TECHNICAL MEMORANDUM- Task C

Task C: **Safety Analysis in Support of Traffic Operations: TxDOT Project 58-6XXIA002**
A SYSTEMIC APPROACH TO PROJECT SELECTION FOR HIGHWAY WIDENING

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A SYSTEMIC APPROACH TO PROJECT SELECTION FOR HIGHWAY WIDENING

This report presents the application of a proposed systemic approach to project selection for highway widening with a focus on reducing single-vehicle run-off-road (SVROR) and opposite-direction (head-on) crashes. The main focus is related to crashes occurring on two-lane rural highways with a total paved width less than 24 ft and traffic volume equal to 400 or more vehicles per day in the Texas Department of Transportation (TxDOT) roadway network. This report is divided into two sections. The first section covers the literature review on highway pavement widening, while the second section presents the analysis results on project selection. The analytical process of this report is based on the one initially documented in the report titled *Developing Methodology for Identifying, Evaluating, and Prioritizing Systemic Improvements*.

1. Literature Review

This section summarizes the breadth of the literature pertaining to the relationship between pavement width and crash risk. The review covers two core topics:

- Current design standards and guidelines on pavement width.
- Safety effects of widening pavements.

1.1 Introduction

The width of the highway pavement, or typically the width of lanes and paved shoulders, is an important criterion in the highway design process. Generally, wider lanes and paved shoulders tend to improve highway capacity and level of service as well as reducing crash risk up to a certain width. According to a few research studies (Hauer 2000; Bahar et al. 2009; Gross and Jovanis 2007), however, very wide pavement width could increase crash risk. Furthermore, wider pavement can increase costs associated with right-of-way acquisition, construction, and maintenance.

Design standards for pavement width (i.e., lane and shoulder widths) are usually dependent on the roadway functional classification, traffic volume, and design speed (Zegeer et al. 1980; AASHTO 2011; TxDOT 2014a). Local roads, collectors, and highways with low volumes can usually be designed with narrow pavements. With the increase in traffic volume and safety concerns, there may be a significant need for widening highways that were already built with smaller pavement widths. This is also reflected by the large number of current TxDOT projects that are focused on widening existing roadways (TxDOT 2014b). Before implementing a pavement widening project, it is necessary to better understand the effect of pavement widths on crash risk. This section summarizes the literature on this topic.

Pavement width plays a different role depending on the classification and category of highways (Hauer 2000). Previous studies on pavement width have focused on rural two-lane roadways (Zegeer et al. 1988; Griffin and Mak 1987; Harwood et al. 2000), multilane highways (Lord et al. 2008; Harwood et al. 2003), urban arterials (Potts et al. 2007; Wu and Sun 2015; Wood et al. 2015), and frontage roads (Lord and Bonneson 2007; Li et al. 2011). For the purpose of this project, the literature review in this report is primarily directed at rural two-lane undivided highways. The lane width in this report is defined as the width of a single lane on normal segments; widths of other lanes, such as bicycle/pedestrian lanes, are excluded. The pavement width is defined as total width of all lanes and paved shoulders of both directions on the segments.

1.2 Design Standards on Pavement (Lane and Shoulder) Width

Considering the effect of pavement width on safety, highway capacity, and level of service (AASHTO 2011; TRB 2010), design manuals or guidelines specify standards for lane and shoulder widths.

The American Association of State Highway and Transportation (AASHTO) Green Book in 2011 (AASHTO 2011) suggests that a 12 ft-lane width is desirable on both rural and urban highways, while a lane width of 11 ft or below can be acceptable in urban areas. Specific characteristics, such as low-speed (less than 45 mph) and low-volume (typically, average daily traffic (ADT) less than or equal to 400 vehicles per day) roads in rural and residential areas, allow a minimum lane width of 9 ft.

The AASHTO Green Book recommends 10 ft-shoulder width along high-speed and high-volume facilities. A 12 ft width is preferable for highways that experience a large number of heavy trucks. Generally, 6 to 8 ft-shoulder widths are preferable for low-volume highways in consideration of a 2 ft minimum shoulder width. Table 1-1 presents the minimum width of lane and shoulder on rural two-lane highways by functional class, design speed, and traffic volume documented in the AASHTO Green Book. It is recommended that two-lane highways in rural area should be designed with at least 9 ft for lane width and 2 ft for shoulder width. It means that the pavement width should be at least 22 ft on rural two-lane highways.

According to TxDOT's *Roadway Design Manual* (RDM) (TxDOT 2014a), the minimum lane width should be 12 ft for high-speed facilities, such as freeways and rural arterials. For low-speed urban streets, an 11 ft- or 12 ft-lane width is generally recommended. The minimum lane and shoulder widths for two-lane rural highways vary according to the volume and design speed. Table 1-2 presents the specific design criteria for rural two-lane highways in the RDM.

Table 1-1. Lane and Shoulder Widths on Rural Two-Lane Highways (AASHTO 2011).

Functional Class	Element	Design Speed (mph)	Minimum Width[1](ft) for future ADT of:			
			<400	400–1500	1500–2000	>2000
Arterial	Lanes (ft)	40	11	11	11	12
		45	11	11	11	12
		50	11	11	12	12
		55	11	11	12	12
		60	12	12	12	12
		65	12	12	12	12
		70	12	12	12	12
		75	12	12	12	12
	Shoulders (ft)	All	4	6	6	8
Collector	Lanes (ft)	20	10[2]	10	11	12
		25	10[2]	10	11	12
		30	10[2]	10	11	12
		35	10[2]	11	11	12
		40	10[2]	11	11	12
		45	10	11	11	12
		50	10	11	11	12
		55	11	11	12	12
		60	11	11	12	12
		65	11	11	12	12
	Shoulders (ft)	All	2	5	6	8
Local	Lanes (ft)	15	9	10	10	11
		20	9	10	11	12
		25	9	10	11	12
		30	9	10	11	12
		35	9	10	11	12
		40	9	10	11	12
		45	10	11	11	12
		50	10	11	11	12
		55	11	11	12	12
		60	11	11	12	12
		65	11	11	12	12
	Shoulders (ft)	All	2	5	6	8

Notes:

[1] On roadways to be reconstructed, an existing 22-ft traveled way may be retained where the alignment is satisfactory and there is no crash patter suggesting the need for widening.

[2] A 9-ft minimum width may be used for roadways with design volumes under 250 veh/day.

Table 1-2. Lane and Shoulder Widths on Texas Rural Two-Lane Highways (TxDOT 2014a).

Functional Class	Element	Design Speed (mph)	Minimum Width[1, 2](ft) for future ADT of:			
			<400	400–1500	1500–2000	>2000
Arterial	Lanes (ft)	All	12	12	12	12
	Shoulders (ft)	All	4[3]	4[3] or 8[3]	8[3]	8–10[3]
Collector	Lanes (ft)	30	10	10	11	12
		35	10	10	11	12
		40	10	10	11	12
		45	10	10	11	12
		50	10	10	12	12
		55	10	10	12	12
		60	11	11	12	12
		65	11	11	12	12
		70	11	11	12	12
		75	11	12	12	12
		80	11	12	12	12
	Shoulders (ft)	All	2[4,5]	4[5]	8[5]	8-10[5]
Local[6]	Lanes (ft)	30	10	10	11	12
		35	10	10	11	12
		40	10	10	11	12
		45	10	10	11	12
		50	10	10	11	12
	Shoulders (ft)	All	2	4	4	8

Notes:

1. Minimum surfacing width is 24 ft for all on-system state highway routes.
2. On high riprapped fills through reservoirs, a minimum of two 12 ft lanes with 8 ft shoulders should be provided for roadway sections. For arterials with 2,000 or more ADT in reservoir areas, two 12 ft lanes with 10 ft shoulders should be used.
3. On arterials, shoulders fully surfaced.
4. On collectors, use minimum 4 ft shoulder width at locations where roadside barrier is used.
5. For collectors, shoulders fully surfaced for 1,500 or more ADT. Shoulder surfacing not required but desirable even if partial width for collectors with lower volumes and all local roads.
6. Applicable only to off-system routes that are not functionally classified at a higher classification.

1.3 Safety Effects of Pavement Width

There are two conventional impacts of pavement width on traffic safety. The first impact is that wider lane or shoulder can result in fewer crashes. The benefit of wider lane(s) and shoulder(s) to safety is usually assumed because wider lanes increase the lateral space between vehicles in adjacent lanes and provide a wider buffer to absorb any deviation of vehicles from their intended path. In addition, wider lanes and shoulders provide more room for driver correction in near-collision circumstances. For example, on a roadway with narrow lane(s) and no paved shoulder, a moment's inattention can lead a vehicle over the pavement edge-drop and collision onto roadside objects, but if the lane(s) are wider and paved shoulder(s) exist, it will provide additional time to maintain a vehicle on the paved surface (example adapted from Bahar et al. [2009] and Hauer [2000]). Actually, the conventional wisdom has been demonstrated on rural two-lane highways (Harwood et al. 2000; Potts et al. 2007). A second impact of wider pavement width on traffic safety is that drivers tend to increase vehicle speed on wider highways. Higher operating speeds give drivers less time to avoid crashes and/or result in increased force of impact when crashes occur. In the studies regarding the crash risk factors, higher vehicle speeds significantly increase injury severity (Klop and Khattak 1999; Zegeer et al. 2005).

The safety effect of lane and shoulder widths can be explained by its crash modification factor (CMF), a multiplicative factor used to compute or modify the expected number of crashes for highway segments (FHWA 2010). Harwood et al. (2000) reviewed a broad range of literature (Zegeer et al. 1988; Zegeer et al. 1980; Zegeer et al. 1994; Miaou 1996; Griffin and Mak 1987) and summarized the CMFs for lane and shoulder widths on rural two-lane highways, individually. The CMFs for lane and shoulder widths on rural two-lane highways were then adopted by the Federal Highway Administration's *Interactive Highway Safety Design Model* (FHWA 2013) and AASHTO's *Highway Safety Manual* (HSM) (AASHTO 2010). They are now widely accepted in highway safety planning, managements, and crash prediction. For example, based on a 12 ft-lane width, if a particular roadway section of interest has an 10 ft-lane-width with greater than 2,000 ADT, the CMF for the lane width is 1.30 (see Table 1-3). This implies that a two-lane roadway segment with a 10-ft lane would be expected to experience 30 percent more targeted crashes (i.e., SVROR, head-on, and sideswipe) compared to a roadway section with 12 ft-lane and greater than 2,000 ADT (Harwood et al. 2000). In addition, for shoulder width, the CMF of a 4-ft shoulder width on the segments with greater than 2,000 ADT is 1.15 (see Table 1-3). It is expected that 15 percent more targeted crashes might occur at a segment with a 4-ft shoulder than that with 6 ft.

Table 1-3. CMFs for Lane and Shoulder Widths (Harwood et al. 2000).

ADT	Lane Width (ft)				Shoulder Width (ft)				
	9	10	11	12 (Base)	0	2	4	6 (Base)	8
≤400	1.05	1.02	1.01	1.0	1.1	1.07	1.02	1.0	0.98
400–2000	1.05–1.5	1.02–1.3	1.01–1.05	1.0	1.10–1.5	1.07–1.3	1.02–1.15	1.0	0.98–0.87
≥2000	1.5	1.3	1.05	1.0	1.5	1.3	1.15	1.0	0.87

Hauer (2000) conducted a detailed review of literature on lane width and safety from published and unpublished documents from the 1950s through 1999. He also reanalyzed some of the data using improved research methods than those available when the original studies were completed (Bahar et al. 2009). Some studies related to this project are summarized following.

Belmont (1954) examined the crashes occurred on rural two-lane highways in California for understanding the relationship between shoulder width and the crash risk. According to Belmont’s analysis, 6 ft-shoulders were safer than narrower shoulders, but wider shoulders (>6 ft) were observed to experience more crashes on segments with traffic volumes over 5,000 vehicles per day. Hauer (2000) reanalyzed Belmont’s data and included lane width in the regression model. CMFs for lane width on two-lane highways were further derived from the modeling result, as shown in Table 1-4. Based on this result, an 11 ft-wide lane on two-lane highways is expected to experience the lowest number of crashes. When the lane width is less than 11 ft, the expected number of crashes dramatically increases as the pavement becomes narrower. As the lane width increases from 11 ft to 13 ft, the CMF augments at a relatively slow rate (from 1.0). However, when the lane width is greater than 14 ft, it was found that the expected number of crashes increases quickly.

Table 1-4. CMFs for Lane Width (Hauer 2000).

Lane Width (ft)	9	10	11	12	13	14	15
CMF	1.21	1.05	1	1.01	1.06	1.13	1.21
TTI researchers' notes: The result in this table was analyzed based on data collected in the 1950s. Since conditions such as roadway design standards, vehicles, etc. have changed significantly in the last 60 years or so, it may not be applicable to the current roadway conditions.							

Cope (1955) conducted the first before-after study related to lane widening. The data were collected based on 11 lane widening projects, most of which were widening lanes from 9 to 11 ft. Overall, the crash rate (crashes per million vehicle miles traveled) decreased by about 30 percent after widening the pavement. Hauer (2000) reanalyzed Cope's data and considered the regression-to-mean bias. He concluded that the CMF for widening the lanes from 9 to 11 ft is 0.7. This is equivalent to an 8 percent reduction per foot of lane widening up to 11 ft. Zegeer et al. (1980) studied the effect of lane and shoulder widths on crash benefits on rural two-lane highways in Kentucky. The main conclusions are: run-off-road (ROR) and head-on crashes were the only types found to be associated with narrow lanes. They concluded that widening lanes from 8 ft to 11 ft would be expected to reduce ROR and head-on crashes by 36 percent. Wider shoulders were associated with lower crash rates. It is expected that ROR and head-on crashes decreased by 16 percent with widening shoulders (both sides of the road) from 1.6 to 8.2 ft. Another important finding from this study is that crash rates for other types of crashes increase as lane width increases. This was due to faster operating speed on wider lanes.

Griffin and Mak (1987) examined the benefits that could be achieved by widening rural two-lane farm-to-market (FM) roads in Texas and concluded that pavement width has no demonstrable effect on multivehicle crash rate. Pavement widening can reduce rates of single-vehicle crashes, which accounted for about 67 percent of total crashes (Griffin and Mak 1987; Hauer 2000). This proportion is consistent with the latest analysis for this type of roads in Texas documented in Walden et al. (2014).

The Work Codes within TxDOT's *Highway Safety Improvement Program Manual* (TxDOT 2013) suggests that 30 percent of collisions (same direction sideswipe and head-on) will be reduced after widening the pavement to maximum 28 ft from segments with less than 24 ft on two-lane highways.

Hauer (2000) discussed important highway characteristics associated with pavement width. Narrower roads are usually designed with lower standards, such as smaller minimum radius and lower design speed, and also narrower roads tend to carry less traffic. Although this connection makes the isolated evaluation of pavement width difficult, the overall safety effects of pavement or lane widths from previous studies (Belmont 1954; Cope 1955; Zegeer et al. 1988) are similar. Generally, widening pavement width reduces the occurrence of SVROR and head-on crashes.

Gross and Jovanis (2007) applied a case-control design to identify CMFs for lane and shoulder widths on rural two-lane undivided highways. The result is generally consistent with the CMFs in the HSM. A wave-shaped trend was observed for the CMF associated with lane widths (see Table 1-5). The CMFs for lane width of both less than 10 ft and 13 ft are lower that of 12-ft lanes. However, the CMFs for lane widths of 11 ft and 13 ft are higher than that of 12-ft lanes. It indicates that crash risk for a narrow lane (i.e., less than 10 ft) tends to increase with widening (up to 11 ft) and then decrease until a 13-ft lane; finally, the crash risk increases for lane width greater than 13 ft. This study concludes lower risk on narrow lanes (i.e., less than 10 ft) than on 12-ft lanes, which is contrary to the general expectation of higher crash risk on narrow lane. The researchers described that the unexpected lower CMF on narrow lanes (i.e., less than 10 ft) is due to safer driver behavior and under-reporting. Drivers may be responding to narrow lanes with more cautious behavior, and they are less likely to report crashes with relatively low severity outcomes than with higher ADTs where the crash is visible by more individuals and traffic congestion may be more likely to occur. Later, the data used in the study of Gross and Jovanis (2007) were reanalyzed using cross-sectional method by Gross and Donnell (2011). They presented similar results with the previous one.

Table 1-5. CMFs for Lane and Shoulder Widths (Gross and Jovanis 2007; Hauer 2000).

	Lane Width (ft)						Shoulder Width (ft)				
	<10	10	11	12	13	>13	0	2	4	6	8
CMF	0.81	1.03	1.11	1	0.85	1.11	1.26	1.19	1.08	1	0.96

Potts et al. (2007) evaluated the relationship between lane width and safety for urban and suburban arterials. Despite the fact that the analysis was not based on rural two-lane highways, it was concluded that there was no indication of an increase in crash frequencies as lane width decreased for arterial roadway segments. The impacts of lane width on crash risk are different by roadway function (urban and suburban arterials versus rural two-lane highways). Recently, Wu and Sun (2015) analyzed the safety performance of urban expressways with different lane widths in Shanghai, China. The study showed that 3.75 m (12.3 ft) lanes experienced the lowest crash frequency for all crash types. Crashes occurred more frequently on urban expressways with narrow or wide lanes. Dong et al. (2015) assessed the effects of highway geometric design features on the frequency of truck-involved crashes. Lane width was found to be associated with these crash types. Widening lanes were found to reduce both car-truck and truck-only crashes. This is probably due to the fact that trucks, especially large body styles, require wider lanes when compared to passenger cars. Thus, widening the lanes could bring relatively more safety benefits to trucks than other vehicle types.

For the relationship between pavement width and safety, study results based on different data sources tend to be inconsistent. For example, according to Hauer (2000), total width of the lanes on rural two-lane highways shows a U-shaped relationship with safety. Twenty or 22 ft-pavement has the lowest crash risk. However, based on the CMFs in HSM, lane and shoulder widths have monotonic relationships with safety. When the lane and shoulder widths are within a certain range, the wider they are, the lower the crash risk is. To date, no consensus has been reached on the CMF for pavement width on rural two-lane highways. (Note that the CMFs in HSM are presented for lane width and shoulder width separately; no CMF for combined pavement width is available in HSM.) One possible reason is that safety effects of lane and shoulder widths were conducted individually in most of the previous studies. Another possible reason is that the same pavement width with different lane and shoulder combinations can influence safety differently. For example, for a fixed pavement width of 24 ft, a configuration of two 12 ft-lanes with no shoulder can affect crash risks differently than a configuration of two 11 ft-lanes with two 1 ft-shoulders. Gross et al. (2009) evaluated the safety effectiveness of various lane-shoulder width configurations for fixed total paved widths to the target crashes (i.e., ROR, head-on, and sideswipe). In general, wider pavement widths are associated with fewer crashes than narrower paved widths. Based on the estimated safety effectiveness (see Table 1-6), specific lane-shoulder configurations have the potential to reduce crashes on rural two-lane undivided roads differently.

Table 1-6. CMFs for Combination of Lane and Shoulder Widths (Gross et al. 2009; Hauer 2000).

Pavement Width (ft)	26.0	26.0	26.0	28.0	28.0	28.0	30.0	32.0	34.0	34.0	36.0	36.0
Lane Width (ft)	10.0	11.0	12.0	10.0	11.0	12.0	11.0	10.0	10.0	11.0	10.0	12.0
Shoulder Width (ft)	3.0	2.0	1.0	4.0	3.0	2.0	4.0	6.0	7.0	6.0	8.0	6.0
CMF	**1.13**	**1.12**	**1.85**	**1.2**	**1.19**	**1.16**	**1.14**	**1.06**	**0.84**	**0.87**	**0.38**	**1**

Note: CMFs are based on the condition of the combination of 12 ft for lane width and 6 ft for shoulder width.

1.4 Summary

In summary, the literature review has shown that lane and shoulder widths vary depending on roadway function, traffic volume, and design speed. According to the geometric design manuals, higher traffic volume and design speed require wider lanes and shoulders. In the literature review focusing on the safety effects of widening pavement width, there is evidence of the benefits of widening pavement on rural two-lane highways. Widening pavement (lane/shoulder) width reduces the occurrence of SVROR, same- and opposite-direction crashes. However, some studies have pointed out that very wide lanes or shoulders might increase crash risk. Although no consensus has been reached on the CMF for pavement width, there are several CMFs for lane and shoulder widths available from the HSM and other related literature. TTI researchers recommend using the CMFs in HSM (Table 1-3 above) for the analysis in this study.

2. APPLICATION OF SYSTEMIC APPROACHES ON PROJECT SELECTION FOR HIGHWAY PAVEMENT WIDENING

This section describes the application of the systemic approach for highway pavement widening. The section is divided into three parts and covers the target crash type and facilities, risk factors, and risk assessment, respectively. As discussed above, the analysis is based on the procedure documented in a previously published report.

2.1 Target Crash Type and Facility

According to the TxDOT Crash Records Information System (CRIS), there were 8,416 single-vehicle KA (Fatal and Injury Type A or Incapacitated) crashes from 2010 to 2014 (see Figure 2-1). ROR crashes are the predominant crash type, especially in rural areas. Most of SVROR crashes collided with fixed objects, such as trees or a fence, or overturned after leaving the roadway. More importantly, 27 percent of SVROR KA crashes occurred on two-lane rural highways with a total pavement width of less than 24 ft. Figure 2-1 shows a crash tree of single-vehicle KA crashes.

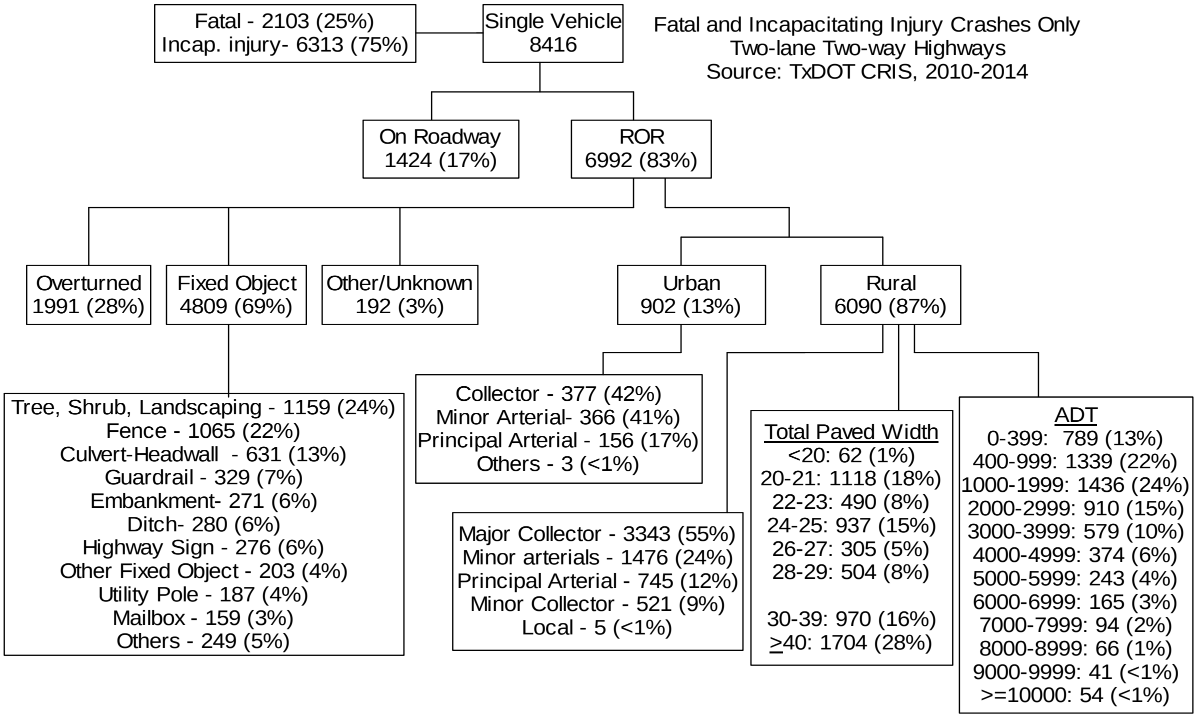


Figure 2-1. Single Vehicle Crash Tree Diagram.

Based upon the TxDOT CRIS data, there were fewer head-on crashes than SVROR from 2010 to 2014 (see Figure 2-2). However, head-on collisions resulted in more fatal injuries compared to SVROR crashes, as expected. Fatal crashes due to a head-on collision accounted for a half of total head-on KA crashes, while less than one third for SVROR fatal crashes (compared to SVROR KA crashes). Most head-on collisions occurred in rural areas.

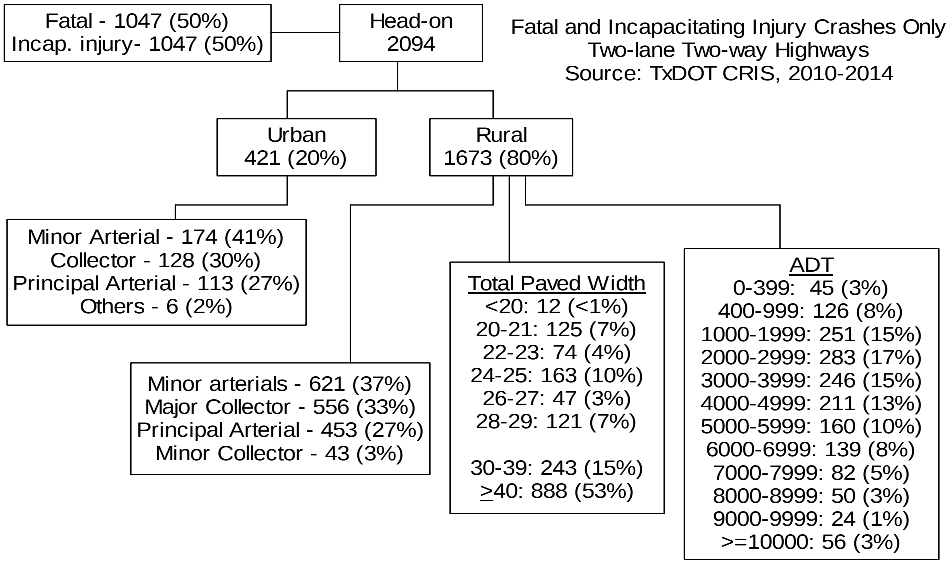


Figure 2-2. Head-On Crash Tree Diagram.

2.2 Risk Factors

This section describes the risk factors for SVROR and head-on collisions. In order to identify these factors, TTI researchers collected KA crashes using TxDOT CRIS that occurred for the 2010–2014 time period. The crashes were then categorized by crash types—SVROR and head-on. SVROR and head-on crashes on two-lane rural highway with a total pavement width of less than 24 ft were categorized by variables, such as lane and shoulder widths, ADT, truck presence, and alignment.

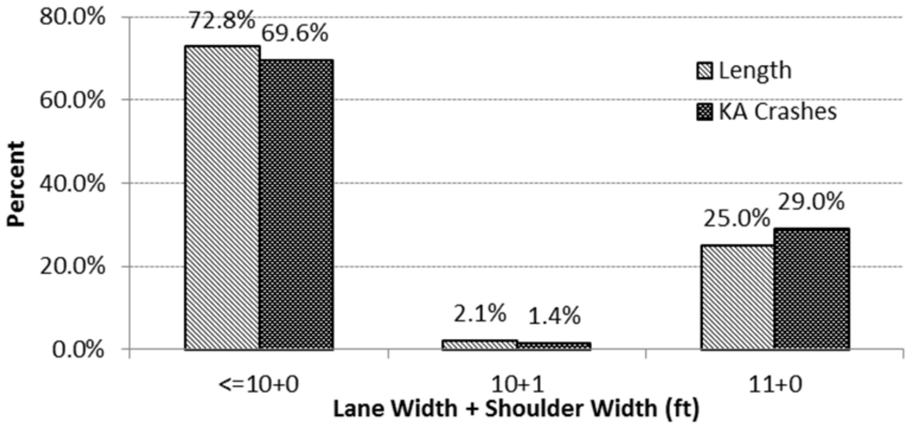
2.2.1 Risk Factors for SVROR

To identify risk factors associated with SVROR crashes, TTI researchers compared the proportion of KA crashes for a specific range or value of a variable with the proportion of existing highway mileage within the respective range or value. To remove the biased selection of higher-volume roads, the ADT variable is divided into three groups: low-volume (400–

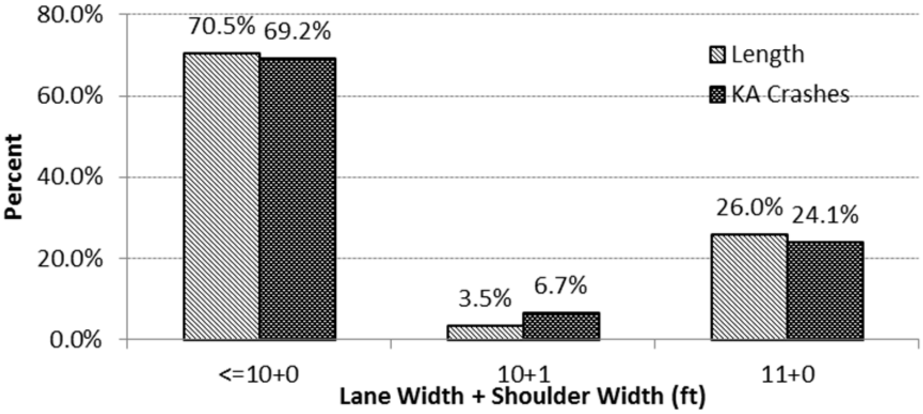
700 ADT), moderate-volume (701–1,500 ADT), and high-volume (>1,500 ADT). The categorization was based on approximately equal mileage in each group.

Figures 2-3 to 2-5 show the proportions of SVROR KA crashes by different variables (lane and shoulder pavement width, truck presence, and alignment) for traffic volume groups. For low-volume group, SVROR crashes are over-represented on two-lane rural highways with 1) an 11 ft-lane width without paved shoulder, 2) truck volume less than or equal to 15 percent, and 3) presence of curved sections. For example, on two-lane rural highways with 0 to 8 percent truck volume, SVROR crashes account for about 33 percent of total SVROR KA crashes, while they constitute 26.7 percent of total highway mileage. SVROR KA crashes are over-represented by 6.3 percent (the difference between 33 percent and 26.7 percent).

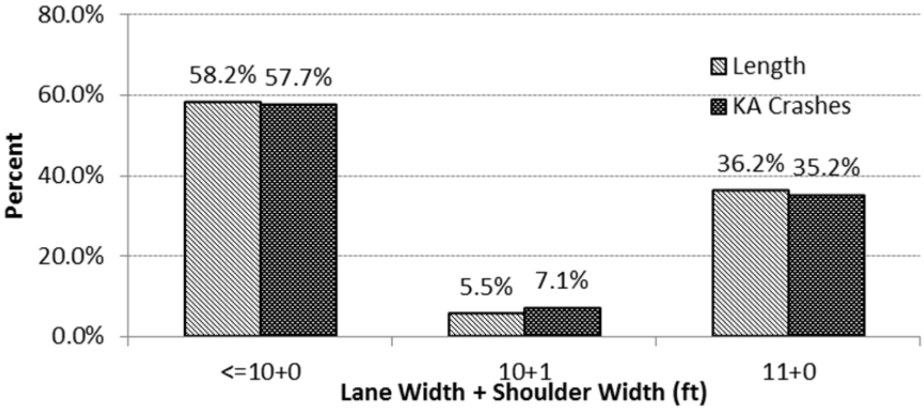
For the moderate-volume group, SVROR KA crashes are over-represented on two-lane rural highways with 1) a 10 ft-lane and a 1-ft paved shoulder width, 2) less than or equal to 8 percent truck volume and 3) presence of curved sections. The analysis for high-volume group shows similar results as that associated with the moderate-volume group. SVROR KA crashes are over-represented on the segments with 1) 10 ft for lane width and a foot for paved shoulder width, 2) truck volume of less than or equal to 15 percent, and 3) the presence of curved sections.



(a) Low volume (400≤ADT≤700)

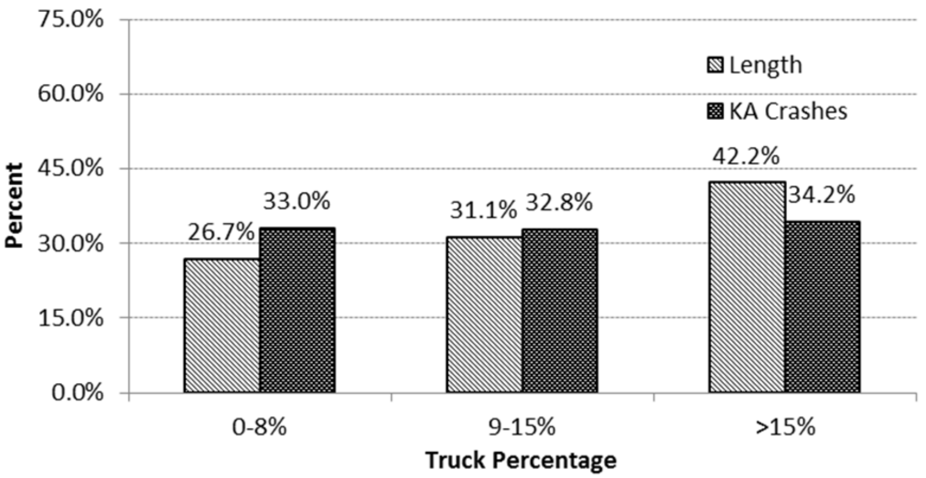


(b) Moderate volume (700<ADT≤1,500)

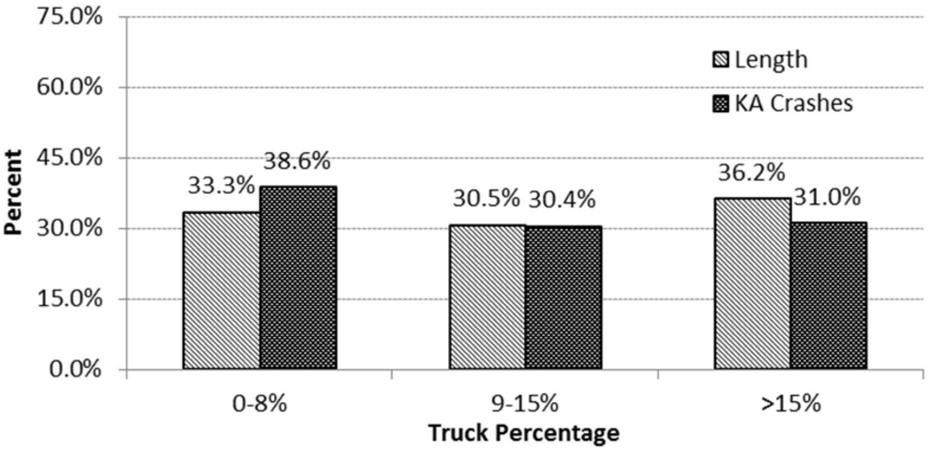


(c) High volume (ADT>1,500)

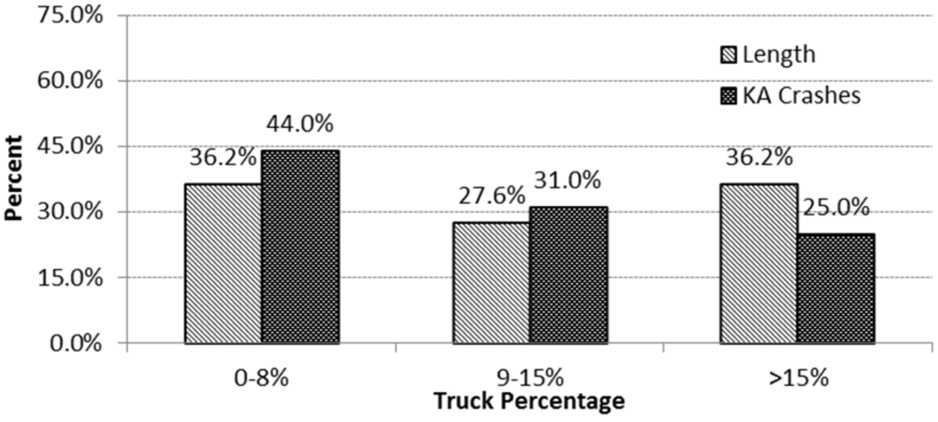
Figure 2-3. SVROR Crashes by Lane and Shoulder Widths on Two-Lane Rural Highways.



(a) Low volume (400≤ADT≤700)

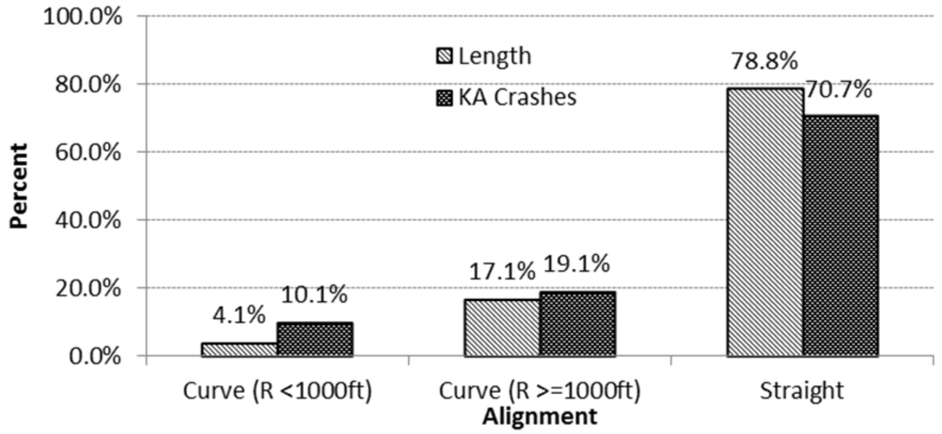


(b) Moderate volume (700<ADT≤1,500)

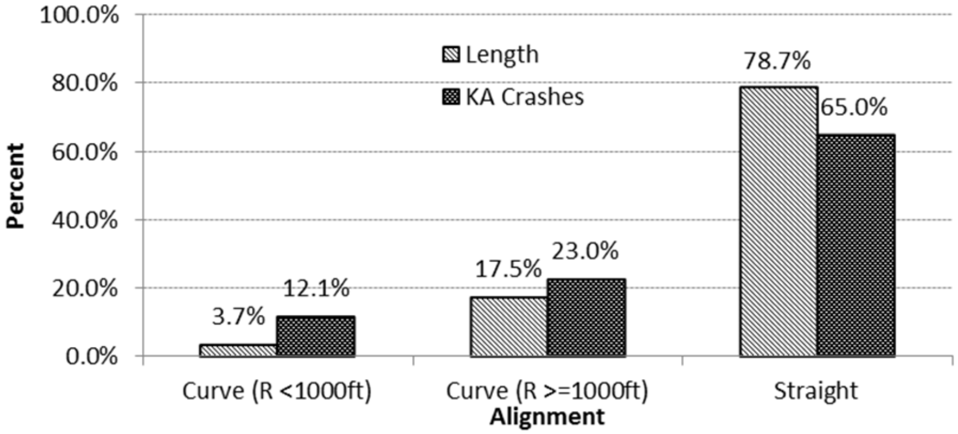


(c) High volume (ADT>1,500)

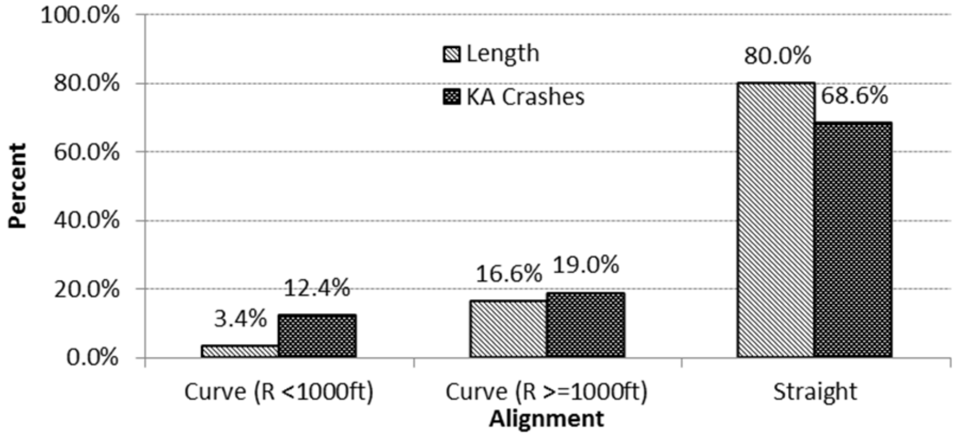
Figure 2-4. SVROR Crashes by Truck Presence on Two-Lane Rural Highways.



(a) Low volume (400≤ADT≤700)



(b) Moderate volume (700<ADT≤1,500)

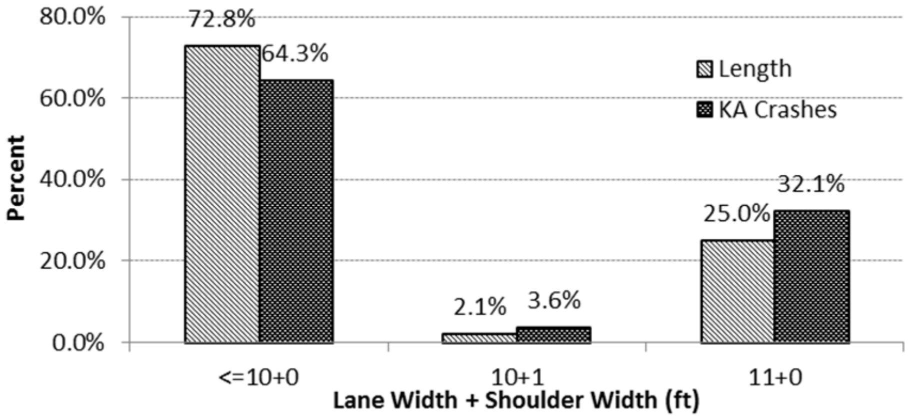


(c) High volume (ADT>1,500)

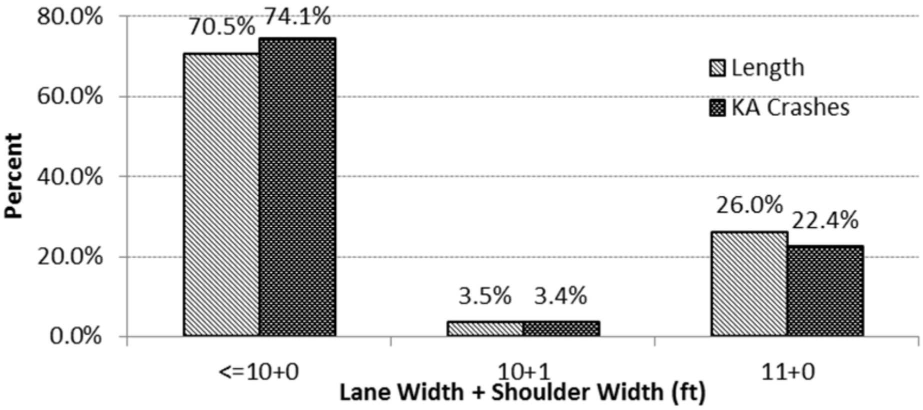
Figure 2-5. SVROR Crashes by Alignment on Two-Lane Rural Highways.

2.2.2 Risk Factors for Head-on Crashes

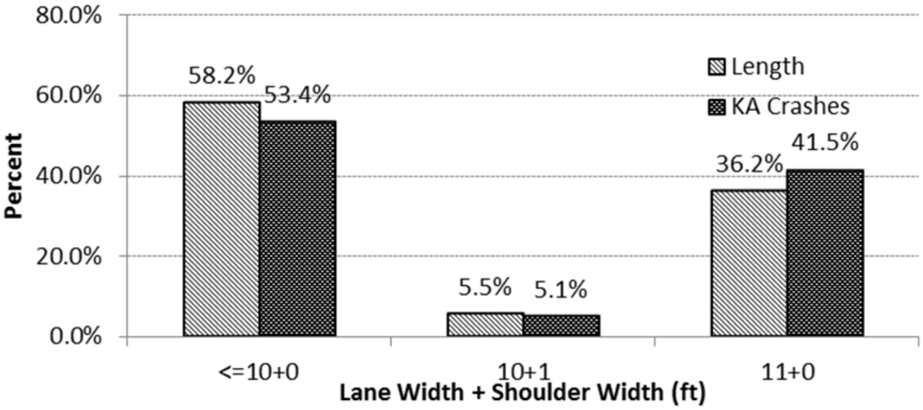
For the low-volume group (see Figures 2-6 to 2-8), head-on crashes on two-lane rural highways are over-represented for 1) a 10 ft-lane and a foot paved shoulder width, 2) an 11 ft-lane with no shoulder, 3) truck volume between 9 and 15 percent, and 4) presence of curved sections. For the moderate-volume group, head-on KA crashes are over-represented on two-lane rural highways for 1) a 10 ft-lane or less with no shoulders, 2) truck volume greater than or equal to 9 percent, and 3) the presence of curved sections. For the high volume group, head-on crashes are over-represented on segments with 1) an 11 ft-lane width without paved shoulder, 2) less than or equal to 8 percent truck presence, and 3) presence of curved sections.



(a) Low volume (400≤ADT≤700)

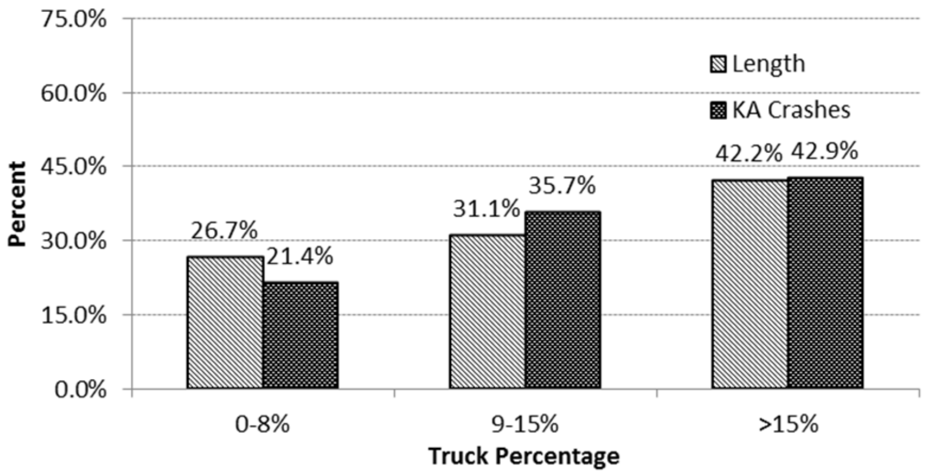


(b) Moderate volume (700<ADT≤1,500)

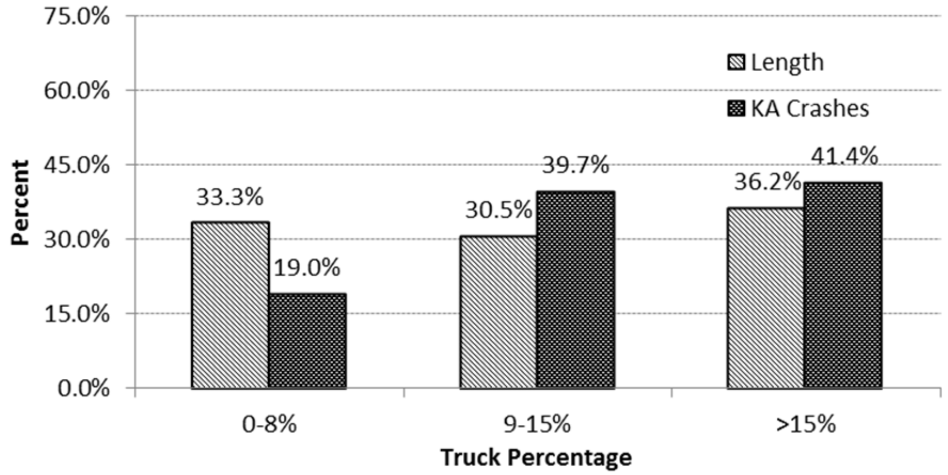


(c) High volume (ADT>1,500)

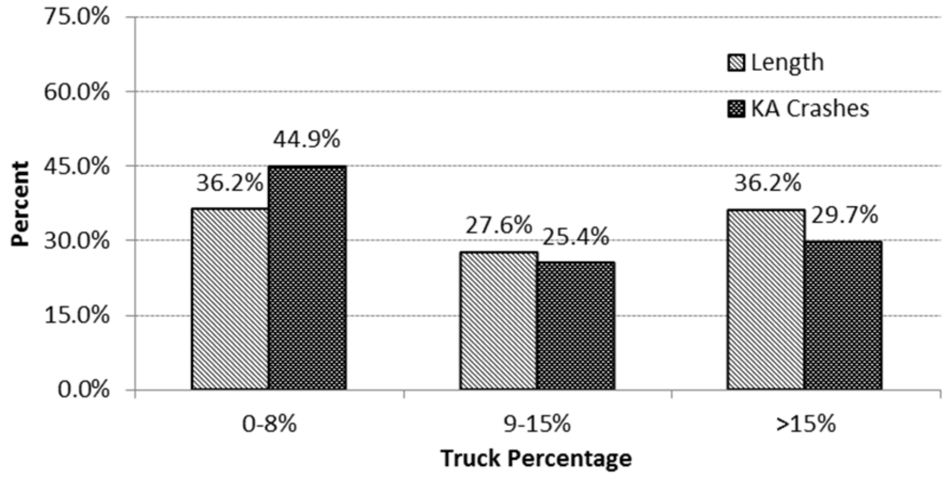
Figure 2-6. Head-on Crashes by Lane and Shoulder Widths on Two-Lane Rural Highways.



(a) Low volume (400≤ADT≤700)

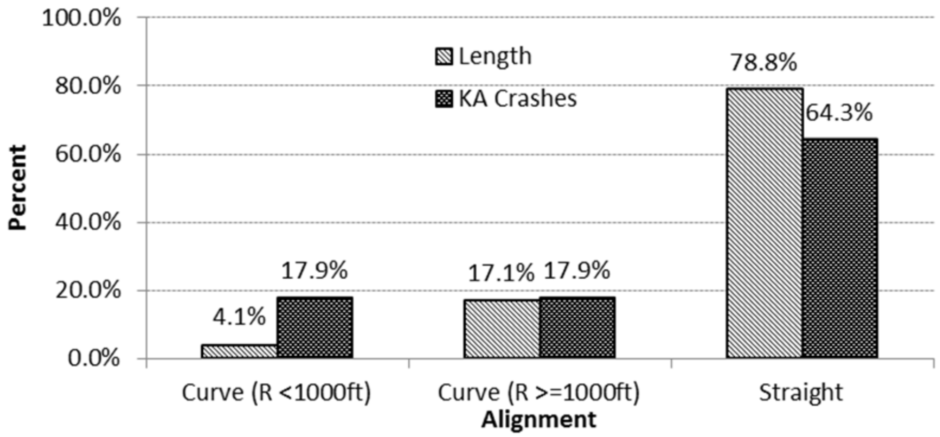


(b) Moderate volume (700<ADT≤1,500)

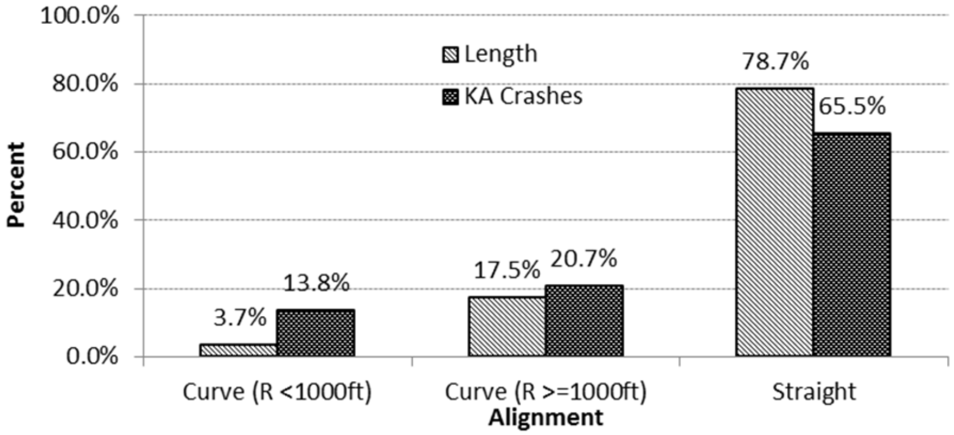


(c) High volume (ADT>1,500)

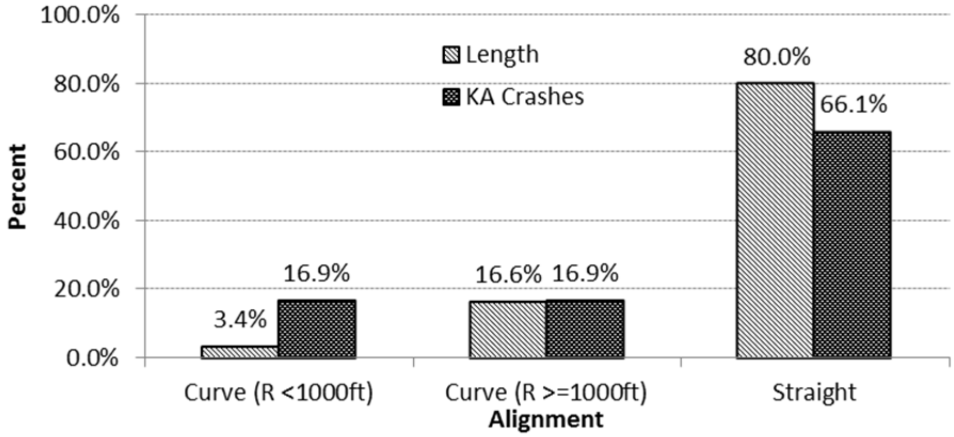
Figure 2-7. Head-on Crashes by Truck Presence on Two-Lane Rural Highways.



(a) Low volume (400≤ADT≤700)



(b) Moderate volume (700<ADT≤1,500)



(c) High volume (ADT>1,500)

Figure 2-8. Head-on Crashes by Alignment on Two-Lane Rural Highways.

2.3 Risk Assessment

In the risk assessment, roadway network elements are prioritized using risk factor weights. Table 2-1 provides the risk factor weights criteria based on the proportion of crash over-/under-representation and crash total when compared to highway mileage. Crash over-representation exists when the proportion of crashes for a specific range or value of a variable is higher than that of the proportion of existing highway mileage within that range or value. On the contrary, crash under-representation exists when the proportion of crashes is lower than that of the proportion of highway mileage. Table 2-1 provides the difference of proportions between crashes and highway mileage.

Table 2-1. Risk Factor Weight Criteria.

Category	Weight (points)										
	0	1	2	3	4	5	6	7	8	9	10
Crash Total	≥0% and <10%	≥10 and <20%	≥20 and <30%	≥30 and <40%	≥40 and <50%	≥50 and <60%	≥60 and <70%	≥70 and <80%	≥80 and <90%	≥90 and <100%	100%
Crash Over-Representation	0%	>0% and <2%	≥2% and <3%	≥3% and <4%	≥4% and <5%	≥5% and <6%	≥6% and <7%	≥7% and <8%	≥8% and <9%	≥9% and <10%	≥10% and ≤100%
Crash Under-Representation	0%	>0% and <2%	≥2% and <3%	≥3% and <4%	≥4% and <5%	≥5% and <6%	≥6% and <7%	≥7% and <8%	≥8% and <9%	≥9% and <10%	≥10% and ≤100%

Based on weights provided in Table 2-1, the total weight (W_t) for a particular crash type is calculated using the following equation:

$$W_t = 10 + CT + CO - CU \tag{1}$$

Where

CT = weight based on crash total.

CO = weight based on crash over-representation.

CU = weight based on crash under-representation.

Tables 2-2 and 2-3 summarize the total risk factor weights for SVROR and head-on KA crashes, respectively, on two-lane rural highways with a total pavement width of less than 24 ft. The step-by-step process for obtaining the results in Table 2-2 is presented in Appendix A.

Table 2-2. SVROR Crash Risk Factor Prioritization Results.

Risk Factor		Weight (points)		
		Low Volume (400≤ADT≤700)	Moderate Volume (700<ADT≤1,500)	High Volume (ADT>1,500)
Lane and Shoulder Width	≤10+0	13	15	14
	10+1	9	13	11
	11+0	16	11	12
Truck Percentage	≤8%	19	18	21
	9–15%	14	12	16
	>15%	5	8	2
Alignment	Curve (R <1000 ft)	17	19	20
	Curve (R ≥1000 ft)	13	17	13
	Straight	9	6	6

Table 2-3. Head-on Crash Risk Factor Prioritization Results.

Risk Factor		Weight (points)		
		Low Volume (400≤ADT≤700)	Moderate Volume (700<ADT≤1,500)	High Volume (ADT>1,500)
Lane and Shoulder Width	≤10+0	8	20	11
	10+1	11	9	9
	11+0	20	9	19
Truck Percentage	≤8%	7	1	22
	9–15%	17	22	10
	>15%	15	19	6
Alignment	Curve (R <1000 ft)	21	21	21
	Curve (R ≥1000 ft)	12	15	12
	Straight	6	6	6

There are two different weight tables; Table 2-2 represents SVROR, and Table 2-3 represents head-on crashes. The combined weight (W_{comb}) resulted from combining different weights (W_s: weight for SVROR, W_h: weight for head-on) is calculated using the following equation:

$$W_{comb} = W_s + p * C * W_h \tag{2}$$

Where

p= proportion of the number of head-on crashes with respect to SVROR.

C = proportion of the crash cost of head-on crashes with respect to SVROR.

On two-lane rural highways with a total paved width less than 24 ft and traffic volume equal to 400 or more vehicles per day in the TxDOT roadway network, there were 1,245 SVROR and 204 head-on crashes. Based on these numbers, the proportion (p) is 0.164 (=204/1,245). The crash cost by different collision types for the non-intersection locations is provided in Table 4-17 of the HSM. According to this table, the cost of a head-on collision is \$375,100, and the costs of SVROR roll-over and SVROR fixed object collisions are \$239,700 and \$94,700, respectively. The chance of SVROR crash resulting in roll-over, fixed object collision, and other/unknown, according to Figure 2-1, is 28 percent, 69 percent, and 3 percent, respectively. If the other/unknown crash type is distributed proportionately, then the chance of a roll-over crash is 29 percent and the fixed object collision is 71 percent. Thus, the approximate cost of a SVROR collision is \$136,750 (=0.29*\$239,700+0.71*\$94,700). Based on these costs, the proportion of crash cost (C) is 2.743 (=\$375,100/\$136,750).

Table 2-4 shows the combined results of risk factor weights. For example, 13 and 8 points are given to segments having a 10 ft-lane width or less without paved shoulder (i.e., ≤10+0) on low-volume rural highways for SVROR and head-on crash type, respectively (see Tables 2-2 and 2-3). When those weights (13 points of W_s and 8 points of W_h) and proportions (p= 0.164; C= 2.743) are considered in Eq. (1), the combined weight (W_{comb}) of ≤10+0 on low-volume rural highways is 16.60 (i.e., 13 + 0.164*2.743*8).

Table 2-4. Combined Crash Risk Factor Prioritization Results.

Risk Factor		Weight (points)		
		Low Volume (400≤ADT≤700)	Moderate Volume (700<ADT≤1,500)	High Volume (ADT>1,500)
Lane and Shoulder Width	≤10+0	16.60	24.00	18.95
	10+1	13.95	17.05	15.05
	11+0	25.00	15.05	20.55
Truck Presence	≤8%	22.15	18.45	30.90
	9–15%	21.65	21.90	20.50
	>15%	11.75	16.55	4.70
Alignment	Curve (R <1000 ft)	26.45	28.45	29.45
	Curve (R ≥1000 ft)	18.40	23.75	18.40
	Straight	11.70	8.70	8.70

2.4 Summary

According to the crash tree analyses with the crashes from 2010 to 2014, SVROR and head-on KA crashes are dominant crash type in rural areas. Fatal crashes due to a head-on collision accounted for a half of total head-on KA crashes. This report identified risk factors of SVROR and head-on KA crashes on two-lane rural highways with a total pavement width of less than 24 ft and traffic volume of 400 or more vehicles per day and presented the selection criteria for highway widening projects.

From the comparison using the proportions of crashes and highway mileage, risk factors in SVROR and head-on KA crashes were first identified. Then, the risk factors for each crash type were weighted using the proportions based on the crash over- or under-representation and crash total. Two different weights—one for SVROR and the other for head-on—were combined using a derived equation that accounts for both crash frequency and severity to obtain the combined weight. As a result, for low-volume and high-volume groups, an 11 ft-lane without paved shoulder, truck volume with less than or equal to 8 percent, and curves with less than 1,000 ft radius were found to be primary risk factors. For moderate-volume groups, a 10 ft-lane width or less without paved shoulder, 9 to 15 percent truck volume, and curves with less than 1,000 ft radius are identified as primary factors. Especially, horizontal curves with less than 1,000 ft radius are common risk factors for SVROR and head-on KA crashes on rural two-lane highways in all traffic volume groups.

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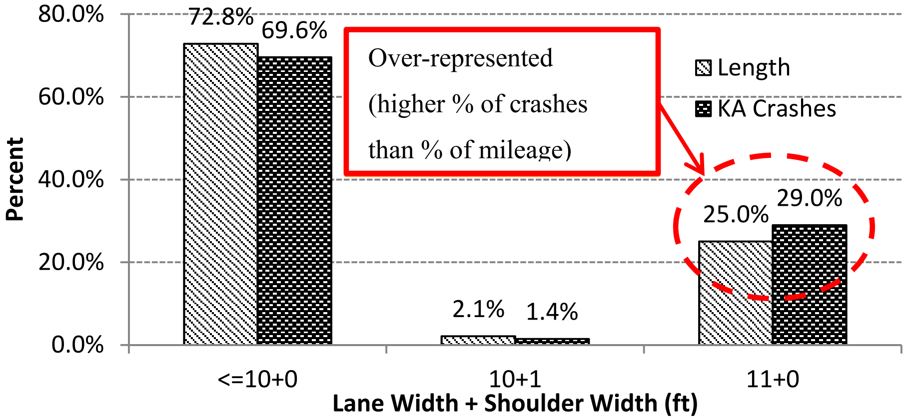
APPENDIX A. STEP-BY-STEP PROCESS FOR RISK FACTOR PRIORITIZATION

This section presents a step-by-step description of risk factor prioritization. An example is provided to understand the process. In total, there are five steps in this process.

Step 1. Identify Risk Factors

The graphs (Figure 2-3 [a]) show the percentages of highway mileage and SVROR KA crashes by lane and shoulder width. Only for an 11 ft-lane with no shoulder (i.e., 11+0), the percentage of KA crashes is higher than the proportion of highway mileage with that cross-sectional width. It means 11+0 is only over-represented risk factor group related to the analysis of cross-sectional width for low-volume highways. Note that a 10 ft-lane width or less without paved shoulder and a 10 ft-lane with 1 ft paved shoulder are under-represented risk factors because the proportion of crashes is lower than that of the proportion of highway mileage associated with those cross-sectional widths.



a) Low-volume group

Step 2. Apply Crash Over- and Under-Representation Weights

Table 2-1 presents weighting points by crash total and crash over-/under-representation. In Step 1, we identified 11+0 as the only over-represented group for lane and shoulder widths in the analysis of SVROR crashes on low-volume highways. The percentages of SVROR KA crashes and highway mileage on 11+0 are 29.0 percent and 25.0 percent, respectively. SVROR crashes on 11+0 are over-represented by 4 percent (the difference between those percentages). Based on the weight criteria, four points are given for the crash over-representation and zero points for the crash under-representation.

Table 2-1 Risk Factor Weight Criteria

Category	Weight (points)										
	0	1	2	3	4	5	6	7	8	9	10
Crash Over-Representation	0%	>0% and <2%	≥2% and <3%	≥3% and <4%	≥4% and <5%	≥5% and <6%	≥6% and <7%	≥7% and <8%	≥8% and <9%	≥9% and <10%	≥10% and ≤100 %
Crash Under-Representation	0%	>0% and <2%	≥2% and <3%	≥3% and <4%	≥4% and <5%	≥5% and <6%	≥6% and <7%	≥7% and <8%	≥8% and <9%	≥9% and <10%	≥10% and ≤100 %
Crash Total	≥0% and <10%	≥10 and <20%	≥20 and <30%	≥30 and <40%	≥40 and <50%	≥50 and <60%	≥60 and <70%	≥70 and <80%	≥80 and <90%	≥90 and <100%	100%

Step 3. Apply Crash Total Weighting Criteria

The second weighting criteria are related to the percentage of KA crashes. For example, the percentage of SVROR KA crashes on 11+0 on low-volume highways is 29 percent. Based on the crash total weight criteria in Table 2-1, 2 points will be given to 11+0. No point will be given when the percentage of crashes is less than 10 percent.

Table 2-1 Risk Factor Weight Criteria

Category	Weight (points)										
	0	1	2	3	4	5	6	7	8	9	10
Crash Over-Representation	0%	>0% and <2%	≥2% and <3%	≥3% and <4%	≥4% and <5%	≥5% and <6%	≥6% and <7%	≥7% and <8%	≥8% and <9%	≥9% and <10%	≥10% and ≤100 %
Crash Under-Representation	0%	>0% and <2%	≥2% and <3%	≥3% and <4%	≥4% and <5%	≥5% and <6%	≥6% and <7%	≥7% and <8%	≥8% and <9%	≥9% and <10%	≥10% and ≤100 %
Crash Total	≥0% and <10%	≥10 and <20%	≥20 and <30%	≥30 and <40%	≥40 and <50%	≥50 and <60%	≥60 and <70%	≥70 and <80%	≥80 and <90%	≥90 and <100%	100%

Step 4. Calculate the Total Weight Points of Crash Over- or Under-Representation and Crash Total

From Steps 2 and 3, we can obtain the weight points for crash over- and under-representation and crash total. Equation 1 is used to obtain the total weight for 11+0 category in low-volume group as follows:

$$W_t = 10 + CT + CO - CU$$

$$W_t = 10 + 2 + 4 - 0 = 16$$

Step 5. Repeat Step 1 to 4 for Other Risk Factors

APPENDIX B. AGGREGATED WEIGHT CALCULATIONS

SEGMENT LEVEL WEIGHT CALCULATION

This section presents a three-step process on how weights were developed for each roadway segment, where each segment is a homogenous section that may consist of multiple horizontal curves and/or tangent sections. An example is provided to understand the process.

Step 1. Identify Horizontal Curves on the Segment

The TxDOT's Geometric (GEO-HINI) database for year 2012 is used to extract the horizontal curve information on each homogenous roadway segment. A segment is considered homogenous if it has a relatively constant cross section, constant traffic volume, and similar geometric design features along its length. The control section number and the Distance from Origin (DFO) are used to combine the horizontal curves with the roadway segments. An example is provided here.

A roadway segment on FM3363 in Brownwood District starts at DFO of 0.00 and ends at 0.445. It has a paved width of 22 ft with no shoulders, traffic volume of 695 vehicles per day in 2014, and a truck percentage of 11.5. After merging with the GEO-HINI data, researchers found that there are three horizontal curves on this segment. The first curve starts at DFO 0.129 and ends at 0.152 and has a radius of 149 ft. The second curve with a radius of 1,273 ft goes from 0.153 to 0.210, while the third one, with a radius of 305 ft, starts at 0.349 and ends at 0.408. The properties of various sections on the segment are summarized below.

Section	Length (miles)	Radius (ft)	ADT (veh/day)	Truck Presence (%)	Lane Width (ft)	Paved Shoulder Width (ft)
Horizontal Curve 1	0.023	149	695	11.5	11	0
Horizontal Curve 2	0.057	1273				
Horizontal Curve 3	0.059	305				
Straight	0.306	--				

Step 2. Apply the Risk Factor Weights

Based on the geometric and traffic variables, the crash risk factor weights are assigned. The weights based on three volume groups and risk factors are provided in Table 2-4 of the main part of this report. The particular road segment presented in Step 1 falls under low volume category. The weights based on each risk factor are presented below.

Section	Weight (points)			
	Alignment	Truck presence	Lane and Shoulder Width	Total
Horizontal Curve 1	26.45	21.65	25.00	73.10
Horizontal Curve 2	18.40			65.05
Horizontal Curve 3	26.45			73.10
Straight	11.70			58.35

The total points are calculated by summing the weight points assigned to alignment type, truck presence, and lane and shoulder width. For example, for horizontal curve 1, total points = 26.45+21.65+25.00=73.10.

Step 3. Calculate Aggregated Weight

Once individual points are assigned to each section on the segment, a combined weight for the whole segment is then calculated. The weighted average procedure is used with the weights based on the section length. The following equation is used to calculate the aggregated weight.

$$W_{agg} = \frac{\sum_{i=0}^{n} W_i L_i}{\sum_{i=0}^{n} L_i}$$

Where,

W_i= Weight (points) awarded to section i on the segment.

L_i= Length of section i.

n = Total number of individual sections on the segment.

The table below shows the aggregated weight calculations.

Section	Length (L_i)	Weight (W_i)	Product of Length and Weight ($W_i L_i$)
Horizontal Curve 1	0.023	73.10	1.68
Horizontal Curve 2	0.057	65.05	3.71
Horizontal Curve 3	0.059	73.10	4.31
Straight	0.306	58.35	17.86
Sum	**0.445**		**27.56**
$W_{agg} = \frac{\sum_{i=0}^{n} W_i L_i}{\sum_{i=0}^{n} L_i} = \frac{27.56}{0.445} = 61.93$			

PROJECT LEVEL WEIGHT CALCULATION

This section presents the weight calculations at a project level. A project can span a few miles long and may include multiple homogenous segments. The start and end of a horizontal curve are not considered a change in homogeneity. However, a horizontal curve will have a different weight than a straight section. This difference is already accounted for in calculating the weights for homogenous segments. The spreadsheet that is included with this report has the weights for each and every homogenous segment that has traffic volume of at least 400 vehicles per day and paved width less than 24 ft. However, although very rare, some segments may have been excluded if they have missing or erroneous values. In those situations, consider the weight of an adjacent segment that has similar properties to the missing segment. The equation presented in the step 3 of the segment level weight calculation can be used here to calculate the aggregated weight for the project:

$$W_{agg\_proj} = \frac{\sum_{j=0}^{m} W_j L_j}{\sum_{j=0}^{m} L_j}$$

where,

W_j= Weight (points) given to homogenous segment j.

L_j= Length of segment j.

m = Total number of individual homogenous segment included in the project.