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16. Abstract

This research effort identified the operational and safety implications of using reduced lane and shoulder widths for a variety of freeway configurations. The research team used speed, crash, and geometric data for freeways in Dallas, Houston, and San Antonio.

The operational analysis identified an increase of about 2.2 mph in speed for a 12-ft lane as compared to an 11-ft lane. The shoulder width is significant when the adjacent lane is 11-ft wide, but not when it is 12-ft wide which suggests that left shoulder width is more important with a reduced lane width. Operating speeds on Texas freeways are 2 mph lower during night time (with roadside lighting present) than during the day. Speeds were higher (by 1.5 mph) on the weekends (Saturday) than on the week day studied (Wednesday).

The safety analysis determined a crash difference when comparing freeways with 12 ft to 11 ft lanes. There is a reduction in KAB crashes that ranges from 5% for 2-lane freeways up to 12% for 5-lane freeways, other roadway characteristics equal. Similarly, there are crash reductions associated with each additional lane, increased left shoulder widths, and increased right shoulder widths. While constructing an additional lane is beneficial in terms of safety, a larger safety detriment caused by narrow lanes or shoulders annuls such benefit. However, if it is possible to increase the total paved width when adding a travel lane, the safety model allows the analyst to identify lane and shoulder widths so that the number of crashes along the corridor will expectedly remain unchanged.

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REDUCING LANE AND SHOULDER WIDTH TO PERMIT AN ADDITIONAL LANE ON A FREEWAY: TECHNICAL REPORT

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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LIST OF ACRONYMS

Abbreviation or Acronym	Description
AADT	Annual Average Daily Traffic
CMF	Crash Modification Factor / Function
CRIS	Crash Records Information System
DA	Dallas
EB	Empirical Bayes
FFS	Free Flow Speed
HCM	Highway Capacity Manual
HOV	High Occupancy Vehicle (lane)
HSM	Highway Safety Manual
KAB	Fatal and serious injury crashes
KABCO	Total crashes (severity scale)
NB	Negative Binomial
pc/hr/ln	Passenger cars per hour per lane
RHiNo	Road-Highway Inventory Network
SPF	Safety Performance Functions
TMC	Traffic Management Center
TRB	Transportation Research Board
TxDOT	Texas Department of Transportation
VMT	Vehicle miles traveled

CHAPTER 1. INTRODUCTION

As the demand for additional capacity on urban Texas freeways continues to increase, there is a need to better understand how to optimize the lane and shoulder configurations to improve capacity without adversely impacting the operating speed or increasing crashes. The overall objective for this research effort was to identify the operational and safety implications of using reduced lane and shoulder widths for a variety of freeway configurations. To effectively assess the influence of the geometric features, the operational analysis only incorporated uncongested speed data. The research team used detailed speed data, acquired from a variety of sensors located along freeway corridors in Dallas, Houston, and San Antonio. In addition, the evaluation of the safety implications of narrowed freeway lane and shoulder widths used crash data that extended from 2010 to 2013. Using exploratory analysis and statistical evaluations, the research team ultimately assessed how influential the various lane and shoulder widths can be on the overall corridor.

This report includes a literature review (Chapter 2) of operational and safety studies related to freeway lane and shoulder widths. Included in the literature review is a summary of typical lane and shoulder width values followed by a review of the studied operational effects of lane and shoulder widths. Similarly, the corresponding safety effects are then summarized. In some cases, the operational and safety effects have been jointly evaluated, so the literature review concludes with a summary of this literature.

Chapter 3 identifies the candidate data collection elements followed by a review of site identification and selection for this study. The detailed analysis of operational and safety effects of freeway lane and shoulder widths are then included in Chapter 4 and 5, respectively. The report concludes with a summary of findings (Chapter 6). This concluding chapter also highlights the individual findings and presents equations that can be used to assess unique lane and shoulder width configurations. A companion spreadsheet is available to simplify these calculations.

CHAPTER 2. LITERATURE REVIEW

TYPICAL FREEWAY LANE AND SHOULDER WIDTHS (STATE-OF-THE-PRACTICE)

A Policy on Geometric Design of Highways and Streets (AASHTO, 2011), the standard highway design reference document in the United States, recommends lane and shoulder widths for freeway facilities. This document, commonly referred to as the *Green Book*, identifies unique features for urban freeways that are depressed, elevated, ground-level, or a combination of these three configurations. The *Green Book* recommended dimensions for urban freeway corridors include lane widths of 12 ft, right shoulder widths of 10 ft, left shoulder widths of 4 ft for corridors with 2 lanes in each direction, and 10 ft for corridors with 3 or more lanes in each direction.

In Texas, the *Roadway Design Manual* (TxDOT, 2013) establishes the criteria for roadway dimensions. It indicates that lane widths for high-speed facilities such as freeways should have a minimum width of 12 ft (3.6 meters). In addition, the *Manual* indicates that inside shoulders should be 4 ft (1.2 meters) wide at 4 lane sections or 10 ft (3.0 meters) wide at locations with 6 or more lanes, while outside shoulders should be 10 ft (3.0 meters) wide. These recommendations are consistent with the *Green Book* values. This Texas design criteria further indicates that at locations with sight distance constraints due to horizontal curvature, the shoulder width on the inside of the curve may be increased to 8 ft (2.4 meters) and the shoulder width on the outside of the curve decreased to 2 or 4 ft (0.6 or 1.2 meters).

The highway design standards for states may vary, but the freeway lane and shoulder widths generally comply with the *Green Book* recommendations. As an example, the freeway lane and shoulder width design criteria for a sample of states with major urban freeways are presented in Table 1. As shown, the travel lane width of 12 ft (3.6 meters) is consistent between agencies; however, the shoulder widths vary. In California, for example the paved shoulder width is defined as the minimum continuous usable width and wider values are encouraged. This width varies from 5 up to 10 ft depending on location and roadway cross-section.

Table 1. Sample Freeway Design Criteria for Other States.

State	Lane Width (ft)	Shoulder Width (ft)			Source
		Description[1]	Paved Left	Paved Right	
California	12	2 lanes	5	8[2]	(Caltrans, 2012)
		3 or more lanes	10	10	
Florida	12	2 lanes	4	10	(FDOT, 2014)
		3 or more lanes	10	10	
		HOV lane	10	N/A	
Georgia	12	Freeways or Interstates	10	12	(GDOT, 2013)
Nevada	12	Freeways or Interstates	8 desirable 4 minimum	12 desirable 8 minimum	(NVDOT, 2011)
New York	12	General	4	10 (8 permitted if mountainous)	(NYDOT, 2013)
		Where trucks exceed 250 directional design hourly volume	--	12 desirable 10 minimum	
		3 or more lanes	10 desirable 4 minimum	--	
		3 or more lanes & trucks exceed 250 directional design hourly volume	12 desirable 4 minimum	--	

[1] Total number of lanes in each direction.
[2] 10 ft width preferred. If shoulder is adjacent to an abutment wall, retaining wall in cut locations, or a noise wall, the 10 ft width is then required.

NON-FREEWAY ROADWAYS

Most previous studies evaluated operating speed on rural two-lane highways, with a limited number of studies evaluating operating speed on multilane highways or freeways. For a study on rural four-lane highways in Kentucky, the researchers developed a speed prediction model that included consideration of lane (inside and outside), horizontal curve length or radius, and indicatory variables for shoulder type (surfaced) median barrier presence, pavement type (concrete or asphalt), approaching section grade, and curve presence on approach (Gong and Stamatiadis, 2008). Himes and Donnell (2010) also found different speeds in the left and right lanes for rural and urban four-lane highways and identified the following variables as relevant to their study: heavy vehicle percentage, posted speed limit, and adjacent land use.

Because horizontal curves have such a notable effect on operating speed, the available literature is greater for that roadway feature. Only a few previous studies have attempted to quantify speed prediction on tangent sections including work by Polus et al. (2000) and Donnell et al. (2001). Polus et al. considered tangent length and the previous and following curve radii including grouping the radii into different categories in their attempts to develop usable speed prediction equations. Donnell et al. used a combination of field data and simulation-generated data. They found predicting truck speed prior to a horizontal curve to be a function of radius of curve, length of approach tangent, grade of approach tangent, and the length of approach tangent-radius interaction term.

OPERATIONAL EFFECTS OF FREEWAY LANE AND SHOULDER WIDTHS

Designers recognize operating speed as a measure of roadway consistency and driver expectancy. Predicting operating speed allows designers to assess the expected speed of individual vehicles traversing successive roadway segments. As documented in the Transportation Research Board (TRB) *Modeling Operating Speed Synthesis Report* (TRB, 2011), several factors influence operating speed, with most studies focusing on how horizontal curvature influences the free-flow speed selected by roadway users. For example for rural two-lane highways, studies by Krammes et al. (1995), Fitzpatrick et al. (2000), and Schurr et al. (2002) developed speed prediction equations for horizontal curves that included characteristics of the horizontal curve (e.g., degree or radius of curve, length of curve, deflection angle) and tangent speed (e.g., the measured or assumed 85th percentile speed or the posted speed limit). Additionally, several studies (Fitzpatrick et al., 2000; Donnell et al. (2001) report vertical alignment has a significant impact on speeds, especially those of heavy vehicles.

In 2010, TRB published the most recent version of the *Highway Capacity Manual* (HCM). This document includes information that can be used to estimate the relationship between freeway lane widths, lateral clearances, and the resulting capacity and free flow speed (FFS). In addition, a variety of research efforts have explored the effects of reducing lane and shoulder widths. Many of these are temporary lane reductions at work zone locations; however, the use of reduced lane and shoulder widths in constrained urban environments are becoming more common. The following sections review the expected influences of these lane and shoulder width reductions.

Lane Width

The 2010 HCM establishes a base condition lane width value of 12 ft for freeway facility operations. As shown in Table 2, lane widths of 12 ft or greater are not expected to be directly associated with reductions in FFS of the corridor. This means that unless a standard width lane has additional variables such as high traffic volumes, steep grades, or similar, a wider lane width will not directly affect the corridor speed. As the lane width is reduced, however, FFS is also expected to lower. For lane reductions of 1 ft or less, FFS will be reduced by approximately 1.9 mph below that expected for the 12-ft base condition. As depicted in Table 2, lane widths as narrow as 10 ft will substantially reduce FFS by values up to 6.6 mph. These FFS values are based on freeway speeds ranging from 55 mph up to approximately 75 mph (a value of 75.4 mph is used in HCM as this value most closely represented measured field data used to develop this information).

Table 2. FFS Adjustment Based on Freeway Lane Width.

Average Lane Width (ft)	Reduction in FFS (mph)
≥ 12	0.0
≥ 11–12	1.9
≥ 10–11	6.6

Source: Highway Capacity Manual, Exhibit 11-8, p. 11-11 (TRB, 2010)

A limited number of studies have evaluated the influence of lane width on freeway corridor operations. In many cases, operations are represented by the associated speed. In other cases, lane keeping and total capacity values are used as indicators of the associated traffic operations.

The Danish Road Directorate (1998) performed an evaluation of the capacity implications associated with adding a lane to a freeway in Paris. They found that heavy trucks moved closer to the edge lines, and although the addition of a travel lane was expected to result in an increase in the total capacity, they found a minimal capacity improvement with congestion levels remaining very close to those observed prior to construction of the additional lane.

Chitturi and Benekohal (2005) evaluated the influence of the lane width on the speeds of cars and heavy vehicles in work zones. This Illinois freeway work zone study noted that the observed speed reductions for freeway work zones were much larger than the values commonly associated with lane reductions (per the HCM) (TRB 2000). Chitturi and Benekohal determined that the freeway work zone speed reductions should be 10, 7, 4.4, and 2.1 mph for lane widths of 10, 10.5, 11, and 11.5 ft, respectively.

Though the number of freeway lane width studies is limited, a variety of studies evaluated the influence narrower lanes have on the capacity of non-freeway road types. Fitzpatrick et al. (2001) examined influential factors on four-lane suburban arterials. While this research team did not explicitly consider speed limit as a predictor, they did determine that lane width had a significant association to operating speed at tangent roadway sections. Ma et al. (2010) examined a video dataset for urban arterials in the city of Hangzhou, China. They selected nine road segments with similar characteristics and traffic patterns but with varying lane widths. Ma et al. observed larger mean and 85th percentile speeds at sites with wider lanes.

Other researchers evaluated the influence of lane width at the approach to signalized intersections. For example, Potts et al. (2007) used data for 25 intersection approaches located in nine cities and five states to investigate how saturation flow rates change with lane width. They found that the saturation flow rates vary in direct proportion to lane width. Kuan and Wanchao (2011) evaluated signalized intersections in Beijing to determine how the effect of lane width on saturation flow rate changes with varying percentage of heavy vehicles. They collected video data from five urban intersections in Beijing and observed that the saturation flow reduction associated with narrower lanes decreased with increasing percentages of heavy vehicles.

Some of the published research, however, challenges the operational impacts of narrower lanes. Most of these research efforts are driver simulator studies and evaluated driver perception issues as they relate to lane width. The road types considered for these simulator studies varied but were generally focused on rural roadway configurations.

Godley et al. (2004) proposed that speed reduction will occur when the roadway is configured to give the driver the perception of a reduced width even though the actual lane width may remain constant. After evaluating 28 experienced drivers in a driver simulator environment, Godley et al. determined that a speed reduction can be induced by delineating narrower lanes while relocating the extra roadway width toward a painted median.

Rosey et al. (2009) conducted a study where they tested the effect of lane width within a simulated environment. They based their study site on an actual field location, and the research team evaluated actual before and after operational data for a lane width reduction/shoulder increase project. Rosey et al. concluded that narrower lanes did not affect the choice of speed, but that the vehicle position shifted toward the right side of the road. Although it was not discussed by the authors, upon closer examination of the data presented in this paper, it does appear that the field study data did experience a statistically significant reduction of speed. Speeds changed from 95 to 92 km/h (approximately 59 to 57 mph) when the lane was reduced from 3.3 to 3.0 meters (11 to 10 ft) and the shoulder width was increased by 0.3 meters (1 ft). This difference is statistically significant for the large sample sizes presented (i.e., at least 67,000 data points per direction of travel for the smallest of the dataset configurations). Rosey et al. based their conclusions on simulated results that reflected an increase in mean speed following a lane reduction. The overall width remained the same for this analysis (the extra width removed from the lane was transferred to the adjacent shoulder). This observation suggests that perhaps the lane width operations are not independent of the shoulder configuration.

Shoulder/Lateral Offset

Often a shoulder width may be narrowed so that additional travel lanes can be constructed within a fixed width roadway section. For urban freeway locations, this narrowed shoulder then enables roadside objects to be physically located closer to the active travel lanes. As noted in the HCM (TRB, 2010), this right-side lateral clearance extends "from the right edge of the travel lane to the nearest lateral obstruction." This reduced lateral clearance can influence a driver's selected speed at these locations. As shown in Table 3, speed reductions will begin to occur when the right-side lateral clearances are less than 6 ft. The speed reductions can range from as little as 0.1 mph (for right-side lateral clearances of 5 ft and roads with at least 5 lanes in one direction of travel) up to 3.6 mph (for locations with no available right-side lateral clearance and 2 lanes in one direction of travel).

The HCM also indicates that median-side lateral clearances that are greater than or equal to 2 ft have little influence on freeway operations. Estimated speed reductions for median-side lateral clearances less than 2 ft are not available.

Table 3. FFS Reduction (mph) for Freeway Right-Side Lateral Clearance.

Right-Side Lateral Clearance (ft)	Lanes in One Direction			
	2	3	4	≥ 5
≥ 6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.5

Source: Highway Capacity Manual, Exhibit 11-9, p. 11-12 (TRB, 2010)

The Chitturi and Benekohal (2005) study, reviewed in the previous lane width section, similarly assessed the effect of using no shoulder or lateral offset on either side of the travel lanes at freeway work zones. They determined that the freeway work zone speed reductions would be approximately 5.6 mph for roads with lane widths of 12 ft and no available shoulder on the left or right side.

Ben-Bassat and Shinar (2011) used a driver simulator study with 20 volunteer drivers to evaluate the influence of shoulder width and guardrail placement on traffic operations. The research team determined that the presence of a guardrail plays an important part in the overall speed selection. For locations where the paved shoulder width varied, but a guard rail was not located adjacent to the road, the speed remained relatively constant. This means that the shoulder width may not play as critical of a role as the actual lateral offset to the nearest roadside object. A second observation in this simulator study was that road sections with tangents or curves to the right resulted in higher travel speeds when a guardrail was present than when it was not (suggesting the guardrail was not perceived to be too close to the travel lane and may have even assisted in better delineating the edge of the paved surface). A final observation by the research team focused on lane position. For narrow roads with narrow shoulders, the drivers tended to position their vehicles toward the left edge of the active travel lane. As the shoulder width became wider, the drivers shifted the vehicle position to the center of the lane. Finally, at locations where a guardrail was not present, the driver's positioned the vehicle toward the right edge of the travel lane for all observed shoulder widths.

Combined Operational Effects

According to the HCM (TRB, 2010), one direction of travel for a freeway segment with 2 lanes, lane widths of 10 ft, and no right-side lateral clearance is expected to have a FFS reduction of 10.2 mph when compared to a base condition segment with 2 12-ft wide travel lanes with 6 ft right-side clearances. As shown in Table 4, this reduced lane and right-side lateral clearance combination directly corresponds to a reduction in the capacity of the travel lanes. For this example, an approximate 10 mph FFS reduction from 75 to 65 mph would be equivalent to a reduction of 80 passenger cars per hour per lane (pc/hr/ln) for a target level of service of D. These example values are shaded for emphasis in Table 4.

Table 4. Maximum Service Flow Rates (pc/hr/ln) for Freeways.

FFS (mph)	Target Level of Service				
	A	B	C	D	E
75	820	1310	1750	2110	2400
70	770	1250	1690	2080	2400
65	710	1170	1630	2030	2350
60	660	1080	1560	2010	2300
55	600	990	1430	1900	2250

Note: All values rounded to the nearest 10 pc/hr/ln

Source: Highway Capacity Manual, Exhibit 11-17, p. 11-23 (TRB, 2010)

Melo et al. (2012) conducted a driving simulator study at the University of Porto, Portugal, where they examined speed choice as a function of geometric road features located on rural two-lane highways. Their simulator study included field validation of actual speed values for six physical locations with equivalent conditions. Melo et al. found that both lane and shoulder had an effect on speed choice, but that the assumptions of independent additive effects in the HCM should be revisited; when both lane and shoulder widths were reduced, they found greater changes in FFS than the independent additive effects would have explained.

A Texas study (Robertson et al., in press) generated speed prediction equations (see Table 5) for freeways with posted speed limits up to 80 mph and multilane highways with posted speed limits up to 75 mph. Those equations were used to develop suggested procedures for calculating FFS on freeways and multilane highways that could be considered for a future edition of the HCM (see Table 6). The researchers considered lane width in the statistical evaluations; however, ultimately the lane width variable was determined not to be significant (possibly due to the very limited range of widths available in the dataset). As shown in Table 7 while freeway lane width did include a few sites with 13-ft lanes, the average lane width for the dataset was only 12.06 ft and the majority of the sites had lanes that were 12-ft wide. Similarly, the study did not include any sites with lanes 11-ft wide.

Table 5. TTI Speed Prediction Equations for Freeways and Multilane Highways.

Freeway	Free-flow speed on basic freeway segments with a posted speed limit of 65 mph to 80 mph: $FFS_{65\text{-}80} = 77.5 - f_{PSL} + 0.01012 \times MW + 0.3893 \times SW\_L - 0.664 \times TRD$ Where: $FFS_{65\text{-}80}$ = FFS on basic freeway segment with a PSL of 65 to 80 mph (mph) f_{PSL} = adjustment for posted speed limit (mph) = If PSL = 80 mph, the reduction in free-flow speed is 0.0 mph = If PSL = 75 mph, the reduction in free-flow speed is 3.5231 mph = If PSL = 70 mph, the reduction in free-flow speed is 4.6514 mph = If PSL = 65 mph, the reduction in free-flow speed is 7.1769 mph MW = median width, typical distance between pavement edges in the median (ft) SW_L = shoulder width left, typical left side (inside) shoulder width (ft) TRD = total ramp density, using HCM definition (ramps/mi)
	Limitations: It is advisable to limit the application to freeways with the following characteristics: • Median widths ranging from 32 ft to 266 ft. • Left shoulder widths ranging from 4 ft to 6 ft. • Posted speed limits ranging from 65 mph to 80 mph. • Total ramp density ranging from 0 ramps/mi to 1.667 ramps/mi. Values of variables included in the HCM methodology, but not found to be statistically significant: • Lane width ranged from 12 ft to 13 ft. • Total lateral clearance is always greater than 6 ft, the HCM's default value.
Multilane Highway	Free-flow speed on multilane highways with a posted speed limit of 65 mph to 75 mph: $BFFS_{65\text{-}75} = 71.7 - f_{PSL} - 0.0266 \times HCA + 0.0071 \times MW + 1.5127 \times SW\_L - 0.4058 \times SW\_R$ Where: $BFFS_{65\text{-}75}$ = base free-flow speed for multilane highway segments with a posted speed limit of 65 to 75 mph (mph) f_{PSL} = adjustment for posted speed limit (mph) = If PSL = 75 mph, the reduction in free-flow speed is 0.0 mph = If PSL = 70 mph, the reduction in free-flow speed is 1.3004 mph = If PSL = 65 mph, the reduction in free-flow speed is 2.1535 mph HCA = horizontal curve angle, the typical angle for horizontal curves on the multilane highway (degrees) MW = median width (ft) SW_L = shoulder width on the left side of the traveled way (ft) SW_R = shoulder width on the right side of the traveled way (ft)
	Limitations: It is advisable to limit the application to multilane highways with the following characteristics: • Median width ranging from 0 ft to 200 ft. • Left shoulder width ranging from 0 ft to 10 ft. • Right shoulder width ranging from 0 to 10 ft. • Posted speed limit ranging from 65 mph to 75 mph. • Horizontal curve angle (when present) ranging from 5.7 degrees to 42.0 degrees. Values of variables included in the HCM methodology, but not found to be statistically significant: • Access point density ranged from 0 to 15.8 points/mi. • Lane width ranged from 12 ft to 12.5 ft. • Median type is either none or divided, there were no two-way left turn-lane facilities. • Total lateral clearance is always greater than 6 ft, the HCM's default value.

Source: Robertson et al., in press

Table 6. 2010 HCM Variables Considered in the TTI Speed Prediction Equations.

Variable	Freeways		Multilane Highways	
	2010 HCM	TTI	2010 HCM	TTI
Access Point Density	-	-	Yes	-
Access Points	-	-	-	*NS*
Base Free-Flow Speed	-	-	Yes	-
Horizontal Curve Angle, Downstream	-	*NS*	-	Yes
Horizontal Curve Angle, Upstream	-	*NS*	-	*NS*
Horizontal Curves, Downstream	-	*NS*	-	*NS*
Horizontal Curves, Upstream	-	*NS*	-	*NS*
Lane (Inside or Outside)	-	Yes	-	Yes
Lane Width	Yes	*NS*	Yes	*NS*
Light Level (Day or Night)	-	*NS*	-	Yes
Median Type	-	-	Yes	-
Median Width	-	Yes	-	Yes
Posted Speed Limit	-	Yes	-	Yes
Percent Heavy Vehicles	-	Yes	-	*NS*
Ramp Density, Total	Yes	-	-	-
Ramp Points	-	Yes	-	-
Shoulder Width Left	-	Yes	-	Yes
Shoulder Width Right	-	*NS*	-	Yes
Total Lateral Clearance	Yes	-	Yes	-
Vehicle Type (Car or Truck)	-	Yes	-	Yes

NS = evaluated but found to be not significant. Variable not included in the final model
Yes = included in final model
\- = not included in model

Source: Robertson et al., in press

Table 7. TTI Speed Prediction Equation Summary Statistics for Site Characteristics.

Variable	Freeways			Multilane Highways		
	Min	Max	Average	Min	Max	Average
Access Points	-	-	-	0	6	1.82
Horizontal Curve Angle, Downstream	5.08	55.66	18.01	5.70	41.95	15.50
Horizontal Curve Angle, Upstream	5.08	55.66	18.01	5.70	41.95	15.50
Horizontal Curves, Downstream	0	2	0.25	0	3	0.67
Horizontal Curves, Upstream	0	2	0.25	0	3	0.67
Lane Width	12	13	12.06	12	12.5	12.04
Median Width	32	266	69.44	0	200	64.14
Ramp Points	0	10	3.56	-	-	-
Shoulder Width Left	4	6	4.41	0	6	3.71
Shoulder Width Right	10	10	10	0	10	9.21

Source: Robertson et al., in press

SAFETY EFFECTS OF FREEWAY LANE AND SHOULDER WIDTHS

In recent years, the development and application of statistically robust safety assessment procedures has continued to mature. Researchers have focused a limited number of these evaluation techniques on the broad topic of the safety effects of freeway lane and shoulder widths. In many cases, lane and shoulder width values have been jointly evaluated for their associated safety influences.

It is generally recognized that narrower lanes are associated with poorer safety performance than their wider lanes counterparts. One way the published literature has addressed safety assessment is through the use of crash modification factors (CMFs). A CMF is a multiplicative factor that represents the predicted influence a change may have on the number of crashes. A CMF value of 1.0 indicates that little, if any, changes in safety performance can be expected for a specific treatment or combination of treatments (multiplying by a value of 1.0 would not alter the number of predicted crashes). A CMF value greater than 1.0 represents an increase in the number of crashes. For example, a CMF with a value of 1.11 represents an 11 percent increase in crashes.

Chapter 13 of the *Highway Safety Manual* (HSM) (AASHTO, 2010) presents CMFs that target adding additional freeway lanes within the current right-of-way limits. This content is based on research performed by Bauer et al. (2004). The CMFs included in this section of the HSM are applicable to urban freeways equipped with median barriers. The base conditions (where the CMF = 1.0) assume lane widths of 12 ft. Table 8 demonstrates that for all crash severities noted, a 4-lane to a 5-lane urban freeway conversion or a 5- to 6-lane conversion can be expected to generally increase crashes. However, using a confidence interval and the standard error shown, the observed changes cannot always be expected to increase the number of crashes by the factors of 3 to 11 percent as indicated by the CMF values, but this general overall trend of increasing the number of crashes can, on average, be anticipated. In addition, the values shown in Table 8 only apply to the traffic volumes and base conditions as indicated.

Table 8. Crash Effects of Adding Lanes by Narrowing Existing Lanes and Shoulders.

Treatment	Traffic Volume AADT (vehicles/day)	Crash Type (Severity)	CMF	Std. Error
4 to 5 lane conversion	79,000 to 128,000 one direction	All types (All severities)	1.11	0.05
		All types (Injury and Non-injury tow-away)	1.10	0.07
		All types (Injury)	1.11	0.08
5 to 6 lane conversion	77,000 to 126,000 one direction	All types (All severities)	1.03	0.08
		All types (Injury and Non-injury tow-away)	1.04	0.10
		All types (Injury)	1.07	0.10
Base Condition: 4 or 5 lanes (12 ft wide) depending on initial roadway geometry				

Source: Adapted from the Highway Safety Manual, Table 13-5, p. 13-10 (AASHTO, 2010)

Bauer et al. (2005) specifically evaluated the safety effects of using narrow lanes and shoulder-use lanes as a way to increase urban freeway capacity in California. Bauer et al. examined freeway segments associated with reconstruction projects where the California Department of Transportation added a travel lane without expanding the available paved width. The researchers developed safety performance functions (SPFs) from a larger pool of sites that did not undergo the lane addition and used these SPFs, in combination with the observed number of crashes at the sites, for a period of two years prior to the lane change implementation. They then used this information to predict the expected number of crashes for the six years following the installation of the new travel lanes as compared to the actual crashes that occurred during the period. They concluded that widening the number of lanes from 4 to 5 did have an impact on the number of crashes equivalent to an increase of approximately 11 percent in total crashes and 10.6 percent in fatal and injury crashes.

A similar analysis for the 5- to 6-lane conversion did not provide statistically different crash values; however, the actual observed changes in the number of crashes are positive, suggesting an increasing trend in crashes. Although the authors discuss other potential operational factors that may be confounding their results (such as shifting of bottleneck locations), these effects are common items that can be expected to be present in similar cross-section conversion efforts.

In Texas, Bonneson and Pratt (2009) developed the *Roadway Safety Design Workbook*. Chapter 2 of this manual synthesizes the work of a previous research effort by Bonneson et al. (2005). The work summarized by these two studies presents CMFs, developed using the Empirical Bayes (EB) technique, which address lane width and shoulder width safety for Texas freeways. The *Roadway Safety Design Workbook* includes CMFs that apply to rural and urban freeway conditions. The base condition lane width is 12 ft (this corresponds to a CMF equal to 1.00). As shown in Table 9, urban freeways with lane widths less than 12 ft may be associated with an increase in injury and fatal crashes that extends up to 7 percent (i.e., CMF = 1.07) for corridors with 2 lanes or 5 lanes of travel per direction and lanes widths of 10 ft. The *Workbook* includes equations and proportional adjustments, but the values in this table reflect the final CMF after performing these calculations that would be applied to the total number of observed injury and fatal crashes. The *Workbook* also includes similar adjustments for rural freeways, but this information is not included since the focus of this effort is the urban freeway.

Table 9. Lane Width CMF Values for Texas Urban Freeways (Injury + Fatal Crashes).

Lane Width (ft)	Number of Through Lanes (in One Direction)			
	2	3	4	5
10	1.07	1.06	1.06	1.07
10.5	1.06	1.05	1.05	1.05
11	1.04	1.03	1.03	1.03
11.5	1.02	1.02	1.02	1.02
12	1.00	1.00	1.00	1.00
Base Condition: Lane width of 12 ft				

Source: Developed from procedures presented in the Roadway Safety Design Workbook (Bonneson and Pratt, 2009)

The *Roadway Safety Design Workbook* also includes information about the expected safety effects of varying shoulder widths for Texas urban freeways (see Table 10 and Table 11). The outside or right paved shoulder is assumed to have a base condition width of 10 ft for corridors with 2 or more through lanes. The resulting CMFs are applicable to outside shoulder widths ranging from 6 to 12 ft. Shoulder widths less than 6 ft are assumed to have comparable safety effects as those determined for the 6-ft wide outside shoulders. The most extreme CMFs have a value of 1.06 (or a 6 percent increase in crashes) for urban freeways with 2 through lanes per direction and outside shoulders that are less than or equal to 6 ft wide. Shoulder widths greater than 10 ft provide negligible safety benefits (CMFs that range from 0.97 to 0.99).

The inside (left) shoulder base condition is different for an urban freeway with 2 through lanes per direction when compared to corridors with 3 or more through lanes per direction. The use of an inside shoulder that is 4 ft wide is associated with the freeway sections with 2 through lanes per direction. In general, this narrower shoulder width is used with the assumption that a vehicle must only cross one active travel lane (to the right) to reach a wide outside shoulder. As the freeway cross-section widens and more lanes are added, the inside shoulder is then also widened with a base condition value of 10 ft. As shown in Table 11, the safety effects associated with the inside lane for an urban freeway with 2 lanes per direction of travel range from an increase in crashes up to 7 percent (when no inside shoulder is available) to a reduction in crashes of 10 percent (when the inside shoulder width is 10 ft). Texas urban freeway sections with 3 or more lanes per direction of travel and no inside shoulder are expected to experience an increase in crashes of approximately 15 percent.

Table 10. Outside (Right) Shoulder Width CMF Values for Texas Urban Freeways (Injury + Fatal Crashes).

Outside (Right) Shoulder Width (ft)	Number of Through Lanes (in One Direction)			
	2	3	4	5
≤ 6	1.06	1.04	1.03	1.03
7	1.05	1.03	1.02	1.02
8	1.03	1.02	1.01	1.01
9	1.02	1.01	1.01	1.01
10	1.00	1.00	1.00	1.00
11	0.99	0.99	0.99	0.99
12	0.97	0.98	0.99	0.99
Base Condition: Outside shoulder width of 10 ft				

Source: Developed from procedures presented in the Roadway Safety Design Workbook (Bonneson and Pratt, 2009)

Table 11. Inside (Left) Shoulder Width CMF Values for Texas Urban Freeways (Injury + Fatal Crashes).

Inside (Left) Shoulder Width (ft)	Number of Through Lanes (in One Direction)			
	2	3	4	5
0	1.07	1.16	1.14	1.15
1	1.05	1.14	1.12	1.13
2	1.04	1.12	1.11	1.12
3	1.02	1.11	1.09	1.10
4	1.00	1.09	1.08	1.08
5	0.98	1.07	1.06	1.07
6	0.97	1.06	1.05	1.05
7	0.95	1.04	1.04	1.04
8	0.93	1.03	1.02	1.03
9	0.92	1.01	1.01	1.01
10	0.90	1.00	1.00	1.00
Base Condition: Inside shoulder width of 4 ft for 2 lanes in one direction, and 10 ft for ≥ 3 lanes in one direction.				

Source: Developed from procedures presented in the Roadway Safety Design Workbook (Bonneson and Pratt, 2009)

A similar study by Gross et al. (2009) examined the crash databases for two-lane rural highways in Pennsylvania and Washington. The focus of their analysis included run-off-road, head-on, and sideswipe crashes. Gross et al. found that the cross-sectional analysis for Pennsylvania data yielded remarkably similar CMFs to those developed in a Texas study (Bonneson et al., 2007). In general, both studies determined that wider lanes, shoulders, and paved surface (on rural two-lane highways) are associated with a reduction in the number of crashes. Based on these findings, they recommended that lane widths should range from 11 to 12 ft. Gross et al. also stressed that the safety effects of lane and shoulder widths should be considered jointly.

Bonneson et al. (2011) developed a prediction methodology for freeways and interchanges using crash and road data from California, Maine, and Washington. They supplemented their database with information collected from aerial photographs. This additional data included width of cross-section elements, barrier location, horizontal curvature, and median type. They then developed a lane width CMF for fatal and injury crashes. Ultimately, the models and CMFs developed for this project will be included in a future edition of the HSM. The resulting three-state CMF for lane width can be represented by the following equation:

$$CMF = e^{-0.0376\times(W_l-12)}$$

This CMF is applicable for lane widths ranging from 10 ft up to 13 ft. For lane widths that are greater than or equal to 13 ft, a constant CMF value of 0.96 (or a 4 percent crash reduction from the base condition) is expected (see Table 12).

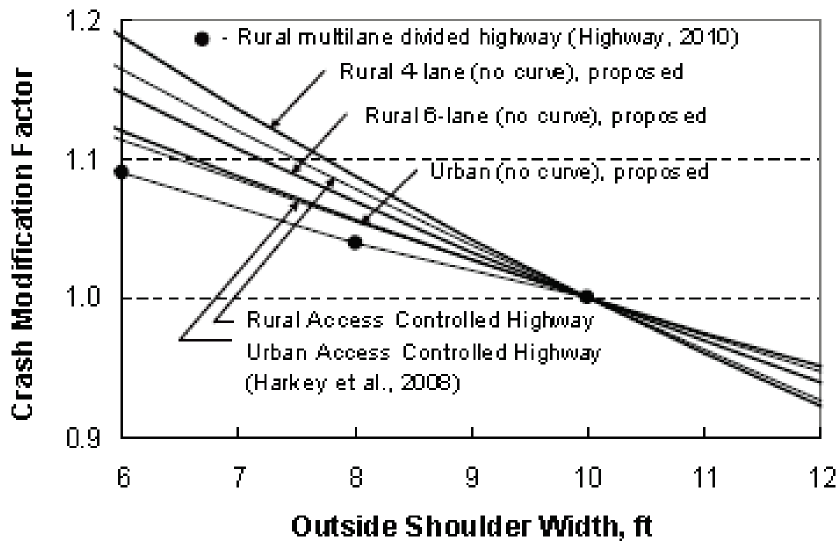
Table 12. Lane Width CMF Values for Three-State Freeway Model (Injury + Fatal Crashes).

Lane Width (ft)	CMF Value
10	1.08
10.5	1.06
11	1.04
11.5	1.02
12	1.00
12.5	0.98
≥ 13	0.96
Base Condition: Lane width of 12 ft	

Source: Developed from procedures presented in the Roadway Safety Design Workbook (Bonneson and Pratt, 2009)

The shoulder CMF values, as determined by Bonneson et al. (2011), varied in character. For the outside (right) shoulder width, the researchers determined that the outside shoulder did not have a direct influence on multiple-vehicle crashes. Consequently, the outside shoulder width

CMF should only be applied to single vehicle crashes. In addition, the influence of this CMF can be expected to vary depending on the horizontal curvature of the freeway, if present. The equation for this CMF is more complex and the combined, no-curve segment influence is better represented by the graphic shown in Figure 1. In this figure, thicker trend lines represent the area type and through lane combinations. The outside shoulder CMF is applicable for widths ranging from 6 to 14 ft with an assumed base condition of 10 ft. The figure also depicts similar CMFs (shown with thin lines) that have been developed by others.



Source: Bonneson et al., 2011

Figure 1. Outside Shoulder Width.

The safety effects for inside shoulders, as determined by Bonneson et al. (2011), can be represented by the following equation:

$$CMF = e^{-0.0172 \times (W_{is} - 6)}.$$

The inside shoulder CMF equation applies to shoulders with widths ranging from 2 to 11 ft. The base condition (CMF = 1.00) occurs when the inside shoulder width is 6 ft (see Table 13). The CMF shown represents fatal plus injury crashes and indicates an increase in fatal and injury crashes of 7 percent (CMF = 1.07) for 2-ft wide inside shoulders up to a reduction in fatal and injury crashes of 8 percent (CMF=0.92) for inside shoulder widths of 11 ft.

Table 13. Inside Shoulder Width CMF Values for Three-State Freeway Model (Injury + Fatal Crashes).

Inside Shoulder Width (ft)	CMF Value
2	1.07
3	1.05
4	1.03
5	1.02
6	1.00
7	0.98
8	0.97
9	0.95
10	0.93
11	0.92
Base Condition: Inside shoulder width of 6 ft	

Source: Developed from procedures presented in the Roadway Safety Design Workbook (Bonneson and Pratt, 2009)

Stamatiadis et al. (2011) developed crash prediction functions for multilane rural roads, focusing on the safety effects of lane width, shoulder width, and median width. They used data from California, Kentucky, and Minnesota and found CMFs comparable to the HSM for median and shoulder widths. In general, they indicated an observed crash reduction associated with wider shoulders. Due to the consistent use of lanes with widths of 12 ft, they were not able to evaluate the safety effects of lane widths.

Chen and Tian (2012) evaluated crash data for 490 kilometers of expressways and found that the impact of shoulder on expected crash frequency and mortality rates varies, but did observe that wider shoulders were associated with fewer crashes. Manuel et al. (2014) performed a cross-sectional analysis using negative binomial (NB) SPFs with datasets assembled from crash records, traffic-survey, and roadway-inventory data from Edmonton, Canada. When evaluating the lane width, they found that road width is negatively associated with crashes, but that the magnitude of that effect is reduced in proportion to how much traffic there is along the roadway segment. They also noted that segments with a midblock change in their road width tended to be less safe than segments with uniform widths.

SIMULTANEOUS OPERATIONAL AND SAFETY EVALUATION

In 1978, McCasland examined both operational and safety effects of converting sections of 4-lane freeways with widths of 12 ft (located at U.S. 59 Southwest Freeway in Houston) into 5 lanes with widths of 10.5 ft by restriping and encroaching into the right shoulder (McCasland, 1978). This study also included a conversion of another section of the same freeway from 3 to 4 lanes with the same before and after lane widths. This effort identified clear operational benefits (in terms of level of service and delay reduction) and presumed safety benefits resulting from the operational improvements of reducing congested driving conditions. The statistical methods used in this study, however, pre-date the development of currently acceptable statistical practices that account for issues such as regression to the mean and deviations from a homogeneous (or Poisson) distribution.

More recently in Texas, Cooner and Ranft (2006) examined the safety of buffer-separated high occupancy vehicle (HOV) lanes at I-35 East and I-635 in the Dallas area. These lanes were implemented by reducing travel lane width and converting the inside shoulder to an HOV lane. Cooner and Ranft evaluated the operational impact by measuring the speed differential between the HOV and other standard use lanes. Both study sites experienced an increase in crash rates following the implementation of HOV lanes. The increase in crashes, however, occurred primarily in the HOV lane and the adjacent standard use lane. The researchers linked this increase in crashes to the differential of speed between the two lanes and recommended the use of a buffer between the HOV and general purpose lanes.

GAPS IN KNOWLEDGE

The published literature included information regarding inside shoulder, outside shoulder, and lane widths with specific consideration for the operational and safety performance of these critical design features. A few gaps in the literature are notable. In some cases, it may simply be that a configuration has not been widely used; however, these items merit note as the Texas research effort moves forward. The following list summarizes these observed gaps:

- Lane widths are generally assumed to be equivalent across all lanes in one direction of travel (wider outside lanes and narrower center lanes were not noted in the literature).
- Speed reductions for inside (referred to as median-side) clearances less than 2 ft are not available per the HCM.
- Safety analysis for outside (right) shoulders narrower than 6 ft are generally treated as if they are 6-ft wide (widths less than this were not included).

CHAPTER 3. SITE SELECTION AND DATA COLLECTION

The published literature identified a wide variety of data collection elements and techniques commonly used for evaluating the operational and safety performance of lane and shoulder widths. The following sections briefly identify the specific elements and data collection analysis techniques, operational performance (speed) site identification and data collection information, and safety data site identification and collection.

ELEMENTS

The data required for evaluating the operations and associated safety along an urban freeway corridor and expected to in some way contribute to the performance of the lane and shoulder widths can be divided into three general categories: roadway characteristic data, operational data, and safety data. As shown in Table 14, a wide variety of potential data sources may be used for this evaluation. These data elements are consistent with those identified in the published literature. Because the intent of this study was to evaluate the direct effect of lane and shoulder widths, the research team attempted to identify study sites located remotely from influential site features, such as ramp gores, so that the evaluation could focus on the impacts of the lane and shoulder width.

DATA COLLECTION STRATEGIES

Data collection strategies include site selection and data collection techniques. The research team worked closely with the Texas Department of Transportation (TxDOT) to identify candidate sites based on recent freeway lane and shoulder narrowing projects and/or site specific knowledge of candidate locations. For the purposes of this study, this approach to site selection did constrain the study locations to select cities (in this case Dallas, Houston, and San Antonio).

The data collection techniques required to determine the impacts of lane and shoulder widening vary; however, the published literature overwhelming indicated the use of cross-sectional speed and capacity analyses for determining traffic operations. Ideally, a more precise approach would be to use before-after data at the same location so that roadways with similar users, traffic volume, truck percentage, and physical site features could be directly evaluated. In the published literature, most of the studies were conducted as cross-sectional evaluations. The project team used this cross-sectional approach for the operational analysis component of this study. For the safety analysis, most of the data were cross-sectional, but longitudinal data were available for some study sites. As a result, the project team selected a statistical methodology for the safety analysis such that data with both longitudinal and cross-sectional characteristics could be accommodated.

Table 14. Data Collection Elements and Sources.

Data Element	Data Source
Roadway Characteristic Data (used for Operational and Safety Analysis)	
Number, Width, and Configuration of Lanes	Roadway/Highway Network Inventory (RHiNo) and Aerial Photos
Shoulder Widths	Aerial Photos
Horizontal Geometry	Aerial Photos, and Site Inspection via Google Street View
Type and Placement of Barrier	Aerial Photos and Site Inspection via Google Street View
Posted Speed Limit	Site Inspection via Google Street View
Operational Data	
Traffic Volume Average (Annual Daily Traffic [AADT] and Design Hour Volume [DHV])	RHiNo, CRIS, Site Sensors
Operating Speed (spot speed data)	Traffic Management Center (TMC) archived data [TranStar, DalTrans, TransVISION, and TransGuide], historic permanent loop data
Safety Data	
Crash Data (three years) – Includes crash type and crash severity	TxDOT Crash Records Information System (CRIS)
Boundaries of Homogeneous Segments	RHiNo and Aerial Photos

Ideally, use of the exact same set of sites for the operational and the safety analysis would simplify the data collection and enable direct comparisons, but in many cases a site that was suitable for the safety analysis (based on a homogeneous segment of some length) could not be used for the speed analysis (based on availability of speed sensor locations). Consequently, the operational and safety data summaries are presented separately, though there was significant overlap between the datasets.

CANDIDATE VARIABLES

Table 15 provides descriptions of the specific geometric variables considered for the analyses. Table 16 similarly lists additional variables included in the study. The research team gathered the information for the variables listed in Table 15 primarily by using the measurement tool available in Google® Earth. These variables were selected because they have been shown to be potentially influential on operating speed or safety. The research team acquired the posted speed limit information by using the StreetView feature available in the Google Earth suite of tools.

Table 15. Description of Candidate Geometric Variables.

Variable Name	Description
NLanes	Number of general purpose lanes, not barrier separated, moving in same direction
PSL	Posted speed limit (mph)
Lane_W	Lane width for a given lane (ft)
All_Lanes_W	Width of all general purpose lanes (ft)
Ave_Lane W	Average lane width for all general purpose lanes (ft)
L_Shld_W	Left shoulder width (ft)
R_Shld_W	Right shoulder width (ft)
MW	Median width, measured from edge line to edge line (i.e., includes left shoulder widths in the measurement) (ft)
MW-Shld	Median width, excluding left shoulder widths (ft)
Med_Type_Grass	Type of median, either barrier or grass with a value of 1 if grass median, otherwise 0
Med_Type_Barrier	Type of median, either barrier or grass with a value of 1 if concrete barrier is present in the median, otherwise 0
To_Right_Shld	Value of 1 if right shoulder is present to the right of the lane, otherwise 0
To_Right_SCL	Value of 1 if speed change lane is present to the right of the lane, otherwise 0
To_Left_B+P	Value of 1 if buffer plus pylons are present to the left of the lane, otherwise 0
To_Left_Shld	Value of 1 if left shoulder is present to the left of the lane, otherwise 0
Ramp_Up_D	Upstream distance to nearest ramp, measured to gore (ft)
Ramp_Dwn_D	Downstream distance to nearest ramp, measured to gore (ft)
Ramp_Up_N	Number of ramps upstream within 1.5 miles
Ramp_Down_N	Number of ramps downstream within 1.5 miles
HC	Based on engineering judgment, is it possible that the horizontal alignment could affect speed (yes or no)
VC	Based on engineering judgment, is it possible that the vertical alignment could affect speed (yes or no)

Table 16. Description of Candidate Supplemental Variables.

Variable Name	Description
City	Dallas, Houston, or San Antonio
S	Average operating speed per lane for a 5-minute time period (mph)
$V_{5\text{-min/lane}}$	5-minute traffic volume for the freeway lane of interest (vehicles/5-minutes)
NLight	Natural light level during 5-minute speed bin – either daytime or nighttime (the 5-min speed data increments that were within 30 minutes of either dawn or dusk were removed)
Day_of_Week	Either Wednesday or Saturday

OPERATIONAL ANALYSIS SITE SELECTION AND DATA COLLECTION

A primary characteristic for the candidate operational analysis sites was the presence of speed measurement devices and the availability of speed data. Sensors are present in several major Texas cities to collect speed and volume data.

Operational Analysis Speed Sensor Characteristics

For the purposes of this study, the research team selected locations in Dallas, Houston, and San Antonio.

Dallas

The TxDOT DalTrans Traffic Management Center (TMC) is responsible for monitoring traffic conditions, collecting traffic data, and storing traffic data within the Dallas District of TxDOT. As of 2013, DalTrans deployed closed-circuit television at 342 locations and vehicle detection units at 291 locations. Vehicle detection units (i.e., Wavetronix SmartSensor and video image vehicle detection system) are installed on local freeways and are used to measure traffic speeds, traffic volumes, lane occupancy, and long vehicle volumes. These units are mounted alongside freeways and the information from the vehicle detection units is transmitted to the TMC. The traffic data are archived by date/time (five minute intervals), detector name (location), detector ID (unique identifier), and detector status (normal, error, out of service, no data, incomplete).

Houston

For the Houston sites, the research team used speed values acquired from Smart Sensors, which are digital wave radar devices used for vehicle detection. The devices measure vehicle volume, occupancy, speed, and classification. The information is used to develop the speed map shown on the TxDOT website and to generate travel times displayed on the dynamic message signs on freeways. The data are stored in five-minute increments.

San Antonio

Freeway traffic conditions in San Antonio, Texas, are monitored and managed by the TxDOT's TransGuide intelligent transportation system. Two primary types of input are received by the system's operators: video feeds and detector/sensor data. Three types of detector/sensing technologies are used: inductance loops (configured in each freeway lane as a two-loop speed trap), microwave radar, and Bluetooth®. Inductance loops are the oldest technology used by the system and were the initial detector type used when the system was first installed in the early 1990s. Over time, the loops have been displaced by radar detectors for ease of maintenance and reduced cost. These more traditional traffic sensors (i.e., loops and radar) provide TransGuide operators with both speed and lane-by-lane count data.

Data from all three sensing technologies are used by TransGuide operators to aid in detecting freeway incidents and monitoring the onset and extent of freeway congestion. Data from all sensors are stored in archived data files by hour, day, and month. Each file contains data for all freeway sensors in the TransGuide system regardless of detector type. The files contain a time stamp, link name (which includes the freeway corridor name and sensor milepoint location), lane name (which includes the link name and lane designation code), speed (mph), volume, and occupancy. The TransGuide central management software accumulates sensor data by polling sensors every 20 or 30 seconds. Within each 20- or 30-second period, each sensor reports the count over that time segment and a calculated average speed and percent occupancy. These data are not processed further (for archiving purposes) by the TransGuide central software (TxDOT's Lonestar) but are simply accumulated and stored by hour. For use in this TxDOT study, the research team binned the data into five-minute increments to match the time frame of data available for Houston and Dallas.

Operational Analysis Study Sites

Members of the research team identified sites with 11-ft freeway lanes within each of the three major Texas cities via team or panel member knowledge or by using aerial photographs to assess the lane width for several freeways within one of the three Texas cities. Due to the limited number of freeways with 11-ft lanes, more 12-ft lane sites were identified than 11-ft lane sites. Table 17 lists the number of lanes that are 12-ft wide (121 lanes) and the number of lanes 11-ft wide (83 lanes) included in the operational analysis database.

Table 17. Number of Lanes in Database.

City	Lanes with 11-ft Width	Lanes with 12-ft Width	Total Number of Lanes
Dallas	52	30	82
Houston	16	47	63
San Antonio	15	43	58
Total	**83**	**121**	**204**

The push pins in Figure 2 show the Dallas operational assessment site locations, and Table 18 provides companion cross section dimensions.

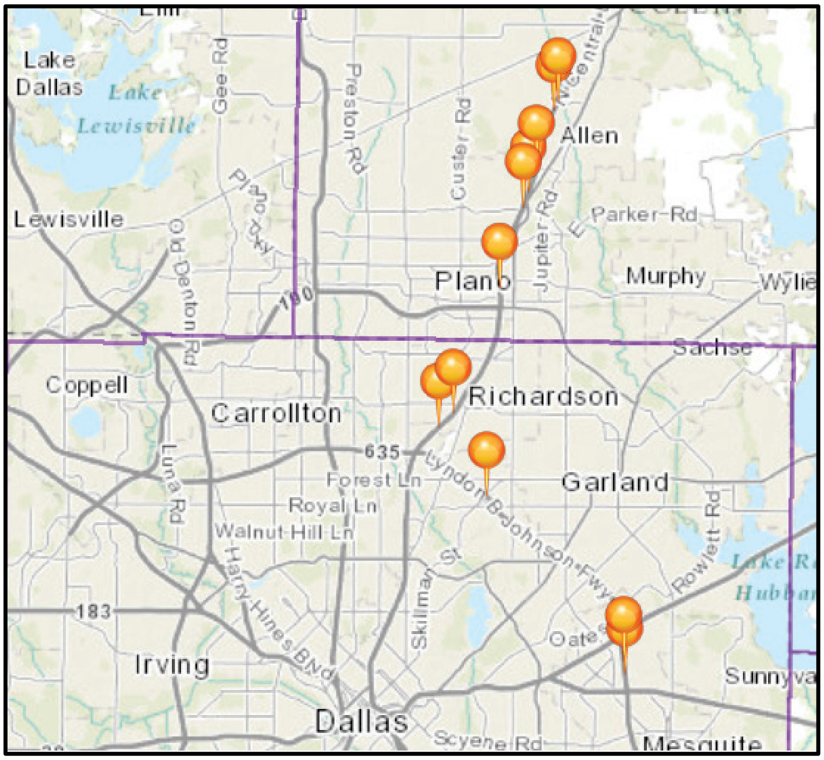


Figure 2. Dallas Operational Assessment Sites.

Table 18. Dallas Speed Study Sites.

Site – Direction*	Number of Lanes	Posted Speed Limit (mph)	Left Shoulder Width (ft)	Average Lane Width (ft)	Right Shoulder Width (ft)
635-CenVil - NB	5	60	5	11	7
635-CenVil - SB	5	60	5	11	10
635-Skill - EB	5	60	5	11	10
635-Skill - WB	4	60	5	11	10
635-TwnCen - NB	5	60	10	12	10
635-TwnCen - SB	5	60	10	12	10
635-TwnEast - NB	5	60	10	12	9
635-TwnEast - SB	5	60	10	12	9
75-15th - NB	5	60	3.5	11	11
75-15th - SB	4	60	3.5	11	11
75-Allen - NB	3	65	1.5	12	9
75-Allen - SB	3	65	12	12	8
75-Exch - NB	3	65	13.5	12	9
75-Exch - SB	3	65	13.5	12	9.5
75-Legacy - NB	3	65	3	11	6
75-Legacy - SB	3	65	3	11	9.5
75-Midpark - NB	5	60	3.5	11	10
75-Midpark - SB	5	60	3.5	11	9
75-Ridge - NB	3	65	3.5	11	8
75-Ridge - SB	3	65	3.5	11	9
75-SprCre - NB	3	65	3.5	11	9
75-SprCre - SB	4	65	3.5	11	9
75-Valley - NB	4	60	3.5	11	10
75-Valley - SB	4	60	3.5	11	9

*See Table 15 for descriptions of geometric variables.

Figure 3 shows the Houston locations identified for the operational assessment evaluation, and Table 19 depicts the companion cross section information. San Antonio operational study sites and their cross-section characteristics are identified in Figure 4 and Table 20, respectively.

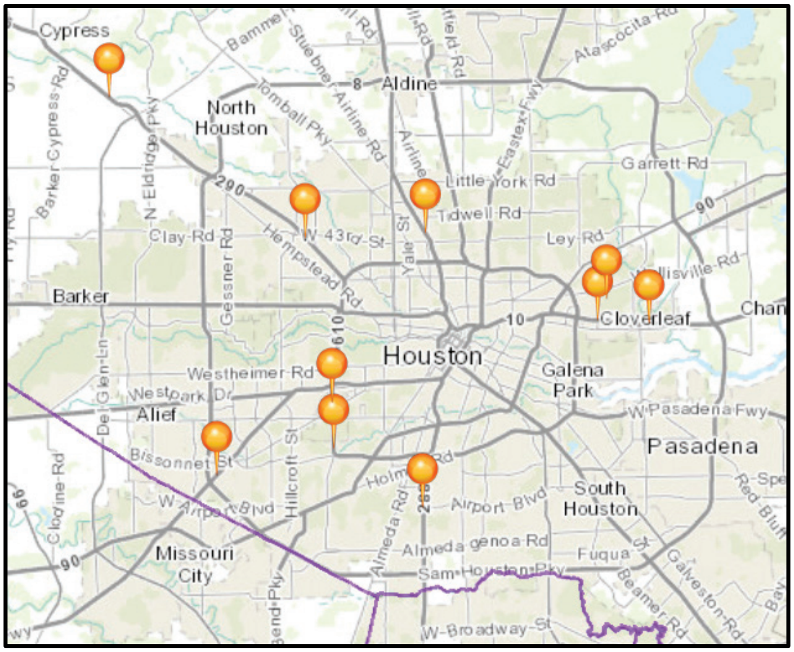


Figure 3. Houston Operational Assessment Sites.

Table 19. Houston Speed Study Sites.

Site – Direction*	Number of Lanes	Posted Speed Limit (mph)	Left Shoulder Width (ft)	Average Lane Width (ft)	Right Shoulder Width (ft)
10-Bunk - EB	5	60	5	12	10
10-Mer - EB	4	60	5	11	12
10-Mer - WB	4	60	10	12	12
10-Norm - EB	4	60	12	12	11
10-Norm - WB	4	60	11	12	12
288-Air - NB	3	60	10	12	10
288-Air - SB	3	60	10	12	10
290-43 - EB	3	60	1.5	11	12
290-43 - WB	3	60	1.5	11	12
290-Telge - EB	3	65	1.5	11	7
45N-Tidwell - SB	4	60	2	11	12
59-Air - NB	4	60	10	12	12
59-Air - SB	4	60	10	12	12
610-Braes - NB	5	60	11	12	4
610-Four - NB	5	60	11	12	11
610-Four - SB	5	60	11	12	10
90-Hunt - EB	3	60	10	12	11
90-Hunt - WB	3	60	10	12	11

*See Table 15 for descriptions of geometric variables.

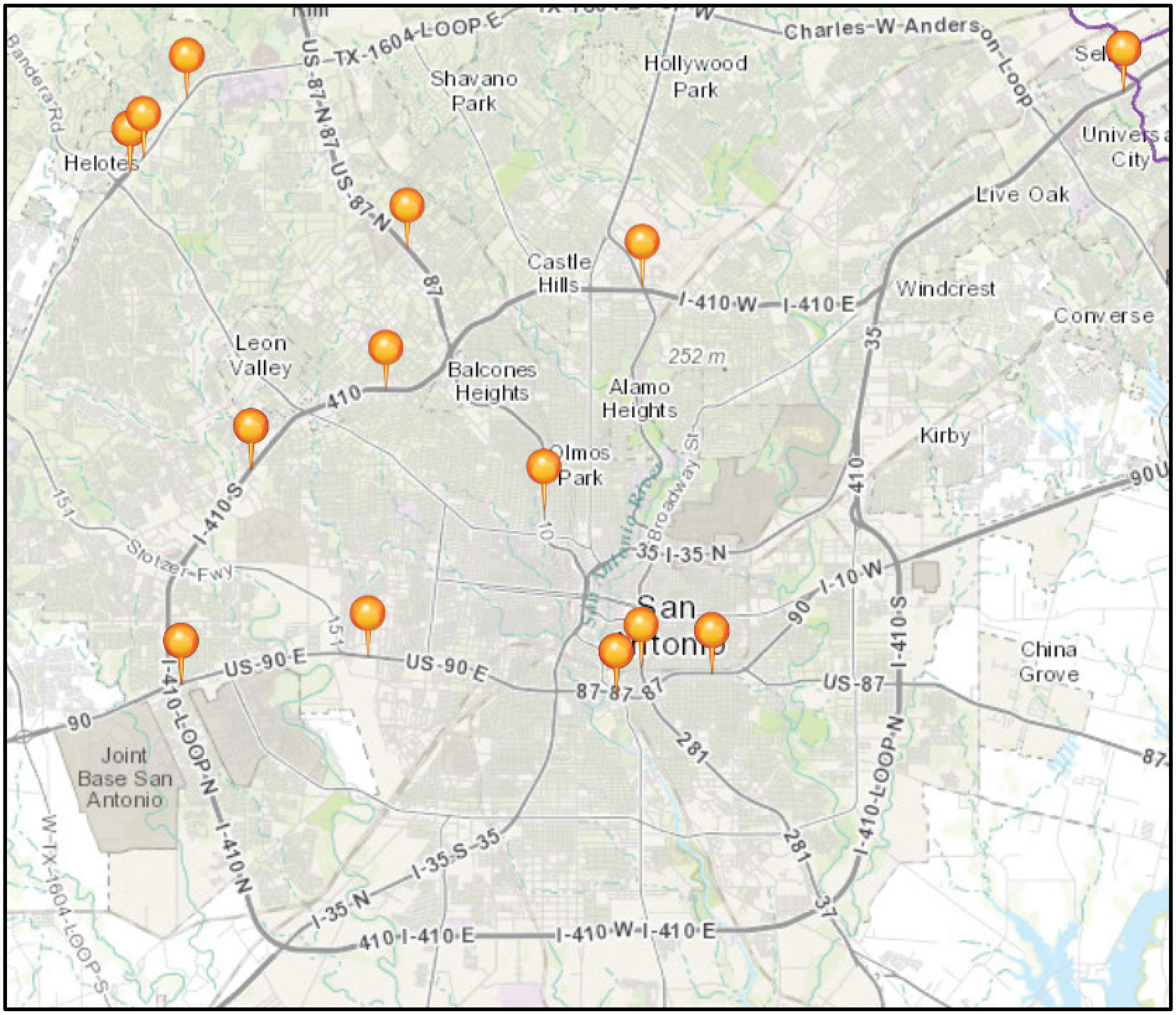


Figure 4. San Antonio Operational Assessment Sites.

Table 20. San Antonio Speed Study Sites.

Site – Direction*	Number of Lanes	Posted Speed Limit (mph)	Left Shoulder Width (ft)	Average Lane Width (ft)	Right Shoulder Width (ft)
010E - 561.169	4	65	11	12	9
010E - 574.117	4	65	11.5	12	4
010E - 576.264	3	65	23	12	10
010W - 561.169	4	65	7	12	15
010W - 574.117	4	65	11	12	11
010W - 576.264	3	65	19.5	12	10
035N - 173.506	3	65	5	11	11
035S - 173.506	3	70	9	11	7
037S - 140.348	4	65	10	12	5
090E - 564.048	2	65	20	12	10
090W - 564.048	2	70	20	12	10
090W - 568.156	4	65	8.5	12	11
1604E - 028.549	2	60	5	12	10
1604W - 028.549	2	70	5	12	10
1604W - 029.042	2	70	10	12	4
1604W - 030.638	2	70	5	12	10
281N - 149.431	3	65	9	12	11
410E - 015.107	5	65	10	11	7
410N - 011.100	5	65	11	11	8
410S - 011.120	4	65	8	11	20
U10E - 568.248	3	65	9	12	11.5

*See Table 15 for descriptions of geometric variables.

Operational Analysis Data Collection

Shoulder widths were measured to the middle of the lane line and rounded to the nearest 0.5 ft. The lane width data element was typically obtained by measuring all lanes and then dividing by the number of lanes, rounding to the nearest foot. At locations where a ramp merged onto the freeway, the outside lane could be wider than the typical lane width. This atypically wide lane was noted as a merging lane and removed from the study. Through the use of aerial photographs, the research team determined that all but two of the sites had roadway lighting present near the speed sensors.

The amount of available speed data is very large. To have a more manageable sample size and to enable the research team to perform a statistical analysis on the data, members of the team limited the speed data request to only two days in a month. The resulting dataset included data from a Wednesday and a Saturday for each month in 2013 (pending data availability for the requested day). In general, the team selected the second week of a month so as to avoid the majority of the holidays (e.g., Thanksgiving). For some of the datasets, the week selected was shifted due to lack of data in the second week of a month.

For Dallas and Houston, the format of the available speed data included bins of 5-minute increments. For San Antonio, the data are in 20 or 30-sec bins. These bins were combined into 5-minute bins to match the time period in other cities.

To address prevailing lighting conditions, the following rules were applied:

- If any part of the 5-minute time period occurred within 30 minutes (before or after) of the sunrise, the time interval was classified as dawn lighting conditions.
- If any part of the 5-minute time period occurred within 30 minutes (before or after) of the sunset, the time interval was classified as dusk lighting conditions.
- If the 5-minute time period occurred more than 30 minutes after sunrise or more than 30 minutes before sunset, the light condition was classified as daytime.
- If the 5-minute time period occurred more than 30 minutes after sunset or more than 30 minutes before sunrise, the light condition was classified as nighttime.
- If the 5-minute time period occurred within 30 minute of sunrise or sunset, the associated speed data were removed from subsequent evaluation.

Table 21 shows the associated sunrise and sunset times for Dallas, Houston, and San Antonio.

The focus of the operational analysis was to determine the effect of geometric features on operating speed. To eliminate the potential effects of congestion, the research team removed data from the dataset when speeds were less than 50 mph or when 5-minute volumes were greater than 250 vehicles. The modeling effort used the pooled database from all three cities. A total of 667,297 speed records were available with about an even split between speed data for 11-ft lanes (340,695 speed measurements) and 12-ft lanes (326,602 speed measurements). Table 22 shows the number of speed measurements by number of lanes on the freeways.

Table 21. Sunrise and Sunset Times for Dallas, Houston, and San Antonio.

Date for Dallas Data	Time for Sunrise, Dallas	Time for Sunset, Dallas	Date for Houston Data	Time for Sunrise, Houston	Time for Sunset, Houston	Date for San Antonio Data	Time for Sunrise, San Antonio	Time for Sunset, San Antonio
01/23/13	7:27	17:51	01/09/13	7:18	17:39	01/09/13	7:29	17:51
01/26/13	7:26	17:53	01/12/13	7:18	17:42	01/12/13	7:30	17:54
02/09/13	7:16	18:07	02/13/13	7:03	18:08	02/13/13	7:15	18:21
02/13/13	7:12	18:10	02/16/13	7:00	18:11	02/16/13	7:12	18:23
03/09/13	6:45	18:30	03/13/13	7:34	19:28	03/13/13	7:46	19:40
03/20/13	7:31	19:38	03/16/13	7:30	19:30	03/16/13	7:43	19:42
04/13/13	7:00	19:55	04/10/13	7:01	19:45	04/10/13	7:13	19:57
04/24/13	6:47	20:03	04/13/13	6:57	19:47	04/13/13	7:10	19:59
05/08/13	6:34	20:13	05/08/13	6:34	20:03	05/08/13	6:46	20:15
05/11/13	6:31	20:16	05/11/13	6:31	20:08	05/11/13	6:44	20:16
06/08/13	6:19	20:34	06/12/13	6:20	20:22	06/12/13	6:33	20:34
06/12/13	6:18	20:35	06/15/13	6:21	20:23	06/15/13	6:33	20:35
07/24/13	6:35	20:32	07/10/13	6:29	20:25	07/10/13	6:41	20:37
07/27/13	6:37	20:30	07/13/13	6:30	20:25	07/13/13	6:42	20:36
08/24/13	6:56	20:03	08/14/13	6:49	20:04	08/14/13	7:01	20:16
08/28/13	6:59	19:58	08/17/13	6:50	20:01	08/17/13	7:02	20:13
09/07/13	7:05	19:45	09/11/13	7:04	19:33	09/11/13	7:16	19:45
09/11/13	7:08	19:40	09/14/13	7:06	19:29	09/14/13	7:18	19:41
10/23/13	7:37	18:46	10/09/13	7:19	18:58	10/09/13	NA	NA
10/26/13	7:40	18:43	10/12/13	7:21	18:55	10/12/13	NA	NA
11/16/13	6:58	17:26	11/13/13	6:44	17:27	11/13/13	NA	NA
11/20/13	7:02	17:24	11/16/13	6:47	17:26	11/16/13	NA	NA
12/18/13	7:24	17:23	12/11/13	7:07	17:23	12/11/13	NA	NA
12/21/13	7:25	17:25	12/14/13	7:09	17:24	12/14/13	NA	NA

NA = not necessary as speed/volume data for this date not available

Table 22. Number of Speed Measurements by Number of Freeway Lanes.

11-ft Lane Width		12-ft Lane Width	
Number of Lanes	**Frequency**	**Number of Lanes**	**Frequency**
2	0	2	3,005
3	108,715	3	110,575
4	123,684	4	87,119
5	108,296	5	125,903
All	**340,695**	All	**326,602**

Table 23 depicts the range of variables including the average value for left-shoulder width, right-shoulder width, median width, median width without including left shoulder widths, and number of ramps upstream and downstream of the speed measurement location. For 12-ft lanes, the average left and right shoulder widths were similar (10.0 ft and 10.2 ft), while the shoulder widths were not similar for 11-ft lanes (3.6 ft and 9.7 ft). The average left-shoulder width for 11-ft lanes (3.6 ft) was smaller than the average left-shoulder width for 12-ft lanes (10.0 ft). The indication of a more restricted cross section for segments with 11-ft lanes is also apparent by the median width variable. The maximum median width is only 27 ft for 11-ft lane segments as compared to 125 ft median width for a 12-ft lane segment.

The posted speed limits included in the dataset ranged between 60 and 70 mph. Table 24 lists the number of speed measurements by posted speed limit. Most of the data reflected 60 mph sites with very few sites having 70 mph for the posted speed limit. The number of speed measurements, based on the use of the space to the left and to the right of the lane, is shown in Figure 5 and Figure 6, respectively. In most cases the use of the space to the left of the lane is another lane or the inside shoulder. Buffers with vertical pylons (Buf+pyl) were present to the left of the lane for several sites containing 11-ft lanes. All of these sites were in the Dallas region.

Table 23. Range of Values for Key Variables.

Lane Width (ft)	Value	Left-Shoulder Width (ft)	Right-Shoulder Width (ft)	Median Width (ft)	Median Width Minus Shoulder (ft)	Number of Upstream Ramps	Number of Downstream Ramps
11.0	Minimum	1.5	6.0	6.0	3.0	1.0	2.0
	Average	3.6	9.7	8.2	3.0	3.7	3.8
	Maximum	11.0	20.0	27.0	7.0	7.0	7.0
12.0	Minimum	1.5	4.0	10.0	3.0	1.0	1.0
	Average	10.0	10.2	33.0	10.1	3.8	3.8
	Maximum	23.0	14.9	125.0	100.0	6.0	6.0

Table 24. Number of Speed Measurements by Posted Speed Limit.

Posted Speed Limit (mph)	Frequency of Data for Lanes with 11-ft Width	Frequency of Data for Lanes with 12-ft Width	Grand Total
60	237,032	243,649	480,681
65	103,380	80,755	184,135
70	283	2,198	2,481
Grand Total	340,695	326,602	667,297

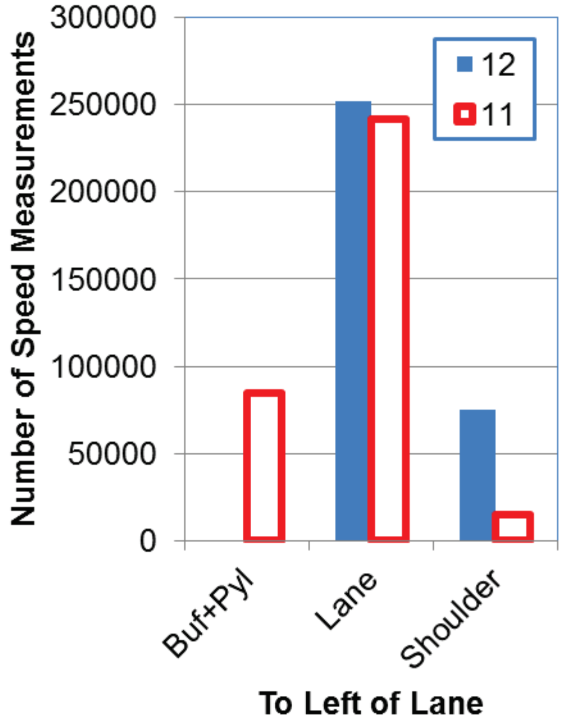


Figure 5. Number of Speed Measurements by Space to the Left of the Lane.

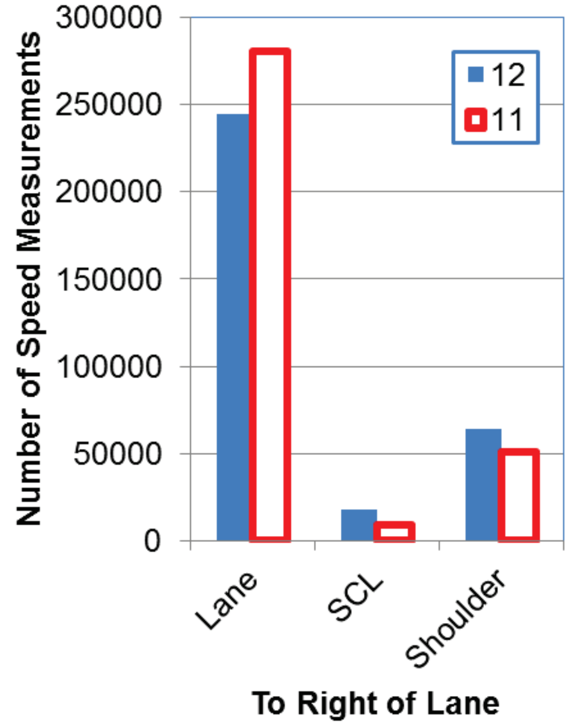


Figure 6. Number of Speed Measurements by Space to the Right of the Lane.

SAFETY ANALYSIS SITE SELECTION AND DATA COLLECTION

In addition to identifying candidate sites and features for the operational analysis data collection effort, the research team also acquired data for the purposes of quantifying the relationship between safety and lane and shoulder width. The following section reviews this Texas crash data and study sites.

Safety Analysis Study Sites

Initial site selection for this effort occurred in parallel with the operational analysis data collection. As part of this effort, the research team again identified 11-ft lane freeway sites located in Dallas, Houston, and San Antonio. Candidate sites were identified based on previous knowledge of freeway sections and a systematic review of city freeways via aerial photographs. The research team observed that the number of freeways with 11-ft lanes is somewhat limited. As a result, the final dataset included more 12-ft lane width than 11-ft lane width sites. Due to the physical separation of opposing directions of travel on a freeway and the intent to isolate the effects of cross-sectional elements beyond those of the median, the research team elected to analyze the sites for each direction of travel. The search concentrated on obtaining data from one-direction freeway sections with three, four, and five lanes. The research team also identified two additional freeway sites, a San Antonio site with two lanes per direction and a Houston site with six lanes per direction of travel. The resulting sites are depicted as push pins in Figure 7 (Dallas), Figure 8 (Houston), and Figure 9 (San Antonio).

The majority of the safety sites were located in the vicinity of the operational analysis locations; however, additional sites were identified and collected for each task. For example, an important difference is that an operations site provides spot speed per lane at one point, but a safety site requires a segment as uniform in its cross section as possible, yet long enough to have a sufficient likelihood of crashes occurring. A safety site consisted of a freeway segment with a uniform cross section in terms of number of lanes and lane or shoulder width. The segment did not include any freeway on or off ramps within its limits. Therefore, a typical segment would normally begin some distance after an entrance or exit ramp and would end some distance prior to an entrance or exit ramp. A segment was typically about 2000 ft long.

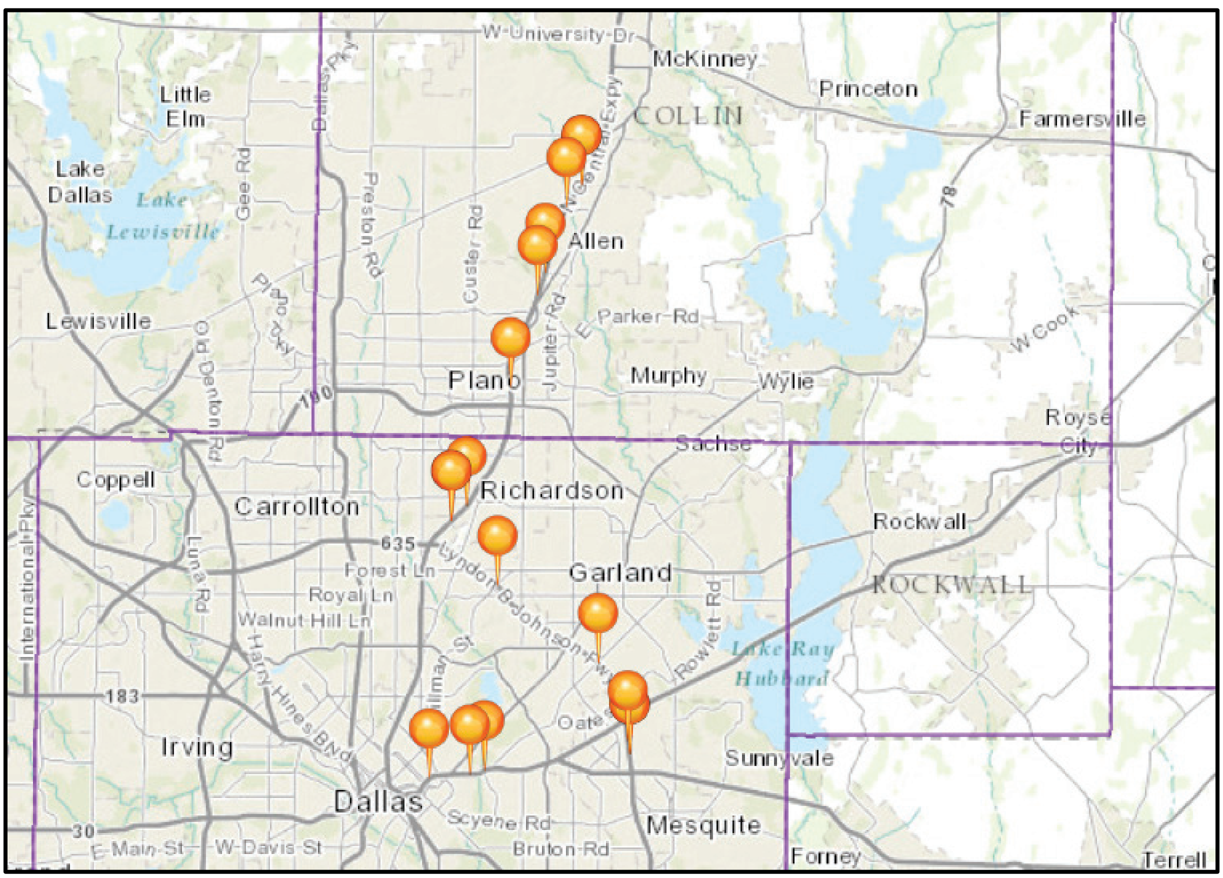


Figure 7. Dallas Safety Assessment Sites.

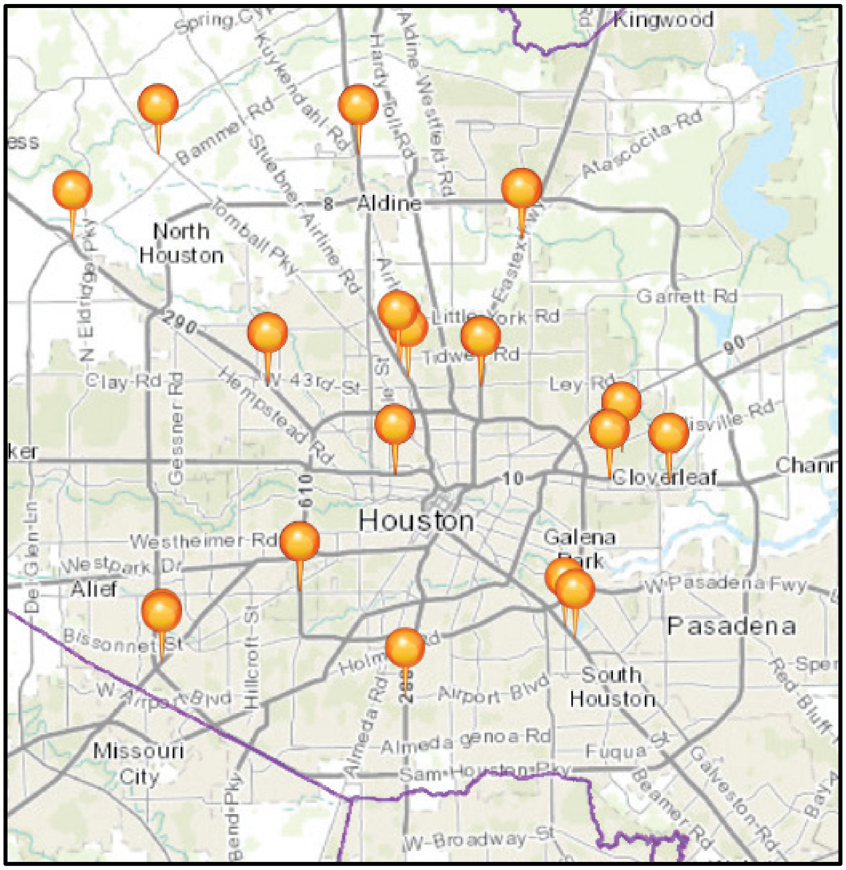


Figure 8. Houston Safety Assessment Sites.

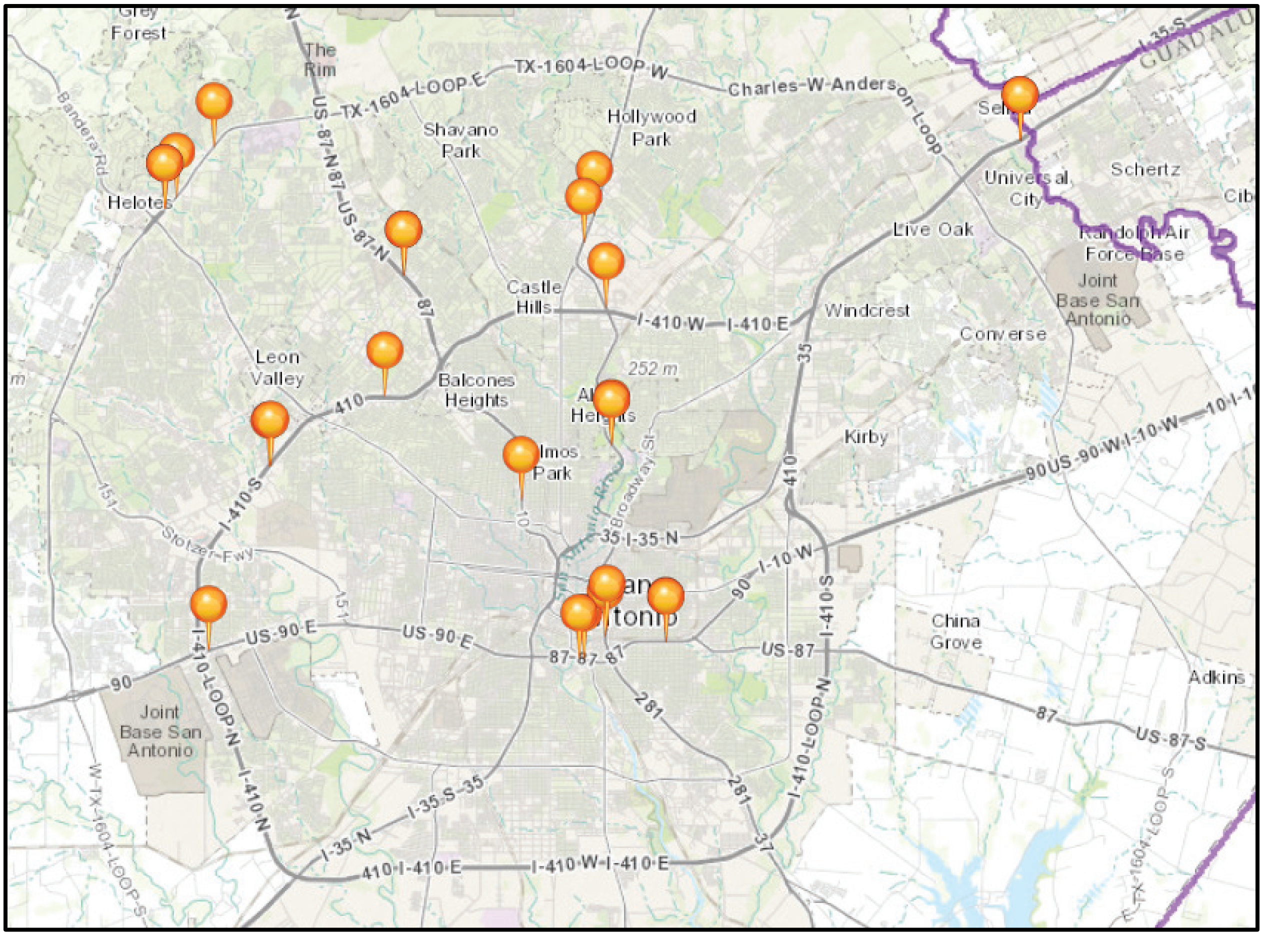


Figure 9. San Antonio Safety Assessment Sites.

The next section describes some basic information collected from each location in the safety dataset.

Safety Analysis Data Collection

The research team collected individual site geometric information for variables previously identified in Table 15 by using the measurement tool available in Google Earth. These variables were selected because literature indicates they are potentially influential on the safety of freeway sections. Lane and shoulder widths were measured to the middle of the lane pavement marking stripe. The lane width was measured individually. The research team then contrasted the sum of all lane widths against the sum of measuring across all lanes. Measurements were repeated if this contrast yielded a difference larger than 5 percent of the width of all lanes.

In contrast to the extremely large dataset available for the operational analysis, the amount of crash data necessary for a robust safety evaluation depended greatly on the team's ability to collect data for a sufficiently large number of sites, with detailed geometric data and crash data from each site. By combining the data collection effort for the operations and safety tasks, the research team was able collect geometry from a sizeable number of freeway segments (73 in total). However, an absolute minimum of 100 data points is recommended in order to perform a robust statistical analysis based on Maximum Likelihood Estimation, as error estimation from this type of analysis relies on a relatively large dataset to provide reliable results. It is also recommended that there be at least 30 data points per explanatory variable included in the analysis. For example, if it is anticipated that eight variables should be accounted for, then there should be at least 8 × 30=240 data points for statistical inference to be realistic.

The research team obtained the minimum required sample size for analysis by aggregating the data into six-month periods at each site. In other words, crash data were not aggregated per site for the whole 2010 to 2013 period of time. Rather, the database was designed such that each record represents a six-month period, though some records were adjusted to represent shorter periods because construction was suspected to have taken place within the six-month period. The research team selected a statistical technique capable of accounting for this data grouping structure, as will be detailed later in this document.

Safety Analysis Dataset Characteristics

The most obvious advantage of analyzing six-month periods, as opposed to data aggregated for four years from one site, is the number of data points available for analysis. There is a potential pool of 73 segments × 4 years × 2 periods/year = 584 segment-periods for analysis compared to just 73 data points representing crash counts aggregated at each site for the four years under study. An additional advantage is that the analysis can explicitly capture within-site variation, not only variation between sites. Finally, by using this approach, the research team was able to include sites where the cross-section changed during the study period. Although only a few sites with cross sectional changes were identified, the research team believes it is important to include these modified sites because the objective of this research is to provide information to support decision making regarding changes in freeway cross-section.

Construction periods should not be considered for this effort because of special signage, temporary markings, temporary barriers, construction equipment, and shifting conditions that prevail during construction activity. Based on satellite imagery, the research team identified 16 complete six-month periods with active construction, and removal of these sites reduced the potential pool of six-month periods to 568 for the 73 sites.

Range of Right Shoulder Widths

The research team identified one site with an atypical shoulder width, as can be observed in Figure 10. This site had a 20-ft paved right shoulder, wider than any of the actual travel lanes. Additionally, this four-lane site is located just upstream of a merging zone (as shown in Figure 11), where the number of lanes is subsequently reduced to three. The proximity between this site and a downstream merging zone increases the chances of additional weaving maneuvers and the likelihood of crashes at this location. For those reasons, this site was removed from the formal analysis.

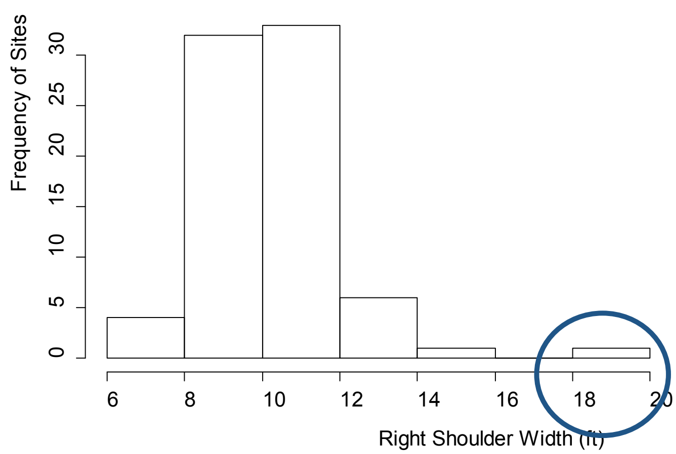


Figure 10. Frequency by Right Shoulder Width.

Figure 11. Satellite Image for Site 19-R-SA-4.

Sites where Changes Occurred over Time

Having sites where physical changes occurred during the period of analysis offer the opportunity to compare the effect of changing cross-sectional elements and implicitly accounting for other unobserved elements unique to each site (e.g., land use, driving population, and commuting patterns). For this reason, the research team made every effort to preserve as many of these sites in the database as feasible. Initially, 11 such sites with cross-sectional changes were identified, as indicated in the second column of Table 25. The research team observed counter-intuitive findings that the width of lanes or shoulders increased during the period of analysis. A closer examination found various explanations for these changes and prompted the research team to re-classify these sites.

Table 25. Distribution of Sites by Geometry Changes during the Analysis Period.

Type of Change within Period of Analysis	Number of Sites Originally Identified	Number of Sites After Revision
None	61	62
Lane or Shoulder Reduction	8	7
Lane or Shoulder Expansion	3	0
Total:	72	69

In some instances, the sites originally identified as having experienced changes actually had the changes occur outside of the analysis period, and thus were reclassified as sites with no changes for the purpose of this study. The three sites with apparent lane width increases were all located in Dallas. These sites are locations with the movable median barrier system, or zipper.

This barrier system accommodates the operations of reversible managed lanes that change three times during a 24-hour cycle on week days. These sites were removed from the analysis, as the variables of interest actively varied throughout a single day.

The research team also noted that other sites with shoulder width increases had also experienced simultaneous lane width reductions. These changes were often followed by the appearance of additional barriers, construction equipment, and additional lanes in the satellite photographic record. These sites retained their original classifications, whenever it was clear that construction was not ongoing.

After incorporating these changes, a total of 536 six-month segment-periods from 69 sites remained available for analysis. The last column of Table 25 shows the site distribution of this reduced dataset. Only seven sites with changes in their cross section remained in the dataset (10 percent of all sites). Table 26 shows the distribution of the dataset by number of time periods available for analysis. With the exception of one site, at least six periods are available for analysis from each site. Due to photographic evidence of construction, several time periods for this Houston site were excluded.

Table 26. Distribution of Sites by Number of Time Periods for Analysis.

Number of Six-Month Periods Available for Analysis	Number of Sites
8	62
7	2
6	4
2	1

Reduced Time Periods for Analysis

The final dataset excluded 16 segment-periods (i.e., complete six-month-long periods from a segment) because the data collectors noted evidence of ongoing construction activity. The research team identified additional segment-periods when it was evident that construction had ceased sometime before the end of the six-months. Instead of excluding these segment-periods completely, the research team included only those months where construction had clearly ceased. As a result, the research team retained segment-periods shorter than six months from 23 sites. Table 27 shows the distribution of sites by average length of time periods available in the dataset. Even though 23 sites had at least one shortened time period, the average study duration is at least 4.8 months for all 69 sites. The next subsection provides more detailed summary statistics for the reduced dataset.

Table 27. Distribution of Sites by Length of Time Periods Available for Analysis.

Average Length of Time Period	Number of Sites
6 months	47
Between 5.4 and 6.0 months	15
Between 4.8 and 5.4 months	7

Geometric Data Summaries

The research team made a preliminary distinction between sites with narrow lanes (narrower than 11.5 ft) and sites with standard lanes (wider than 11.5 ft) when collecting the geometric data. Table 28 shows the number of periods available and the average lane width for each of these categories in the three study cities.

Table 28. Number of Segment-Periods Available for Analysis by City and Average Lane Width.

City	Total Number of Available Segment-Periods	Number of Segment-Periods from Narrow-Lane Sites	Average Lane Width for Narrow-Lane Sites (ft)	Number of Segment-Periods from Standard-Lane Sites	Average Lane Width for Standard-Lane Sites (ft)
Dallas	120	72	11.0	48	12.1
Houston	226	66	11.4	160	12.1
San Antonio	190	55	11.3	135	12.0

Table 29 shows the key variables acquired for the Dallas sites. Similarly, Table 30 and Table 31 depict data from Houston and San Antonio, respectively.

Table 29. Dallas Safety Study Sites.

Site ID	No. Periods	Number of Lanes	Posted Speed Limit (mph)	Left Shoulder Width (ft)	Average Lane Width (ft)	Right Shoulder Width (ft)
01-R-DA-3	8	3	65	2.4	11.0	9.3
02-R-DA-3	8	3	65	3.2	10.8	9.1
03-R-DA-3	8	3	65	3.1	10.8	9.8
04-S-DA-3	8	3	65	14.1	12.1	8.9
05-S-DA-3	8	3	65	13.4	12.1	9.9
06-S-DA-3	8	3	65	13.2	12.1	10.3
07-R-DA-4	8	4	60	3.3	11.2	8.9
08-R-DA-4	8	4	60	5.7	11.0	9.6
09-R-DA-4	8	4	60	2.9	11.0	7.8
13-R-DA-5	8	5	60	1.3	11.1	9.8
14-R-DA-5	8	5	60	3.2	11.4	10.4
15-R-DA-5	8	5	60	1.9	11.1	10.8
16-S-DA-5	8	5	60	11.5	12.0	11.0
17-S-DA-5	8	5	60	12.1	11.9	9.9
18-S-DA-5	8	5	60	11.1	12.2	10.3

Table 30. Houston Safety Study Sites.

Site ID	No. Periods	Number of Lanes	Posted Speed Limit (mph)	Left Shoulder Width (ft)	Average Lane Width (ft)	Right Shoulder Width (ft)
01-R-HO-3	6	3	65	6.5	11.2	8.8
02-R-HO-3	6	3	65	5.9	11.5	9.6
03-R-HO-3	8	3	60	1.4	11.3	12.2
04-S-HO-3	8	3	60	10.2	12.5	12.2
05-S-HO-3	8	3	60	13.3	12.2	10.0
06-S-HO-4	8	4	60	10.5	11.8	10.6
07-R-HO-4	6	4*	60	8.3	11.4	10.4
08-R-HO-4	8	4	60	6.4	11.2	13.5
09-R-HO-4	8	4	60	1.9	11.5	12.5
10-S-HO-4	8	4	60	12.6	12.2	11.9
11-S-HO-4	8	4	60	2.7	11.9	9.9
12-S-HO-4	8	4	60	10.4	12.1	13.2
13-S-HO-5	8	5	60	10.3	12.1	9.9
14-S-HO-5	8	5	60	11.8	12.2	10.2
15-S-HO-5	8	5	60	10.3	12.1	9.4
16-S-HO-5	8	5	60	14.5	12.2	10.4
17-S-HO-5	6	5	60	8.9	12.3	8.9
18-S-HO-6	8	6	60	11.6	12.2	10.6
19-R-HO-3	8	3	65	2.0	11.0	12.0
20-S-HO-3	8	3	60	9.8	12.2	11.1
21-S-HO-4	8	4	60	10.8	12.2	10.4
22-R-HO-4	8	4	60	10.0	12.0	12.0
23-R-HO-4	8	4	60	6.8	11.5	12.1
24-S-HO-4	8	4	60	12.7	11.9	11.9
25-S-HO-5	8	5	60	9.7	12.1	10.4
26-S-HO-5	8	5	60	14.4	11.9	9.3
27-S-HO-4	8	4	60	11.0	12.0	10.3
28-S-HO-4	8	4	60	12.9	12.3	10.0
29-S-HO-5	2	5	60	6.8	12.1	9.6
30-S-HO-5	8	5	60	9.4	12.3	12.0

* Site had 4 lanes during 2010 and 5 lanes during 2012 and 2013.

Table 31. San Antonio Safety Study Sites.

Site ID	No. Periods	Number of Lanes	Posted Speed Limit (mph)	Left Shoulder Width (ft)	Average Lane Width (ft)	Right Shoulder Width (ft)
01-S-SA-2	8	2	65	19.6	11.9	9.0
02-S-SA-2	8	2	70	4.7	12.0	10.8
03-S-SA-2	8	2	70	4.6	12.1	10.5
04-S-SA-2	8	2	65	18.9	11.9	10.3
05-S-SA-2	8	2	60	4.6	12.3	11.2
06-S-SA-2	8	2	60	4.9	12.2	9.3
07-S-SA-3	8	3	65	10.3	12.0	9.7
08-S-SA-3	8	3	65	8.9	12.0	9.9
09-S-SA-3	8	3	65	20.8	11.9	9.3
10-S-SA-3	8	3	65	22.9	12.1	11.8
11-R-SA-3	8	3	70	10.3	11.5	12.3
12-R-SA-3	7	3	65	10.0	11.7	10.5
13-R-SA-3	8	3	65	10.4	11.9	7.9
14-S-SA-4	7	4	65	11.5	11.9	9.2
15-S-SA-4	8	4	65	11.0	11.8	9.2
16-S-SA-4	8	4	65	10.9	11.9	11.2
17-S-SA-4	8	4	65	11.0	12.2	11.4
18-S-SA-4	8	4	65	10.7	12.3	8.4
20-R-SA-4	8	4	60	2.5	11.2	9.3
21-R-SA-4	8	4	60	3.7	11.0	9.1
22-S-SA-5	8	5	65	10.5	12.2	6.0
23-S-SA-5	8	5	65	10.3	12.1	10.8
24-R-SA-5	8	5	65	2.8	11.0	9.7
25-R-SA-5	8	5	65	11.2	10.9	9.0

Site 07-R-HO-4 is the only site in the dataset where an additional lane was added and that became operational during the study period. Photographic record indicates that there are four general purpose lanes until March 1, 2011. There was an additional speed change lane that was already operational after May 1, 2011, at this site. Construction seems to have been minimal, which explains the short period of time between the two cross sections becoming operational; however, both six-month periods from 2011 were excluded so as to avoid any transition periods before and after the addition of the lane.

Matching AADT to Study Sites

The research team retrieved Annual Average Daily Traffic (AADT) from the Road-Highway Inventory Network (RHiNo) for years 2010 to 2012. Each year was matched to the corresponding time period. At the time of the data collection, AADT was not available for year 2013. The research team used simple linear regression to estimate AADT for year 2013. For each site, the research team obtained a 2013 AADT estimate using the three AADT values from 2010 through 2012.

Safety Analysis Crash Data

The research team retrieved crash data from the TxDOT Crash Records Information System (CRIS) for years 2010 to 2013 from all freeways in the three cities under study. From the crash-level file, the research team obtained records including geo-location, date, route location, environmental factors, severity of outcome, and number of vehicles, among other variables. The research team obtained additional data from the vehicle-level file, including direction of travel, among other variables.

Only crashes geo-located within a distance of 150 ft of a freeway section were extracted and preliminarily matched to the study sites. At this stage, the research team excluded any crashes classified as occurred on HOV lanes or frontage roads, per the CRIS database.

Because the sites represent only one direction of travel, the matching of geometric data to crash data obtained from CRIS required considering the direction of travel variable available from the vehicle file in CRIS. Crashes when the vehicles were traveling in the opposite direction were excluded for each freeways section. For example, if the travel direction of a study site is northbound, then all crashes with an indication of vehicles traveling southbound were excluded from the directional dataset. The crashes were assigned to their corresponding segment-periods and a subtotal was obtained for fatal or severe injury (KAB) crashes (i.e., the highest three categories in the total crash or KABCO scale severity classification, containing only fatal and injury crashes). Table 32 shows summary statistics for the assembled dataset.

Table 32. Summary Statistics for Available Dataset for Years 2010–2013 (n=536).

Variable	Mean	Std. Dev	Min	Max	Total	N
Total Crashes	4.1	4.85	0	37	2202	536
KAB Crashes	0.8	1.08	0	6	407	536
Period Length (yr)	0.48	0.07	0.08	0.50	-	536
AADT (vpd)	152,163.0	59,511.34	200	281,450	-	536
Segment Length (ft)	1897.2	735.82	618	4510	-	536
Number of Lanes	3.8	0.98	2	6	-	536
All Lanes Width (ft)	45.2	11.78	24	73	-	536
Average Lane Width (ft)	11.8	0.48	10.8	12.5	-	536
Left Shoulder Width (ft)	9.1	4.87	1.3	22.9	-	536
Right Shoulder Width (ft)	10.3	1.46	2.0	14.8	-	536
Closest Downstream Ramp (ft)	1861.2	1503.32	17	6938	-	536
Closest Upstream Ramp (ft)	1738.7	1208.59	320	7170	-	536

The lowest AADT value of 200 vpd is quite notable. This low AADT value is associated with sites 04-S-HO-3 and 20-S-HO-3, both sections of the Crosby Freeway. This freeway section was under construction between 2008 and 2009 and became operational sometime during year 2010. An aerial photograph from January 2010 (Figure 12) shows that these sections are almost ready to be opened to the public, but did not have any active traffic at the time of the photograph. The next photograph dated March 2011 (Figure 13) shows some traffic on this facility. Notably, the RHiNo database does not offer AADT readings for years earlier than 2010 for this site. For years 2011 and 2012, the AADT values for this new section of freeway were 19,480 and 21,000 vpd, respectively. Since there is record of traffic for year 2010 in the RHiNo database, this site was retained for subsequent safety analysis.

Figure 12. Satellite Image for Sites 04-S-HO-3 and 20-S-HO-3: January 2010.

Figure 13. Satellite Image for Sites 04-S-HO-3 and 20-S-HO-3: March 2011.

CHAPTER 4. OPERATIONAL ANALYSIS

INITIAL VARIABLE SELECTION

The operational dataset contained speeds per freeway lane. This detailed level of data enabled consideration of how the space on either side of the lane may have influenced driver's speed choice. Common knowledge is that freeway drivers operate at higher speeds when driving in the left-most lane as compared to the right-most lane. The "To_Left" and "To_Right" variables previously identified in Table 15 account for how the space to the left or to the right of a given lane is being used. When a shoulder is to the right of a lane, this variable indicates that the lane is the right-most lane for the freeway. The expectation is that operating speed is lower on this freeway lane compared to the other lanes.

The research team elected to model the relationship between operating speed and volume as a second degree curve, based on evidence from classical models (i.e., the Greenshields curve) and current characterizations (i.e., three-regime speed versus volume curves) that clearly shows that the relationship between speed and volume is not linear, but rather curvilinear.

The variable posted speed limit was removed from the analysis because only five sites in San Antonio had freeways with speed limits of 70 mph. While the posted speed limits for the freeways in San Antonio ranged from 60 to 70 mph, the freeways in Houston and Dallas only had either 60 or 65 mph speed limits. Because the city variable and the posted speed limit variable are confounded, only one of these variables should be included in the model. The research team selected the city variable for the subsequent model development activities.

FULL MODEL

The first step in the model development process is the construction of a full model that includes all variables that the literature suggested may have an impact on operating speed. Table 33 shows the results for the full model with significant variables highlighted (see final column). As noted in the table, several variables were not significant including variables of great interest to this research, lane width and shoulder width. The results indicated that the following variables are important:

- Volume.
- Natural light level of daytime or nighttime (NLight).

- Day of the week (Day_of_Week).
- Use of the space neighboring the lane (To_Left and To_Right).
- Median type (Med_Typ_Grass).

REDUCED MODEL

The next model development step was to remove the insignificant variables that were of lower interest to this research. Table 34 shows the results of the reduced model, which indicate that speeds are about 2.1 mph higher for 12-ft lanes as compared to 11-ft lanes. Additional left shoulder and right shoulder width may also be associated with faster speeds; however, those effects, if they exist, are too small to be determined as statistically significant in this model. It is possible that the differences may not be noticeable because of the limited range of shoulder width values. The HCM only includes adjustments to FFS when the right-side lateral clearance (or right shoulder) is 5 ft or less (see Table 3). For this dataset, the right shoulder widths were a minimum of 6 ft for 11-ft lane widths and 4 ft for 12-ft lane widths. In other words, very few sites in this Texas dataset had right shoulder widths in the range that other researchers have found to influence speeds on a freeway.

The model indicates that when a lane has a shoulder located to the immediate right (i.e., the lane on the far right of the freeway), the speed on that lane is about 7.2 mph lower than when a lane is located between two lanes. This observation is statistically significant and based on the assumption that everything else remains constant. The opposite effect is suggested for the left-most lane (with an adjacent left shoulder) where speeds are higher by approximately 1.7 mph when contrasted to a lane that is located between two lanes, but this finding was not statistically significant.

Table 33. Parameter Estimates for Full Model.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	67.625	3.956	663,641	17.094	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-1.8×10^{-04}	1.0×10^{-06}	663,641	−146.103	$<10^{-05}$	***
NLanes	0.113	0.812	51	0.139	0.890	
Med_Typ_Grass	4.483	2.158	51	2.077	0.043	**
L_Shld_W	0.041	0.128	132	0.319	0.750	
R_Shld_W	0.275	0.188	132	1.467	0.145	
Lane_W	1.070	1.299	51	0.826	0.413	
Ramp_Dwn_D	-3.4×10^{-04}	4.0×10^{-04}	51	−0.849	0.400	
Ramp_Up_D	-3.2×10^{-04}	5.0×10^{-04}	51	−0.682	0.498	
Ramp_Up_N	−0.125	0.607	51	−0.205	0.838	
Ramp_Dwn_N	−0.021	0.499	51	−0.042	0.967	
To_Left_B+P	3.674	0.890	132	4.127	1.0×10^{-04}	***
To_Left_Shld	4.184	2.581	132	1.621	0.107	
To_Right_SCL	−4.284	1.177	132	−3.641	4.0×10^{-04}	***
To_Right_Shld	−7.004	1.961	132	−3.571	5.0×10^{-04}	***
HC	−1.092	1.814	51	−0.602	0.550	
VC	0.088	1.432	51	0.062	0.951	
CityHouston	2.187	1.682	51	1.300	0.200	
CitySanAntonio	1.229	1.406	51	0.874	0.386	
NLight	−2.004	0.028	663,641	−71.708	$<10^{-05}$	***
Day_of_Week	−1.471	0.009	663,641	−171.533	$<10^{-05}$	***
MW-Shld:Med_Type_ Barrier	−0.810	0.627	132	−1.292	0.199	
MW-Shld:Med_Type_ Grass	−0.017	0.033	132	−0.514	0.608	

Where:

- Lane_W = {1 for 12 ft, otherwise 0}
- Med_Type_Grass = {1 if Grass, otherwise 0}
- To_Left_B+P = {1 if Buffer plus Pylons, otherwise 0}
- To_Left_Shld = {1 if Shoulder, otherwise 0}
- To_Right_SCL = {1 if Speed Change Lane, otherwise 0}
- To_Right_Shld = {1 if Shoulder, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)
- CityHouston = {1 for Houston, otherwise 0}
- CitySanAntonio = {1 for San Antonio, otherwise 0}

Significance values are as follows: ~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$

Table 34. Parameter Estimates for Reduced Model.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	67.695	0.701	663,641	96.570	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-1.8×10^{-04}	$<10^{-05}$	663,641	−146.108	$<10^{-05}$	***
Med_Typ_Grass	4.861	1.697	60	2.865	0.006	**
L_Shld_W	0.038	0.124	134	0.303	0.762	
R_Shld_W	0.289	0.184	134	1.575	0.118	
Lane_W	2.050	0.991	60	2.068	0.043	*
To_Left_B+P	3.569	0.879	134	4.060	1.0×10^{-04}	***
To_Left_Shld	1.718	1.378	134	1.247	0.215	
To_Right_SCL	−4.336	1.170	134	−3.706	3.0×10^{-04}	***
To_Right_Shld	−7.248	1.910	134	−3.795	2.0×10^{-04}	***
NLight	−2.004	0.029	663,641	−71.708	$<10^{-05}$	***
Day_of_Week	−1.471	0.009	663,641	−171.533	$<10^{-05}$	***

Where:

- Lane_W = {1 for 12 ft, otherwise 0}
- Med_Type_Grass = {1 if Grass, otherwise 0}
- To_Left_B+P = {1 if Buffer plus Pylons, otherwise 0}
- To_Left_Shld = {1 if Shoulder, otherwise 0}
- To_Right_SCL = {1 if Speed Change Lane, otherwise 0}
- To_Right_Shld = {1 if Shoulder, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)

Significance values are as follows: ~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$

The results indicate that Texas freeway drivers operate their vehicles at 2 mph lower speeds during nighttime conditions (with roadway lighting present). They also operate at higher speeds (1.5 mph) on the weekends (Saturday as compared to Wednesday). Speeds are about 4.9 mph higher on freeways with a grass median as compared to freeways with concrete median barriers (statistically significant).

Because the focus of this research effort is to determine the influence of the lane and shoulder width on corridor speeds, this reduced model retained the insignificant shoulder width variables; however, in order to further simplify the equation to predict speeds, the equation can be further reduced. This refinement of the reduced model, for practical speed estimation purposes, is included in the following section.

REFINEMENT OF THE REDUCED OPERATIONS MODEL

Table 35 depicts the significant variables in the final reduced model. With the removal of the shoulder width variables, every coefficient is now significant. A reduction in the AIC value of six points (from a value of 3,563,197 for the model shown in Table 34 to 3,563,191 for the model shown in Table 35) is evidence of a better balance between model complexity and goodness of fit. With the removal of the insignificant variables, the coefficients for some of the variables have minor changes, for example, the difference in speed between an 11-ft lane and a 12-ft lane is 2.05 mph when the insignificant variables are present (see Table 34) and increases slightly to 2.22 mph when the insignificant variables are removed (see Table 35). A moderate change occurs for the To_Right_Shld variable, going from −7.25 in Table 34 to −4.39 in Table 35.

Table 35. Parameter Estimates for Refined (Final) Reduced Operations Model.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	67.808	0.698	663,641	97.209	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-1.8×10^{-04}	$<10^{-05}$	663,641	−146.108	$<10^{-05}$	***
Med_Typ_Grass	4.606	1.687	60	2.731	0.008	***
Lane_W	2.215	0.984	60	2.250	0.028	*
To_Left_B+P	3.615	0.878	136	4.117	1.0×10^{-04}	***
To_Left_Shld	2.028	0.599	136	3.385	9.0×10^{-04}	***
To_Right_SCL	−3.890	1.135	136	−3.429	8.0×10^{-04}	***
To_Right_Shld	−4.387	0.589	136	−7.447	$<10^{-05}$	***
NLight	−2.004	0.028	663,641	−71.709	$<10^{-05}$	***
Day_of_Week	−1.471	0.009	663,641	−171.533	$<10^{-05}$	***

Where:

- Lane_W = {1 for 12 ft, otherwise 0}
- Med_Type_Grass = {1 if Grass, otherwise 0}
- To_Left_B+P = {1 if Buffer plus Pylons, otherwise 0}
- To_Left_Shld = {1 if Shoulder, otherwise 0}
- To_Right_SCL = {1 if Speed Change Lane, otherwise 0}
- To_Right_Shld = {1 if Shoulder, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)

Significance values are as follows: ~ $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$

The exclusion of the shoulder width variable, however, should not be interpreted as indicating that a shoulder does not influence speed choice. It is possible, for example, that speed choice is only influenced on outer lanes or at locations where shoulders are very narrow. The direct influence of the shoulder on the speeds in the adjacent lanes is further addressed in the following sections.

There may be a need to predict the speed for roadway corridors that fit within the boundary conditions observed for the sites studied in this research effort. The resulting equation, based on values presented in Table 35, is represented by the following equation:

$$\text{Speed} = 67.80 - 0.00018V^2_{5\text{-min/lane}} + 4.60(\text{Med\_Type\_Grass}) + 2.22(\text{Lane\_W}) + 3.62(\text{To\_Left\_B+P}) + 2.03(\text{To\_Left\_Shld}) - 3.89(\text{To\_Right\_SCL}) - 4.39(\text{To\_Right\_Shld}) - 2.00(\text{NLight}) - 1.47(\text{Day\_of\_Week})$$

Where:

$V_{5\text{-min/lane}}$ = Volume per 5-minute time period per lane (Ranges from 0 to 250 veh/5 minutes).

Variables as described in Table 35.

An application of this procedure is included in the following scenario.

Scenario 1
A transportation agency would like to know the expected daytime operating speed on a weekday for a freeway lane with the following characteristics: Hourly volume rate=1200 vehicles per hour, Number of lanes = 3, Median type = concrete barrier, Lane width = 12 ft, and Lane position = center lane.
<u>Solution:</u> The following conditions will apply to this calculation: • An hourly volume rate of 1200 veh/hr corresponds to 100 veh/5-min = (1200 veh/hr)/(20 5-min/hr periods)]. • The center lane in a 3-lane freeway section has a lane on both the right and left. • Wednesday can be considered a representative weekday. $\text{Speed} = 67.80 - 0.00018(100)^2_{5\text{-min/lane}} + 4.60(0) + 2.22(1) + 3.62(0) + 2.03(0) - 3.89(0) - 4.39(0) - 2.00(0) - 1.47(1) = 66.8$ mph
<u>Conclusion:</u> An operating speed of approximately 67 mph can be expected for the freeway lane.

LANE NEXT TO LEFT SHOULDER MODELS

The research team developed additional models to focus the investigation on the lane next to a shoulder and whether this lane is affected by the shoulder width. Figure 14 is a graph of the average speed (per site) on the lane next to the left shoulder contrasted to the left shoulder width. The data are subdivided by the lane width of 12 ft or 11 ft. As illustrated in Figure 14, the range of left shoulder widths is greater for the sites with 12-ft lanes (between 5 and 23 ft) as compared to sites with 11-ft lanes (between 1.5 and 11 ft).

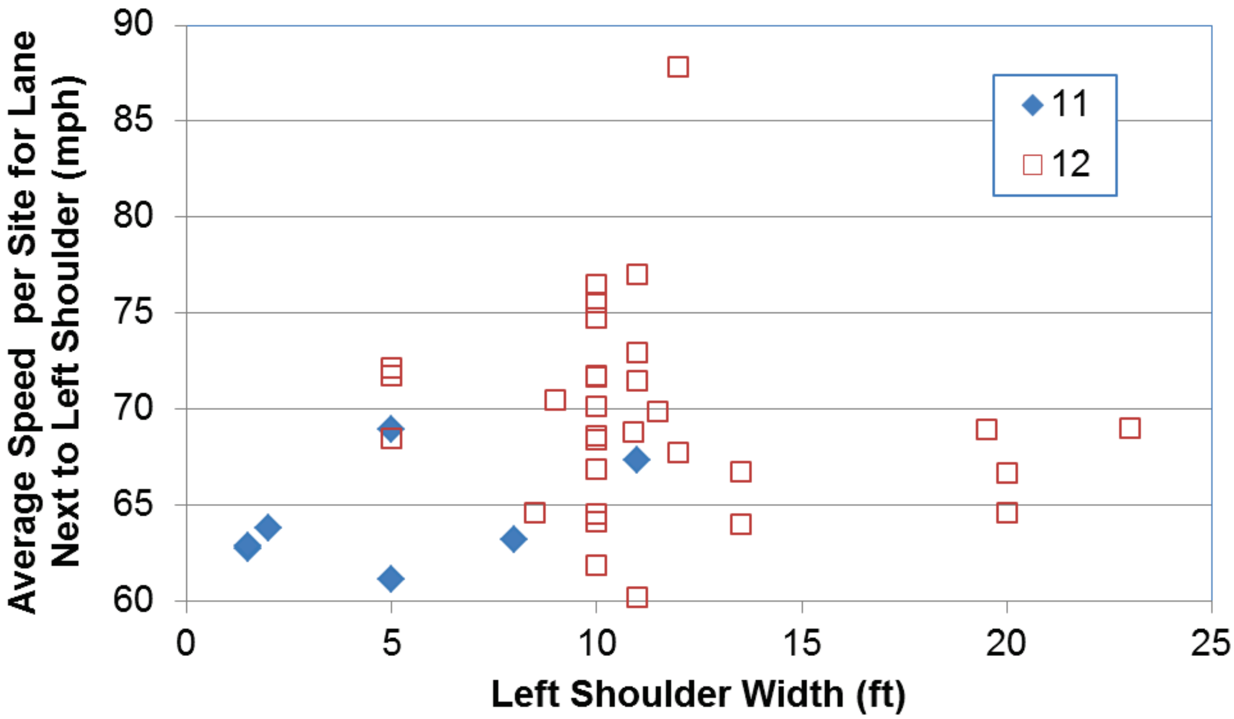


Figure 14. Average Speed per Site for Lane Next to Left Shoulder by Left Shoulder Width.

Table 36 provides the parameter estimates when the lane next to the left shoulder is 12 ft while Table 37 shows a similar analysis for 11-ft lanes. For 12-ft lanes, left shoulder width is not a significant variable. Left shoulder width is a significant variable for 11-ft lanes. Speeds increase by about 1.1 mph for each additional foot of shoulder width. Finding left shoulder width significant for 11-ft but not 12-ft lanes suggests that left shoulder width is more important with a reduced lane width.

Similar to the findings for the reduced model that combined all lane widths, the variables that are statistically significant are volume, natural light level, and the day of the week. The city was also significant with speeds being higher in Houston when compared to Dallas (about 5.5 mph) for 12-ft lanes. Speeds were similar for San Antonio and Dallas 12-ft lane sites. For 11-ft lanes, speeds were higher in Houston than San Antonio (about 8.0 mph). A comparison with Dallas sites was not possible for the 11-ft lane group because all Dallas sites with 11-ft lanes had a managed lane between the left-most general purpose lane and the left shoulder. Data for managed lanes were not included in this analysis.

Table 36. Parameter Estimates for 12-ft Lane Next to Left Shoulder.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	65.951	3.607	74,626	18.289	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-3.0×10^{-04}	5.0×10^{-06}	74,626	−64.180	$<10^{-05}$	***
Med_Typ_Grass	5.859	2.818	28	2.080	0.047	*
L_Shld_W	0.195	0.267	28	0.729	0.472	
CityHouston	5.491	2.574	28	2.133	0.042	*
CitySanAntonio	0.058	2.550	28	0.023	0.982	
NLight	−1.549	0.093	74,626	−16.569	$<10^{-05}$	***
Day_of_Week	−1.500	0.029	74,626	−51.127	$<10^{-05}$	***

Where:

- Lane_W = {1 for 12 ft, otherwise 0}
- Med_Type_Grass = {1 if Grass, otherwise 0}
- To_Left_B+P = {1 if Buffer plus Pylons, otherwise 0}
- To_Left_Shld = {1 if Shoulder, otherwise 0}
- To_Right_SCL = {1 if Speed Change Lane, otherwise 0}
- To_Right_Shld = {1 if Shoulder, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)
- CityHouston = {1 for Houston, otherwise 0}
- CitySanAntonio = {1 for San Antonio, otherwise 0}

Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001

Table 37. Parameter Estimates for 11-ft Lane Next to Left Shoulder.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	64.999	1.391	14,792	46.720	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-2.4×10^{-04}	8.7×10^{-06}	14,792	−27.855	$<10^{-05}$	***
L_Shld_W	1.141	0.394	5	2.893	0.034	*
CitySanAntonio	−8.028	2.690	5	−2.985	0.031	*
NLight	−2.080	0.183	14,792	−11.362	$<10^{-05}$	***
Day_of_Week	−1.582	0.059	14,792	−26.697	$<10^{-05}$	***

Where:

- CitySanAntonio = {1 for San Antonio, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)

Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001

LANE NEXT TO RIGHT SHOULDER MODELS

Next, the research team developed models for the right-most lane (i.e., the lane next to the right shoulder). The right shoulder width does not show statistical significance in either the 12-ft-lane model (see Table 38) or the 11-ft-lane model (see Table 39). Note that the adjustments in the HCM are for right-side lateral clearance of 0 to 6 or more feet. All of the 12-ft lane width sites in this dataset had 6 ft or more right shoulder width (lateral clearance). For 11-ft lane width sites, only four of the 37 sites had either 4-ft or 5-ft right shoulder widths.

Similar to left shoulder width, there is an increase in the size of the effect for right shoulder when the model is fitted to 11-ft lanes as compared to 12-ft lanes. The estimated effect per additional foot of shoulder width was an increase of 0.5 mph next to 12-ft lanes, compared to 1.1 mph next to 11-ft lanes. This observation suggests the possibility that the right shoulder width may be more important on segments with reduced lane widths. However, this increased effect is still not statistically significant.

Table 38. Parameter Estimates for 12-ft Lane Next to Right Shoulder.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	57.377	5.657	63,732	10.143	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-2.3×10^{-04}	5.0×10^{-06}	63,732	−44.484	$<10^{-05}$	***
Med_Typ_Grass	4.796	2.962	22	1.619	0.120	
R_Shld_W	0.518	0.556	22	0.931	0.362	
CityHouston	2.338	3.233	22	0.723	0.477	
CitySanAntonio	0.025	3.365	22	0.007	0.994	
NLight	−1.719	0.091	63,732	−18.785	$<10^{-05}$	***
Day_of_Week	−1.479	0.026	63,732	−56.491	$<10^{-05}$	***

Where:

- Med_Type_Grass = {1 if Grass, otherwise 0}
- CityHouston = {1 for Houston, otherwise 0}
- CitySanAntonio = {1 for San Antonio, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)

Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001

Table 39. Parameter Estimates for 11-ft Lane Next to Right Shoulder.

Parameter	Value	Std. Error	DF	t-value	p-value	Pr(>|z|)
Intercept	50.903	6.334	50,861	8.036	$<10^{-05}$	***
$V^2_{5\text{-min/lane}}$	-1.2×10^{-04}	4.0×10^{-06}	50,861	−32.126	$<10^{-05}$	***
R_Shld_W	1.118	0.655	11	1.707	0.116	
CityHouston	−5.300	2.508	11	−2.113	0.058	~
CitySanAntonio	0.288	2.768	11	0.104	0.919	
NLight	−1.880	0.088	50,861	−21.458	$<10^{-05}$	***
Day_of_Week	−1.077	0.027	50,861	−40.385	$<10^{-05}$	***

Where:

- CityHouston = {1 for Houston, otherwise 0}
- CitySanAntonio = {1 for San Antonio, otherwise 0}
- NLight = {1 for Night, otherwise 0}
- Day_of_Week = {1 for Wednesday (representing weekday), otherwise 0 (representing Saturday or weekend)

Significance values are as follows: ~ $p<0.1$; * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$

OPERATIONAL ANALYSIS SUMMARY AND CONCLUSIONS

The overall objective for the research effort reviewed in this chapter was to identify the operational implications of using reduced lane and shoulder widths for a variety of freeway configurations. The review of the literature identified several variables that could influence speed on a freeway lane including:

- Lane and shoulder widths,
- Use of the space to the right or left of the lane,
- Number and distance to ramps near the speed measurement point,
- Presence of horizontal or vertical curves,
- Natural lighting condition (i.e., day or night),
- Median width,
- Median type,
- Posted speed limit, and
- Vehicle type (passenger car or truck).

Because of the nature of the speed data available for this study, the analysis could not consider the type of vehicle. The data available were average speeds for 5-minute increments along with the number of vehicles within the same 5-minute period. The data were for individual lanes, allowing consideration of the effects of other lanes on the speed within a specific lane.

The dataset included speed and volume data for 121 lanes with 12-ft widths and 83 lanes with 11-ft widths. The analysis included urban freeways in Dallas, Houston, and San Antonio with 2 to 5 lanes per direction. The speed data were obtained for several hours on a Wednesday and a Saturday for each month in 2013 where data existed. In general, the team selected the second week of a month to avoid the majority of the holidays (e.g., Thanksgiving). Speed data, collected within 30 minutes of sunrise or sunset, were removed from the evaluation. To remove the potential effects of congestion, data when speeds were less than 50 mph or when 5-minute volume exceeded 250 vehicles were removed from the dataset. The modeling effort used the pooled database from all three cities. A total of 667,297 speed records were available with about an even split between 11-ft lanes (340,695 speed measurements) and 12-ft lanes (326,602 speed measurements).

The analysis found that there is an increase of about 2.2 mph in speed for a 12-ft lane as compared to an 11-ft lane. Additional left shoulder and right shoulder width may also be associated with faster freeway speeds; however, when evaluating 12-ft and 11-ft lane widths in the same model, those effects, if they exist, are too small to be found statistically significant within this dataset. Another possibility is that a difference may be present if smaller shoulder widths were available. For this dataset the right shoulder widths were a minimum of 6 ft for 11-ft lane widths and 4 ft for 12-ft lane widths. When evaluating the impacts of shoulder width on the lane next to the shoulder, the research team noted a statistically significant relationship between left shoulder width and speed on the left-most lane. Speed can be expected to increase by about 1.1 mph for each additional foot of shoulder width. Finding the left shoulder width significant for 11-ft but not 12-ft lanes implies that left shoulder width is more important with a reduced lane width.

The model indicates that the lane on the far right of the freeway has a speed that is about 4.4 mph lower (compared with a lane located between two other lanes), everything else equal (statistically significant). The results also indicate that Texas freeway drivers operate with 2 mph lower speeds during night time (with roadside lighting present) and at higher speeds (1.5 mph) on the weekends (Saturday as compared to Wednesday).

Posted speed limits have been found to be significant for other functional classification roads such as arterials (TRB, 2011); however, the posted speed limit variable for this freeway evaluation was not found to be significant in preliminary analyses. This finding is likely due to the small (60 to 70 mph) range of speed limits with most of the data associated with the 60 mph speed limit. Similarly, this study did not determine the number of freeway lanes to be significant in the models.

The HCM includes adjustments to the freeway FFS for lane width and right-side lateral clearance. The result of this Texas study indicates that the reduction in FFS is slightly greater for 11-ft lanes (2.2 mph) than the value present in the HCM (1.9 mph). The HCM provides FFS reductions when the right-side lateral clearance is less than 6 ft. For left-side (or median-side) lateral clearances, the HCM comments that clearances 2 ft or more have little influence on freeway operations. The findings from this Texas study support the HCM right-side recommendations for lateral clearances of 6 ft and greater in that no adjustments are needed to the FFS. The findings from this Texas study did indicate that modifications to the HCM with respect to left-side lateral clearances may be appropriate under select conditions. Table 40 shows the adjustments to FFS of an 11-ft, left-most lane due to left-side lateral clearances of less than 10 ft, based on the findings from the evaluation that focused on the impact of left shoulder width on left-most lane.

Table 40. Adjustment to FFS for Left-Most Lane Due to Left-Side Lateral Clearance on Freeway with 11-ft Lane Based on Findings from Evaluation that Focused on the Impact of Left Shoulder Width on Left-Most Lane.

Left-Side Lateral Clearance (ft)	Adjustment to FFS (mph)
10 ft or more	0.0
9	1.1
8	2.2
7	3.3
6	4.4
5	5.5
4	6.6
3	7.7
2	8.8
1	9.9

The research team developed a final reduced model for use in estimating speed, as demonstrated in Scenario 1. This model can be used by decision makers to balance the various geometric considerations, but should only be used for scenarios that adhere to its associated boundary conditions.

CHAPTER 5. SAFETY ANALYSIS

In preparation for developing models to predict the number of crashes for a specific freeway configuration, the research team examined marginal plots of the most relevant variables. Figure 15 shows a direct proportion between the number of crashes and how they tend to increase with increasing AADT. This observation is expected since it is known that there are more opportunities for crashes in proportion to the AADT.

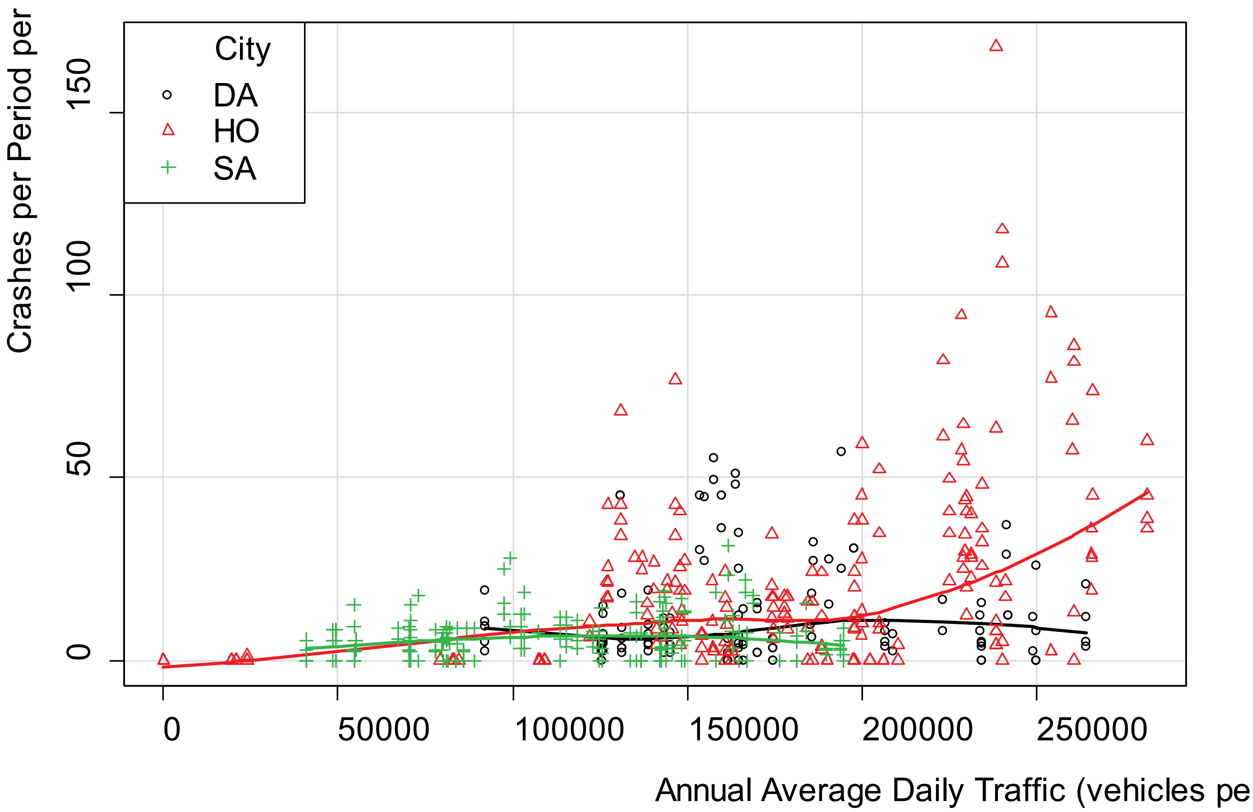


Figure 15. Crashes per Mile vs. AADT.

There are two exposure measures in the dataset: Number of Years (i.e., the length in time represented by a database record, expressed in years) and Segment Length (length of a Site segment, expressed in miles). The exploratory analysis helped to identify potential trends of the variables of interest, when controlling preliminarily by exposure and AADT. For this purpose, the research team calculated the quantity (yearly crashes per vehicle miles traveled [VMT]) × 1000, which is the rate of 1000 crashes per vehicle-mile-traveled per year and contrasted this variable to the cross-sectional elements of interest.

Figure 16 shows the trend of this variable versus the average lane width. Except for 2-lane freeways (representing lanes wider than 11.8 ft only), there is a clear decreasing trend, though there is a significant amount of unexplained variability, probably associated with differences in other critical variables.

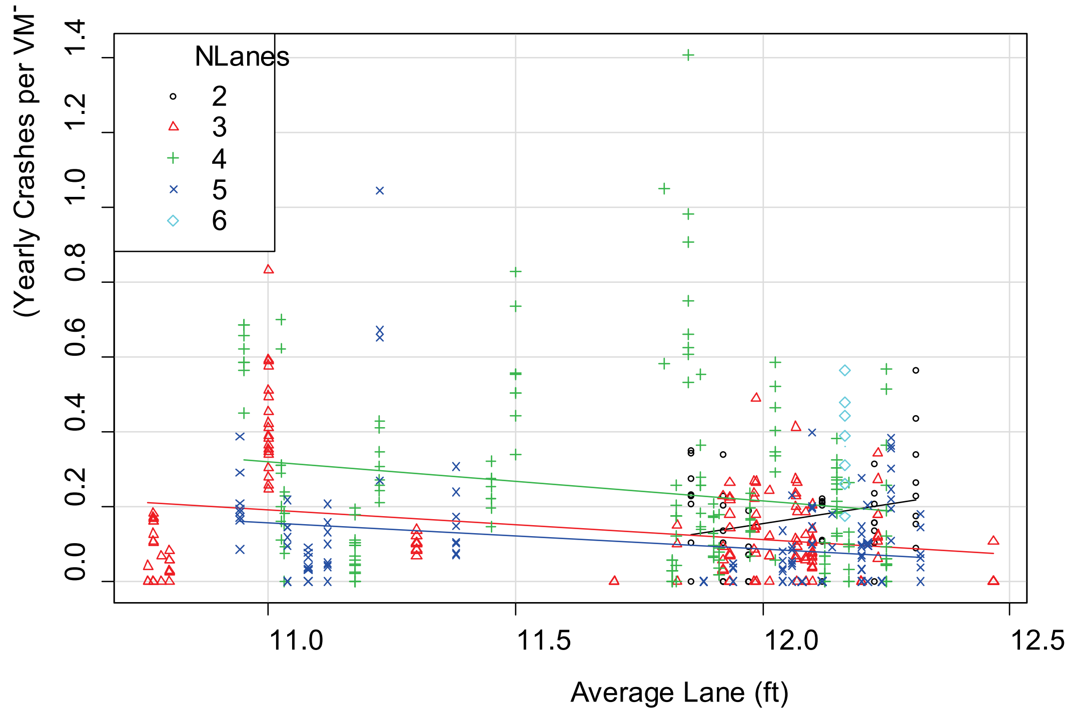


Figure 16. (Yearly Crashes per VMT) × 1000 vs. Average Lane Width.

As shown in Figure 17, the trend for left shoulder width, however, is more distinct. Again, only 2-lane freeways appear to have a flat trend line.

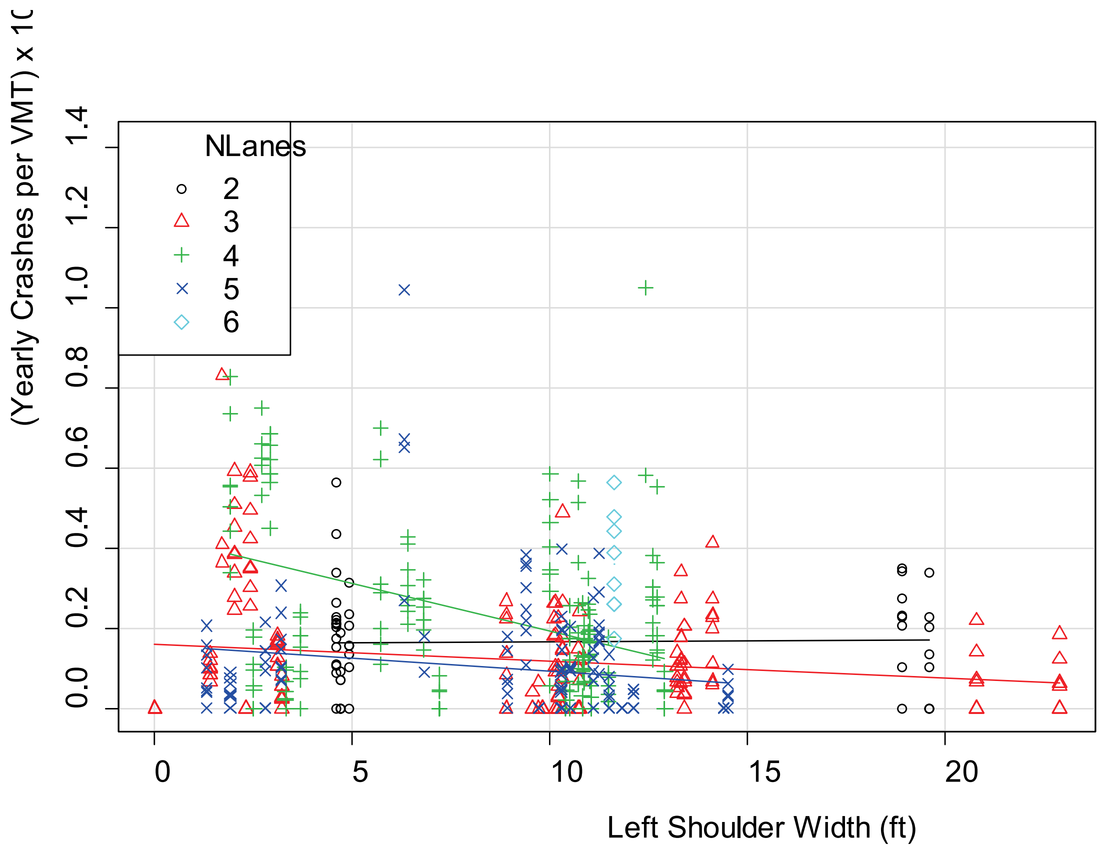


Figure 17. (Yearly Crashes per VMT) × 1000 vs. Left Shoulder Width.

Next, the research team examined the relationship between the right shoulder and crashes. Figure 18 shows a preliminary assessment of this relationship. In this case, although there are a few sites with relatively narrow shoulders and a few sites with 15 ft shoulders, this variable is representative of a narrow range with most shoulders being between 9 and 12 ft.

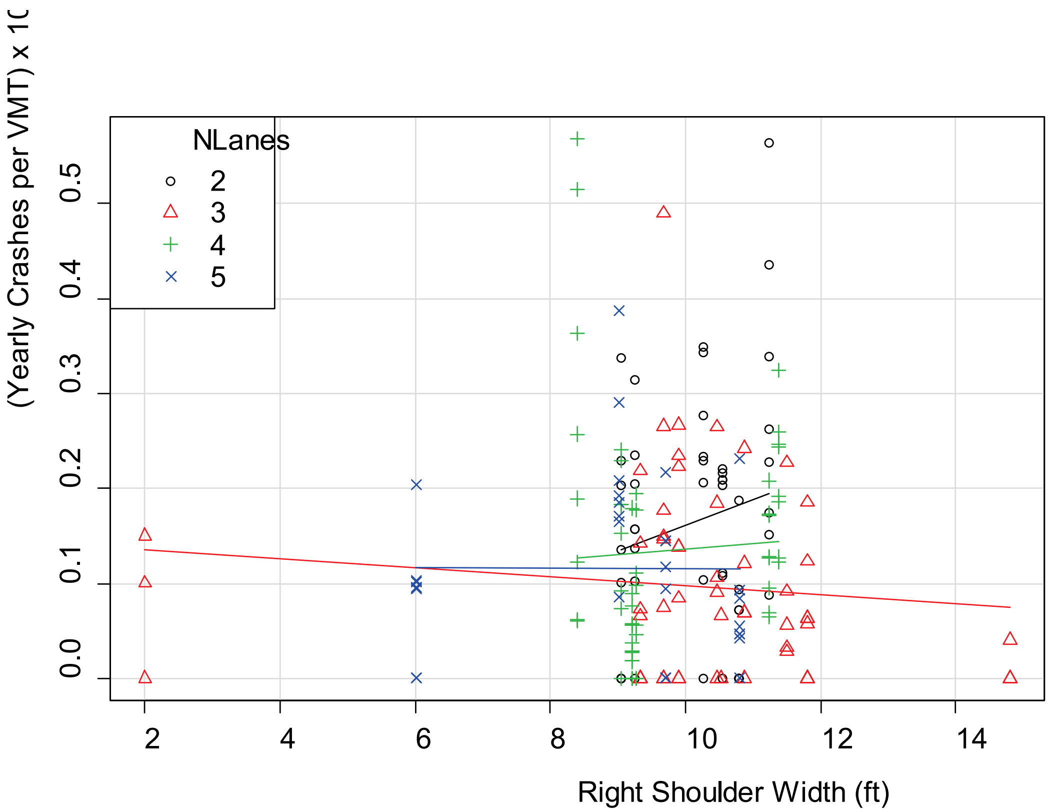


Figure 18. (Yearly Crashes per VMT) × 1000 vs. Right Shoulder Width.

A gap in data is noticeable between 2 ft and 6 ft right shoulders. The three segment-periods with a 2-ft right shoulder correspond to one site in San Antonio, where a concrete barrier was present between October 2012 and September 2014 (see Figure 19). The implications of having this site in the analysis will be reviewed later in this section.

Figure 19. Street View of Site with Narrowest Right Shoulder Width.

Although this exploratory analysis suggests that the number of crashes tends to be smaller for wider cross-sectional elements, a formal evaluation of that relationship requires controlling for other influential variables. The next section describes the statistical methodology and analysis results for this formal evaluation.

STATISTICAL MODEL

Every statistical evaluation is based on a set of assumptions about the data, and how that data relates to mathematical structures and statistical distributions. The following section provides an overview of the statistical methodology selected for this research.

Statistical Methodology

Because the data included more than one time period from each site, the statistical methodology had to explicitly consider the grouping structure in the data. All crashes from a common space unit (i.e., site) should be considered a cluster that shares an expected baseline number of crashes. The methodology in this effort includes random effects as the modeling tool to account for this baseline of crashes. Any contributions to the number of crashes at a site that due to unobserved variables or factors is implicitly captured in the mentioned baseline for that site, after controlling for the effects of the known variables.

A Poisson-lognormal Generalized Linear Mixed model has the required ability to account for both random and fixed effects simultaneously. The model is constructed under the assumption that the number of crashes at study sites for a given time period follows the Poisson (or random) distribution. The random effect variability is modeled as white noise around the average of crashes at the reference level in the sample of segment-periods of analysis.

Poisson-Lognormal Mixed Model

There are several analysis periods for a given site *i* in the dataset. The model specifies that all observed crashes at site *i* from all available *j* analysis periods can be reasonably described by the Poisson distribution, whose probability function is given by:

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

where:

N_i = Number of crashes at any given analysis period for the i-th site.

n_{ij} = An actual count of crashes for the j-th analysis period at the i-th site, such that $n_{ij} \in \{0, \mathbb{Z}^+\}$.

λ_i = Poisson distribution parameter at the i-th site.

It can be shown that the expected number of crashes at the i-th site is simply $E(N_i) = \lambda_i$ for the Poisson distribution.

The research team constructed the database to represent time periods of different lengths (all shorter than a year, half a year at the most); additionally, each site was characterized by different homogeneous cross-section freeway lengths. It is necessary to control for these differences explicitly.

The product of the time period length (expressed in years) and the segment length (expressed in miles) for each record in the database has units of mile-years (mi-yr). This product quantifies the amount of exposure to the crash generation process that resulted in n_{ij} observed crashes. Therefore, for a given segment-period with amount of exposure γ, a model can be established such that:

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

where:

ϑ_i has units of crashes/mi-yr.

Since $\gamma = 1.0$ when segment length = 1 mi, and period length=1 year, ϑ_i can be estimated by regression techniques, such that the interpretation of the results is in terms of the change in expected yearly crashes per mile corresponding to changes in the critical observed variables (named fixed effects from this point forward).

The exponential function is used to parameterize the quantity ϑ_i so that it links crash counts from each site to a corresponding set of critical observed variables. For the i-th site, the parameter ϑ_i is such that:

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

where:

AADT	=	Annual Average Daily Traffic (vpd).
α	=	Fixed exponent.
X	=	Vector of fixed effects (i.e., explanatory variables).
T	=	Represents the matrix operation of transposition, necessary to multiply vectors X and β.
β	=	Vector of fixed-effects coefficients.
RE_i	=	Random effect for i-th site.

All other variables as previously defined.

As indicated by the sub-index, the model estimates a unique RE_i for each site i. The distribution of all RE_i should roughly be log-normal, a characteristic that must be verified after the model estimation. This requirement is represented by the following equation form:

$$RE_i \sim \text{LogNormal}(\mu, \sigma^2)$$

where:

μ = Location parameter of lognormal distribution.

σ^2 = Scale parameter of lognormal distribution.

All other variables as previously defined.

If the above condition holds, then it can be shown that:

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

where:

ϑ = is the expected yearly crashes per mile, given AADT and the variables represented in $\boldsymbol{X}$.

The above equation applies to a population of sites, given the sites in the database are representative of the larger population. This representativeness is easily established if the data at hand were a random sample of sites. For this study, the site selection process was not completely random for a variety of reasons including the need to co-locate crash analysis sites with operational sites where possible. However, statistical inference is still possible but in reference to a theoretical underlying population of sites.

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., α and β). The quantity ϑ represents the expected number of yearly crashes per mile, at any site, after accounting for the particular values of its fixed-effects since:

$$E(N) = \lambda = \gamma \cdot \vartheta = \vartheta | \gamma = 1.0$$

The next section reviews results from estimating the model from the methodology just described.

PRELIMINARY MODELS FOR TOTAL CRASHES

As a first step, the research team selected the variables to be included as fixed effects in the model and the variables that define exposure. These variables were selected based on the findings of previous studies and as published in the associated literature. These initial model variables included AADT, segment length, number of lanes, and proximity of ramps. The researchers also included an indicator variable for the associated city so as to account for differences among the three study cities that may be due to other characteristics not directly captured by the variables. The cross-sectional elements (lane and shoulder width) were also included at this point to explore their influence on the number and type of crashes. Table 41 shows the coefficients for the set of initial candidate variables.

Table 41. Full Model Estimates.

Parameter	Estimate	Std. Error	z-val	p-val	Pr(>|z|)
$\boldsymbol{\alpha}$	4.89×10^{-01}	2.21×10^{-01}	2.213	0.027	*
Ave_Lane_W	2.54×10^{-01}	3.42×10^{-01}	0.741	0.459	
NLanes	-4.66×10^{-01}	1.81×10^{-01}	−2.569	0.010	*
Leftmost_Cond_Grass	−1.32	9.82×10^{-01}	−1.342	0.180	
Leftmost_Cond_Barrier	-1.20×10^{-01}	6.33×10^{-01}	−0.189	0.850	
R_Shld_W	-7.88×10^{-02}	4.50×10^{-02}	−1.749	0.080	~
L_Shld_W	-1.06×10^{-01}	3.86×10^{-02}	−2.741	0.006	**
CityHouston	3.66×10^{-01}	5.26×10^{-01}	0.697	0.486	
CitySanAntonio	3.27×10^{-01}	5.30×10^{-01}	0.616	0.538	
Ramp_Up_D	-2.39×10^{-04}	1.08×10^{-04}	−2.212	0.027	*
Ramp_Dwn_D)	-2.02×10^{-04}	9.62×10^{-05}	−2.104	0.035	*
Posted Speed Limit	-3.08×10^{-02}	6.67×10^{-02}	−0.462	0.644	
$\boldsymbol{\mu}_{\mathbf{ln}(\boldsymbol{RE})}$	5.06×10^{-02}	6.36	0.008	0.994	
$\boldsymbol{\sigma}^{\mathbf{2}}{}_{\mathbf{ln}(\boldsymbol{RE})}$	1.104				
Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001					

Several of the coefficients shown in Table 41 do not have significant influences for explaining crash counts. In particular, (1) there are no significant differences between sites from the three cities under study, and (2) there are no significant differences among the three left-most conditions (i.e., beyond the left shoulder) of the segments represented in the database: (a) buffer/pylons separating HOV lane from the general purpose lanes; (b) grass median; and (c) concrete barrier.

However, the number of lanes and shoulder widths are statistically significant variables, even when the model includes many other insignificant variables. As these variables increase (e.g., when wider shoulders are present), fewer crashes occur. The number of lanes is associated with a crash reduction, in contrast to the insignificant average lane width value. The research team performed a step-wise model reduction, a procedure that arrived at the coefficients shown in Table 42.

Table 42. Reduced Total Crash Model Estimates.

Parameter	Estimate	Std. Error	z-val	p-val	Pr(>|z|)
$\boldsymbol{\alpha}$	5.40×10^{-01}	2.19×10^{-01}	2.467	0.014	*
Ave_Lane_W	1.05×10^{-01}	2.87×10^{-01}	0.367	0.714	
NLanes	-3.02×10^{-01}	1.54×10^{-01}	−1.961	0.050	*
R_Shld_W	-7.31×10^{-02}	4.38×10^{-02}	−1.667	0.096	~
L_Shld_W	-8.09×10^{-02}	3.19×10^{-02}	−2.541	0.011	*
Ramp_Up_D	-2.04×10^{-04}	1.06×10^{-04}	−1.932	0.053	~
Ramp_Dwn_D	-2.00×10^{-04}	9.46×10^{-05}	−2.111	0.035	*
$\boldsymbol{\mu}_{\ln(\boldsymbol{RE})}$	−1.50	4.22	−2.41	1.59×10^{-02}	*
$\boldsymbol{\sigma}^{\boldsymbol{2}}{}_{\ln(\boldsymbol{RE})}$	1.168561				
Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001					

Following the systematic removal of the posted speed limit, left-most condition, and city variables, the remaining variables previously depicted in Table 41 maintained their statistical significance. The only critical variable without a significant effect is the average lane width.

After a closer examination of the explanatory variables, the research team determined that an important correlation exists between two critical variables: left shoulder and average lane widths. This correlation influences the relative magnitudes and statistical significance of the estimates for the involved variables. Figure 20 illustrates this issue. The widest left shoulders in the dataset tend to be paired with the widest average lane widths, regardless of the number of lanes in the cross section.

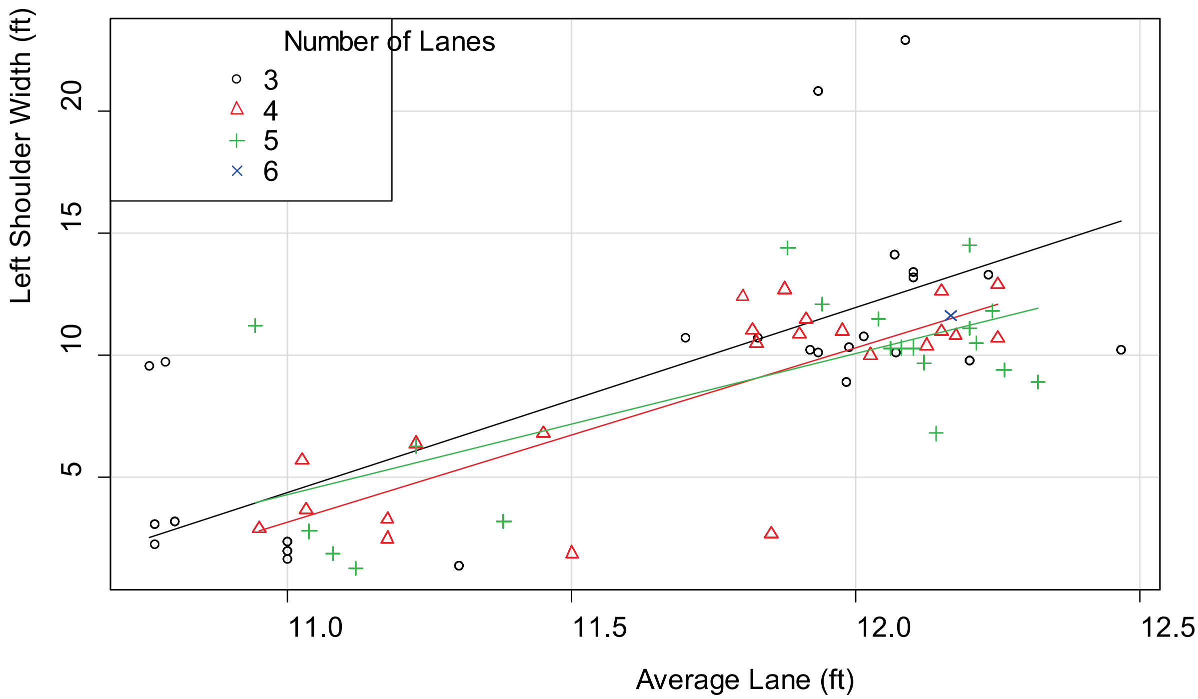


Figure 20. Left Shoulder Width vs. Average Lane Width.

In contrast, the variable width of all lanes (All_Lanes_W) is relatively independent of the left shoulder width, as can be seen in Figure 21. This figure also shows that the variable All_Lanes_W is distinct for segments with different numbers of lanes; all segments with the same number of lanes have a range for All_Lanes_W that does not overlap with the range of segments with any other number of lanes. This implies that for segments with the same number of lanes, the additional variability of All_Lanes_W is due to differences in the width of the average lane. Accordingly, the mathematical relationship among Ave_Lane_W, All_Lanes_W, and NLanes establishes that there is only one possible value for one variable, given that the other two are fixed:

(Ave_Lane_W) = (All_Lanes_W) / (NLanes)

Another important observation is that All_Lanes_W is a direct substitute for Ave_Lane_W for a fixed NLanes value because of the distinct relationship between All_Lanes_W and NLanes.

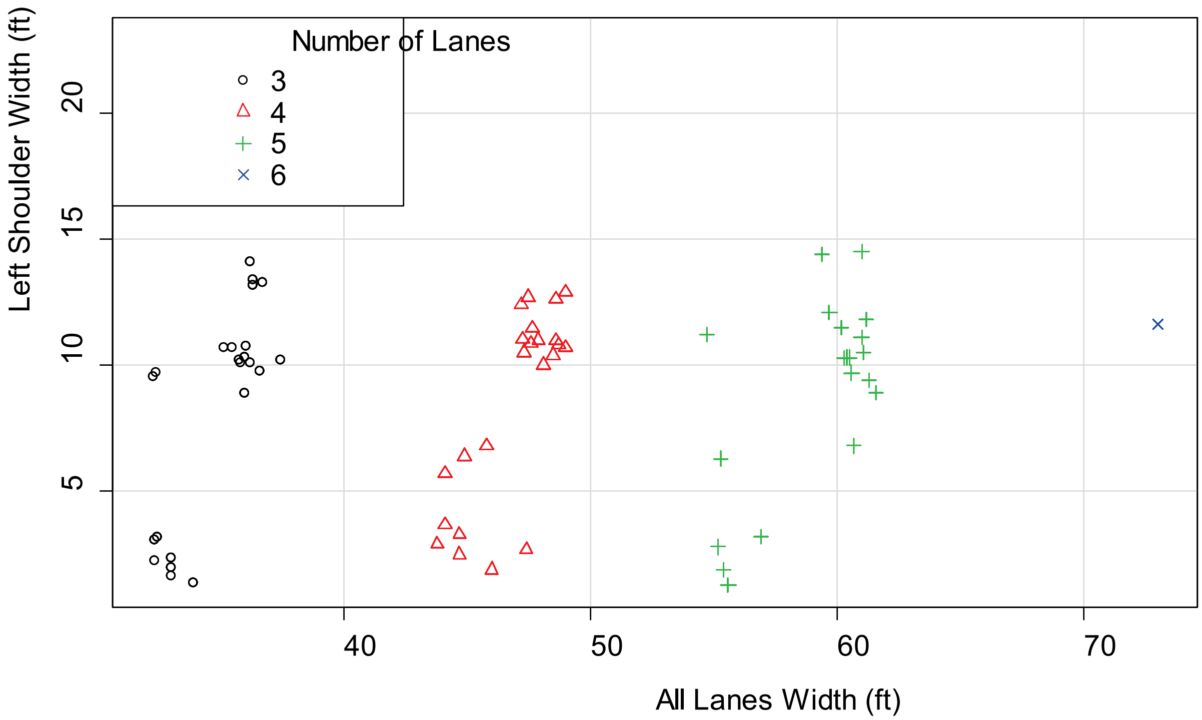


Figure 21. Left Shoulder Width vs. All-Lanes Width (All_Lanes_W)

Considering the advantages of using All_Lanes_W instead of Ave_Lane_W, the research team fit a model by substituting All_Lanes_W for the two variables (Ave_Lane_W and NLanes). Table 43 shows the final total crash model.

Table 43. Final Reduced Model Estimates for Total Crashes

Parameter	Estimate	Std. Error	z-val	p-val	Pr(>|z|)
α	5.39×10^{-01}	2.19×10^{-01}	2.459	0.014	*
All_Lanes_W	-2.41×10^{-02}	1.30×10^{-02}	−1.854	0.064	~
R_Shld_W	-7.35×10^{-02}	4.33×10^{-02}	−1.696	0.090	~
L_Shld_W	-6.46×10^{-02}	2.20×10^{-02}	−2.933	0.003	**
Ramp_Up_D	-1.94×10^{-04}	1.02×10^{-04}	−1.901	0.057	~
Ramp_Dwn_D	-2.06×10^{-04}	9.21×10^{-05}	−2.238	0.025	*
$\mu_{\ln(RE)}$	-5.73×10^{-01}	2.66	−3.44	5.76×10^{-04}	
$\sigma^2_{\ln(RE)}$	1.151329				
Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001					

This model establishes that there is an inverse relationship between the number of crashes and the following variables: All_Lanes_W, R_Shld_W, L_Shld_W, Ramp_Up_D, and Ramp_Dwn_D. More details on these relationships will be provided later in this chapter. The model can be presented in the following equation format:

$$N_{\text{Total}} = 1.0027 \times L \times AADT^{0.539} \times e^{[-1.0243(\text{Ramp\_Up\_D})-1.0877(\text{Ramp\_Dn\_D})-0.0241(\text{NLane}\times\text{Lane\_W}_{\text{Avg}})-0.0735(\text{R\_Shld\_W})-0.0646(\text{L\_Shld\_W})]}$$

Where:

N_{Total} = Total number of predicted crashes (crashes per year).

L = Length of study segment.

AADT = Annual average daily traffic in one direction (vpd).

Ramp_Up_D = Distance to closest upstream ramp (ft).

Ramp_Dn_D = Distance to closest downstream ramp (ft).

NLane = Number of travel lanes in a single direction.

$Lane\_W_{Avg}$ = Average lane width (ft).

R_Shld_W = Width of right shoulder (ft).

L_Shld_W = Width of left shoulder (ft).

MODEL FOR KAB CRASHES

The association of the lane and shoulder width on frequency of total crashes, while important, may not be as critical as the relationship between these road characteristics and injury crashes (specifically KAB crashes). To evaluate this relationship, the research team used the total crash model and developed a corresponding KAB crash model. The resulting coefficients have trends that are consistent to those previously observed for total crashes. Table 44 presents the KAB model.

Table 44. Final Model Estimates for KAB Crashes.

Parameter	Estimate	Std. Error	z-val	p-val	Pr(>|z|)
α	6.62×10^{-01}	2.65×10^{-01}	2.495	0.013	*
All_Lanes_W	-2.53×10^{-02}	1.10×10^{-02}	−2.295	0.022	*
R_Shld_W	-9.56×10^{-02}	5.08×10^{-02}	−1.883	0.060	~
L_Shld_W	-5.47×10^{-02}	2.23×10^{-02}	−2.455	0.014	*
Ramp_Up_D	-2.99×10^{-04}	9.36×10^{-05}	−3.195	0.001	**
Ramp_Dwn_D	-1.64×10^{-04}	7.29×10^{-05}	−2.249	0.024	*
$\mu_{\ln(RE)}$	−3.18	3.05	−3.85	1.17×10^{-04}	
$\sigma^2_{\ln(RE)}$	0.4186				
Significance values are as follows: ~ p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001					

This model can be written in the following equation format:

$$N_{KAB} = 0.0514 \times L \times AADT^{0.662} \times e^{[-1.5787(RampUp_{Dist})-0.8659(RampDn_{Dist})-0.0253(NoLn\times LaneW_{Avg})-0.0956(RShld)-0.0547(LShld)]}$$

DISCUSSION OF RESULTS

The coefficients for the KAB crashes model indicate that:

- There is a safety improvement associated with increased lane width for lanes up to and not exceeding 12-ft wide. Each coefficient estimate represents the rate of change for the natural logarithm of KAB crashes per unit of change for the independent variable. In the case of average lane width, the rate can be derived from the coefficient for All_Lanes_W as follows:

$$\frac{\partial}{\partial Ave\_Lane\_W} \ln E[KAB_{Crashes}] = (\beta_{All\_Lanes\_W}).(No\_Lanes)$$

Using this relationship, Table 45 shows the safety benefit of 12-ft lanes compared to 11-ft lanes, based on the number of travel lanes per direction, when there are no changes in the other variables included in the model.

Table 45. Safety of Lane Width (KAB Crashes).

NLanes	Multiplicative Effect in Model	KAB 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%

- Similarly, there is a safety improvement associated with each additional lane. This effect can be also derived from the coefficient for All_Lanes_W. For a constant lane width, when there are no changes in the other model variables, calculating the reduction in crashes for an additional lane can be determined using the following relationship:

$$\frac{\partial}{\partial NLanes} \ln E[KAB_{Crashes}] = (\beta_{All\_Lanes\_W}).(Ave\_Lane\_W)$$

Table 46 shows the safety benefit per additional lane, given different average lane widths.

Table 46. Safety Change per Additional Lane (KAB Crashes).

Average Lane Width (ft)	Multiplicative Effect	Reduction of KAB Crashes per Additional Lane
11.0	0.76	24%
11.5	0.75	25%
12.0	0.74	26%

- There is a safety improvement associated with increased left shoulder widths. This effect is a reduction of crashes by 5 percent (5 percent = $1 - \exp(-5.47\times10^{-02})$) per additional foot of left shoulder, when there are no changes to the other model variables.
- There is a safety improvement associated with increased right shoulder widths. This effect is a reduction of crashes by 9 percent (9 percent =$1 - \exp(-9.56\times10^{-02})$) per additional foot of right shoulder, when there are no changes in the rest of variables in the model.

Sensitivity of the Results for the Right Shoulder Effect

The research team reviewed how the results are affected by including data from site 13-R-SA-3 when right shoulder was reduced to 2 ft (see Figure 19). This is the narrowest right shoulder width in the dataset and a sizable gap exists between this minimum value and the next shoulder width value of 6 ft (see Figure 18). The effect of right shoulder in the model is distinct and significant for the range of right shoulders represented when this site is included in the analysis (2 ft to 14.8 ft). However, when the data from this site are not included in the analysis, the effect of right shoulder is statistically insignificant (0.790 p-value), with the range of the represented right shoulder widths represented being significantly reduced as well (6 ft to 14.8 ft).

The research team carefully examined the data from this site, but did not find any valid reasons to not include it in the analysis. Furthermore, this site is one of the few in the dataset where changes in the cross section were detected in the aerial photographs. Table 47 presents the data corresponding to the two periods when this site had distinctly different widths for critical cross-section elements. Unfortunately, the two periods differ in variables other than just the right shoulder that impedes an intuitive, direct comparison of the effect of right shoulder. For example, the AADT has expectedly increased, and the distances to the closest upstream and downstream ramps have also changed, indicating the addition of new ramps and the removal of older decommissioned ramps.

Table 47. Changes in Cross Section and Crashes for Site 13-R-SA-3.

Feature	Before Period	After Period
Years	2010–2012	2012–2013
Period Length in Dataset	2.3 years	1.1 years
AADT	138,008 vpd	162,800 vpd
Right Shoulder	11.5	2.0
Ramp_Up_D	0.29 mi	0.41 mi
Ramp_Dwn_D	0.93 mi	0.35 mi
Yearly Total Crash Expectation	6.22 crashes/yr	7.99 crashes/yr
Predicted Total Crashes for Period	14.30	8.79
Observed Total Crashes for Period	13	10
Yearly KAB Crash Expectation	1.73 crashes/yr	3.42 KAB/yr
Predicted KAB for Period	3.98	3.76
Observed KAB Crashes for Period	4	4

The data presented in Table 47 corresponds to the site with the largest change in right shoulder identified for this study. The researchers calculated the yearly crash expectations as shown in Table 47 using the coefficients from the models in Table 43 and Table 44. These yearly expectations indicate increases in both total crashes and KAB crashes between the periods with different cross sections. The research team does not consider the trends observed at this site anomalous at any level other than the unusually narrow right shoulder for the second time period; on the contrary, the expected change in yearly crashes corresponds very closely with the actual crash frequencies observed for each period.

Even when the analysis appropriately accounts for the crash trends observed at the site with the narrowest right shoulder, the research team recognizes that the statistical significance of the effect for right shoulder in the analysis is dependent upon including the data from this site. This observation will be noted in the conclusions.

Safety Associated with Freeway Sections

Using the statistical model developed in this study, it is possible to make calculations of the expected safety changes associated with various scenarios. The research team developed a spreadsheet to help with the model calculations; however, the calculations can be manually performed as demonstrated in the following scenario.

Scenario 2
A transportation agency would like to know the expected total number of crashes and number of injury crashes for a freeway section with the following characteristics: Length = 0.5 miles AADT = 150,000 NLanes = 4 lanes Ramp_Up_D = 0.5 mi Ramp_Dwn_D = 1.0 mi Ave_Lane_W = 12 ft lanes (or All_Lanes_W = 48 ft) R_Shld_W = 10 ft L_Shld_W = 6 ft
$N_{Total} = 1.0027 \times (0.5) \times 150{,}000^{0.539} \times e^{[-1.0243(0.5)-1.0877(1.0)-0.0241(4\times12)-0.0735(10)-0.0646(6)]} = 6.39$ $N_{KAB} = 0.0514 \times 0.5 \times 150{,}000^{0.662} \times e^{[-1.5787(0.5)-0.8659(1.0)-0.0253(4\times12)-0.0956(10)-0.0547(6)]} = 1.08$
Conclusion: A total number of approximately 6 crashes, including 1 injury crash, can be expected for the freeway location.

The research team prepared additional scenarios where the intent is to estimate the impact on expected number of crashes associated with changes in cross sectional elements. In order to address these scenarios, some of the variables present in the model are not necessary -- only the variables where changes are expected.

The marginal safety change associated with the change for a particular variable is simply:

$$\Delta\, KAB_{Crashes} = \exp\left[\left\{\frac{\partial}{\partial Variable}\ln E[KAB_{Crashes}]\right\}.(\Delta Variable)\right]$$

By extension, to calculate the total change in crashes due to changes in multiple variables, the expression inside the brackets on the right side of the equation can include additional summands corresponding to marginal changes of each variable. Scenario 3 and Scenario 4 demonstrate this procedure.

Scenario 3
A transportation agency is considering adding a general purpose lane to the freeway section introduced in Scenario 2, but would like to maintain the same width of the paved surface. Adding a lane requires reducing the width of the current the lanes and shoulders. The agency would like to know the expected change in KAB crashes due to the change in the cross section. If the 64 ft of available cross-sectional space were to be converted to 5 freeway lanes with an average lane width of 11 ft, a right shoulder of 8 ft, and a left shoulder of 1 ft, then the expected change in the number of crashes can be estimated as follows:
$Change\ in\ Crashes = \exp[\{(-2.53) \times 10^{-02}\} \times (55 - 48) + \{(-9.56) \times 10^{-02}\} \times (8 - 10) + \{(-5.47) \times 10^{-02}\} \times (1 - 6)] = 1.33$
Conclusion: If there are no other changes to the site variables, this would then represent an increase of 33% in the number of KAB crashes. The primary contributing factor to this predicted increase in crashes is the reduction of the shoulder widths. This resulted in larger adverse safety effects than the positive safety effects of adding a new lane. In fact, the analysis indicates that a net adverse safety effect is expected for any shoulder reduction that corresponds to an equal increase in the total width of the travel lanes, since the magnitude of coefficients corresponding to the shoulder widths are substantially larger than the coefficient for total lanes width.

Scenario 4

Consider the same scenario as in Scenario 3 but, in this case, the total paved surface width can be increased by up to 10 ft. To minimize pavement costs, however, it is of interest to only widen the road as much as needed to have no net change in the number of KAB crashes. The two key questions would then be:

- What is the minimal additional pavement width needed so that the number of KAB crashes does not increase?
- How should this additional pavement width be allocated between lanes and shoulders?

This evaluation can be performed as follows:

$$Change\ in\ Crashes = \exp[(-2.53) \times 10^{-02} \times (TotalLanes\_W_{new} - 48) + (-9.56) \times 10^{-02} \times (R\_Shld\_W_{New} - 10) + (-5.47) \times 10^{-02} \times (L\_Shld\_W_{New} - 6)] = 1.0$$

Optimization: It is clear that the safety impact of reducing shoulders outweighs the safety benefit of increasing the width assigned to the travel lanes (i.e., per foot of paved width). Therefore, an optimal solution should minimize the reduction of current shoulder width, if reduction of shoulders is at all necessary.

Although it is possible to manually explore solutions to this problem, convenient tools such as the Excel optimization tool can be used to evaluate this issue. One optimal solution to this problem (specifying that the number of KAB crashes should remain unchanged) results in the following values:

- All_Lanes_W = 55.6 ft
- R_Shld_W = 10.2 ft
- L_Shld_W = 2.2 ft

This solution corresponds to a total paved width of 68 ft (4 ft of additional road width), with an average lane width of 55.6/5=11.1 ft. If the problem is modified to also allow for solutions associated with fewer crashes, then a slightly narrower width of 67.8 ft is expected to achieve a very modest safety improvement:

- All_Lanes_W=55 ft
- R_Shld_W=10 ft
- L_Shld_W=2.8

The associated number of KAB crashes is virtually unchanged (slightly reduced by 0.2%):

$$Change\ in\ Crashes = \exp[\{(-2.53) \times 10^{-02}\} \times (55 - 48) + \{(-9.56) \times 10^{-02}\} \times (10 - 10) + \{(-5.47) \times 10^{-02}\} \times (2.8 - 6)] = 0.998$$

SUMMARY AND CONCLUSIONS

The objective of this crash analysis was to quantify the safety implications of adding a lane to a freeway segment cross section with limited space for expansion where cross-sectional element widths are reduced.

The research team collected geometric, operational, and safety data from urban freeways in three cities in Texas: Dallas, Houston, and San Antonio. This dataset represents the period from 2010 to 2013. The research team estimated the safety effects of changing the width of various cross-sectional elements using this dataset, after accounting for other influential variables, such as AADT.

This analysis demonstrated that the adverse effect on the number of crashes due to reducing shoulders outweighs the safety benefit of adding lanes, under the scenario that the total paved width (lanes and shoulders) was not changed. However, results also show that if it is possible to increase the total paved width when adding a travel lane, it is feasible to identify lane and shoulder widths so that the number of crashes will remain consistent and safety along the corridor will not be compromised. Any lane and shoulder widths identified using this procedure, however, must be contrasted with recommended values in design manuals.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The research effort summarized in this report documents the analyses of lanes and shoulders to determine how changing (narrowing) their widths can impact the overall operational and safety performance of a Texas freeway facility. For the operational impacts, the review of the literature identified several variables expected to influence freeway speed. They included:

- Lane width.
- Shoulder widths.
- Use of the space to the right or left of the lane.
- Number and distance to ramps near the speed measurement point.
- Presence of horizontal or vertical curves.
- Natural lighting condition (i.e., day or night).
- Median width.
- Median type.
- Posted speed limit.
- Vehicle type (passenger car or truck).

Due to the nature of the speed data available for this study, the analysis could not consider the type of vehicle.

The research team evaluated average speed data per lane for 5-minute increments along with the number of vehicles within the same 5-minute period. The study locations were in Dallas, Houston, and San Antonio. These data included speed and volume data for 121 lanes with 12-ft widths and 83 lanes with 11-ft widths for freeways with 2 to 5 lanes per direction of travel. The speed data were obtained for several hours on a Wednesday and a Saturday for each month in 2013 where data existed. To remove the potential effects of congestion, speeds less than 50 mph and 5-minute volumes greater than 250 were removed from the dataset.

The operational analysis determined the following:

- There is an increase of about 2.2 mph in speed for a 12-ft lane as compared to an 11-ft lane.
- Wider left shoulder and right shoulder widths appear to be associated with faster freeway speeds; however, when evaluating 12-ft and 11-ft lane widths in the same model, those effects, if they exist, are too small to be found statistically significant. Note that the

smallest right shoulder width in the evaluation was 4 ft. For left shoulders, the minimum shoulder width was 1.5 ft, which was only present when the lanes were a reduced lane width of 11 ft. The freeways with 12 ft lanes had 5 ft as the minimum left shoulder width.

- When evaluating the impacts of shoulder width (ranging from 1.5 to 12 ft) on the lane next to the left shoulder, speed can be expected to be higher by about 1.1 mph for each additional foot of shoulder width.
- The shoulder width is significant when the adjacent lane is 11-ft wide, but not when it is 12-ft wide. This suggests that left shoulder width is more important with a reduced lane width.
- The right-most freeway lane has a speed that is about 4.4 mph lower than a lane that is located between two other lanes.
- Operating speeds on Texas freeways are 2 mph lower during night time (with roadside lighting present) than during the day.
- Speeds were higher (by 1.5 mph) on the weekends (Saturday) than on the week day studied (Wednesday).

For freeway locations with similar boundary conditions (minimum and maximum values) to those present in the study database, the equation depicted in Table 48 can be used to predict per lane freeway speeds.

The research team also evaluated how changing the lane and shoulder widths will influence the number of crashes. The unique nature of a specific lane width and shoulder width, in combination with the number of lanes and proximity of nearby on or off ramps, collectively influence the number of total and KAB crashes.

The safety analysis determined the following:

- There is a crash reduction associated with increased wider lane widths. When comparing freeways with 12 ft lanes to freeways 11 ft lanes, there is a reduction in KAB crashes that ranges from 5 percent for 2-lane freeways up to 12 percent for 5-lane freeways, other segment characteristics equal. The corresponding range for the reduction in total crashes is from 5 percent for 2-lane freeways to 11 percent for 5-lane freeways.
- Similarly, there is a crash reduction associated with each additional lane. Such crash reduction also depends on the average lane width. For a constant lane width, when there are no changes in other variables, there is a reduction in KAB crashes per additional lane

of 24 percent for 11-ft lanes and 26 percent for 12-ft lanes. For total crashes, the reduction is 23 percent for freeways with 11-ft lanes and 25 percent for freeways with 12-ft lanes.

- There is a crash reduction associated with increased left shoulder widths. Other segment characteristics equal, there are 5 percent fewer KAB crashes and 6 percent fewer total crashes per additional foot of left shoulder.
- There is evidence of a crash reduction associated with increased right shoulder widths. Other segment characteristics equal, there are 9 percent fewer KAB crashes and 7 percent fewer total crashes per additional foot of right shoulder. However, the evidence supporting this finding depends on the inclusion of data representing an uncommonly narrow right shoulder width. These data are associated with one site where the right shoulder was substantially reduced from 11.5 to 2.0 ft during the time period covered in this study. The magnitude and significance of the estimated effect substantially change when the data for this site are dropped from the model. The research team recommends further research on this issue, ideally including data from multiple sites where right shoulder widths range from 2.0 to 6.0 ft. However, finding such sites would be challenging in all likelihood, given that this is an uncommon range for right shoulder width.
- There is an adverse safety effect for any shoulder reduction that corresponds to an equal increase in the total width of the travel lanes, other segment characteristics equal. While constructing an additional lane is beneficial in terms of safety, a larger adverse effect resulting in an increase in crashes due to reducing the shoulder widths offsets this benefit.
- However, if it is possible to increase the total paved width when adding a travel lane, the safety model allows the analyst to identify lane and shoulder widths so that the number of crashes along the corridor will expectedly remain unchanged.

The safety analysis resulted in two crash prediction models for the total and KAB crashes, respectively. Table 49 presents the resulting equations.

Finally, the use of calculations similar to those shown in Table 48 and Table 49 can create challenges as math errors are easy to make. Therefore, the research team developed a companion spreadsheet that automatically performs these calculations based on user input.

Table 48. Final Freeway Operating Speed Predictive Equation.

Variable Definitions
S = Estimated operating speed per lane for a 5-minute time period $V = V_{5\text{-}min\ /lane}$ = The five minute traffic volume for the freeway lane of interest (vehicles/5-minutes) $MedType_{Grass}$ = Value of 1 if grass median, otherwise 0 $LaneW$ = Lane Width (ft) $ToLeft_{B+P}$ = Value of 1 if buffer plus pylons located to left of lane, otherwise 0 $ToLeft_{Shld}$ = Value of 1 if shoulder located to left of lane, otherwise 0 $ToRight_{SCL}$ = Value of 1 if speed change lane located to right of lane, otherwise 0 $ToRight_{Shld}$ = Value of 1 if shoulder located to right of lane, otherwise 0 $NLight$ = Value of 1 if night time conditions, otherwise 0 $DayofWeek$ = Value of 1 if Wednesday (representing weekday), otherwise 1 (weekend)
Boundary Conditions for Freeway Operating Speed Equations
Applicable to freeway corridors with the following: $0 \leq V_{5\text{-}min\ /lane} \leq 250$ *LaneW* rounded to 11 ft or 12 ft $2 \leq$ *Number of Lanes* ≤ 5 4.0 ft $\leq$ *Right Shoulder Width* $\leq$ 20.0 ft 1.5 ft $\leq$ *Left Shoulder Width* $\leq$ 23.0 ft 6.0 ft $\leq$ *Median Width* $\leq$ 125.0 ft 60 mph $\leq$ *Posted Speed Limit* $\leq$ 70 mph
Estimating Operating Speed for a Texas Freeway Lane
$S = 67.80 - 0.00018(V^2) + 4.60(MedType_{Grass}) + 2.21(LaneW) + 3.62(ToLeft_{B+P}) + 2.03(ToLeft_{Shld}) - 3.89(ToRight_{SCL}) - 4.39(ToRight_{Shld}) - 2.00(NLight) - 1.47(DayofWeek)$

Table 49. Texas Freeway Crash Prediction Models for Lane and Shoulder Width Changes.

Variable Definitions
N_{Total} = Total number of predicted crashes (crashes per year) N_{KAB} = Total number of predicted KAB crashes (crashes mile per year) *AADT* = Annual Average Daily Traffic in one direction (vpd) *L* = Length of study segment (mi) *NLane* = Number of travel lanes in a single direction *Ave_Lane_W* = Average lane width (ft) $RShld_W$ = Width of right shoulder (ft) $RampUp_{Dist}$ = Distance to closest upstream ramp (ft) $RampDn_{Dist}$ = Distance to closest downstream ramp (ft)
Boundary Conditions for Freeway Crash Prediction Equations
Applies to homogeneous segment from 0.10 to 1.25 miles in length Applicable to freeway corridors with AADT values up to 280,000 vpd $2 \leq NLane \leq 5$ $11.0 \text{ ft} \leq Ave\_Lane\_W \leq 12.0 \text{ ft}$ $2.0 \text{ ft} \leq RShld_W \leq 15.0 \text{ ft}$ $1.0 \text{ ft} \leq LShld_W \leq 10.0 \text{ ft}$ $0.0 \text{ mi} \leq RampUp_{Dist} \leq 1.5 \text{ mi}$ $0.0 \text{ mi} \leq RampDn_{Dist} \leq 1.5 \text{ mi}$
Equation to Predict Total Texas Freeway Crashes due to Lane and Shoulder Width Changes
$N_{Total} = 1.0027 \times L \times AADT^{0.539} \times e^{[-1.0243(RampUp_{Dist})-1.0877(RampDn_{Dist})-0.0241(NLane\times Lane\_W_{Avg})-0.0735(RShld)-0.0646(LShld)]}$
Equation to Predict KAB Texas Freeway Crashes due to Lane and Shoulder Width Changes
$N_{KAB} = 0.0514 \times L \times AADT^{0.662} \times e^{[-1.5787(RampUp_{Dist})-0.8659(RampDn_{Dist})-0.0253(NoLn\times LaneW_{Avg})-0.0956(RShld)-0.0547(LShld)]}$

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