashes</th>
<th>Average AADT</th>
<th>Average Length (miles)</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 1 Foot</td>
<td>1-2 Foot</td>
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<td>12.6%</td>
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<td>19.1%</td>
<td>27.4%</td>
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<td>0.0%</td>
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<td>76.9%</td>
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<td>60.0%</td>
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<td>39978</td>
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<td>0.0%</td>
<td>100.0%</td>
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<td>Total</td>
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<td>0.0%</td>
<td>0.0%</td>
<td>100.0%</td>
<td>8851</td>
<td>18617</td>
<td>218,531</td>
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**CRASH PREDICTION MODELS**

This section presents the models estimated for freeway facilities with HOV lanes using the data described in the previous section. This section includes both the analysis framework and the resulting models.

**Analysis Framework**

Crash Prediction Models are also referred to as Safety Performance Function (SPFs) or Safety Prediction Models (SPMs). 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)". Sometimes, 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"...

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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/Crash Prediction Models” (consistent with the NSCHRP 17-45) or “Safety Performance Functions” as defined in the introduction to the HSM. The models may be represented as:

\[ N = \exp(\alpha + LN(L) + \beta LN(AADT) + \beta_1 V_1 + \beta_2 V_2 + \beta_3 V_3 + ... + \beta_K V_K) \]  

Equation 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
- \( \alpha, \beta, \beta_1, \ldots, \beta_K \) = Regression coefficients or parameters.

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 1. An alternate approach would be to estimate separate equations for each separation type; however data availability limits our ability to develop such models. Other variables such as shoulder width are also considered. 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. Note that the coefficient on the segment length variable is fixed to 1 (customary in most 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 most of the current HSM models. However, researchers 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 \((20)\). 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 seen in Equation 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. Therefore, estimates of PDO crashes may be obtained by subtracting out the estimated FI crashes from the estimated all crashes. Further, for each level of severity, separate equations are estimated depending on the total number of lanes (6, 8, 10, and 12) in the freeway. Thus a total of eight equations are developed for facilities with HOV lanes. 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 direction and the total number of
lanes in each direction is equal. Given the word-limit considerations, graphical representations of
the estimated equations are not presented here; but these are available in the project final report
(19). A spreadsheet implementation of the those modes for predictive analysis is also available
from the Florida Department of Transportation.

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 2. The table
also presents the 90% confidence interval for the estimated coefficients. 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.

<p>| TABLE 2. Models for 6-lane Freeways with HOV Lanes |
|---------------------------------|---------------------------------|
|                                  | Fatal and Injury Crashes (FI)   |</p>
<table>
<thead>
<tr>
<th>Variable</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>90% Confidence Interval</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>90% Confidence Interval</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>Upper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ln (length in miles)</td>
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<td>Fixed</td>
<td>1.000</td>
<td>Fixed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ln (AADT in veh/day)</td>
<td>1.760</td>
<td>0.267</td>
<td>1.322</td>
<td>2.199</td>
<td>1.648</td>
<td>0.251</td>
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<tr>
<td>ln (left shoulder width in feet)</td>
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<td>0.019</td>
<td>-0.069</td>
<td>-0.008</td>
<td>-0.074</td>
<td>0.028</td>
</tr>
<tr>
<td>California (0 or 1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.537</td>
<td>0.193</td>
</tr>
<tr>
<td>Over Dispersion Parameter</td>
<td>0.571</td>
<td>0.073</td>
<td>0.462</td>
<td>0.704</td>
<td>0.589</td>
<td>0.064</td>
</tr>
</tbody>
</table>

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

\[
N_{FI} = 0.2 \times \exp(-16.174 + \ln(L) + 1.760 \ln(AADT) - 0.039 \ln(LSW))
\]

\[
N_{all} = 0.2 \times \exp(-14.07 + \ln(L) + 1.648 \ln(AADT) - 0.074 \ln(LSW) + 0.537(CA))
\]

In the above equations, \(N_{FI}\) represents the number of fatal and injury crashes per year and
\(N_{all}\) represents the number of total 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).

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 method were employed in a before-and–after analysis (as outlined in the HSM) or to estimate the expected crash frequency of a segment.

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 3. The overall structure of this table is similar to the one presented in the context of 6-lane freeways.

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

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

\[ N_{FI} = 0.2 \times \exp(-4.41 + \ln(L) + 0.757 \ln(AADT) - 0.051 \ln(LSW) + 0.382(FL)) \]

\[ N_{all} = 0.2 \times \exp(-3.31 + \ln(L) + 0.759 \ln(AADT) - 0.026 \ln(LSW)) \]

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 (these models are available in project final report [19]). 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.

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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fatal and Injury Crashes (FI)</th>
<th>All Crashes (All)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coeff.</td>
<td>Std. Error</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Constant</td>
<td>-9.441</td>
<td>2.144</td>
</tr>
<tr>
<td>ln (length in miles)</td>
<td>1.000</td>
<td>Fixed</td>
</tr>
<tr>
<td>ln (AADT in veh/day)</td>
<td>1.171</td>
<td>0.172</td>
</tr>
<tr>
<td>Painted Stripe (0 or 1)</td>
<td>0.180</td>
<td>0.103</td>
</tr>
<tr>
<td>Buffer 2-3 Foot (0 or 1)</td>
<td>-0.124</td>
<td>0.075</td>
</tr>
<tr>
<td>ln (left shoulder width in feet)</td>
<td>-0.093</td>
<td>0.049</td>
</tr>
<tr>
<td>Over Dispersion Parameter</td>
<td>0.304</td>
<td>0.029</td>
</tr>
</tbody>
</table>

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

\[ N_{FI} = 0.2 \times \exp( -8.861 + \ln(L) + 1.12\ln(AADT) - 0.055\ln(LSW) + 0.522(FL) + 0.310(WA) - 0.141(BW23) ) \]

\[ N_{all} = 0.2 \times \exp( -9.555 + \ln(L) + 1.277\ln(AADT) - 0.084\ln(LSW) + 0.126(PS) ) \]

In the above equations, 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 the HOV and general purpose lanes 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. Buffer separation (instead of painted stripe) is correlated fewer
total crashes on 10-lane freeways. However, increasing the width of the buffer is not correlated
with additional total crash reductions. At the same time, the benefit of a wider buffer (2-3 feet) is
that it is correlated with 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 (these models are available in project
final report (19)). The results from these models are consistent with the findings from the models
estimated using data from all three states.

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
5.
TABLE 5. Models for 12-lane Freeways with HOV Lanes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>90% Confidence Interval</th>
<th>Coeff.</th>
<th>Std. Error</th>
<th>90% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln (length in miles)</td>
<td>1.000</td>
<td>Fixed</td>
<td>1.000</td>
<td>Fixed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ln (AADT in veh/day)</td>
<td>0.972</td>
<td>0.403</td>
<td>0.310</td>
<td>0.860</td>
<td>0.394</td>
<td>0.212</td>
</tr>
<tr>
<td>Over Dispersion Parameter</td>
<td>0.438</td>
<td>0.066</td>
<td>0.342</td>
<td>0.561</td>
<td>0.500</td>
<td>0.406</td>
</tr>
</tbody>
</table>

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

\[
N_{FI} = 0.2 \times \exp(-7.109 + \ln(L) + 0.972\ln(AADT))
\]

\[
N_{all} = 0.2 \times \exp(-4.409 + \ln(L) + 0.860\ln(AADT))
\]

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.

SUMMARY AND CONCLUSIONS

HOV 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. 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 lanes. The scope of the research is limited to urban freeway segments. 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. All the estimated models have been implemented in a spreadsheet program which will enable analysts to apply these equations for crash prediction purposes.

The models 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.

In the developed models, 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 lanes 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). 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.

Overall, we envision this study as an important empirical contribution to the safety analysis of freeway segments with HOV lanes. At the same time, the study has also highlighted that the safety analysis of facilities with HOV lanes pose certain challenges that are different when compared to the analysis of other types of facilities already covered by the HSM. Specifically, certain design features (such as separation type) 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 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.

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. Finally, future efforts should also seek 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.

ACKNOWLEDGEMENTS
This study was funded by the Florida Department of Transportation. The authors would like to express their sincere appreciation to several staff members of the FDOT Roadway Design Office for their guidance, assistance, and feedback throughout the project.
REFERENCES


