# Safety Implications of Managed Lane Cross Sectional Elements

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15. Supplementary Notes

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16. Abstract

The objective of this project was to investigate the relationship between crashes and buffer-separated manage lane dimensions. The results from several previous research studies have demonstrated that reductions in freeway lane width or shoulder width are associated with more crashes. A wider managed lane envelope widths (i.e., left shoulder, managed lane, and buffer width combined) are also associated with fewer freeway crashes for both all severity levels and fatal and injury severity levels. Wider envelopes are associated a reduction of 2.8 percent (in Texas) or 2.0 percent (in California) in total freeway crashes (all severities) for each additional foot of envelope width. In California, wider envelopes are associated with a reduction of 4.4 percent in managed lane-related crashes (fatal and injury severity levels) for each additional foot of envelope width. The analysis was conducted on non-weaving managed lane segments that included a single managed lane separated from the general purpose lanes with a flush buffer area. The dataset included crashes on 128.0 miles in California (all 128.0 miles with flush buffers) and 60.4 miles in Texas (41.7 miles with pylon buffers and 18.7 miles with flush buffers). The California sites included freeways with three or four general-purpose lanes while the Texas freeways had three to five general-purpose lanes.

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| | |
|---|---|
| AADT | Annual average daily traffic |
| AADTHV | Annual average daily traffic for the managed lane |
| AADTMainL | Annual average daily traffic for the general-purpose lanes |
| AASHTO | American Association of State Highway and Transportation Officials |
| Avg | Average |
| Buf_Type | Analysis variable; buffer type between managed lane and general-purpose freeway lanes – either pylons or flush |
| Buf_W | Analysis variable; buffer width |
| Dir | Direction |
| DOT | Department of transportation |
| EB | Eastbound |
| F | Flush buffer |
| FHWA | Federal Highway Administration |
| ft | Foot or feet |
| GP_Adj_W | Analysis variable; general-purpose lanes, width of lane adjacent to the managed lane |
| GP_All_Ln_W | Analysis variable; general-purpose lanes, width of all general-purpose lanes |
| GP_Avg_Ln_W | Analysis variable; general-purpose lanes, average lane width |
| GP_Ent | Analysis variable; general-purpose lanes, number of entrance ramps within the segment |
| GP_Exit | Analysis variable; general-purpose lanes, number of exit ramps within the segment |
| GP_NumLn | Analysis variable; general-purpose lanes, number of general-purpose lanes that are not barrier separated and are moving in same direction |
| GP_R_Shld_W | Analysis variable; general-purpose lanes, right shoulder width |
| GP_Trvl_W | Analysis variable; general-purpose lanes, travel width for general-purpose lanes, determined as number of lanes multiplied by average lane width |
| GP_Weave | Analysis variable; general-purpose lanes, number of weaving areas within the segment |
| HOT | High-occupancy toll |
| HOV | High-occupancy vehicle |
| HSIS | Highway Safety Information System |
| HV | Abbreviation used for HOV or managed lanes in analysis |
| Hwy | Highway |
| m | Meter |
| Max | Maximum |
| mi | Mile |
| Min | Minimum |
| ML | Managed lane |
| MLB | Managed lane or buffer related crashes |
| ML_L_Shld_W | Analysis variable; managed lane, left shoulder width |

| | |
|---|---|
| ML_Ln_W | Analysis variable; managed lane, lane width |
| ML_Env | Analysis variable; managed lane envelope which is the sum of left shoulder width, lane width, and buffer width |
| MRI | Midwest Research Institute |
| MUL | Managed use lane |
| NB | Northbound |
| NCHRP | National Cooperative Highway Research Program |
| NW Length | Sum of the lengths for non-weaving segments within the corridor |
| OLCR | Optimal lane changing region |
| P | Pylons present within buffer area |
| PSL | Posted speed limit |
| SB | Southbound |
| T_Trvl_W | Analysis variable; total travel width |
| veh | Vehicle |
| WB | Westbound |
| yr | Year |

# CHAPTER 1: INTRODUCTION

This report is part of a Federal Highway Administration (FHWA) research project entitled "Synthesis of Operational Aspects and Safety Implications of Reduced Cross Sectional Elements (Buffer Width vs. Shoulder Width vs. Lane Width)".

## BACKGROUND

Managed lanes (ML) are designated lanes and roadway facilities located on or adjacent to controlled access urban highways that are actively operated and managed to preserve preferential service over comparable general traffic lanes. Preferential service often implies faster travel speeds and better reliability than would be observed on adjacent general-purpose (GP) lanes that are not subject to the same level of active management. Various geometric strategies are employed to preserve these benefits such as wider lane widths or wider buffer widths with or without pylons.

## STUDY OBJECTIVE

The objective of this project was to identify managed lane facilities that are currently employed in the United States in order to inventory the array of strategies regarding lane, buffer, and shoulder (inside and outside) widths. Selected strategies were then to be evaluated to determine the impacts of narrowed widths on safety.

## STUDY APPROACH

The research was conducted in a series of tasks as follows:

- **Task A—Project Initiation**. The research team met with FHWA staff to discuss the project direction, scope, and work plan.
- **Task B—Collect, Review, and Evaluate Available Literature and Practices**. The research team reviewed existing literature on freeway and managed lane safety. Geometric information was obtained for a sample of existing managed lanes. This information was used to aid in identifying potential study locations. The team also identified the availability of crash data suitable for the study.
- **Task C—High Occupancy Vehicle/Managed Use Lane Pooled Fund Study Panel Discussion to Develop a Short List of Candidate Facilities for Detailed Evaluation**. This task involved meeting with the High Occupancy Vehicle (HOV)/Managed Use Lane (MUL) Pooled Fund Study panel to identify a short list of approximately 12 sites that will be evaluated as part of Task E. More than 12 sites were included in the study to expand the potential of finding statistical relationships between cross section width and crashes.
- **Task D—Develop Methodology for Evaluation.** This task involved the development of an evaluation methodology that was followed in Task E.
- **Task E—Evaluation of Safety and Operational Implications of Reduced Cross-Sectional Elements**. This task involved the review and analysis of the crash data and site data to identify potential relationships between cross section (lane, shoulder, and buffer) width and crash frequency or severity.

- **Task F—Research Report**. This task involved the development of this research report to document aspects of the study's activities and findings.
- **Task G—Project Meetings and Teleconference.** This task included participation in the following project meetings and teleconferences: kick-off meeting/teleconference, teleconferences spaced throughout the project, and HOV/MUL Pooled Fund Study Annual Meeting held April 2015.

## REPORT ORGANIZATION

This report includes the following chapters:

- **Chapter 1: Introduction.** This chapter presents general background information along with the research objectives.
- **Chapter 2: Literature Review.** This chapter presents findings from the literature on managed lane and freeway safety.
- **Chapter 3: Site Selection.** This chapter describes the methodology used to select sites included in this research.
- **Chapter 4: Data Collection.** This chapter describes the methodology used to collect the geometric data and the crash data.
- **Chapter 5: Analysis.** This chapter describes the evaluation of the datasets and presents the results from the statistical analyses.
- **Chapter 6: Summary, Conclusions, and Recommendations for Future Research.** This chapter provides a summary and the conclusions of the research, and presents future research needs.
- **Chapter 7: References.** This chapter provides the details on the references used in the report.

# CHAPTER 2: LITERATURE REVIEW

Managed lanes (ML) can provide safety and operational performance benefits over general-purpose (GP) facilities, but the managed lane strategy must be appropriate for the intended user group. Specific benefits in crash reduction seen at one facility do not necessarily translate to another facility, so the selected strategy must account for the conditions unique to a particular facility. This section presents a summary of recent freeway and managed lane safety research.

## MANAGED LANES

### Crashes within the Managed Lane Facility

Crashes on managed lanes are assumed to most likely be related to access and sight distance issues. For some situations, a failure to appreciate driver expectancy that differs for managed lanes as compared to general-purpose lanes may contribute to crashes, for example, when drivers need to exit the managed lane several miles prior to their destination. Adequate attention to placement of traffic control devices can help.

In addition to crashes near access points, crashes can also occur within a managed lane facility. Common types of crashes within a facility can include:

- Rear-end crashes due to congestion.
- Sideswipe crashes due to passing.
- Crashes caused by drivers making unexpected maneuvers in violation of access restrictions, to avoid debris, or circumvent disabled vehicles that may block the travelway.

### Crashes at Access Points

Freeway access points are common sites for crashes, just as crashes can commonly be found at intersections on surface streets. Crashes near access points can involve vehicles entering or leaving the managed lanes (e.g., sideswipe, striking separation device, etc.), and crashes can involve vehicles that are not changing facilities (e.g., rear-end crashes caused by drivers braking to avoid a vehicle entering the facility in front of them). Traffic volumes, the type of access and separation provided, and proximity of managed lanes access to general-purpose entrance and exit ramps may all have an effect on crashes, and these effects may vary from one facility to another.

A California study described comparisons of traffic safety during the morning and afternoon peak hours in extended stretches of eight high occupancy vehicle (HOV) lanes with two different types of access – four corridors with continuous access and the others with limited access. [1, 2] Traffic crash patterns for the two different types of HOV lanes were investigated by evaluating (a) the differences in crash distribution, severity, types of crashes, and per lane traffic utilization; (b) spatial distribution of crash concentrations by using Continuous Risk Profile approach; and (c) crash rates in the vicinity of access points in HOV lanes with limited access. In their study, the researchers conducted detailed analysis on crash data during peak hours in relation to geometry and traffic features. Based on the findings from the assessment on eight routes, the limited-access HOV lanes appeared to offer no safety advantages over the continuous-access

HOV lanes. Although the overall safety seemed comparable, the observed differences between these types of facilities were attributed to more frequent and concentrated distribution of crashes at limited-access HOV lanes.

A recent study examined two facilities in Minnesota: [(3)]

- I-394 freeway, the first dynamically priced high-occupancy toll (HOT) lane, was designed with limited access.
- I-35W, the second HOT corridor, was designed with an open access philosophy where lane changes between the HOT and the general-purpose lanes are allowed everywhere except for a few specific locations.

The authors used shockwave length as a surrogate of safety based on the assumption that the more vehicles involved in a slow-and-go maneuver, the higher the possibility a driver will fail to react in a timely manner. They commented that the source of traffic demands has a notable impact on performance with respect to safety and access. I-394 is operating well with the limited access because the majority of the demand is originating from three specific interchanges. In contrast, I-35W has a higher interchange density so the open-access philosophy is working well on that facility. The authors developed a software tool capable of defining the Optimal Lane Changing Regions (OLCRs) that can be used with planned HOT facilities that adopt a closed access philosophy. The proposed methodology defines OLCRs with respect to the positions of entrance or exit ramps. The second methodology was designed to support decisions for access restrictions on existing HOT facilities. The core is a developed model capable of emulating shockwave propagation on the HOT lane given target densities and speed differential between the HOT and the adjacent general-purpose lane.

### Safety of Buffer-Separated High Occupancy Vehicle Lanes

A 2013 paper reported on an evaluation of the relationship between cross-section design (i.e., lane width, shoulder width, and buffer width) to safety performance for HOV lanes. [(4)] The authors used three years (2005 to 2007) of crash data for 13 southern California segments totaling 153 miles. The segments had the HOV lanes buffer-separated from the general-purpose lanes. Crashes included those that occurred on the median shoulder, in the HOV lane, or in the adjacent general-purpose left lane. Independent variables included geometric attributes and annual average daily traffic (AADT). The authors made the following observations regarding geometric cross section and crashes:

- **HOV lane width**: a wider HOV lane tends to be associated with lower crash frequencies except for the case with a width of 13 ft, which did not have enough segments to draw a conclusion.
- **AADT**: higher AADTs in HOV and left lanes, except injury crashes in the left lane, are positively related to crash frequency, which means that freeway segments with more traffic tend to have higher crash frequencies. However, injury crashes in the left lane show an opposite, negatively correlated pattern, albeit by a very small number. This implies that more traffic leads to fewer crashes in the left lane but the variation is not substantial. The causal effect was not investigated in the study, but the authors offered a potential interpretation that crashes are likely to be more severe when traffic is light due to the likely higher speeds inherent in lower traffic density.

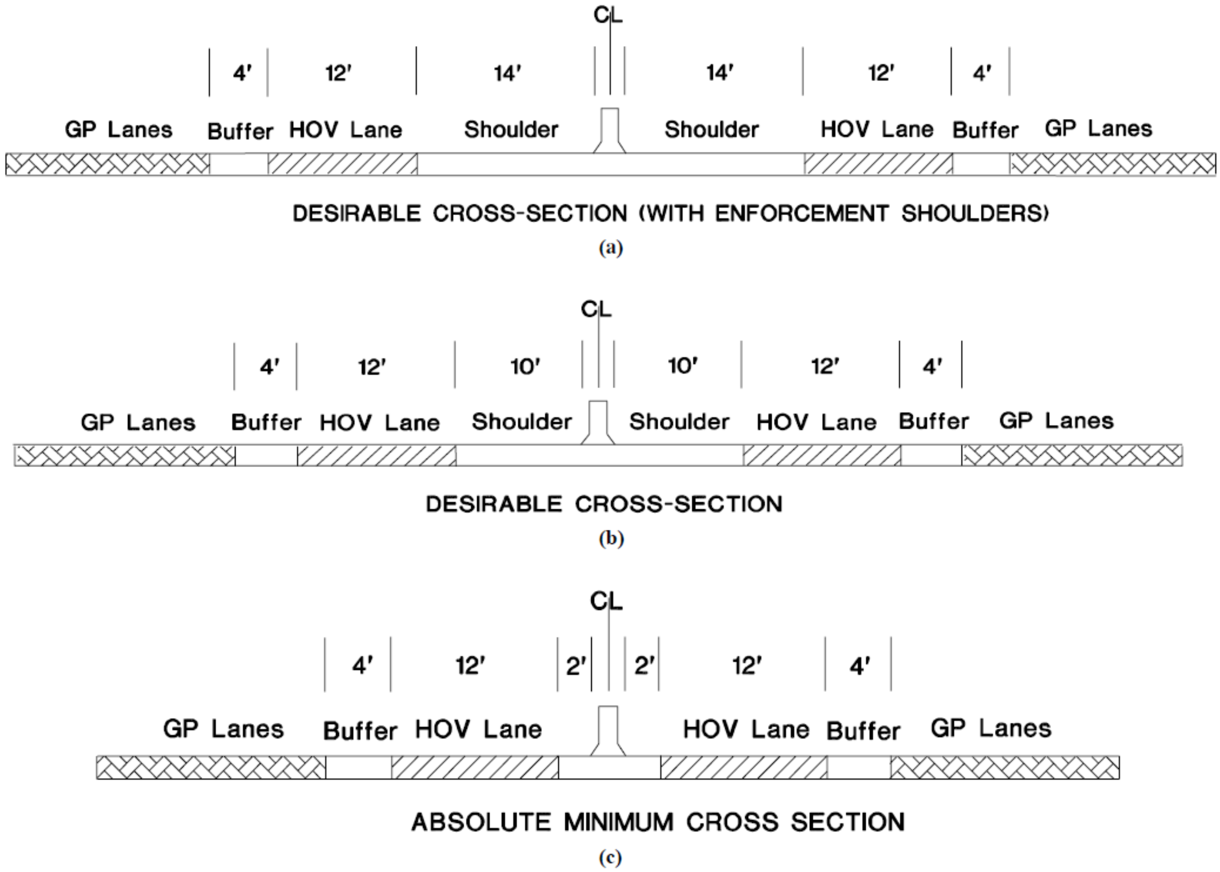
- **Shoulder width**: the estimates indicated that wider shoulder width helps reduce crashes in HOV lanes.
- **Buffer width**: coefficients for buffer widths were not found to be statistically significant at the 10 percent level in the model.
- **Left lane width**: left lane widths were excluded in the estimated model due to their statistical insignificance (i.e., large standard errors); no inference could be drawn.

The authors stated that their findings could be used to determine the optimal cross-section and provided a case study discussion to illustrate the results. For one example, they recommended that a 12 ft lane and 10 ft left shoulder be converted to a 3.6 ft buffer, 12 ft lane, and 6.4 ft left shoulder. Two other examples were also provided in their paper, both of which suggested keeping the 12-ft lanes and shifting some of the left shoulder width into the buffer.

Cothron et al. and Cooner and Ranft reported on Texas research conducted to gain a better understanding of the safety issues and impacts associated with buffer-separated concurrent-flow HOV lanes. (5, 6) They reviewed hard-copy crash reports for multiple years from two urban freeways in Dallas, Texas. The objective was to determine trends and from those trends to make recommendations for absolute minimum and desirable buffer-separated concurrent flow HOV lane cross-section widths. In summary, researchers stipulate that the following factors all contribute to the increased injury crash rates experienced on the two Dallas corridors:

- High daily traffic volumes and extensive congestion in the general-purpose lanes.
- Ramp-pair combinations at or near the minimum ramp terminal spacing as recommended by the American Association of State Highway and Transportation Officials (AASHTO) in *A Policy on Geometric Design of Highways and Streets* (commonly known as the *Green Book*). (7)
- Reduced HOV cross section.
- Speed differential between the HOV and adjacent general-purpose lane traffic.

Figure 1 shows recommendations for desirable and absolute minimum cross sections for future buffer-separated HOV lanes in the Dallas area. The desirable cross-section guidance provides a typical section and a section with enforcement shoulders. Both desirable cross sections provide full inside shoulders and 4-ft buffers with a standard 12-ft lane for HOV traffic.




Source: adapted from Cooner, S., and S. Ranft. Safety Evaluation of Buffer-Separated High-Occupancy Vehicle Lanes in Texas. In Transportation Research Record: Journal of the Transportation Research Board, No. 1959, parts of the text, and Figure 8, p. 176. Copyright, National Academy of Sciences, Washington, D.C., 2006. Reproduced with permission of the Transportation Research Board. (6)

*Note: abbreviations used in figure: GP = general purpose, HOV = high occupancy vehicle.*

**Figure 1. Graphic. Buffer-separated high occupancy vehicle lanes: (a) desirable cross section with enforcement shoulders, (b) desirable cross section, and (c) absolute minimum cross section that should be used only on short-distance interim projects or short sections, e.g., across narrow bridge.**

Cooner and Ranft provided the following summary of previous studies:(6)

> "Golob et al. compared the frequency and characteristics of crashes before and after an HOV lane was added to Riverside Freeway, CA-91, in the Los Angeles, California, area. (8) The HOV lane was created from the inside shoulder of the roadway. The study concluded that the HOV-lane project did not have an adverse effect on the safety of the corridor, and the changes in crash characteristics were attributed to the change in location and timing of traffic congestion.

Sullivan and Devadoss led a California Polytechnic State University study that reported the effects HOV lanes have on the safety of selected California freeways. [9] The study suggested that the observed crash pattern resulted from differences in traffic flow and congestion rather than geometric and operational characteristics of the HOV facilities. The crash hot spots during the peak periods of freeways with and without HOV lanes were a result of localized congestion.

A 1979 FHWA study indicated that the lack of physical separation between the HOV lane and the general-purpose lanes can create several operational and safety problems. [10] The speed differential and the merging into and out of the HOV lane were thought to contribute to increased crash potential. Slow vehicles merging into a high-speed HOV lane of faster vehicles or the HOV-lane vehicles having to decelerate rapidly to merge into the general-purpose lanes can result in either sideswipe or rear-end crashes.

The purpose of a 1995 study conducted by the Hampton Roads Planning District Commission in Virginia was to determine the safety effects of implementing a buffer-separated HOV lane. [11] Data from HOV lane facilities around the country were reviewed to determine the impact of varying buffer widths separating the HOV lane and the general-purpose lanes. The following HOV lane designs were reviewed: 3- to 8-ft buffer, 8-ft buffer raised 6 inches off the pavement, 13-ft buffer, and 0- to 2-ft buffer. The results indicated that the impact of the first three designs was inconclusive. However, the use of a buffer of 0 to 2 ft in width appeared to contribute to an increase in crash rates when compared to the pre-HOV crash rates for the freeways of interest. The speed differential between the HOV lane and the general-purpose lanes was identified as the possible cause of the crash rate increase.

In 2002, the Texas A&M Transportation Institute completed a multiyear research study. [12] In this study, injury crash rates were compared from before and after buffer-separated HOV lanes were implemented in two corridors. There was an increase in injury crash rates for the after condition; however, only one year of after data was available during this study. Several factors that may have contributed to an increase in crash rates were identified. These factors included the loss of the inside shoulder and a reduction in general-purpose lane width from 12 to 11 ft for implementation of the buffer-separated HOV lane.

Other recent research conducted by the Midwest Research Institute (MRI) studied crash data from California on freeways where the inside shoulder was converted to a travel lane and the other lanes were reduced in width. [13] All the freeways examined statistically used the converted inside lane as a concurrent-flow HOV lane. The analysis indicated that crash frequencies increased an average of 11 percent after the freeways were changed in this manner. However, the MRI research team did not attempt to explain the increase in the number of crashes. MRI's primary data source was the Highway Safety Information System database." (Source page 168-169 in reference 6)

### Differences in Crashes between Given Conditions

An Empirical-Bayes statistical estimation procedure was conducted to evaluate the effects of tolling on the I-394 MnPass Lanes in Minnesota, which opened for operation in 2005. [14] AADT data were used from 1998 to 2008. A four-year observation period was used before the start of tolling as well as a two-year post deployment observation period. Crash data of interstate highways in the Minneapolis-St. Paul (Twin Cities) seven-county metropolitan area from the Minnesota Department of Transportation (DOT) were used. The study found the overall number of crashes to be reduced by 5.3 percent, with an economic benefit of $5 million from 2006 to 2008. The authors of the paper stated that they were not confident that their results could be transferred to other HOT lane projects because of the limited research on this issue, and the newness of many HOT lanes that have recently opened.

A 2012 paper presented results of a safety analysis of a time-of-day managed-lane strategy that concurrently allows use of the inner left lanes by high-occupancy vehicles and use of right shoulders as general-purpose lanes during peak hours. [(15)] The crash data (3 years), corresponding annual average daily traffic volumes, and lane-type-specific AADT volumes were identified for various lane types, including the inner left lanes for HOV-only use during peak hours, general-purpose lanes, right shoulder lanes, and all lanes as a whole. Negative binomial regression models were used to estimate the effect of this traffic operations system and other factors relevant to crash frequency. The negative binomial regression model analyses presented no evidence that the interest factors, including the managed-lane strategy during peak hours, AADT volumes, merging and diverging influence areas, weather, light conditions, and existence of pull-off areas affected the crash frequency when aggregated across all lanes. The variable AADT volumes in the specific analysis of general-purpose lanes appear to be significant and show about a 2 percent increase in weekday crashes for each increase of 1,000 vehicles per day in the AADT range of 50,000 to 83,000 vehicles per day. Right shoulder-specific analysis shows that motorist behaviors at the merge and diverge areas during adverse light conditions are significant and shows an increase of about 38 percent in crashes in these areas. The managed-lane strategy does not appear to be significant to the crash frequency in the inner left lanes for HOV, general-purpose lanes, or right shoulders.

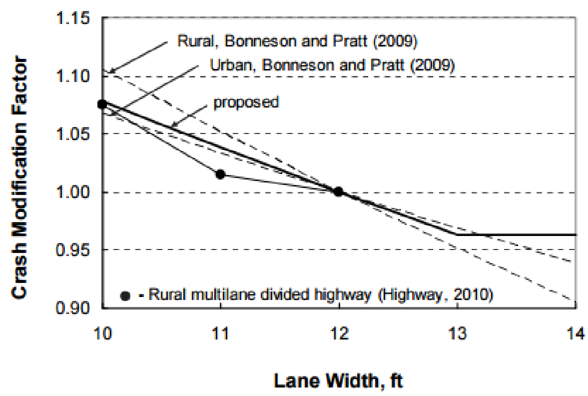
## FREEWAYS

The *Highway Safety Manual* (HSM) now includes crash predictive methods for freeways. [(16)] The developed chapters were based on research conducted as part of National Cooperative Highway Research Program (NCHRP) 17-45. [(17)] The researchers found that reductions in lane widths and inside (left) shoulder widths are associated with increased crashes. The proposed crash modification factor for the HSM along with the findings from other recent work is shown in Figure 2 for lane width and Figure 3 for inside (left) shoulder width. The range of shoulder widths included in the NCHRP 17-45 study was 2 to 12 ft. An inside shoulder width of 6 ft was assumed as the base condition. Some agencies avoid inside shoulder widths greater than 4 ft and less than 8 ft because of concerns that drivers may attempt to seek refuge in a space that does not have sufficient width to accommodate a typical vehicle (6 ft) plus clearance (desirably 1 ft to 2 ft as discussed in the *Green Book*, see Section 4.4.2, page 4-10). [(7)]

## FREEWAY GENERAL-PURPOSE LANE CROSS SECTION

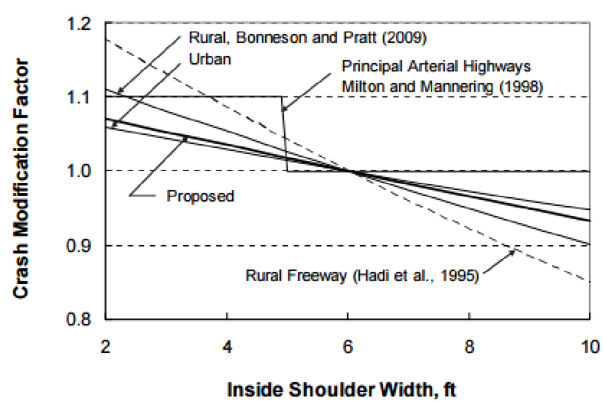
A recent Texas DOT project that examined the tradeoffs of reducing lane and shoulder widths to permit an additional freeway lane also identified increased crashes when the widths of lanes or shoulders are reduced. [(18)] The identified safety improvements included the following:

- Table 1 provides the safety benefit of 12-ft lanes compared to 11-ft lanes, based on the number of travel lanes per direction, when there are not changes in the other variables included in the model.
- The safety improvement associated with increased left shoulder width is a reduction of crashes by 5 percent per additional foot of left shoulder, when there are no changes to the other model variables.
- The safety improvement associated with increased right shoulder width is a reduction of crashes by 9 percent per additional foot of right shoulder, when there are no changes to the other model variables.
- There is a safety improvement associated with each additional lane (see Table 2).




Source: Figure 49 on page 142 of Bonneson, J., A. S. Geedipally, M. P. Pratt, and D. Lord (2012). *Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges* (NCHRP Project 17-45, online final report). Reproduced with permission of the Transportation Research Board. (17)

**Figure 2. Chart. Proposed crash modification factor for lane width. (17)**




Source: Figure 51 on page 144 of Bonneson, J., A. S. Geedipally, M. P. Pratt, and D. Lord (2012). *Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges* (NCHRP Project 17-45, online final report). Reproduced with permission of the Transportation Research Board.(17)

**Figure 3. Chart. Proposed crash modification factor for inside shoulder width. (17)**

**Table 1. Safety of lane width (fatal and serious injury crashes).** [18]

| Number of Lanes | Multiplicative Effect in Model | Fatal and Serious Injury Crash Reduction of a 12-ft Lane Compared to 11-ft |
|---|---|---|
| 2 | 0.95 | 5% |
| 3 | 0.93 | 7% |
| 4 | 0.90 | 10% |
| 5 | 0.88 | 12% |

Source: Table 45 on page 76 from Dixon, K., K. Fitzpatrick, R. Avelar, M. Perez, S. Ranft, R. Stevens, S. Venglar, and T. Voigt (2015) *Reducing Lane and Shoulder Width to Permit an Additional Lane on a Freeway: Technical Report.* FHWA/TX-15/0-6811-1.

**Table 2. Safety change per additional lane (fatal and serious injury crashes).** [18]

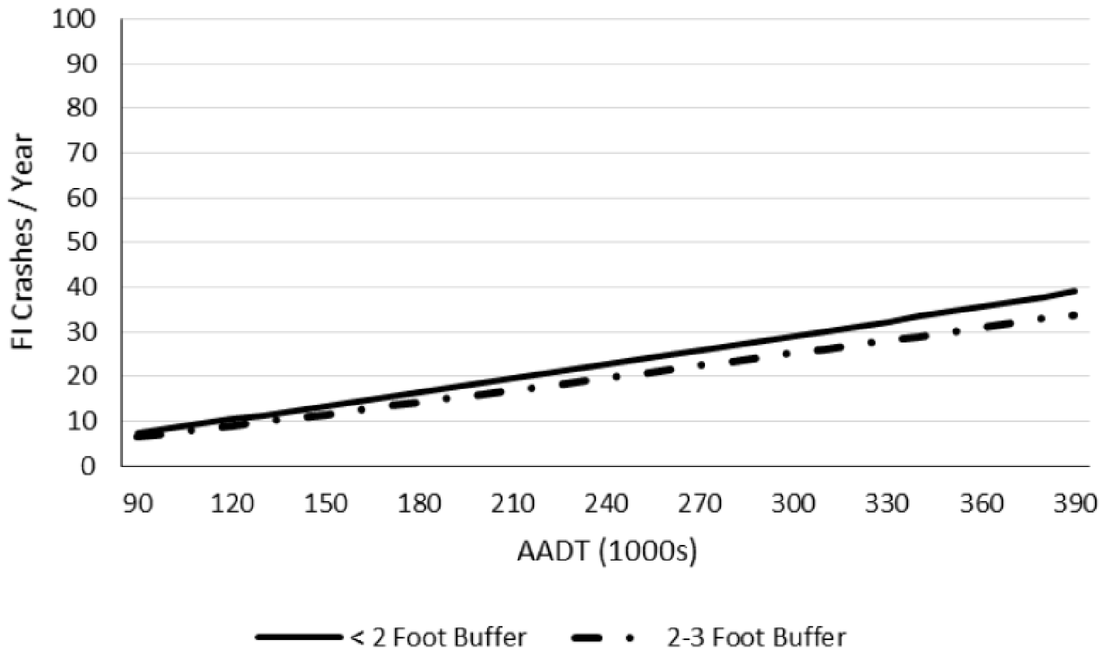
| Average Lane Width (ft) | Multiplicative Effect | Reduction of Fatal and Serious Injury Crashes per Additional Lane |
|---|---|---|
| 11.0 | 0.76 | 24% |
| 11.5 | 0.75 | 25% |
| 12.0 | 0.74 | 26% |

Source: Table 46 on page 77 from Dixon, K., K. Fitzpatrick, R. Avelar, M. Perez, S. Ranft, R. Stevens, S. Venglar, and T. Voigt (2015) *Reducing Lane and Shoulder Width to Permit an Additional Lane on a Freeway: Technical Report.* FHWA/TX-15/0-6811-1.

While the research also identified that an additional lane can result in reductions in crashes, whether the benefits of the additional lane completely offset the consequences of the reduced lane and shoulder widths would depend upon the conditions present at the site. The authors of the Texas study developed an equation and a spreadsheet that could be used to evaluate the tradeoffs. Note that the Texas work focused on freeways with general-purpose lanes rather than freeways that include a managed lane.

## FREEWAYS WITH HIGH OCCUPANCY VEHICLE OR HIGH OCCUPANCY TOLL LANES

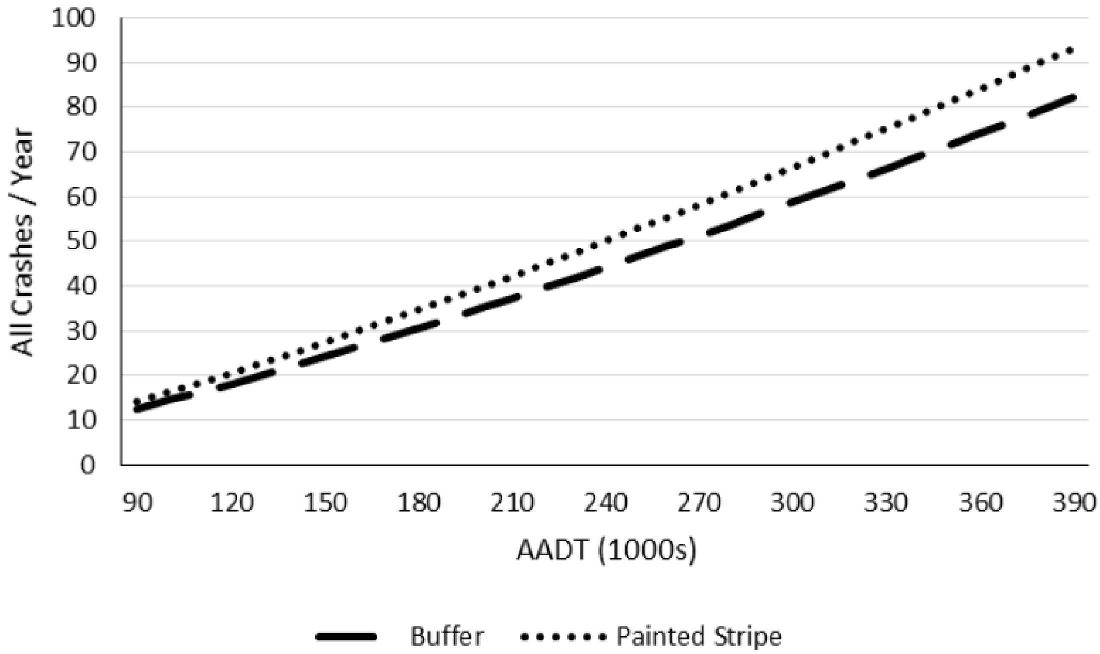
A Florida study developed crash prediction equations for freeways facilities with HOV and HOT lanes. [19] The authors developed unique models by number of freeway lanes. Models were developed for 6-, 8-, 10-, and 12-lane freeways (number of lanes reflect both directions and include the managed lanes). For all the models, segment length and AADT were significant and included. For most of the models, left shoulder width was the only other significant variable. An increase in left shoulder width was associated with decreases in crashes. The effect of buffer type on crashes was found to be statistically significant only in the model for 10-lane freeways with an inclusion of a 2- to 3-ft buffer being associated with fewer fatal and injury crashes. Figure 4 illustrates the findings for fatal+injury crashes and Figure 5 for all crashes.




Source: Figure 4.5 on page 40 from Srinivasan, S., P. Haas, P. Alluri, A. Gan, and J. Bonneson (2015) *Crash Prediction Method for Freeway Facilities with High Occupancy Vehicle (HOV) and High Occupancy Toll (HOT) Lanes. FDOT Contract BDV32-977-04.*

*Note: abbreviations used in figure: FI = fatal and serious injury, AADT = annual average daily traffic.*

**Figure 4. Chart. Variation of fatal and serious injury crashes with annual average daily traffic for 10-lane freeways with high occupancy vehicle lanes from Florida study.** [19]




Source: Figure 4.6 on page 40 from Srinivasan, S., P. Haas, P. Alluri, A. Gan, and J. Bonneson (2015) *Crash Prediction Method for Freeway Facilities with High Occupancy Vehicle (HOV) and High Occupancy Toll (HOT) Lanes. FDOT Contract BDV32-977-04.*

*Note: abbreviation used in figure: AADT = annual average daily traffic.*

**Figure 5. Chart. Variation of all crashes with annual average daily traffic for 10-lane freeways with high occupancy vehicle lanes from Florida study.** [19]

# CHAPTER 3: SITE SELECTION

## SELECTION OF STATES

Cross sections used for managed lanes vary. Some locations separate the managed lane(s) from general-purpose freeway lanes using an exclusive alignment or using barriers. Other locations use a buffer where the buffer consists of a flush area marked with pavement markings and in some cases with supplemental pylons. In many locations, the separation is only a lane line. For this evaluation, efforts were focused on identifying potential sites in the three Highway Safety Information System (HSIS) states with managed lanes (California, Minnesota, and Washington), and in Texas. Based upon the review of variables available within their crash database, the state of California was selected for the study. Data from Texas was also considered due to the availability of latitude and longitude values for many crashes and the use of pylons at several sites.

### Highway Safety Information System Crash Data

California was selected for this study because the state uses a code (Location Type) that classifies crashes as being in the high occupancy vehicle (HOV) lane or the HOV buffer. The California HSIS documentation is available at: http://www.hsisinfo.org/guidebooks/california.cfm. The most recent five years of data available for California was 2007 to 2011. A preliminary filtered dataset of select counties was developed. Table 3 provides the number of crashes within this dataset by code for location of collision. The availability of 15,257 crashes with the HOV code and 437 crashes with the HOV buffer code indicates that the California data can provide valuable insights into HOV (managed lane) related crashes.

### Texas Data

The research team also queried the Texas Crash Records Information System for variables that can be used to identify HOV-specific crashes. In the case of Texas, whether the crash occurred on a segment with a managed lane could be assumed when HOV or Managed Lane is included in the variables Local_Use or Rpt_Street_Descr. Texas data offers additional details in extended fields (e.g. longitude, latitude) or as part of the narratives that would have to be obtained separately. The latitude and longitude information allowed the research team to quickly merge the crash and additional geometric data collected for specific sites. Because of the limited number of HOV-related crashes, the evaluation of the Texas data was limited to using all freeway crashes.

**Table 3. California, number of crashes by location type for several counties.**

| Location Type | Code | 2007 | 2008 | 2009 | 2010 | 2011 | Total |
|---|---|---|---|---|---|---|---|
| Does Not Apply | - | 85 | 66 | 100 | 2 | 76 | 329 |
| Unknown Type | --- | 11527 | 10159 | 9820 | 9969 | 10764 | 52239 |
| Beyond Median Or Barrier Stripe - Driver's Left | A | 208 | 161 | 194 | 181 | 255 | 999 |
| Beyond Shoulder - Driver's Left | B | 2455 | 2386 | 2296 | 2435 | 1941 | 11513 |
| Left Shoulder Area | C | 61 | 60 | 62 | 58 | 45 | 286 |
| Left Lane | D | 17185 | 14726 | 13951 | 15329 | 15965 | 77156 |
| Interior Lanes | E | 19716 | 18324 | 17864 | 18692 | 20130 | 94726 |
| Right Lane | F | 13280 | 12413 | 12104 | 12450 | 13538 | 63785 |
| Right Shoulder Area | G | 428 | 392 | 331 | 359 | 312 | 1822 |
| Beyond Shoulder - Driver's Right | H | 2349 | 2173 | 2197 | 2295 | 2009 | 11023 |
| Gore Area | I | 39 | 34 | 22 | 14 | 25 | 134 |
| Other | J | 489 | 393 | 397 | 442 | 389 | 2110 |
| HOV Lane | V | 3603 | 2924 | 2710 | 3011 | 3009 | 15257 |
| HOV Buffer | W | 78 | 39 | 84 | 106 | 130 | 437 |
| Grand Total | All | 71503 | 64250 | 62132 | 65343 | 68588 | 331816 |

Source: Texas A&M Transportation Institute

## SELECTION OF SITES

With the quantity of managed lane sites available, decisions were needed to focus efforts so to improve the likelihood of identifying usable sites that fit the objective of this project. The following decisions were made during site selection:

- Focus on sites with one (rather than two) managed lane(s) per direction.
- Eliminate sites that have reversible operations.
- Select sites where the managed lane is operational 24 hours per day, seven days per week.
- Focus on locations with a flush buffer with or without pylons. In other words, eliminate sites with concrete barrier separation between the managed lane and the freeway general-purpose lanes.
- Seek sites that represent a range of buffer widths.

For Texas, segments on the following five freeways met the above criteria: I-635 and US 75 in Dallas and US 290, I-10, and US 59S in Houston. For California, a greater number of freeways met the above criteria; therefore, an additional criterion of being in or near the city of Los Angeles was added. The California study locations were on I-105, SR 134, I-210, and I-405. The Texas locations reflect both pylons and flush buffer segments and both Texas and California provide a mix of buffer widths and lane widths. The project requirements were to include a minimum of 12 sites. The research team identified these 18 corridors (nine freeways with each direction uniquely considered) in case some corridors had to be eliminated due to unexpected challenges with the crash data.

# CHAPTER 4: DATA COLLECTION

## DEFINING SEGMENTS

Segments were defined by the location of managed-lane access control change. A new segment would start when access was (or was not) permitted. Each segment was then defined as being managed lane weaving, ramp, or non-weaving segment. For this study only those segments that were non-weaving segments were included in the analysis. The objective of this project was on the effects of cross section dimensions on crashes. Because of limited number of sites with five, six, or seven general-purpose lanes within the preliminary datasets, those California sites were removed from the analysis resulting in the analysis considering crashes on freeways with three and four general-purpose lane freeways in California. For Texas, freeways with three to five general-purpose lanes were included.

The minimum length of segment for California was 0.11 miles with the majority of sites between 0.8 and 1.7 miles. The minimum length of segment for Texas was 0.12 miles, with the majority of sites between 0.9 and 1.4 miles.

After removing sites where weaving was expected, locations undergoing construction, and locations with no annual average daily traffic (AADT) data available, there were 128.0 miles in California (all 128.0 miles with flush buffers) and 60.4 miles in Texas (41.7 miles with pylon buffers and 18.7 miles with flush buffers).

## VARIABLES

For each segment identified, the research team collected geometric characteristics using Google Earth, a software package that allows browsing and measuring satellite imagery. Since this package allows the user to compare satellite images taken at different points in time, the research team annotated the date of the earliest satellite image containing the same managed lane characteristics. In other words, the research team noted the earliest date when the managed lane characteristics matched. In most cases, the change reflected when the managed lane was added to the freeway. This step was done with the purpose of excluding any time period earlier than the date when the managed lane geometric characteristics changed.

Table 4 provides descriptions of the specific geometric variables considered for the analyses along with the average daily traffic variables. The research team gathered the information for the geometric variables by using the measurement tool available in Google Earth. These variables were selected because they have been shown in the literature to be potentially influential on freeway safety. The research team acquired the posted speed limit information by using the StreetView feature available in the Google Earth suite of tools.

**Table 4. Description of candidate variables.**

| Variable Name | Description |
|---|---|
| AADT | Annual average daily traffic for the freeway (vehicle/day) |
| AADTHV | Annual average daily traffic for the managed lane (vehicle/day) |
| AADTMainL | Annual average daily traffic for the general-purpose lanes (vehicle/day) |
| Buf_Type | Buffer type between managed lane and general-purpose freeway lanes – either pylons or flush |
| Buf_W | Buffer width (ft) |
| GP_Trvl_W | General-purpose lanes, travel width for general-purpose lanes, determined as number of lanes multiplied by average lane width (ft) |
| GP_Adj_W | General-purpose lanes, width of lane adjacent to the managed lane (ft) |
| GP_All_Ln_W | General-purpose lanes, width of all general-purpose lanes (ft) |
| GP_Avg_Ln W | General-purpose lanes, average lane width (ft) |
| GP_Ent | General-purpose lanes, number of entrance ramps within the segment |
| GP_Exit | General-purpose lanes, number of exit ramps within the segment |
| GP_NumLn | General-purpose lanes, number of general-purpose lanes that are not barrier separated and are moving in same direction |
| GP_R_Shld_W | General-purpose lanes, right shoulder width (ft) |
| GP_Weave | General-purpose lanes, number of weaving areas within the segment |
| ML_Env | Managed lane envelope, sum of left shoulder width, lane width, and buffer width (ft) |
| ML_L_Shld_W | Managed lane, left shoulder width (ft) |
| ML_Ln_W | Managed lane, lane width (ft) |
| PSL | Posted speed limit (miles per hour) |
| T_Trvl_W | Total travel width (ft) |

Source: Texas A&M Transportation Institute

## DATASET CHARACTERISTICS – GEOMETRICS

Table 5 provides geometric details for the segments being used in the evaluation.

All of the buffers for the California segments were flush (i.e., no pylons) with widths that varied between 1 ft and 12 ft. The buffers generally consisted of white and yellow lane line markings. The larger widths (9 or 12 ft) were associated with preserving space for a downstream managed lane ramp on I-405 as illustrated in Figure 6. I-405 also has narrow buffer widths. Several freeways have buffers with a 4-ft to 5-ft width as shown in Figure 7. Figure 8 shows another example of a wide buffer where a motorcycle is using the available space.

The buffers in Texas include flush buffers and flush buffers with pylons. The Texas sites with flush buffers ranged between 1.5 and 5.0 ft, while the buffers with pylons were between 4.0 and 6.0 ft. The buffer pavement markings in Texas use white lines. Figure 9 shows an example of pylons on a Texas freeway.

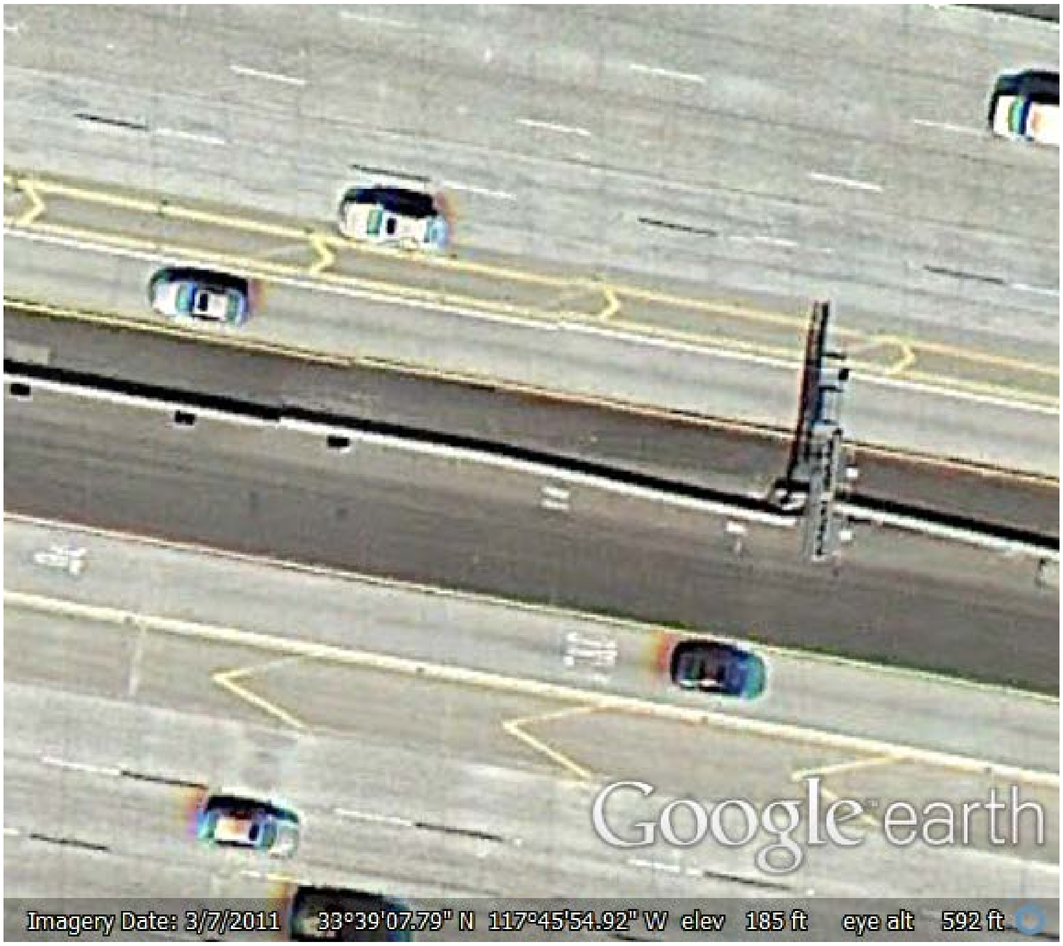
**Table 5. Range of managed lane envelope geometric data by corridor.**

| Hwy | Dir | F or P | NW Length (mi) | SW-Min | SW-Avg | SW-Max | LW-Min | LW-Avg | LW-Max | BW-Min | BW-Avg | BW-Max |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CA 105 | EB | F | 9.44 | 8.5 | 10.8 | 13.0 | 10.5 | 10.9 | 11.5 | 4.5 | 4.8 | 5.0 |
| CA 105 | WB | F | 13.39 | 8.0 | 10.7 | 20.0 | 11.0 | 11.6 | 12.0 | 5.0 | 5.0 | 5.0 |
| CA 134 | EB | F | 8.07 | 1.0 | 3.5 | 15.0 | 10.8 | 11.2 | 12.0 | 1.5 | 1.5 | 1.5 |
| CA 134 | WB | F | 7.55 | 1.0 | 1.3 | 2.0 | 11.0 | 11.2 | 11.5 | 1.0 | 1.6 | 2.0 |
| CA 210 | EB | F | 19.13 | 1.0 | 7.0 | 20.0 | 11.0 | 11.3 | 12.0 | 2.5 | 3.2 | 5.0 |
| CA 210 | WB | F | 14.16 | 1.0 | 7.9 | 20.0 | 11.0 | 11.4 | 12.0 | 2.5 | 3.4 | 5.0 |
| CA 405 | NB | F | 29.7 | 1.0 | 4.0 | 33.0 | 10.0 | 10.7 | 11.5 | 1.0 | 2.6 | 12.0 |
| CA 405 | SB | F | 26.56 | 1.0 | 4.1 | 21.0 | 10.0 | 11.1 | 12.0 | 1.0 | 3.5 | 12.0 |
| TX 75 | NB | P | 11.0 | 3.0 | 3.2 | 3.5 | 11.0 | 11.2 | 11.5 | 4.0 | 4.0 | 4.0 |
| TX 75 | SB | P | 11.0 | 2.0 | 2.0 | 2.0 | 11.5 | 11.5 | 11.5 | 4.0 | 4.0 | 4.0 |
| TX 635 | EB | P | 8.1 | 2.0 | 2.6 | 3.5 | 10.0 | 10.1 | 10.5 | 4.0 | 5.4 | 6.0 |
| TX 635 | WB | P | 7.4 | 1.0 | 1.5 | 2.5 | 10.0 | 10.4 | 10.5 | 5.5 | 5.5 | 5.5 |
| TX 10 | EB | P | 2.3 | 17.5 | 17.8 | 18.0 | 13.0 | 13.3 | 13.5 | 5.0 | 5.3 | 5.5 |
| TX 10 | WB | P | 1.9 | 17.5 | 17.5 | 17.5 | 12.5 | 12.5 | 12.5 | 5.5 | 5.5 | 5.5 |
| TX 59 | NB | F | 7.3 | 10.0 | 11.8 | 13.0 | 11.0 | 11.4 | 12.0 | 1.5 | 3.7 | 5.0 |
| TX 59 | SB | F | 6.0 | 9.0 | 10.6 | 12.0 | 11.0 | 11.8 | 12.0 | 2.0 | 3.2 | 5.0 |
| TX 290 | NB | F | 2.2 | 1.5 | 2.3 | 4.0 | 10.5 | 10.8 | 11.5 | 1.5 | 1.5 | 1.5 |
| TX 290 | SB | F | 3.2 | 1.5 | 1.5 | 1.5 | 11.0 | 11.0 | 11.0 | 2.0 | 2.0 | 2.0 |

Notes on column headings:

- Hwy = State and highway number.
- Dir = direction, where NB = northbound; SB = southbound; EB = eastbound; WB = westbound
- F or P: F=flush buffer and P=pylons present within buffer area.
- NW Length = sum of the lengths for non-weaving segments within the corridor.
- SW = shoulder width (ft), LW = lane width (ft), BW = buffer width (ft).
- Min = minimum width for the highway direction.
- Avg = average width for the highway direction.
- Max = maximum width for the highway direction.

Source: Texas A&M Transportation Institute

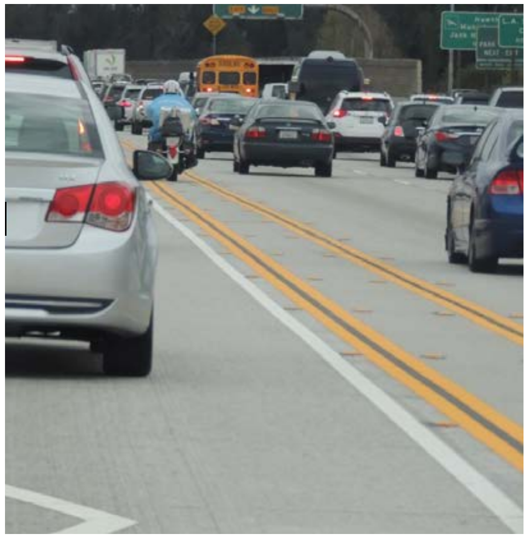



Source: Google Earth

**Figure 6. Graphic. Example of wide buffers on California I-405.**

Source: Texas A&M Transportation Institute

**Figure 7. Graphic. Example of wide buffer in California.**



Source: Texas A&M Transportation Institute

**Figure 8. Graphic. Another example of wide buffer, note motorcycle using the buffer area.**

Source: Texas A&M Transportation Institute

**Figure 9. Graphic. Example of pylons in buffer on Texas freeway.**

## DATASET CHARACTERISTICS – CRASHES

### Texas Crash Data

Table 6 shows the number of crashes identified for each corridor in Texas, including all levels of severity. The number of crashes per year seems consistently increasing at each site, except for sites TX-DA-075[P] and TX-DA-635[P] where year 2009 shows atypically high and low counts, respectively. In the case of TX-DA-075[P], it appears to have been a rare year; in the case of TX-DA-635[P], however, the research team verified that during 2009, geometric characteristics of the managed lanes could not be verified for 11 out of the 20 segments within this site and therefore crashes for those segments are not represented in Table 6. Cells denoting “NA” indicate that no data was available for that corresponding site and year due to construction or a different cross section.

**Table 6. Texas, number of crashes.**

| Site | Dir | Non-Weaving Length (mi) | Crash Type | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| TX-DA-075[P] | NB | 11.0 | Total | 404 | 304 | 347 | 397 | 347 | 380 | 2179 |
| TX-DA-075[P] | SB | 11.0 | Total | 363 | 277 | 329 | 350 | 306 | 351 | 1976 |
| TX-DA-635[P] | EB | 8.1 | Total | 82 | 180 | 208 | 189 | 204 | 257 | 1120 |
| TX-DA-635[P] | WB | 7.4 | Total | 153 | 242 | 261 | 226 | 213 | 267 | 1362 |
| TX-HO-010[P] | EB | 2.3 | Total | 25 | 57 | 57 | 41 | 75 | 86 | 341 |
| TX-HO-010[P] | WB | 1.9 | Total | 0 | 15 | 23 | 22 | 21 | 15 | 96 |
| TX-HO-059[F] | NB | 7.3 | Total | 112 | 112 | 90 | 113 | 101 | 90 | 618 |
| TX-HO-059[F] | SB | 6.0 | Total | 113 | 91 | 89 | 116 | 95 | 89 | 593 |
| TX-HO-290[F] | NB | 2.2 | Total | NA | NA | NA | 11 | 43 | 35 | 89 |
| TX-HO-290[F] | SB | 3.2 | Total | NA | NA | NA | 20 | 65 | 62 | 147 |
| **Grand Total** | **Both** | **60.4** | Total | **1252** | **1278** | **1404** | **1485** | **1470** | **1632** | **8521** |
| TX-DA-075[P] | NB | 11.0 | HOV/ML | 0 | 0 | 2 | 0 | 1 | 8 | 11 |
| TX-DA-075[P] | SB | 11.0 | HOV/ML | 0 | 3 | 2 | 0 | 2 | 7 | 14 |
| TX-DA-635[P] | EB | 8.1 | HOV/ML | 0 | 1 | 0 | 0 | 1 | 2 | 4 |
| TX-DA-635[P] | WB | 7.4 | HOV/ML | 0 | 1 | 1 | 2 | 2 | 2 | 8 |
| TX-HO-010[P] | EB | 2.3 | HOV/ML | 0 | 1 | 1 | 0 | 1 | 1 | 4 |
| TX-HO-010[P] | WB | 1.9 | HOV/ML | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TX-HO-059[F] | NB | 7.3 | HOV/ML | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| TX-HO-059[F] | SB | 6.0 | HOV/ML | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TX-HO-290[F] | NB | 2.2 | HOV/ML | NA | NA | NA | 0 | 0 | 0 | 0 |
| TX-HO-290[F] | SB | 3.2 | HOV/ML | NA | NA | NA | 1 | 1 | 3 | 5 |
| **Grand Total** | **Both** | **60.4** | HOV/ML | **0** | **6** | **7** | **3** | **8** | **23** | **47** |

NA = not applicable because a different freeway configuration was present prior to 2012

Notes on columns:

- Site = TX-YY-###[Z], where TX = Texas; YY = city, with DA = Dallas and HO = Houston; XXX = highway number; Z = buffer type with F = flush buffer and P = flush buffer with pylons.
- Dir = direction, where NB = northbound; SB = southbound; EB = eastbound; WB = westbound
- Non-Weaving Length = sum of the lengths for non-weaving segments within the corridor.
- Crash Type, either high occupancy vehicle or managed lane (HOV/ML) (HOV or managed lane related crashes) or Total (all managed lane, buffer, or general-purpose-lane crashes on the freeway).
- 2009, 2010, 2011, 2012, 2013, and 2014 = number of crashes in the given year.
- Total = total number of crashes in the 2009-2014 time period.

Source: Texas A&M Transportation Institute

From this pool of crashes, the research team identified those that had an annotation of “HOV” or “MANAGED” lane resulting in identifying only 47 crashes. The distribution of these crashes is shown in Table 6. The research team suspects that this table may not include every HOV (or managed lane) crash, since these crashes were identified using annotation fields, instead of coded fields (as is the case in the California data). Since this is a very limited subset, the research team only conducted formal evaluations on total crashes.

### California Crash Data

The research team matched the crash records obtained from HSIS to the mile post limits of the segments identified from satellite imagery. Crashes and traffic characteristics for the four routes selected for analysis were also obtained. The HSIS has AADT data that reflects number of vehicles for both directions on the freeway. The data were matched utilizing the route and county number along with beginning and ending milepost identified for each segment.

AADT counts are also available from the California Department of Transportation Performance Measurement System. This database is available online and provides information regarding the performance of California highways. Through a query on the website, a performance analysis report for each highway was generated. A report was made for the length of the highway in each direction from the years 2007 through 2011. The report includes information regarding the day, hour of the day, mile post where sensor is located, freeway number and direction, and several different methods to calculate AADT to account for missing data from the sensor. The data for HV (abbreviation used for HOV or managed lanes) were used in the analysis with managed-lane crashes.

Table 7 shows the number of managed-lane crashes (i.e., those crashes with a location type code of V (HOV lane) or W (HOV buffer) identified for each corridor in California, including all levels of severity. The top half of Table 7 lists the number of total freeway crashes by highway corridor. The length shown in the table corresponds to the sum of the non-weaving segment lengths included in the dataset. The yearly number of crashes per year seems consistent within each corridor with a general upward trend over time. The year of 2007 frequently has fewer crashes because it does not always reflect a full 12-month of data due to changes in managed-lane cross sections.

**Table 7. California, number of crashes.**

| Highway Number | Dir | Non-Weaving Length (mi) | Crash Type | 2007 | 2008 | 2009 | 2010 | 2011 | Total |
|---|---|---|---|---|---|---|---|---|---|
| 105 | EB | 9.4 | Total | 147 | 313 | 308 | 302 | 322 | 1392 |
| 105 | WB | 13.4 | Total | 138 | 300 | 279 | 310 | 301 | 1328 |
| 134 | EB | 8.1 | Total | 102 | 267 | 282 | 304 | 268 | 1223 |
| 134 | WB | 7.6 | Total | 74 | 250 | 269 | 260 | 262 | 1115 |
| 210 | EB | 19.1 | Total | 125 | 484 | 517 | 598 | 592 | 2316 |
| 210 | WB | 14.2 | Total | 94 | 415 | 374 | 445 | 496 | 1824 |
| 405 | NB | 29.7 | Total | 958 | 1154 | 1069 | 1097 | 1268 | 5546 |
| 405 | SB | 26.6 | Total | 383 | 1061 | 990 | 1066 | 1144 | 4644 |
| **Grand Total** | **Both** | **128.0** | **Total** | **2021** | **4244** | **4088** | **4382** | **4653** | **19388** |
| 105 | EB | 9.4 | MLB | 13 | 28 | 36 | 24 | 33 | 134 |
| 105 | WB | 13.4 | MLB | 16 | 33 | 23 | 24 | 21 | 117 |
| 134 | EB | 8.1 | MLB | 14 | 29 | 18 | 29 | 23 | 113 |
| 134 | WB | 7.6 | MLB | 4 | 14 | 18 | 18 | 24 | 78 |
| 210 | EB | 19.1 | MLB | 15 | 57 | 60 | 60 | 84 | 276 |
| 210 | WB | 14.2 | MLB | 21 | 43 | 50 | 51 | 67 | 232 |
| 405 | NB | 29.7 | MLB | 104 | 119 | 111 | 99 | 115 | 548 |
| 405 | SB | 26.6 | MLB | 40 | 115 | 115 | 108 | 119 | 497 |
| **Grand Total** | **Both** | **128.0** | **MLB** | **227** | **438** | **431** | **413** | **486** | **1995** |

Notes on columns:

- Dir = direction, where NB = northbound; SB = southbound; EB = eastbound; WB = westbound
- Non-Weaving Lengths = sum of the lengths for non-weaving segments within the corridor.
- Crash type, either MLB (managed lane or buffer related crashes) or Total (all managed lane, buffer, or general-purpose-lane crashes on the freeway).
- 2007, 2008, 2009, 2010, 2011 = number of crashes in the given year. Note that 2007 frequently included less than a full 12 months of crashes due to changes in the managed lane cross section.
- Total = total number of crashes in the 2007-2011 time period.

Source: Texas A&M Transportation Institute

# CHAPTER 5: ANALYSIS

## STATISTICAL MODEL / METHODOLOGY

Because more than one time period from each site was used as an analysis unit, the statistical methodology had to consider the grouping structure in the data in an explicit manner. Generalized Linear Mixed models can account for such a structure, as well as handling fixed effects, the type of parametric estimation expected to yield answers to the research questions. These models are constructed under the assumption that crashes at study sites for a given time period follow a given probability distribution. Depending on the dispersion of a particular subset of data, this work utilized Poisson or Negative Binomial distributions.

In the case of the Poisson log-linear mixed effects model, the probability distribution is as shown in

$$P(N_i = n_{ij}) = \frac{\lambda_i^{n_{ij}}}{n_{ij}!} \cdot e^{-\lambda_i}$$

Figure 10.

$$P(N_i = n_{ij}) = \frac{\lambda_i^{n_{ij}}}{n_{ij}!} \cdot e^{-\lambda_i}$$

**Figure 10. Equation. Probability distribution.**

Where:
$N_i$ = Number of crashes at one analysis period at the ith site.
$n_{ij}$ = An actual count of crashes for the jth analysis period at the ith site, such that $n_{ij} \in \{0, Z^+\}$.
$\lambda_i$ = Poisson distribution parameter at the ith site.

The expected number of crashes at the $i^{th}$ site is simply $E(N_i) = \lambda_i$ for the Poisson distribution.

Although most time periods were one-year long, the methodology allows the incorporation of partial years, as this variable is handled as exposure in a way similar to segment length. The exposure variables in the model are defined as the product of the time period length (expressed in years) and the segment length (expressed in miles) for each record in the database. This quantity has units of mile-years (mi-yr). For a given segment-period with amount of exposure $\gamma$, a model can be developed as shown in $\lambda_i = \gamma \cdot \vartheta_i$

Figure 11.

$$\lambda_i = \gamma \cdot \vartheta_i$$

**Figure 11. Equation. Initial equation.**

Where:
$\vartheta_i$ has units of crashes/mi-yr.

Since $\gamma = 1.0$ when segment length = one mile, and period length = one year, $\vartheta_i$ can be estimated by regression techniques, such that the interpretation of the results are in terms of the change in expected yearly crashes per mile corresponding to changes in the critical observed variables.

**The exponential function is used to parameterize the quantity $\boldsymbol{\vartheta_i}$ so that it links crash counts from each site to a corresponding set of critical observed variables. The Equation in**
$\vartheta_{\mathrm{i}} = \mathrm{AADT}^{\alpha} \cdot \mathrm{RE}_{\mathrm{i}} \cdot \exp(\mathrm{X}^{\mathrm{T}} \cdot \beta)$

Figure 12 shows the relationship for the i[th] site.

$$\vartheta_i = AADT^{\alpha} \cdot RE_i \cdot \exp(\boldsymbol{X}^T \cdot \boldsymbol{\beta})$$

**Figure 12. Equation. Equation with crashes per mile-year for i[th] site.**

Where:
$AADT$ = Annual average daily traffic (vehicle/day).
$\alpha$ = Fixed exponent.
$\boldsymbol{X}$ = Vector of fixed effects (i.e., explanatory variables).
$\boldsymbol{\beta}$ = Vector of fixed-effects coefficients.
$RE_i$ = Random effect for ith site.
All other variables as previously defined.

As indicated by the sub-index, the model computes a unique $RE_i$ for each site i. The distribution of all $RE_i$ should roughly be log-normal in the scale of crash counts, a characteristic that was verified after model estimations.

$$\vartheta = AADT^{\alpha} \cdot \exp\left(\mu_{\ln(RE)} + \frac{\sigma^2{}_{\ln(RE)}}{2}\right) \cdot \exp(\boldsymbol{X}^T \cdot \boldsymbol{\beta})$$

**Figure 13. Equation. Equation with model random effect distribution.**

Where:
$\vartheta$ = is the expected yearly crashes per mile, given AADT and the variables represented in X.

The statistical analysis estimates the quantities $\mu_{\ln(RE)}$ and $\sigma^2{}_{\ln(RE)}$ from the site random effects variability alongside the coefficients for the fixed effects (i.e., $\alpha$ and $\boldsymbol{\beta}$). The quantity $\vartheta$ represents the expected number of crashes per amount of exposure at any site. The next section reviews results from estimating the model from the methodology just described.

## OVERVIEW OF VARIABLES CONSIDERED

Initially, variables were selected based on the findings of previous studies along with the variables that define exposure. These initial model variables included either the managed lane components as unique variables (e.g., buffer width, managed lane width, left shoulder width) or as a combined unit (e.g., shoulder, lane, and buffer widths added into a managed lane envelope width variable). For the general-purpose lanes, variables such as number of lanes, lane width (average and per lane values), right shoulder width, number of entrance ramps, and number of exit ramps within the segment were investigated. Later explorations replaced number of lanes and average lane width with total freeway width, as this variable is a compound of the previous two. The use of these combinations was intended to overcome the modeling challenges that handling highly correlated variables impose. In the case of this research, the widths of left shoulder, managed lane, and buffer tended to vary together. In other words, at sites where one of these variables is wide, the other two variables tended to be wider as well.

## MODELS ON FREEWAY CRASHES – CALIFORNIA

### All Severity Levels Crashes

For California, the best model where all the key cross-section variables are present is shown in Table 8. This model is a reference point to observe the trends of each variable, after accounting for the effects of other cross-sectional variable. Fewer crashes are expected when the travel width of the general-purpose lanes is greater because there is more space for vehicles to spread out. The managed lane envelope – which includes the left shoulder width, the managed lane width, and the buffer width – also has an inverse relationship between crashes and width, as expected. The relationship was found statistically significant. Wider envelopes are associated with fewer freeway crashes, a reduction of 2.2 percent in crashes (1-exp(-0.02222)) per additional foot of envelope width.

**Table 8. California, preliminary model for total freeway crashes (all severities).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -12.62701 | 2.69282 | -4.68900 | 0.00000 | *** |
| log(AADT/2) | 1.42194 | 0.22981 | 6.18700 | 0.00000 | *** |
| ML_Env | -0.02222 | 0.00515 | -4.31600 | 0.00002 | *** |
| GP_Trvl_W | -0.00327 | 0.01106 | -0.29600 | 0.76700 | |
| GP_R_Shld_W | 0.01215 | 0.00927 | 1.31000 | 0.19000 | |
| GP_Exit | -0.05070 | 0.05412 | -0.93700 | 0.34900 | |
| GP_Ent | 0.01478 | 0.04664 | 0.31700 | 0.75100 | |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; and *** = $p < 0.001$.

Source: Texas A&M Transportation Institute

A reduced model derived from Table 8 was fitted to exclude variables that are not significantly related to total crashes. This result is shown in Table 9. The results of interest are practically unchanged; a reduction of 2.0 percent in crashes per additional foot of envelope width is shown.

**Table 9. California, refined model for total freeway crashes (all severities).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -12.442053 | 2.666415 | -4.666000 | 0.000003 | *** |
| log(AADT/2) | 1.397905 | 0.225244 | 6.206000 | 0.000000 | *** |
| ML_Env | -0.020306 | 0.005014 | -4.050000 | 0.000051 | *** |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; and *** = $p < 0.001$.

Source: Texas A&M Transportation Institute

Next, the managed lane envelope was split in an effort to investigate if the shoulder, lane, or buffer is more influential with respect to total freeway crashes. Managed lane width became the only significant variable in addition to AADT. The correlation between buffer and left shoulder width (wider buffers are typically present when wider left shoulders are present) is believed to be affecting the significance of those estimates, and potentially others in the model.

In summary, the review of total crashes on California freeways indicates that wider managed lane envelopes are associated with fewer freeway crashes. Additional insight into how the components of the managed lane envelope are affecting freeway crashes is not possible with the available dataset and under the current methodology. An alternative approach was explored, as described in the following section.

### All Severity Levels Crashes – Proportion of Crashes

To continue to explore the potential influence of buffer width on total crashes, a model was evaluated where the proportion of managed-lane crashes to total crashes was the response variable. It is expected that this proportion (modeled as a binomial variable) may capture safety differences associated with differences in the freeway cross section elements. The initial results proved promising, yet a test on the residuals showed moderate overdispersion. This condition affects the standard error of the regression estimates and must be considered. The likelihood of the model was adjusted to represent a quasibinomial distribution (i.e., explicitly correcting for extra-binomial dispersion). The adjusted model is shown in Table 10. This model demonstrates that both the width of the managed lane and the width of the buffer are significant in affecting the proportion of managed-lane crashes with the lane width being the more influential factor.

**Table 10. California, preliminary model of proportion of managed lane or buffer crashes to total freeway crashes (all severities).**

| Variable [a] | Estimate | Standard Error | Degrees of Freedom | t-value | p-value [b] | Significance [c] |
|---|---|---|---|---|---|---|
| (Intercept) | 0.41295 | 0.92882 | 457 | 0.44460 | 0.65680 | |
| AADTMainL | -0.00001 | 0.00000 | 457 | -2.66276 | 0.00800 | ** |
| AADTHV | 0.00004 | 0.00001 | 457 | 4.75961 | 0.00000 | *** |
| ML_L_Shld_W | 0.00084 | 0.01091 | 112 | 0.07676 | 0.93900 | |
| ML_Ln_W | -0.20982 | 0.07266 | 112 | -2.88761 | 0.00470 | ** |
| Buf_W | -0.11736 | 0.03370 | 112 | -3.48293 | 0.00070 | *** |
| GP_Trvl_W | -0.00342 | 0.00637 | 112 | -0.53766 | 0.59190 | |
| GP_R_Shld_W | 0.00776 | 0.00980 | 112 | 0.79257 | 0.42970 | |
| GP_Exit | 0.02081 | 0.04676 | 112 | 0.44501 | 0.65720 | |
| GP_Ent | 0.06890 | 0.04216 | 112 | 1.63419 | 0.10500 | |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

When reducing this model to its most parsimonious form, the results are virtually unchanged for buffer and managed lane width as shown in Table 11. The interpretation of these results is as follows: given that a crash has occurred on a freeway containing a single managed lane and a flush buffer, the odds of that crash being related to the managed lane or the buffer decrease by a factor of 0.77 (exp(-0.2057645)) with each additional foot of width in the managed lane. Similarly, the odds of a crash being related to the managed lane or buffer decrease by a factor of 0.89 (exp(-0.116574)) with each additional foot of width in the flush buffer.

**Table 11. California, refined model of proportion of managed lane to total freeway crashes (all severities).**

| Variable [a] | Estimate | Standard Error | Degrees of Freedom | t-value | p-value [b] | Significance [c] |
|---|---|---|---|---|---|---|
| (Intercept) | 0.32720 | 0.86727 | 457 | 0.37727 | 0.70610 | |
| AADTMainL | -0.00001 | 0.00000 | 457 | -2.94195 | 0.00340 | ** |
| AADTHV | 0.00004 | 0.00001 | 457 | 4.81206 | 0.00000 | *** |
| ML_Ln_W | -0.20576 | 0.07240 | 116 | -2.84188 | 0.00530 | ** |
| Buf_W | -0.11657 | 0.02396 | 116 | -4.86441 | 0.00000 | *** |
| GP_Ent | 0.08092 | 0.03668 | 116 | 2.20598 | 0.02940 | * |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

### Fatal and Injury Crashes

The results from the analysis with fatal and injury only California crashes are shown in Table 12. Similar to all severity levels, the managed lane envelope has a negative association with fatal and injury crashes. However, this relationship did not prove statistically significant. In fact, AADT proved the only significant term in this evaluation.

**Table 12. California, preliminary model for total freeway crashes (fatal and injury severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -8.74762 | 3.258788 | -2.684 | 0.00727 | ** |
| log(AADT/2) | 0.792165 | 0.275917 | 2.871 | 0.00409 | ** |
| ML_Env | -0.0076 | 0.005275 | -1.441 | 0.14951 | |
| T_Trvl_W | 0.012816 | 0.011586 | 1.106 | 0.26868 | |
| GP_R_Shld_W | 0.006659 | 0.008987 | 0.741 | 0.45872 | |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; and *** = $p < 0.001$.

Source: Texas A&M Transportation Institute

Similar to all severity levels, an evaluation was conducted on the proportion of the managed-lane related fatality and injury crashes to freeway fatality and injury crashes. When the managed lane characteristic is represented as an envelope, it is significant (see Table 13); when the envelope is separated into the three components (left shoulder width, lane width, and buffer width) none of the widths are significant. The reason for this result, however, is expected. The resulting coefficients are correlated because the variables are collinear in the dataset. This is a condition resulting from a large overlap between the range of the variables, and thus the estimation of independent effects is greatly limited.

**Table 13. California, proportion of managed lane to total freeway crashes (fatal and injury severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -0.96236 | 0.24899 | -3.865 | 0.000111 | *** |
| ML_Env | -0.0331 | 0.01287 | -2.572 | 0.01012 | * |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

## MODELS ON MANAGED-LANE RELATED CRASHES – CALIFORNIA

### All Severity Levels Crashes

An evaluation was also performed on the crashes that were coded as being on the managed lane or on the buffer. The refined model that only includes the significant variables is shown in Table 14. All three components of the managed lane envelope – left shoulder width, lane width, and buffer width – are significant along with the volume in the managed lane (AADTHV). The coefficients indicate that the lane width is the most influential followed by the buffer width. Per this model, changes in left shoulder width are not as influential in the number of managed-lane related crashes as changes in the buffer or lane width.

**Table 14. California, refined model for managed-lane related crashes (all severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | 1.1378 | 1.89107 | 0.602 | 0.54739 | |
| log(AADTHV) | 0.50131 | 0.14646 | 3.423 | 0.00062 | *** |
| ML_L_Shld_W | -0.03723 | 0.01456 | -2.557 | 0.01055 | * |
| ML_Ln_W | -0.39154 | 0.1063 | -3.684 | 0.00023 | *** |
| Buf_W | -0.07717 | 0.04559 | -1.693 | 0.09049 | ~ |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

### Fatal and Injury Crashes

When only considering fatal and injury severity level managed-lane related crashes, the benefits of the buffer are no longer statistically significant as shown in Table 15. Only the effect of left shoulder is significant, when simultaneously accounting for the other elements of the envelope and AADTHV.

When representing the managed lane elements with the envelope, the resulting model is shown in Table 16. Results indicate that each additional foot of envelope is associated with a 4.4 percent reduction in managed lane and buffer related crashes (1-exp(-0.04471)).

**Table 15. California, initial model for managed-lane related crashes (fatal and injury severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -1.81462 | 3.15819 | -0.575 | 0.5656 | |
| log(AADTHV) | 0.31661 | 0.24558 | 1.289 | 0.1973 | |
| ML_L_Shld_W | -0.04827 | 0.02517 | -1.918 | 0.0551 | ~ |
| ML_Ln_W | -0.14191 | 0.16419 | -0.864 | 0.3874 | |
| Buf_W | -0.01444 | 0.07524 | -0.192 | 0.8478 | |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

**Table 16. California, refinded model for managed-lane related crashes (fatal and injury severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -3.18242 | 2.26283 | -1.406 | 0.159609 | |
| log(AADTHV) | 0.35491 | 0.24097 | 1.473 | 0.140801 | |
| ML_Env | -0.04471 | 0.01271 | -3.518 | 0.000435 | *** |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

## MODELS ON FREEWAY CRASHES – TEXAS

### All Severity Levels Crashes

Similar to California, the research team used several variables for the initial model of total Texas freeway crashes (all severity levels). The results are shown in Table 17. Also similar to California, several variables expected to be significant were not significant (e.g., number of general-purpose lanes) or were counterintuitive (team expected number of crashes to increase rather than decrease as the number of general-purpose entrance ramps increase; however, this relationship was not significant). Because the segments were created to focus on managed lane segments with no access openings, the relationship of crashes to the characteristics present on the neighboring general-purpose lanes would need additional exploration to be able to explain the potential relationships between crashes and those roadway geometric variables. That effort is beyond the scope of this project. If using a 0.10 significance level, the results indicates that more crashes are expected with the presence of pylons. Whether these crashes are occurring at low speed (e.g., a driver attempting to move into or out of the managed lane to avoid congestion) or at high speed cannot be explored with this dataset.

Removing the non-significant variables result in the refined model shown in Table 18. Fewer crashes are expected for wider managed lane envelopes (similar to California). A reduction of 2.8 percent in crashes per additional foot of envelope width is expected (1-exp(-0.02808)).

**Table 17. Texas, initial model for total freeway crashes (all severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | -1.93794 | 8.33268 | -0.233 | 0.8161 | |
| log(AADT/2) | 0.23344 | 0.1274 | 1.832 | 0.0669 | ~ |
| GP_NumLn | 0.1873 | 0.19885 | 0.942 | 0.3462 | |
| GP_Avg_Ln_W | 0.39886 | 0.33511 | 1.19 | 0.234 | |
| GP_R_Shld_W | -0.02831 | 0.09133 | -0.31 | 0.7566 | |
| GP_Ent | -0.27919 | 0.17824 | -1.566 | 0.1173 | |
| GP_Exit | -0.04871 | 0.14623 | -0.333 | 0.7391 | |
| PSL | -0.0234 | 0.11045 | -0.212 | 0.8322 | |
| ML_Env | -0.07842 | 0.03365 | -2.33 | 0.0198 | * |
| Buf_Type=Pylons | 0.92177 | 0.51824 | 1.779 | 0.0753 | ~ |

[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

**Table 18. Texas, refined model for total freeway crashes (all severity levels).**

| Variable [a] | Estimate | Standard Error | z value | Pr(>\|z\|) [b] | Significance [c] |
|---|---|---|---|---|---|
| (Intercept) | 0.42185 | 1.45744 | 0.289 | 0.77224 | |
| log(AADT/2) | 0.23482 | 0.12755 | 1.841 | 0.06563 | ~ |
| ML_Env | -0.02808 | 0.01603 | -1.752 | 0.07979 | ~ |
| Buf_Type=Pylons | 0.66049 | 0.22595 | 2.923 | 0.00346 | ** |

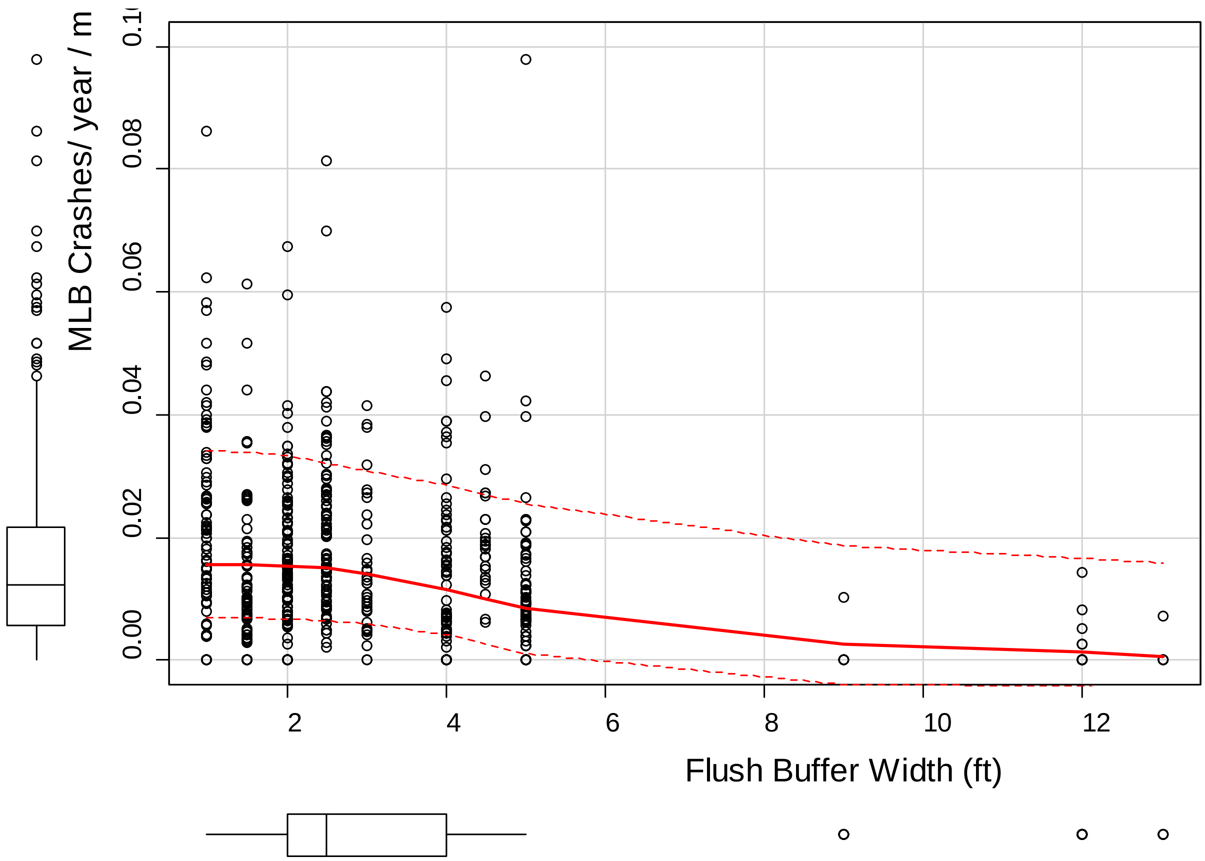
[a] Variables are described in Table 4.
[b] P values reported.
[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Source: Texas A&M Transportation Institute

## A CLOSER LOOK AT BUFFER WIDTHS

Designing managed lane facilities requires several decisions, including whether to meet agency typicals or to accept a practical design that deviates from a set of guidelines. One of those decisions is in the buffer width between a general-purpose lane and the managed lane. For many years the convention was to have at least a 4-ft buffer. Practitioners are now considering buffer widths of less than 4 ft and there is indication that some may be considering adopting a typical buffer width of 2 ft. The datasets available within this project were examined to gain insights on potential crash differences between buffers with about a 2 ft width and buffers that are about 4 ft in width.

Figure 14 shows the managed lane and buffer crashes in California as a rate of crashes per year per mile per 1000 vehicles per day. The solid line on the graph is a trend line for the data with the dashed lines representing a confidence interval. For buffer widths of 1.0, 1.5, 2.0, and 2.5 ft, a similar crash rate is present. For buffer widths of 3 ft or larger, the trend shows fewer crashes with greater decreases in the crash rate as the buffer width increases. An attempt was made to quantify the trend in Figure 14, but the strong correlation of the buffer width, managed lane width, and left shoulder width resulted in strongly correlated estimates, and thus unreliable estimates for these variables.



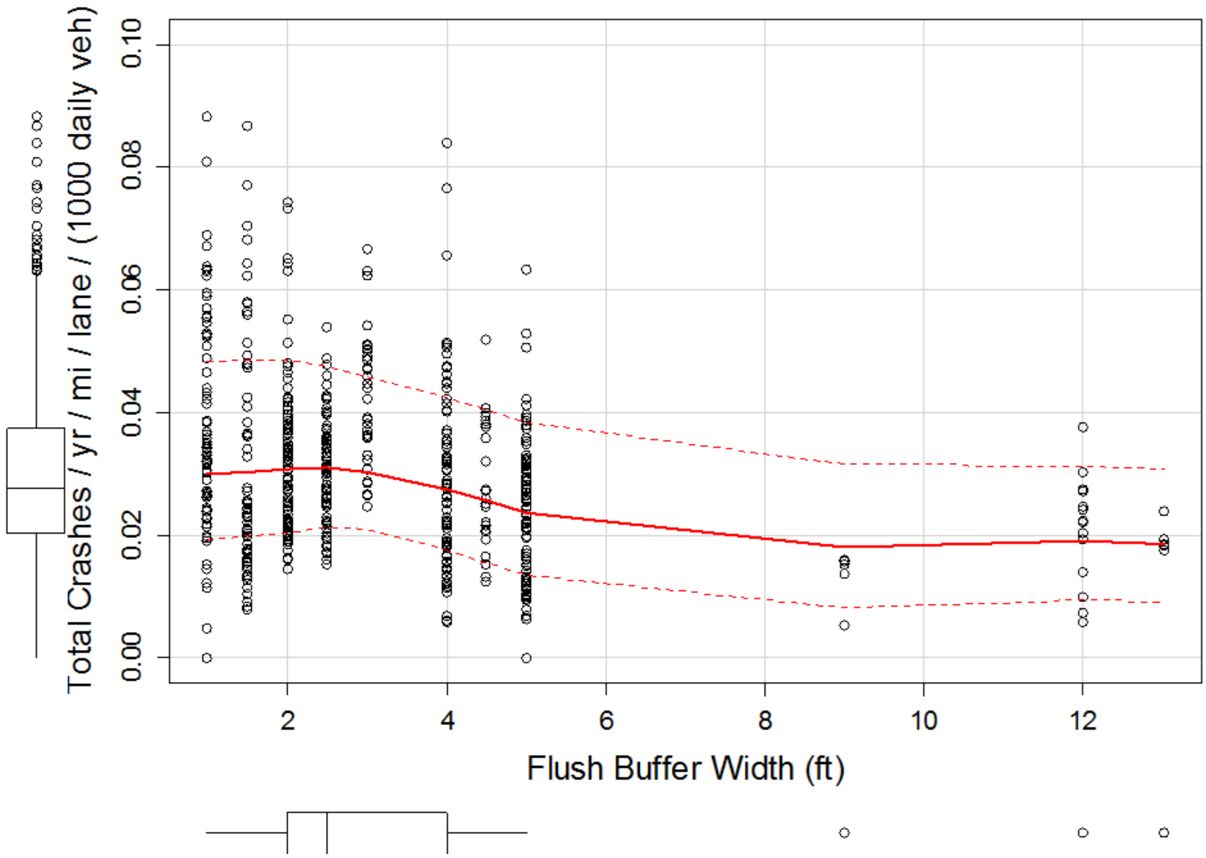

Source: Texas A&M Transportation Institute

Note: MLB = managed lane or buffer related crashes, mi = mile, veh = vehicle, ft = feet.

**Figure 14. Chart. California, managed lane and buffer crashes by buffer width.**

Figure 14 graphs the managed lane and buffer crash rate. To also consider the crashes on general-purpose freeway lanes, Figure 15 (California) and Figure 16 (Texas) were created. Figure 15 illustrates the per lane crash rate for all freeway crashes within the California dataset. Like the findings for managed lane crashes (shown in Figure 14), the per lane crash rates are similar for buffers less than 3 ft. For buffer widths of 4 ft and greater, the trend shows lower crash rates.

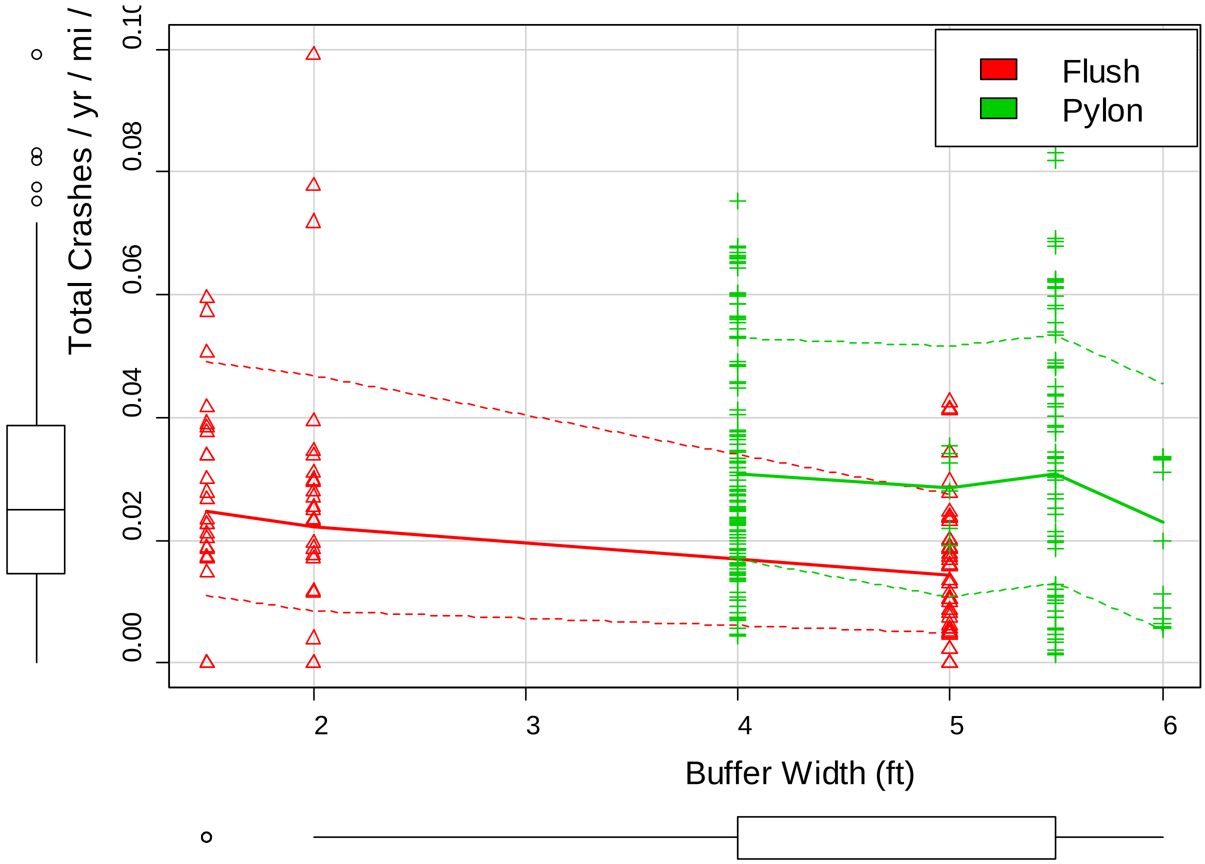
The data for flush buffers in Texas (see Figure 16) show a similar trend of higher crash rates for the more narrow buffers (defined in this dataset as being 2 ft and less) as compared to wider buffers (5 ft, for the Texas dataset). Figure 16 also shows the trend for sites with pylons. When pylons are used, the buffer width is always 4 ft or more. The trend line indicates that pylons used with 6-ft buffers have fewer freeway crashes per lane; however, few sites had the 6 ft buffer. Additional sites are needed to form a strong conclusion regarding the relationship between crashes and the width of buffers with pylons. In addition, the crash dataset used for this analysis included all freeway lanes. Preference would be to use a dataset that only includes crashes on the lanes on either side of the pylons. Given that the Texas crash dataset does not identify the lane for the crash, a research study that uses a crash narrative-review approach would be needed. The data in Figure 16 do show a higher crash rate for sites with pylons in the buffer as compared to sites with a 5-ft flush buffer. This relationship was found to be statistically significant (see Table 18).




Source: Texas A&M Transportation Institute

Note: yr = year, mi = mile, veh = vehicle, ft = feet.

**Figure 15. Chart. California, freeway crashes by buffer width.**




Source: Texas A&M Transportation Institute

Note: yr = year, mi = mile, veh = vehicle, ft = feet.

**Figure 16. Chart. Texas, freeway crashes by buffer width and presence of pylons (triangles for flush buffers without pylons and dashes for buffers with pylons).**

# CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

## SUMMARY

The managed lanes included in this study are designated freeway lanes separated by a buffer and located to the left of the general-purpose lanes. Managed lanes are intended to provide faster travel speeds and better reliability than the adjacent general-purpose lanes. Questions are being asked on whether the improved operations and the potentially additional buffer separation distances are associated with more or less crashes. This study investigated the relationship between crashes and buffer-separated manage lane dimensions.

The findings from the safety literature are clear in that reduction in a freeway left shoulder width is associated with increased number of crashes (see, for example, Figure 3). Safety studies for general-purpose freeway lanes also have found that reduction in lane width is associated with more crashes (see, for example, Figure 2). Previous research has provided the following safety relationships for freeways and managed lanes:

- Crash prediction equations are available in the *Highway Safety* Manual [16] for freeways.
- A Florida study [19] developed crash prediction equations for freeways facilities with high occupancy vehicle (HOV) and high occupancy toll (HOT) lanes for 6-, 8-, 10-, and 12-lane freeways (number of lanes reflect both directions and include the managed lanes). Significant variables were segment length, annual average daily traffic (AADT), and in most cases, left shoulder width. The effect of buffer type on crashes was found to be statistically significant only in the model for 10-lane freeways with an inclusion of a 2- to 3-ft buffer being associated with fewer fatal and injury crashes.
- The increase in crashes associated with reductions in freeway lane and shoulder widths may be offset if the reductions are done to increase the number of freeway lanes. A Texas study [18] developed a methodology and spreadsheet that can be used to evaluate the tradeoffs.
- Freeway access points are common sites for crashes, just as crashes can commonly be found at intersections on surface streets. A California study [1, 2] using eight routes concluded that limited-access HOV lanes appeared to offer no safety advantages over continuous-access HOV lanes. Although the overall safety seemed comparable, the observed differences between these types of facilities were attributed to more frequent and concentrated distribution of crashes at limited-access HOV lanes.
- A California study [4] of 153 miles of buffer-separated HOV lanes found that wider HOV lanes (up to 12 ft) are associated with fewer crashes and that wider left shoulder widths help reduce crashes in the HOV lanes. No conclusions could be drawn regarding buffer width from that study.
- A Texas study [6] that used crash narratives concluded that the reduced HOV cross section, location of general-purpose lane ramps, and speed differential between the HOV and adjacent general-purpose lane all contribute to crashes.

- Several studies have identified AADT and congestion as contributors to more crashes on freeways and HOV lanes.

To better focus this research so to improve the likelihood of identifying usable sites that fit the objective of this project, data collection focused on sites with one (rather than two) managed lane(s) per direction that were operational 24 hours a day, seven days a week. Sites that represented a range of buffer widths with and without pylons were also sought. For this study only those segments that were non-weaving segments were included in the analysis.

The datasets used in this evaluation included 128.0 miles in California (all 128.0 miles were sections with flush buffers) and 60.4 miles in Texas (40.7 miles with pylon buffers and 18.7 miles with flush buffers). The California crash data included the years 2007 through 2011 while the years 2009 to 2014 were used for Texas crash data. The analysis was conducted on non-weaving managed lane segments that included a single managed lane separated from the general purpose lanes with a flush buffer area. The dataset included crashes on 128.0 miles in California (all 128.0 miles with flush buffers) and 60.4 miles in Texas (41.7 miles with pylon buffers and 18.7 miles with flush buffers). The California sites included freeways with three or four general-purpose lanes while the Texas freeways had three to five general-purpose lanes.

All of the buffers for the California segments were flush (i.e., no pylons) with widths that varied between 1 ft and 12 ft. The buffers generally consisted of white and yellow lane line markings. The larger buffer widths (9 or 12 ft) were associated with preserving space for a downstream managed lane ramp. The buffers in Texas include flush buffers and flush buffers with pylons. The Texas sites with flush buffers ranged between 1.5 and 5.0 ft, while the buffers with pylons were between 4.0 and 6.0 ft.

## CONCLUSIONS

The analysis of the Texas and California data showed the following:

- Wider managed lane envelope (i.e., left shoulder, managed lane, and buffer) widths are associated with fewer freeway crashes when considering all severity levels as well as when considering only fatal and injury severity levels.
    - In Texas, wider envelopes are associated a reduction of 2.8 percent in total freeway crashes (all severities) for each additional foot of envelope width.
    - In California, wider envelopes are associated a reduction of 2.0 percent in total freeway crashes (all severities) for each additional foot of envelope width.
    - In California, wider envelopes are associated a reduction of 4.4 percent in managed lane-related crashes (fatal and injury severity levels) for each additional foot of envelope width.

Trends in the data clearly suggest that fewer crashes are associated with wider buffer widths. However, an attempt to quantify this trend resulted in strongly correlated estimates.
When exploring whether a particular component of the managed lane envelope is more influential than another, the simultaneous evaluation on the three envelope components using California freeway crashes (all severity levels) identified the left shoulder width as statistically significant. Another modeling technique of using the proportion of California managed-lane

related crashes to general-purpose crashes revealed that given a crash occurred, the odds of a crash being a managed-lane related crash:

- Decrease with increasing volume in the general-purpose lanes.
- Increase with increasing volume in the managed lane.
- Decrease with increasing managed lane width.
- Decrease with increasing buffer width.
- Increase with increasing number of entrance ramps.

An evaluation was also performed on the crashes that were coded as being on the managed lane or on the buffer. The refined model on managed lane and buffer-related crashes in California that only includes the significant variables found that all three components of the managed lane envelope – left shoulder width, lane width, and buffer width – are significant along with the volume in the managed lane. The results indicate that the lane width is the most influential followed by the buffer width. Changes in left shoulder width are not as influential in the number of managed-lane or buffer related crashes as the buffer or lane width changes.

In summary, the key findings from this study include the following:

- Results from several previous research studies have demonstrated that reductions in freeway lane width or shoulder width are associated with more crashes. Safety prediction equations are available to evaluate the tradeoffs.
- Results from this study, along with other studies, also found that reductions in managed lane envelope widths (shoulder, lane, and buffer width) are associated with more crashes.
- This study also found that narrow buffer widths (defined as being equal to and less than 3 ft) appear to be associated with more crashes as compared to 4-ft to 6-ft buffers.

## RECOMMENDATIONS FOR FUTURE RESEARCH

### Benefits of Pylons

Freeway cross sections used to accommodate managed lanes vary. At some locations, managed lanes are separated from general-purpose freeway lanes using an exclusive alignment or using barriers. Other locations use a buffer where the buffer consists of a flush area marked with pavement markings and in some cases with supplemental pylons. The findings from this research are that wider managed lane envelopes are associated with fewer crashes and pylons appear to be associated with more crashes. The dataset used to identify the pylon crash relationship presented two important challenges: dataset size and use of freeway (rather than managed lane) crashes. If only those crashes near the pylons are considered (say for the lanes on either side of the pylons) different results may be present. The available data for this study were limited in total number of miles and only one state had data with pylons. The benefits (or disadvantages) of using pylons (and the available buffer width present between the travel lane and the pylon) need additional investigations.

### Safety Tradeoffs when Adding a Managed Lane to an Existing Freeway

More crashes are associated with freeway lane and shoulder widths reductions. The increase in crashes may be offset if the reductions are done to increase the number of freeway lanes. A Texas study [18] developed a methodology and spreadsheet that can be used to evaluate the tradeoffs; however, the presence of managed lanes was not included in that research. Research is needed to determine the tradeoffs when the added lane is a managed lane.

**Safety Differences between Managed Lanes with One Lane and with More than One Lane**

This study focused on sites where only one managed lane was present per direction of travel. It is unclear how safety of these sites would compare to sites where additional managed lanes per direction are present. Because of the limited space in urban environments, the decision of adding managed lanes per direction may come at the cost of eliminating general-purpose lanes. The tradeoffs of potential cross-section changes would benefit from research.

**Safety / Operations Differences Considering Congestion Levels**

Improved level of service and reliability are two important attractors for potential users of managed lanes. Freeway operations and safety are expected to change as more users begin to utilize managed lanes, as this pattern is probably coupled with a decrease of traffic and congestion in the general-purpose lanes. It is unknown if such re-balance of the traffic demand and congestion translates into a measurable safety shift.

# CHAPTER 7: REFERENCES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