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PHASE I ASSESSMENT OF GUARDRAIL LENGTH-OF-NEED

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16. Abstract (Limit: 200 words)

Guardrails have commonly been installed to prevent errant vehicles from impacting roadside hazards. However, guardrail impacts have contributed to numerous serious injuries and fatalities, are generally impacted more often when installed closer to the travel way edge, and are usually much longer than the shielded hazard. Thus, in order to reduce the frequency of severe guardrail crashes, an optimized length should be determined. Previously, the American Association of Highway and Transportation Officials Roadside Design Guide (RDG) suggested guardrail runout lengths which were dependent on posted speed limit and traffic volumes, but were considerably longer than those recommended in other studies assessing the optimal length-of-need (LON).

Crash data analyses and simulation using the recently-updated Roadside Safety Analysis Program (RSAPv3) was conducted to evaluate the cost-effectiveness and estimated crash costs associated with different guardrail LONs. Crashes involving Kansas guardrail, which were compliant with recommendations provided in the 2006 AASHTO RDG, and occurring on freeways with divided medians were analyzed. The frequency, rate, and risk of shielded hazard crashes were extremely low. RSAPv3 analysis indicated that there was both an economic and safety benefit to reducing the installed LON, as well as utilizing different runout lengths for left- and right-side departures for divided roadways.

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1 INTRODUCTION

1.1 Problem Statement

Each year, over 12,000 fatalities occur, resulting from errant vehicles departing the roadway. According to the Insurance Institute for Highway Safety and Highway Loss Data Institute (IIHS and HLDI) [1], single-vehicle run-off-road (ROR) crashes accounted for 6,928 fatalities, which is over half of the total number of ROR fatalities in 2009. These run-off-road crashes included vehicles leaving the roadway and rolling over and/or hitting roadside hazards, such as bridge piers, utility poles, trees, fences, culverts, ditches, embankments, highway sign supports, and traffic barriers.

As an attempt to minimize the risks of errant vehicles hitting roadside obstacles, engineers usually try to relocate hazards to be farther from the roadway based on the clear zone concept [2]. However, relocating the hazard is often disadvantageous or impossible due to space limitations. In these circumstances, engineers often choose to shield the hazard using safety devices, such as guardrails. However, guardrails are also a roadside hazard, and crashes with guardrails also result in ROR crash fatalities. Therefore, the use of guardrail should only be advised when the consequences of installing guardrail are less costly to society than other safety treatment options.

For purposes of this study, guardrails are defined as semi-rigid barriers that are capable of absorbing energy during impact and safety redirecting or capturing an errant vehicle. However, more crashes are reported on most roadways after a guardrail is installed than occurred before guardrail installation. Over-exposure to guardrail impact may subject vehicle occupants to additional unnecessary risk. Thus, there exists an optimal guardrail length based on hazard size, crash severity, distance from the roadway, and nominal travel speed. If a guardrail length is too short, a large number of vehicles may run behind the guardrail and hit the hazard. Alternatively, if the guardrail is too long, the crash frequency will increase. The increased crash costs generated from guardrail impacts could even outweigh the benefits from having a guardrail shielding the hazard (i.e., reduced crash cost). As a result, there is a need to determine an optimal guardrail length-of-need (LON). Even though recommended guardrail runout lengths from at least three major research studies are available, these findings could be outdated and/or flawed.

1.2 Objective

The research objectives were two-fold: (1) to quantify the frequency and likelihood of a vehicle travelling behind a guardrail and striking a shielded hazard and (2) to assess whether current guardrail length recommendations found in the AASHTO Roadside Design Guide (RDG) [2,3] are optimized for maximum cost-effectiveness and/or lowest crash costs.

1.3 Scope

The research objectives of this study were accomplished through the following tasks: 1) a literature review of previous LON studies; 2) collection of crash, guardrail length, and highway data; 3) crash report summary and data analysis; 4) benefit-to-cost analysis based on guardrail lengths, and 5) summary and limitations of results.

2 LITERATURE REVIEW

2.1 Fixed-Object Vehicle Crashes

Traffic fatalities caused by fixed-object crashes have accounted for approximately one-fifth of all vehicle crash deaths since 1979. The number of traffic fatalities caused by fixed-object crashes was 10,550 in 1979 and 7,272 in 2010, the most recent year of data at the start of this study, which corresponds to a reduction of 31 percent. During the same time period, the number of vehicle-miles traveled had steadily increased from 1.5 to 3.0 trillion-vehicle-miles traveled. This indicated that the number of motor vehicle crash deaths per 100 million vehicle miles traveled decreased from 3.35 in 1979 to 1.11 in 2010 [1]. The distribution of deaths in fixed-object crashes by object struck in 2010 is shown in Table 1. Tree crashes resulted in the largest number of fatalities, which accounted for half of all deaths in fixed-object crashes in 2010, followed by utility poles and traffic barriers. The traffic barrier category included fatalities related to all concrete barrier, W-beam, box beam, and cable barrier crashes.

Table 1. Distribution of Deaths in Fixed-Object Crashes by Object Struck, 2010 [1]

Object struck	**Number**	**%**
Tree	3,614	50
Utility pole	1,015	14
Traffic barrier	611	8
Embankment	389	5
Ditch	253	3
Culvert	212	3
Fence	175	2
Wall	141	2
Building	139	2
Highway sign support	134	2
Bridge pier	132	2
Other	457	6
Total	**7,272**	**100**

Most fatal fixed-object crashes were single-vehicle crashes, as shown in Table 2. Over 50 percent of fatal fixed-object crashes occurred in rural locations, whereas interstates and freeways represented only 14 percent of fatal crashes, as shown in Tables 2 through 4. Therefore, fatal crashes were more likely to occur in locations with shorter clear-zone distances and limited access control with more hazards located close to the roadway. Travel speeds were likely related to fatal crash risk, since nearly half of these crashes occurred on facilities with a speed limit of 55 mph (88 km/h) or greater, as shown in Table 5.

Table 2. Distribution of Deaths in Fixed-Object Crashes by Crash Type, 2010 [1]

Crash Type	**Deaths**	**%**
Single-Vehicle Crashes	6,928	95
Multiple-Vehicle Crashes	344	5
All Crashes	7,272	100

Table 3. Distribution of Deaths in Fixed-Object Crashes by Land Use, 2010 [1]

Land Use	**Deaths**	**%**
Rural	4,134	57
Urban	3,037	42
Total	7,272	100

Table 4. Distribution of Deaths in Fixed-Object Crashes by Road Type, 2010 [1]

Road Type	**Deaths**	**%**
Interstates and freeways	1,054	14
Other major roads	3,426	47
Minor roads	2,647	36
All road types	7,272	100

Table 5. Distribution of Deaths in Fixed-Object Crashes by Speed Limit, 2010 [1]

Speed Limit	**Deaths**	**%**
No limit	22	<1
<35 mph	1,003	14
35-40 mph	1,389	19
45-50 mph	1,446	20
55+ mph	3,277	45
Total	7,272	100

2.2 Guardrail Crashes

2.2.1 Overview of Guardrail Crashes

W-beam guardrail was impacted during more fatal crashes than any other traffic barrier type, using IIHS data from 2009 [1]. Guardrail was involved in 432 fatal crashes, which represented approximately 6 percent of all fixed-object fatal crashes, as shown in Table 6. Rollovers occurred in approximately 17 percent of fatal guardrail crashes.

Table 6. Distribution of Deaths in Fixed-Object Crashes by Rollover Occurrence and Object Struck, 2010 [1]

	Rollover		No rollover		All crashes	
Object Struck	**Number**	**%**	**Number**	**%**	**Number**	**%**
Tree	589	16	3,025	84	3,614	100
Utility pole	175	17	840	83	1,015	100
Guardrail	73	17	359	83	432	100
Embankment	130	34	259	67	389	100
Ditch	72	28	181	72	253	100
Other	28	12	196	88	224	100
Culvert	70	33	142	67	212	100
Concrete	39	22	140	78	179	100
Fence	35	20	140	80	175	100
Wall	27	19	114	81	141	100
Building	15	11	124	89	139	100
Other post/pole	16	12	118	88	134	100
Bridge pier	16	12	116	88	132	100
Curb	9	8	104	92	113	100
Bridge rail	12	15	69	85	81	100
Boulder	11	28	28	72	39	100
Total	**1,317**	**18**	**5,955**	**82**	**7,272**	**100**

Bryden and Fortuniewicz conducted a study for the New York State Department of Transportation (NYSDOT) which investigated 3,302 traffic barrier crashes between July 1, 1982 and June 30, 1983 to determine the effect of vehicle type and size, barrier type and mounting height, and roadway features on in-service safety performance of traffic barriers [4-5]. Crashes were selected in which the first harmful event was an impact with a traffic barrier. Results of the study are shown in Table 7.

Table 7. Distribution of Crashes by Traffic Barrier [4]

Barrier Type	No. Crashes	%
Light-Post Traffic Barriers	1,887	57.15
Heavy-Post Blocked-Out W-beam	94	2.85
Concrete Safety Shape	90	2.73
Obsolete Barriers	810	24.53
Others, Unknown	421	12.75
Total	**3,302**	**100**

Crash data was segregated into sub-groups for analysis, as shown in Table 8. Historical barriers which did not meet crashworthiness requirements established by NYSDOT were classified as “Obsolete Barriers”, whereas crashes which were in compliance with standards established at the time of the study were classified as “Contemporary Barrier” crashes. All crashes, including end-on, LON, and large-vehicle impacts, were classified in both sub-groups. A separate distinct group, “Ideal Barrier Crashes”, excluded end-on terminal impacts and only considered crashes which occurred within the design range of impact conditions.

Table 8. Injury Severities Recorded for Roadside Crashes [4]

		Percent of Crashes at Severity Level					
Crash Category	**No. of Crashes**	**Fatal**	**A**	**B**	**C**	**All Injury**	**No Injury**
All	270,688	0.71	-	-	-	63.5	35.8
All Roadside	40,163	1.5	-	-	-	74.2	24.3
All Barriers	3,302	1.33	9.45	25.8	22.4	57.7	40.9
Obsolete Barriers	811	2.22	13.19	30.6	23.4	67.2	30.6
Contemporary Barriers	2,071	1.16	9.37	27.0	24.6	61.0	37.9
Ideal Barrier Crashes	1,313	0.53	7.31	25.1	24.7	57.1	42.4

Several trends were observed from the crash data shown in Table 8. Run-off-road crashes resulted in fatalities more than twice as often as occurred in all crashes. Barrier crashes were generally less severe than all roadside crashes, although fatal crashes into obsolete systems occurred at nearly double the rate of contemporary barriers. Crashes which occurred away from end terminals, involved contemporary and well-maintenanced barriers, and which occurred with impact speeds and angles within the design criteria resulted in fewer fatal and serious injuries than barrier crashes which did not meet those criteria. As a result, many fatal and serious injury crashes with guardrail were attributable to problems with maintenance and adherence to design and construction standards, involved older, non-compliant systems, or were impacted with speeds or angles beyond design conditions. Bryden and Fortuniewicz estimated that 94 percent of all-barrier impacts and 97.6 percent of ideal-barrier impacts resulted in no injury or fatality when estimates for non-reported collisions were considered [5].

2.2.2 End Terminal Crash Severity

The misclassification of terminals as longitudinal barriers can also lead to overrepresentation of guardrail crash severity. End terminal crashes are more likely to be reported as compared to crashes occurring within the LON. Thus, terminal crashes may adversely affect guardrail severe crash rates; since, terminal impacts tend to be more severe. For example, Griffin examined the performance of turned-down guardrail ends using data from 1,087 crashes in Texas and compared it to the safety performance of guardrail collisions [6]. He found that fatalities were much more common on turned-down ends, as shown in Table 9.

Table 9. Distribution of Guardrail Crashes on Texas State-Maintained Highways by Point of Impact [6]

		Crashes on Turned Down Ends		Crashes Not on Turned Down Ends	
		No.	**%**	**No.**	**%**
Guardrail Crashes	**Non-Fatal Crashes**	700	95.1	2,784	98.2
	Fatal Crashes	36	4.9	51	1.8

Griffin also found that rollovers occurred in 72 percent of fatal crashes and 36 percent of all turned-down end crashes as compared to 54 percent of fatal crashes and 12 percent of all crashes occurring within the LON. Although this research contributed to the eventual recommendation not to install turned-down ends and thus represents a historical feature, this study demonstrated the disproportionate risk of severe crash results in end-on collisions as compared to crashes occurring within the LON.

2.2.3 Most Harmful Event

It is not always possible to attribute the severity of the crash to the barrier impact only. The first harmful event is usually coded in lieu of the most harmful event, because determination of the most severe event may be subjective. Because of this, the contribution of the barrier to crash severity may be overrepresented. Viner studied the relationship between the first and the most harmful events, and the results are shown in Table 10 [7]. Crashes involving guardrail, concrete barrier, bridge rail, and impact attenuators were commonly the first event during fatal crashes. However, barrier crashes were the most severe event during a crash sequence in less than half of those crashes. This result suggests that guardrail crashes are less severe in general than impacts with other features, but also indicates that vehicles may be involved in a subsequent, severe impact after being redirected by a traffic barrier.

Table 10. Harmful Events in Ran-Off-Road Fatalities [7]

Object Struck / Event Sequence	First Harmful Event (FHE)	Most Harmful Event (MHE)	Ratio MHE /FHE
Tree	2,870	3,246	1.13
Overturn	2,492	4,820	1.93
Utility Pole	1,235	1,298	1.05
Embankment	1,187	601	0.51
Guardrail	1,101	456	0.41
Ditch	750	302	0.40
Other	565	613	1.08
Culvert	537	281	0.52
Curb	506	117	0.23
Other fixed Object	461	219	0.48
Other Post	457	237	0.52
Fence	421	156	0.37
Sign Post	295	99	0.34
Bridge Pier	211	255	1.21
Concrete Traffic Barrier	211	83	0.39
Bridge Rail	194	118	0.61
Luminaire Support	148	146	0.99
Wall	143	127	0.89
Boulder	133	76	0.57
Bridge End	122	95	0.78
Building	101	143	1.42
Immersion	98	354	3.61
Shrubbery	66	13	0.20
Other Noncollision	53	40	0.75
Other Traffic Rail	33	16	0.48
Fire Hydrant	28	9	0.32
Impact Attenuator	7	3	0.43
Overhead Sign Post	6	11	1.83
Unknown	4	272	68
Fire/Explosion	0	229	-
Total	**14,435**	**14,435**	

2.2.4 Severe Barrier Crashes

Recently, the American Association of State Highway and Transportation Officials (AASHTO) adopted the *Manual for Assessing Safety Hardware* (MASH) [8], which reflected the state-of-the-art in crashworthiness testing of roadside features, such as guardrail. Crash test impact conditions and crashworthiness criteria were similar to those presented in the National Cooperative Highway Research Program (NCHRP) Report No. 350 [9]. Those crash conditions were supported by the reconstruction of more than 890 run-off-road crashes occurring between 1997 and 2004 [10]. The 62.1 mph (100.0 km/h) impact event occurring at 25 degrees with respect to the roadway, which was recommended for Test Level 3 (TL-3) impact conditions in both NCHRP Report No. 350 and MASH, represented approximately the 85th percentile impact speed and departure angle of run-off-road crashes. These crash conditions were intended to approximate a practical worst-case crash condition.

Research has shown that barrier penetrations and rollovers are overrepresented with respect to serious crashes, and may be correlated with more energetic impact conditions than are utilized in full-scale crash testing. Albuquerque et al. found that the 85th percentile impact angles associated with crashes occurring on high-speed roadways are higher than the 25-degree impact angle currently recommended by MASH [11]. In fact, Albuquerque et al. found that approximately 30 percent of the single-vehicle run-off-road crashes on interstate highways had an impact angle of 25 degrees or higher, and more than two percent of these crashes had both impact speeds higher than 65-mph and impact angles higher than 25 degrees. Crashes involving these impact conditions would be characterized as collisions that are beyond the performance capability of most TL-3 guardrail systems.

Motorcyclist crashes also contribute to increased severe crash rates. Gabler found that motorcycle crashes are the leading source of fatalities in guardrail crashes, and motorcycle riders account for more fatalities than passengers of any other vehicle type involved in a guardrail collision [12]. He also determined that the relative fatality risk in guardrail collisions for motorcycle riders was more than 80 times higher than for passenger car occupants. Daniello and Gabler found that motorcycle collisions with guardrails are seven times more likely to be fatal than collisions with the ground, and were the most hazardous barrier type due to post strength, post spacing, and barrier stiffness [13]. In Bryden and Fortuniewicz's investigations conducted on New York's state maintained highways, motorcycle crashes had the highest severe crash rate at approximately 50 percent [4]. The remaining 50 percent of identifiable motorcyclist crashes were associated with moderate to minor injuries.

Severe crash rates are also affected by unreported crashes. Over a 12-month span, Galati filmed a 20-mile (32-km) length of median barrier on the Schuylkill freeway in Philadelphia and painted it white once a month over a 12-month period in the 1960s [14]. Scuff marks and other damage were immediately recorded and repaired, and matched with the police report records. A total of 1,085 minor and significant impacts were recorded over this period. Galati concluded that only 13 percent of the crashes were reported. Later, Carlson compiled crash records over a 5-year period in the 1970s to evaluate the safety performance of highway safety devices [15]. He determined that 10 percent of all longitudinal barrier crashes were reported. These research records suggested that less than 15 percent of crashes are reported. Crashes in which the minimum property-damage only (PDO) threshold for repair or replacement was not exceeded, the vehicle was drivable after the crash, or involving individuals seeking to avoid contact with law enforcement may not be reported. Because reported crashes are more likely to involve impaired vehicles and/or injured people, the injury distribution for reported crashes are usually skewed towards higher injury levels than will be globally observed. By accounting for unreported crashes and secondary, more severe impacts, Michie and Bronstad estimated that only

2 to 3 percent of all crashes into contemporary, properly-installed and maintained guardrails may contribute to injury or fatality [16].

Unreported crashes may subsequently require maintenance to the guardrail system, which may be associated with additional costs. Furthermore, the injury severity and frequency of reportable crashes also contributes to increased societal costs. An appropriate LON must be determined for every guardrail installation. The LON must be long enough to capture most errant vehicles, but short enough to prevent the cost of the increased number of crashes resulting from increased exposure from exceeding the benefit of reduced crash severity.

2.3 Guardrail Length-of-Need

Calculation of the necessary LON of guardrail has historically been based on recommendations provided by AASHTO, as shown in Figure 1 [3]. The LON was calculated based on a line drawn from the roadway to the furthest extent of the hazard within the clear zone which warranted shielding. The intersection of that line and the front face of the guardrail corresponded to the beginning of the LON.

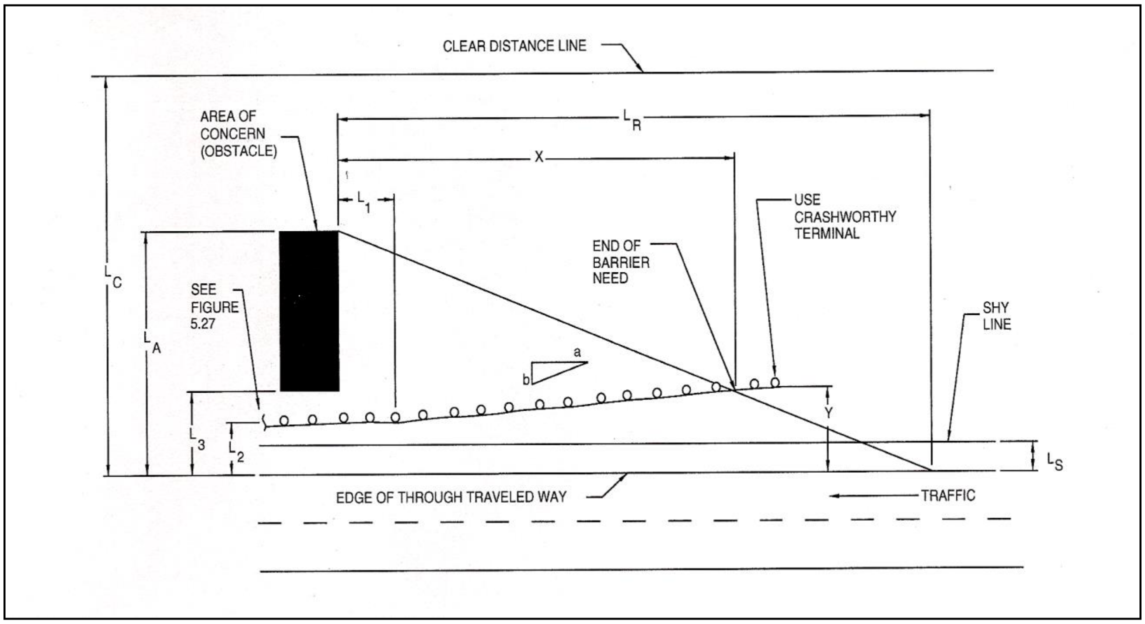


Figure 1. Approach Barrier Layout Variables [3]

The guardrail runout length is therefore the distance that a vehicle would have to travel in order to pass behind the guardrail and strike the hazard, as measured parallel to the roadway. Two research studies used roadside encroachment data to determine guardrail runout lengths: Hutchinson and Kennedy (H&K) in the 1960s [17] and Cooper in the 1970s [18]. However, the validity of these conclusions is the subject of considerable controversy [19]. Criticisms of the H&K research argued that some encroachment distances were measured from vehicle tracks during winter months when medians could be snow-covered, which may have resulted in longer-than-normal encroachments, and there was no means for determining whether these encroachments were controlled or uncontrolled. In addition, the data may be skewed towards longer encroachments since shoulders were paved. Therefore, there was no means to identify vehicle tracks from vehicles which left the road, but stayed within the shoulder area. In contrast, encroachment data from the Cooper study was collected from a wide variety of roadside conditions since many two-lane roadway sections were included. These roadways may have very different cross-section profiles (e.g., some may have steeper slopes than others) that may not compare very well with the typical U.S. interstate highway cross-sections. Runout lengths suggested by H&K are shown in Table 11.

Research performed by Sicking and Wolford, as well as by Coon, has suggested that Cooper's encroachment data provided more accurate and shorter guardrail runout lengths [20-21]. These researchers used benefit-cost analysis techniques to determine the appropriate LON for guardrail. They found guardrail LONs which were much shorter than those recommended by the 2006 RDG [2]. The 2006 RDG guardrail runout lengths are shown in Table 12.

Table 11. Suggested Runout Lengths for Barrier Design by Hutchinson and Kennedy [17]

	Runout Length, m (ft), at Indicated Traffic Volume (ADT)			
Design Speed km/h [mph]	**Over 6,000**	**2,000-6,000**	**800-2,000**	**Under 800**
110 (70)	145 (475)	135 (445)	120 (395)	110 (360)
100 (60)	130 (425)	120 (400)	105 (345)	100 (330)
90 (55)	110 (360)	105 (345)	95 (315)	85 (280)
80 (50)	100 (330)	90 (300)	80 (260)	75 (245)
70 (45)	80 (260)	75 (245)	65 (215)	60 (200)
60 (40)	70 (230)	60 (200)	55 (180)	50 (165)
50 (30)	50 (165)	50 (165)	45 (150)	40 (130)

Table 12. Runout Length Values Recommended in 2006 RDG [2]

	Runout Length Given Traffic Volume (ADT), m (ft)			
Design Speed km/h (mph)	**Over 6,000**	**2,000 to 6,000**	**800 to 2,000**	**Under800**
110 (68)	145 (475)	135 (443)	120 (394)	110 (360)
100 (62)	130 (426)	120 (394)	105 (344)	100 (328)
90 (55)	110 (360)	105 (344)	95 (312)	85 (279)
80 (50)	100 (328)	90 (295)	80 (262)	75 (246)
70 (43)	80 (262)	75 (246)	65 (213)	60 (191)
60 (37)	70 (230)	60 (191)	55 (180)	50 (164)
50 (31)	50 (164)	50 (164)	45 (148)	40 (131)

Furthermore, recent research using real-world crash data was used to evaluate the H&K and Cooper data sets [20]. These studies suggested that guardrail runout lengths recommended by Cooper matched better with their findings as compared to guardrail runout lengths recommended by Hutchinson and Kennedy. Runout lengths suggested by Wolford and Sicking are displayed in Table 13. The 2011 version of the AASHTO RDG [3] adopted much shorter guardrail runout lengths as compared to the 2006 RDG [2], as shown in Table 14.

Table 13. Runout Length Values Recommended by Wolford and Sicking [20]

	Runout Length Given Traffic Volume (ADT), m (ft)			
Design Speed Km/h (mph)	**Over 10,000**	**5,000 to 10,000**	**1,000 to 5,000**	**Under 1,000**
113 (70)	110 (360)	91 (300)	79 (260)	67 (220)
97 (60)	79 (260)	64 (210)	55 (180)	52 (170)
80 (50)	64 (210)	52 (170)	46 (150)	40 (130)
64 (40)	49 (160)	40 (130)	34 (110)	30 (100)
48 (30)	34 (110)	27 (90)	24 (80)	21 (70)

Table 14. Runout Length Values Recommended in 2011 RDG [3]

	Runout Length Given Traffic Volume (ADT), m (ft)			
Design Speed Km/h (mph)	**Over 10,000**	**5,000 to 10,000**	**1,000 to 5,000**	**Under 1,000**
128 (80)	143 (470)	131 (430)	116 (380)	101 (330)
113 (70)	110 (360)	101 (330)	88 (290)	76 (250)
97 (60)	91 (300)	76 (250)	64 (210)	61 (200)
80 (50)	70 (230)	58 (190)	49 (160)	46 (150)
64 (40)	49 (160)	40 (130)	34 (110)	30 (100)
48 (30)	34 (110)	27 (90)	24 (80)	21 (70)

A more recent research study conducted in Europe attempted to determine the required length of guardrails before hazards [22]. Researchers used data from reconstructed vehicle crashes, such as departure velocity and angle, as inputs in computer software to evaluate the trajectory and speed of vehicles travelling behind the guardrail. Researchers determined that the minimum length of a guardrail required to prevent impact with the shielded hazard should be 767 feet (234 meters) at a departure speed of 80 mph (130 km/h). If collision speeds of 24 mph (40 km/h) and 39 mph (64 km/h) are acceptable, the length of guardrail would be reduced to approximately 698 feet (213 m) and 590 feet (180 m), respectively. The authors conclude that, based on real-world crash data, guardrails were too short in 8 percent of passenger run-off-the-road crashes. The authors did not address any additional crash effects caused by the increased length of guardrail.

3 DATA COLLECTION

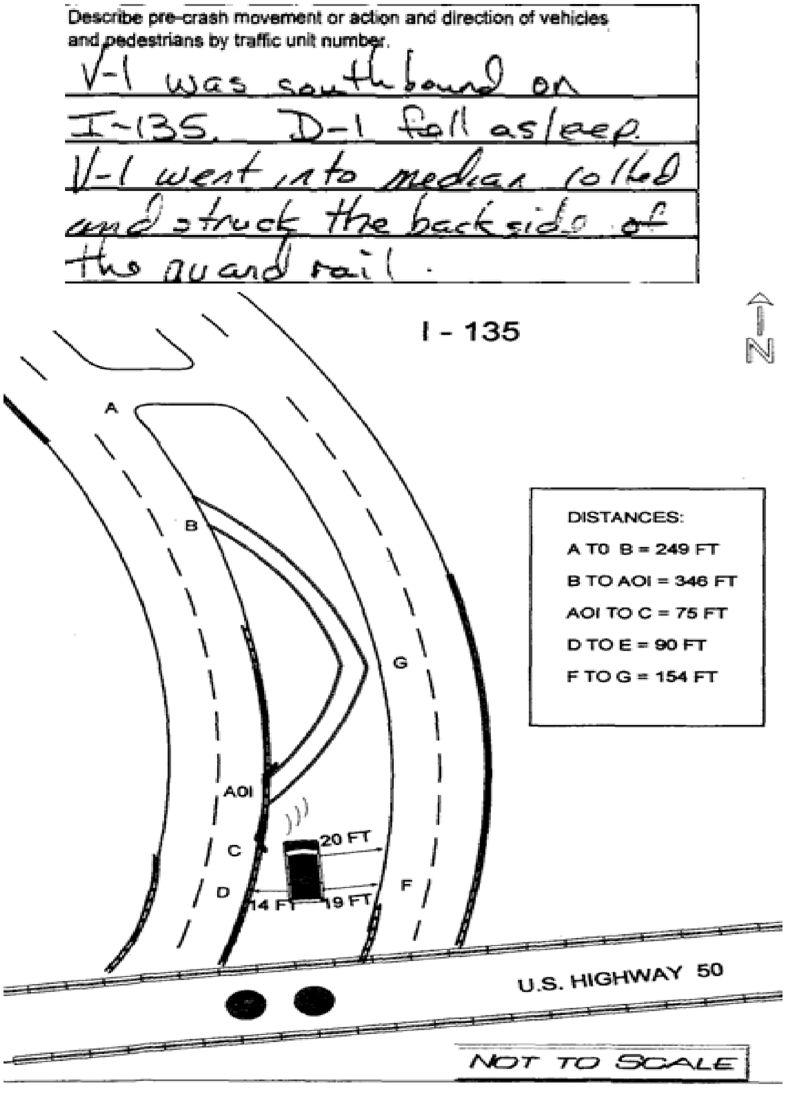
3.1 Crash Data

Guardrail, hazard, traffic volume, and crash data were collected from eight interstate highways in Kansas: I-35, I-70, I-135, I-235, I-335, I-435, I-470, and I-635. Approximately 42,000 crash reports spanning between 2002 and 2006 were reviewed, and crashes that occurred on interstate highways were extracted for further consideration. Non-interstate crashes and crashes in which guardrail was not present were excluded. In addition, guardrail crashes located at interstate ramps, interchanges, or access points were excluded, because those guardrails are infrequently used to shield fixed objects.

Scaled satellite images obtained from Google Maps were used to measure guardrail lengths, offsets from the face of the guardrail to the edge of the travel way, and whether the guardrail was located on the right or left side of the road at crash scenes. Based on estimates derived from scene diagrams and crash narratives, impacts were segregated by impact location which occurred at the first (upstream), second, third, or fourth (downstream) quarter-lengths of guardrail. It was not possible to determine the exact point where the vehicle struck the guardrail; since, this was not recorded and scene diagrams were not drawn to scale. If the impact location occurred near the transition between quarter-segments and if researchers were not confident that the crash could be accurately classified by a single guardrail segment, it was sometimes classified as first/second quarter, second/third quarter, or third/fourth quarter. In addition to guardrail positions, the type of fixed-object hazard, the lateral offset from the edge of the travel way, and the distance from the hazard to the leading edge of the guardrail were also measured.

Crash data included crash severity information, crash location (i.e., milepost, travel direction, and/or point of reference), and recorded crashes in which the vehicle impacted the guardrail terminal, ran behind the guardrail installation, or vehicle struck the shielded obstacle.

An example of a crash in which the vehicle was traveling southbound and drifted off of the road into the median is shown in Figure 2. After passing behind the upstream end of the left-side guardrail into the median, the vehicle redirected back toward the travel lanes, impacted the back side of the left-side guardrail, and rolled.



Describe pre-crash movement or action and direction of vehicles and pedestrians by traffic unit number.

V-1 was southbound on
I-135. D-1 fell asleep.
V-1 went into median rolled
and struck the back side of
the guard rail.

Figure 2. Example Crash Narrative and Diagram

A satellite photograph of the crash scene is shown in Figure 3. Using satellite imagery, the distance between the upstream end of the left-side guardrail and the hazard was measured parallel with the roadway, and was denoted with a red line. The distance between the end of the guardrail and the vertical face of the bridge deck was denoted as “X” which was approximately 430 feet (131.1 m). It was not possible to measure the distance between the hazard and the vehicle in this crash because the overpass obscured the pier.

Figure 3. Plan View of Crash Site

In order to overcome this problem, a tangential bridge width, “y”, was determined using the scaled plan view and determined to be 30 ft (9.1 m), as shown in Figure 4. Then, using the Street View application, the bridge pier was approximately centered with respect to the bottom of the bridge, as shown in Figure 5. Thus, the distance from the upstream end of the guardrail to the hazard was approximately equal to X + ½ y, or 430 ft (131.0 m) + 15 ft (4.6 m), equal to 445 ft (135.6 m). The guardrail was terminated at approximately the downstream end of the bridge pier. The width of the bridge pier was estimated to be 4 ft (1.2 m) and centered with respect to the bridge. Since it was estimated that the guardrail terminated at approximately the downstream edge of the bridge pier measured at an angle parallel to the overpass roadway, an additional 2 ft (0.6 m) was added to account for the outer section of the bridge pier, for a total guardrail length of 447 ft (136.2 m).

Figure 4. Measurement of Bridge Width

Figure 5. Street View of Crash Site

The lateral offset from the front face of the guardrail to the edge of travel way was measured radially with the curve, as shown in the upper-left corner of Figure 3. The lateral offset to the guardrail was determined to be 8 ft (2.4 m) in this crash. Similarly, the lateral offset to the hazard was determined to be 22 ft (6.7 m), which was found by dividing the median width of 48 ft (14.6 m) in half, and subtracting half the diameter of the bridge pier.

3.2 Variables Used and Data Sources

A total of 19 different parameters used to describe each crash are shown in Table 15.

Table 15. Variables Included in the Database

DATA SOURCE	VARIABLE NAME	DESCRIPTION	EXAMPLE
Crash Report	Crash Number	Crash Identification Number	20030036047
	Crash Severity	Highest Injury Level Resulted from the Crash	PDO
	Guardrail Location	Roadside or Median	Median
	Guardrail Portion Struck	First, Second, Third, or Fourth Quarter	Second/Third Quarter
	Terminal Struck	Yes or No	No
	Ran Behind Guardrail	Yes or No	Yes
	Struck Hazard	Yes or No	No
	Interstate Name	I-35, I-70, I-135, I-235, I-335, I-435, I-470, or I-635	I-135
	Milepost Number	Crash Location	33
	Direction of Vehicle Travel	Used to Identify the Direction the Vehicle Was Traveling at the Time of Crash	South
	Reference Point	Used to Help Identifying Crash Location. Especially, Whenever Milepost Information Was Missing.	Exit 34
	Distance and Direction from the Reference Point	Used to Locate Crash Location Using the Reference Point	1.9 miles south
Satellite Maps and Photos	Guardrail Length (ft)	Distance from the Upstream Guardrail End to the Downstream Hazard End.	447
	Guardrail Lateral Offset (ft)	Distance from the Front Face of the Guardrail to the Travel Way Edge.	8
	Hazard Description	Hazard Type	Bridge Pier
	Hazard Lateral Offset (ft)	Distance from the Front Face of the Guardrail to the Back of the Hazard.	26
	Guardrail Site	Identified by Highway Name and Milepost Number. Used to Match Up with Traffic Volume Data (i.e., ADT).	I-135 N, Milepost 3
Kansas DOT	ADT	Average Annual Daily Traffic for Each Year and Guardrail Site.	13,500
	Guardrail and Terminal Cost	Guardrail Cost Per Linear Foot and Terminal Cost Per Unit. Used in the B/C Analysis.	Guardrail = US$ 29.77/ft Terminal = US$ 1,988/Unit

4 DATA ANALYSIS

4.1 Crash and Guardrail Statistics

The crash data was separated by roadway, and the results were compiled in Table 16. Interstates I-70, I-35, and I-135 accounted for 86 percent of the total mileage and 73 percent of the guardrail-related crashes. The interstates with the most frequent crashes were I-235 (1.82 crashes/mile) and I-635 (1.57 crashes/mile).

Table 16. Crash Frequency Distribution by Road Name

Road	Mileage	# Crashes	%
I-635	17.81	28	4.28
I-470	27.44	13	1.99
I-235	33.03	60	9.17
I-435	56.07	54	8.26
I-335	100.35	20	3.06
I-135	191.48	105	16.06
I-35	470.81	147	22.48
I-70	847.54	227	34.71
Total	1,744.53	654	100

Injury distributions were plotted by roadway, as shown in Figure 6. Fatal, injury, and PDO crashes constituted 1, 35, and 64 percent of crashes, respectively. The highest and lowest percent of injury crashes occurred on I-635 and I-35 and were equal to 57 and 26 percent, respectively. One reason for the discrepancy between injury rates on these two roadways was the proximity and frequency of fixed objects located close to the roadway. For example, interstate I-635 is located in an urban area with fixed objects and guardrails placed much closer to the traveled way as compared to most fixed objects and guardrails on interstate I-35, which is mostly located in rural areas.

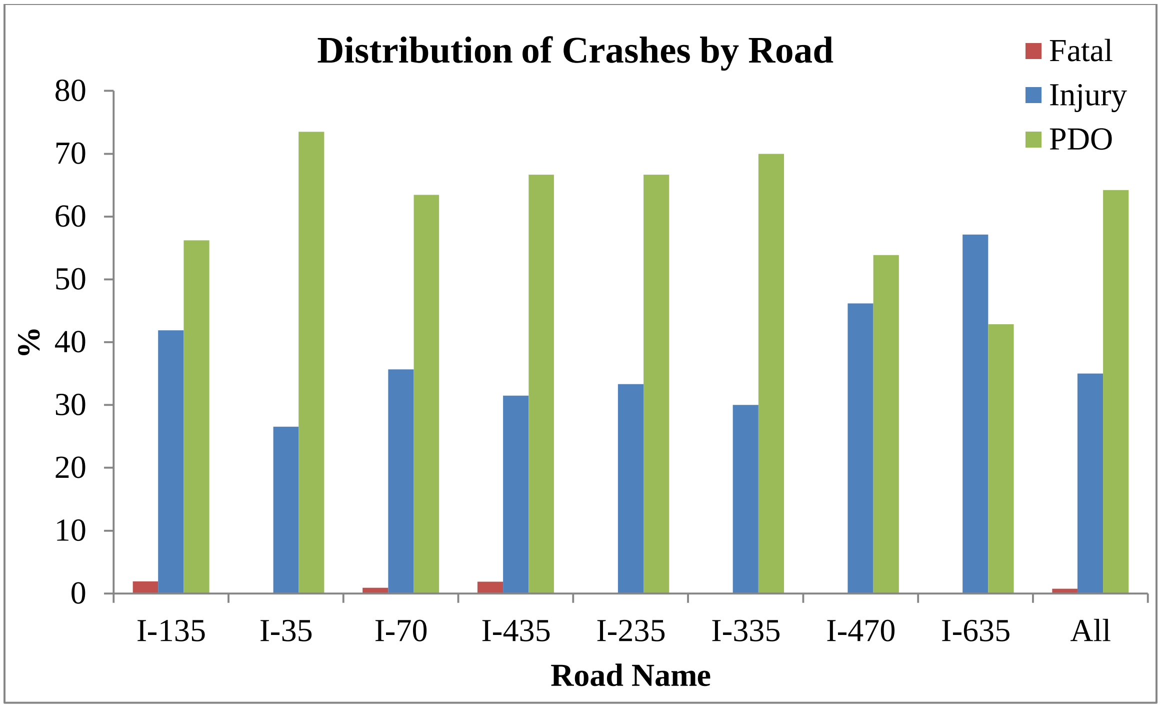


Figure 6. Crash Severity Distribution by Road Name

The mean, median, and 85th percentile values for guardrail length on each interstate highway are shown in Figure 7. The median, mean, and 85th percentile guardrail length values for all of the interstate roadways were 211, 272 and 337 ft (64.3, 82.9, and 102.7 m), respectively. Typical guardrail lengths were the longest on I-70, with median, mean, and 85th percentile values equal to 282, 332, and 392 ft (85.9, 101.1, and 119.4 m), respectively. In contrast, interstate I-635 typically had the shortest guardrail lengths, with median, mean, and 85th percentile values equal to 122, 164, and 211 ft (37.1, 49.9, and 64.3 m), respectively. One reason for longer guardrail lengths on I-70 compared to I-635 was that hazards, which were protected on I-70, were in rural areas. In addition the hazards were usually wider (such as rivers) and located far from the roadway, and required longer guardrail lengths.

The number and type of shielded hazards are shown in Table 17. Slopes and drop-offs at bridge locations and bridge piers were the most common shielded hazards. These hazards accounted for more than 70 percent of all obstacles shielded by guardrails.

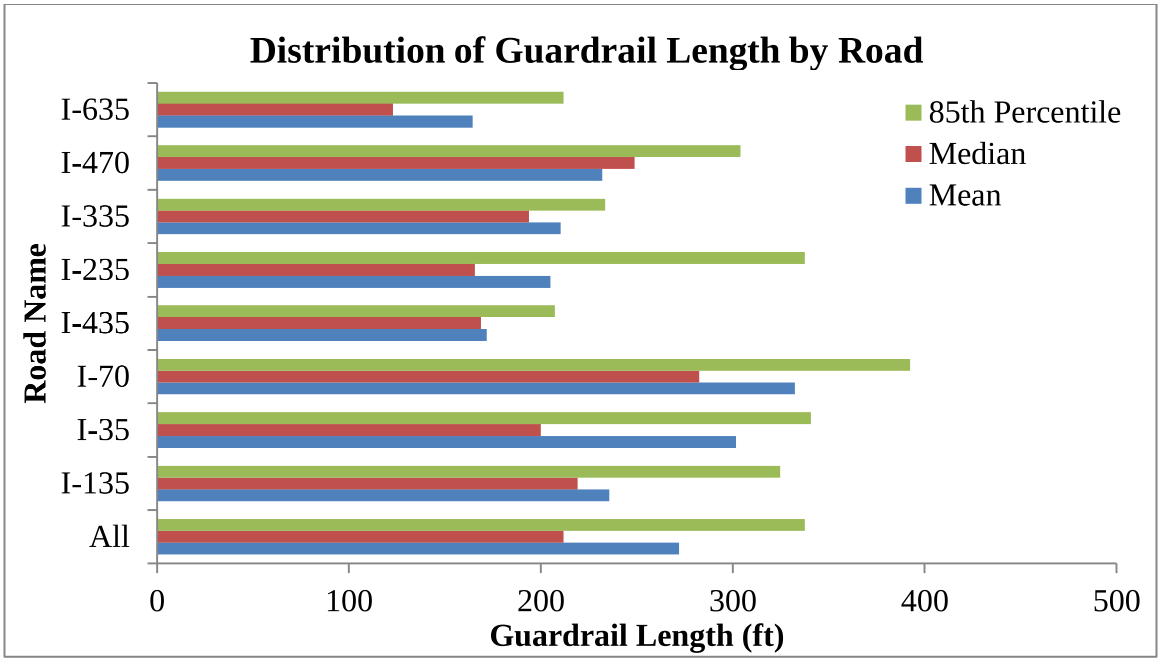


Figure 7. Statistics for Guardrail Length

Table 17. Frequency of Shielded Hazards by Hazard Type

Hazard Type	No. of Hazards	Percent of Hazards
Bridge/Overpass (Bridge Rail)	1,114	39.09
Bridge Pier	984	34.53
Culvert	491	17.23
Sign	190	6.67
Slope	63	2.21
Other	8	0.28
Total	2,850	100.00

Mean, median, and 85th percentile values for guardrail length by shielded roadside hazards are shown in Figure 8. Guardrails which shielded bridge abutments had the highest mean and 85th percentile lengths. This may be attributed to the fact that these systems not only are installed to prevent errant drivers from impacting the bridge abutment, but also to prevent drivers from travelling down steep roadside slopes often found at these locations.. These same concerns apply for guardrail installations located at culverts, which were only slightly shorter than bridge rail counterparts.

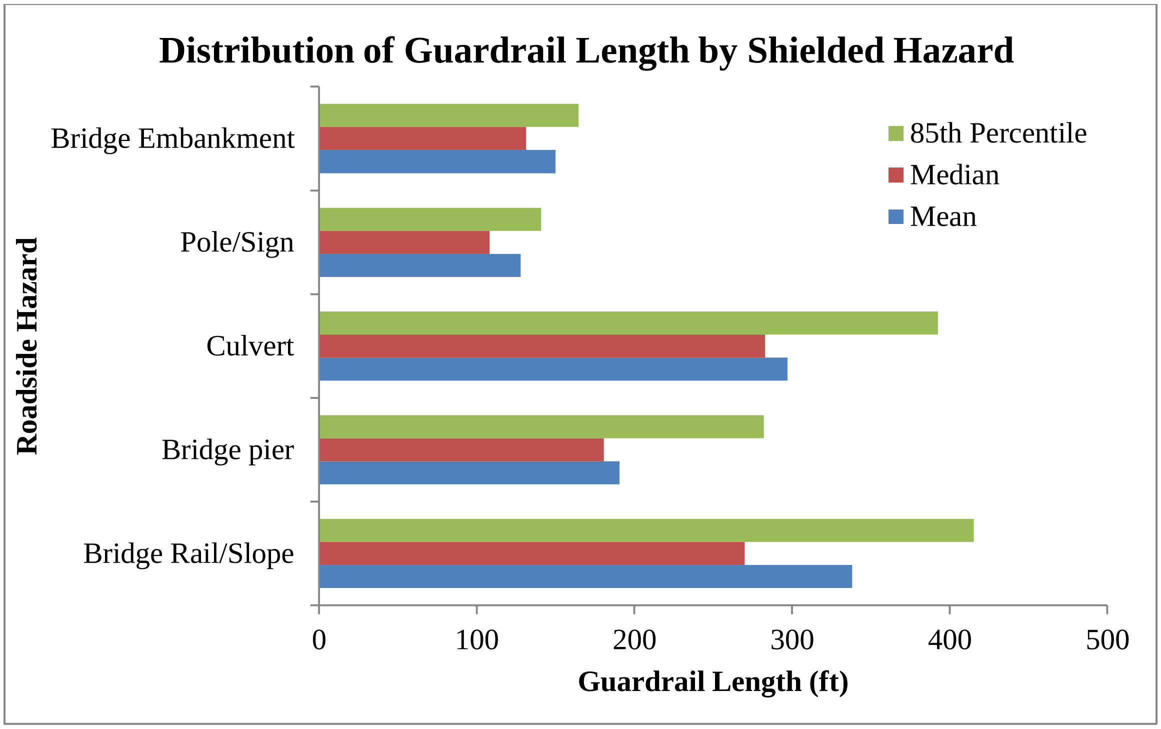


Figure 8. Statistics of Guardrail Length Distances by Shielded Hazard

The mean, median, and 85th percentile values for guardrail lateral offset were approximately 17, 17, and 23 ft (5.2, 5.2, and 7.0 m), respectively, for all roadways, as shown in Figure 9. Likewise, the mean, median, and 85th percentile guardrail offsets plotted by the shielded hazard type are shown in Figure 10. Recall that guardrail lateral offsets were measured between edge of the travel way and the back face of the hazard. Recorded hazard offsets were the largest on I-435, with median, mean, and 85th percentile values equal to 26, 23, and 37 ft (7.9, 7.0, and 11.3 m), respectively. Road I-470 had the shortest guardrail lateral offset.

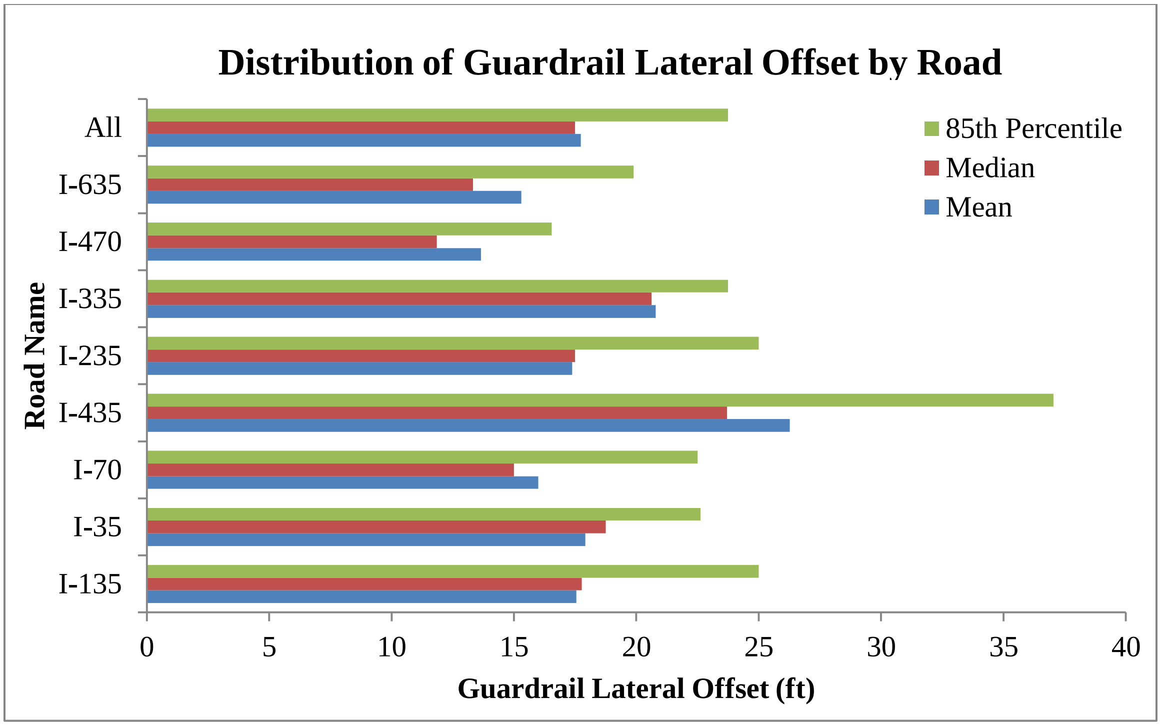


Figure 9. Statistics for Guardrail Lateral Offset

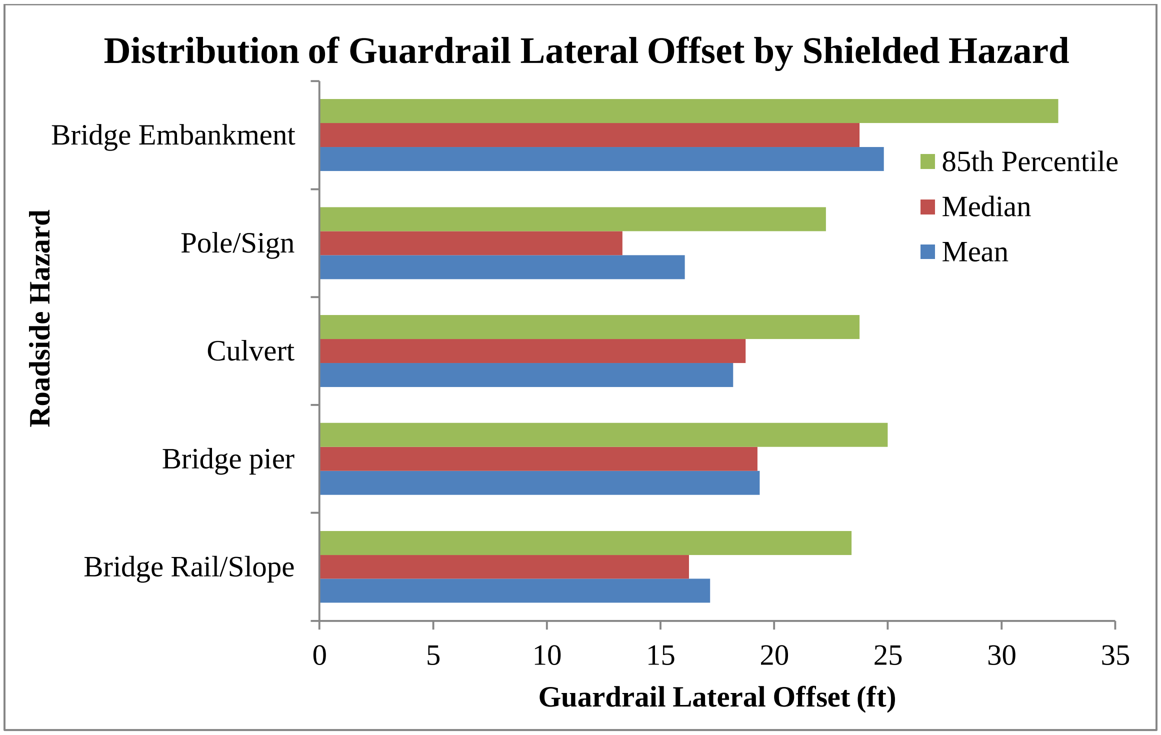


Figure 10. Statistics of Guardrail Lateral Offset Distances by Shielded Hazard

Mean, median, and 85th percentile values for hazard lateral offset were approximately 26, 23, and 40 ft (7.9, 7.0, and 12.2 m), respectively, as shown in Figure 11. Mean, median, and 85th percentile values for hazard lateral offset were also plotted based on shielded hazard, as shown in Figure 12. Recall, hazard lateral offsets were measured as the distance from the traveled way edge to the back of the roadside hazard. Interstate I-135 had the largest hazard offsets on average with a median and mean values equal to 29 and 27 ft (8.8 and 8.2 m), respectively. Hazard offsets were also relatively consistent throughout I-135, with an 85th percentile offset of 32 ft (9.8 m), which was marginally higher than the median and mean offsets of 29 and 27 feet (8.8 and 8.2 m), respectively. Slopes and drop-offs (such as at bridges), roadside slopes, and bridge embankments had the largest lateral offsets, whereas bridge piers, poles, and signs had the lowest lateral offsets.

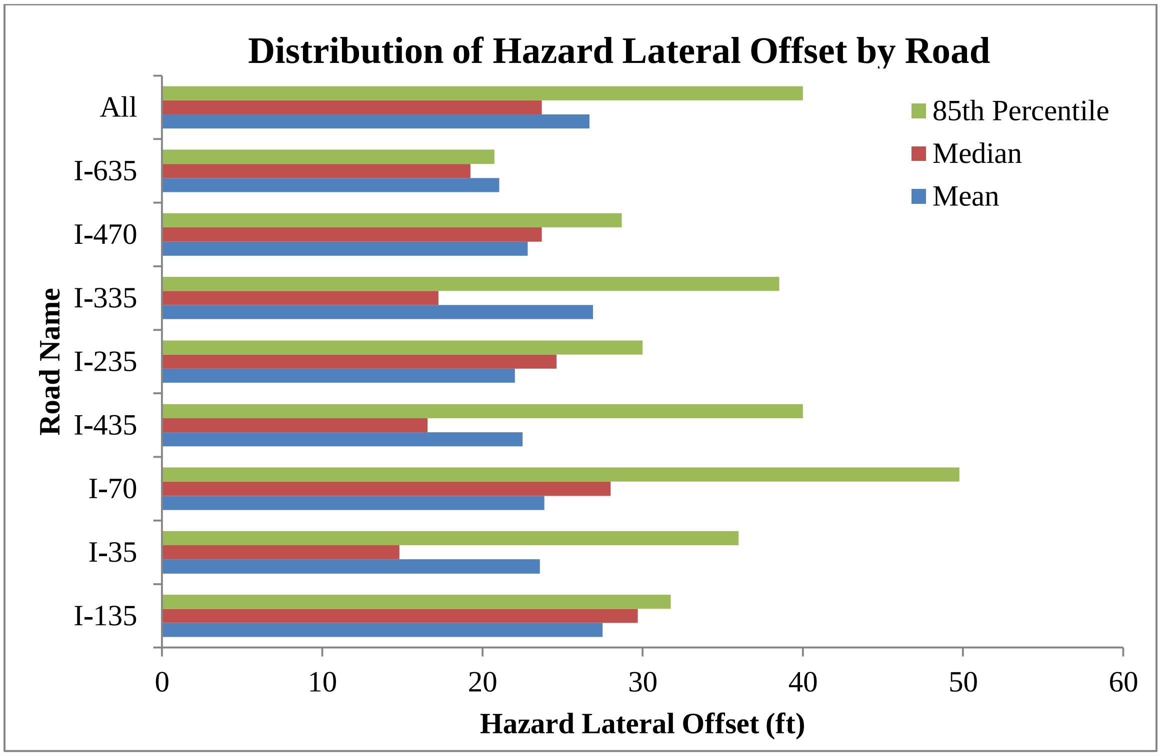


Figure 11. Statistics for Hazard Lateral Offset

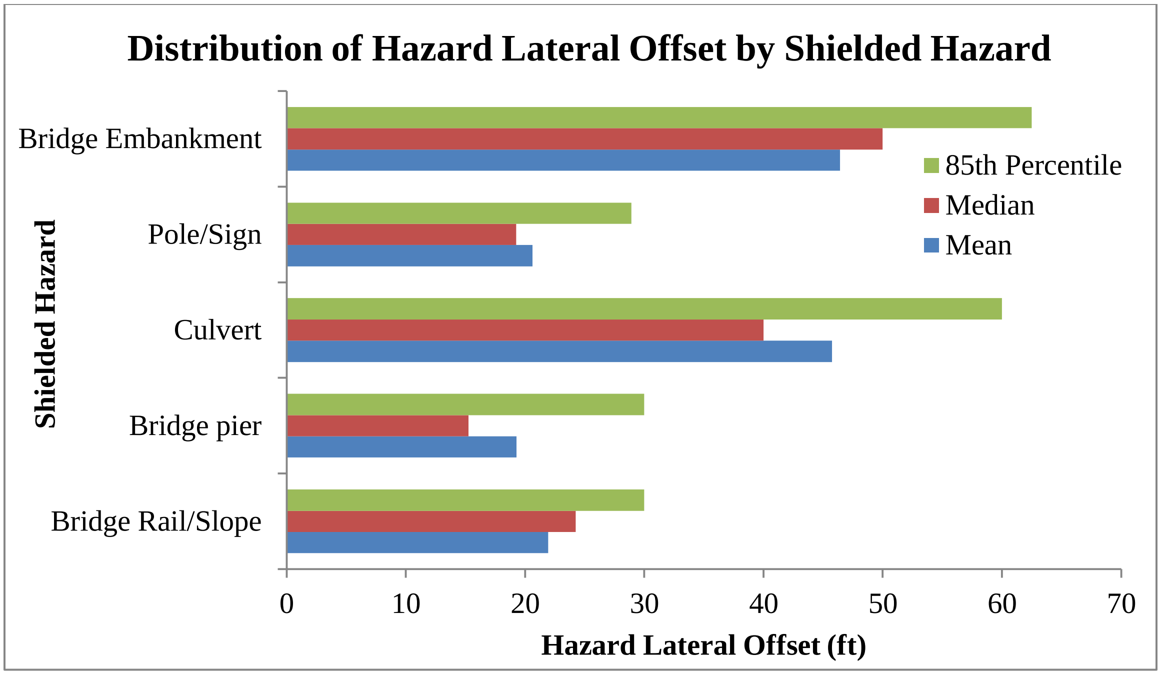


Figure 12. Statistics of Hazard Lateral Offset Distances by Shielded Hazard

Impacts with terminals were also extracted and considered. Fifteen terminal impacts were identified, consisting of 7 injury and 8 PDO crashes, as shown in Table 18. The frequency of fatalities and injuries was approximately 1.32 times larger for terminals than for non-terminal impacts.

Table 18. Distribution of Terminal Crashes by Crash Severity

		Crash Severity	No. of Crashes	Percent of Crashes
Terminal Impacted	**Yes**	Fatal	0	0.00
		Injury	7	46.67
		PDO	8	53.33
	No	Fatal	5	0.78
		Injury	222	34.74
		PDO	412	64.48

The shielded hazards were further segregated by roadway, as shown in Table 19. Bridge piers, roadside slopes (include slopes at bridges), and bridge rail ends were the most common shielded roadside hazards. Culverts, utility poles, and traffic signs were less-commonly impacted. Seven guardrail crashes occurred at locations with bridge embankments. Injury observations for the shielded hazards were determined and are shown in Table 20. Guardrail shielding slope and bridge hazards contributed to four fatalities, and a guardrail shielding a bridge pier contributed to one additional fatality. Crashes into guardrail shielding a culvert had the lowest observations of fatality and injury at 28 percent.

Table 19. Crash Distribution by Shielded Hazard by Road Name

		I-135	**I-35**	**I-70**	**I-435**	**I-235**	**I-335**	**I-470**	**I-635**	**All**
Bridge Embankment	**#**	2	4	1	0	0	0	0	0	7
	%	28.57	57.14	14.29	0	0	0	0	0	100
Pole/Sign	**#**	10	10	10	4	17	0	5	17	73
	%	13.70	13.70	13.70	5.48	23.29	0	6.85	23.29	100
Culvert	**#**	9	20	42	0	0	8	2	0	81
	%	11.11	24.69	51.85	0	0	9.88	2.47	0	100
Bridge Pier	**#**	24	55	57	7	2	8	0	4	157
	%	15.29	35.03	36.31	4.46	1.27	5.10	0.00	2.55	100
Bridge Rail/Slope	**#**	60	58	117	43	41	4	6	7	336
	%	17.86	17.26	34.82	12.80	12.20	1.19	1.79	2.08	100

Table 20. Crash Distribution by Shielded Hazard by Crash Severity

		Crash Severity	**No. of Crashes**	**Percent of Crashes**
Hazard Type	**Bridge Embankment**	Fatal	0	0.00
		Injury	4	57.14
		PDO	3	42.86
	Pole/Sign	Fatal	0	0.00
		Injury	30	41.10
		PDO	43	58.90
	Culvert	Fatal	0	0.00
		Injury	23	28.40
		PDO	58	71.60
	Bridge Pier	Fatal	1	0.64
		Injury	52	33.12
		PDO	104	66.24
	Bridge Rail/Slope	Fatal	4	1.19
		Injury	120	35.71
		PDO	212	63.10

Approximately 62 percent of crashes occurred with guardrails installed on the right side of the roadway, as shown in Figure 13. Crash severities were relatively insensitive to which side of the road the guardrail was installed, as shown in Table 21. The crash severity distribution of right-side crashes is not significantly different from left-side crashes.

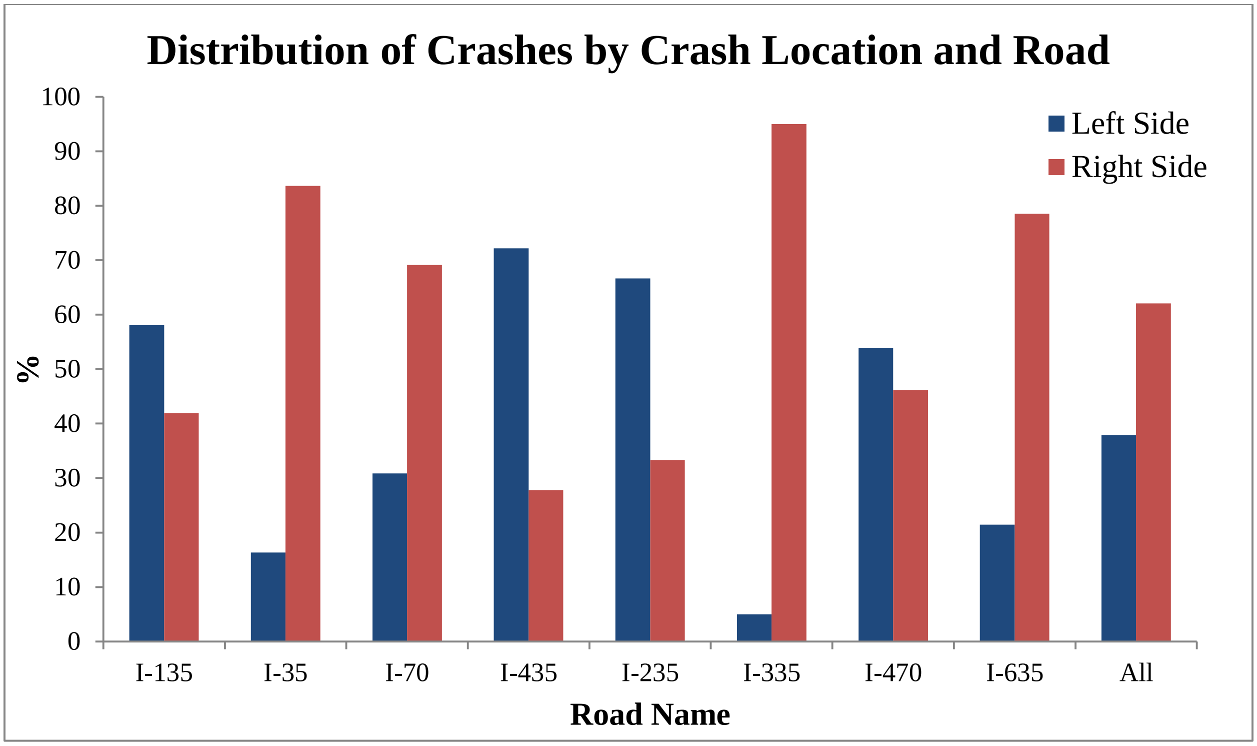


Figure 13. Percent of Crashes per Crash Location

Table 21. Distribution of Crash Severity by Guardrail Location

		Crash Severity	No. of Crashes	Percent of Crashes
Guardrail Location	**Left**	Fatal	4	1.6
		Injury	83	33.5
		PDO	161	64.9
	Right	Fatal	1	0.25
		Injury	146	36.0
		PDO	259	63.8

The guardrail crash severity distribution was segregated by approximate impact location, as shown in Table 22. More than 60 percent of crashes occurred within the upstream quarter of the guardrail. These impact locations were frequently flared away from the travel lanes. Also, the injury distribution did not appear to be dependent on barrier impact location. It was not possible to determine the impact region where the guardrail was struck for many crashes due to crash scene diagrams which were not drawn to scale or which were not completed. A similar distribution of crashes tabulated by the side of the roadway with the guardrail installed had similar results, as shown in Table 23.

Table 22. Crash Distribution by Shielded Hazard by Portion of Guardrail Struck

Injury Level	Portion of Guardrail Struck	#	%
PDO	First Quarter	60	61.2
	First/Second Quarter	12	12.2
	Second Quarter	2	2.0
	Second/Third Quarter	12	12.2
	Third/Fourth Quarter	2	2.0
	Fourth Quarter	0	0.0
Injury + Fatality	First Quarter	52	59.1
	First/Second Quarter	11	12.5
	Second Quarter	4	4.6
	Second/Third Quarter	10	11.4
	Third/Fourth Quarter	5	5.7
	Fourth Quarter	6	6.8

Table 23. Crash Distribution by Guardrail Location by Portion of Guardrail Struck

Guardrail Location	Portion of Guardrail Struck	#	%
Left	First	41	67.2
	First/Second	7	11.5
	Second	1	1.6
	Second/Third	5	8.2
	Third/Fourth	3	4.9
	Fourth	4	6.6
Right	First	71	56.8
	First/Second	16	12.8
	Second	5	4.0
	Second/Third	17	13.6
	Third/Fourth	6	4.8
	Fourth	10	8.0

Vehicle trajectories behind guardrail were identified and tabulated, as shown in Table 24. Approximately 3.5 percent of crashes occurring on I-70 involved vehicles traversing behind the systems, compared to I-35 which experienced only 1.4 percent of crashes traversing behind the guardrail. Furthermore, no fatalities were involved in run-behind guardrail crashes and only five out of the fourteen run-behind guardrail crashes involved injuries, as shown in Table 25.

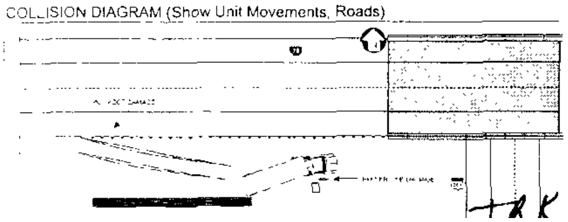
Table 24. Distribution of Ran-Behind Guardrail Crashes

			I-135	I-35	I-70	I-435	I-235	I-335	I-470	I-635	All
Ran-Behind Guardrail	**Yes**	**#**	2	2	8	0	1	1	0	0	14
		%	1.9	1.4	3.5	0.0	1.7	5.0	0.0	0.0	2.1
	No	**#**	103	145	219	54	59	19	13	28	640
		%	98.1	98.6	96.5	100.0	98.3	95.0	100	100	97.9

Table 25. Crash Severity Distribution by Ran-Behind Guardrail Crashes

			#	%
Ran-Behind Guardrail	**No**	**Fatal**	5	0.78
		Injury	224	35.0
		PDO	411	64.2
	Yes	**Fatal**	0	0.0
		Injury	5	35.7
		PDO	9	64.3

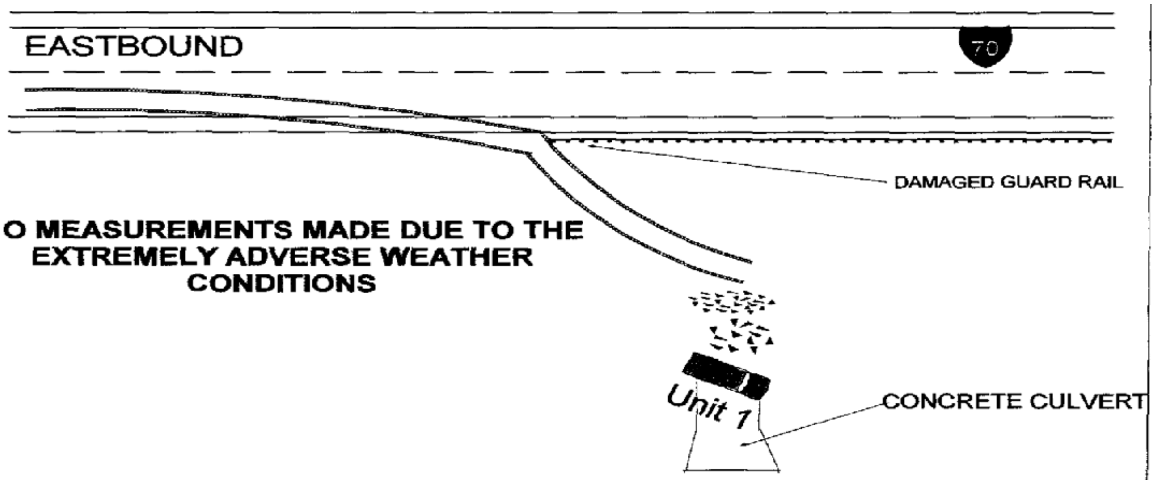
Only two out of the fourteen ran-behind-guardrail crashes involved a vehicle striking the shielded hazard, resulting in one PDO crash and one injury crash, as shown in Figures 14 and 15. Thus, a total of 0.3 percent of all crashes involved a vehicle striking the shielded hazard. One vehicle impacted a utility pole, and the other impacted the upstream end of a guardrail system, traversed behind the system, and rolled over at a culvert.



Describe pre-crash movement or action and direction of vehicles and pedestrians by traffic unit number.

U1 LEFT THE ROAD JUST PAST THE E/B 184 EXIT IN RUSSELL. AS IT WENT DOWN THE EMBANKMENT IT DESTROYED THE POWERLINES KNOWING OUT THE POWER TO THE AREA. IT CAME TO A REST ON ITS SIDE.

Figure 14. Scene Diagram and Crash Narrative, Ran-Behind Guardrail Crash No. 1



UNIT #1 WAS EASTBOUND ON I-70 WHEN THE DRIVER LOST CONTROL ON THE ICY AND SNOWPACKED ROADWAY. UNIT #1 THEN SLID OFF THE ROADWAY, STRUCK A GUARDRAIL, TRAVELLED INTO THE SOUTH DITCH, ROLLED OVER AND CAME TO REST ON ITS WHEELS ON TOP OF A CONCRETE CULVERT. THE TWO OCCUPANTS WERE NOT INJURED. APPROXIMATELY 20 FEET OF GUARDRAIL WAS DAMAGED DUE TO THE IMPACT FROM UNIT #1. THE CONCRETE CULVERT WAS NOT DAMAGED.

Figure 15. Scene Diagram and Crash Narrative, Ran-Behind Guardrail Crash No. 2

Neither of the hazards located behind the guardrail that were impacted during the two ran-behind-guardrail crashes were the primary hazards (i.e., hazards which precipitated the need for a crashworthy barrier). In both crashes, the guardrail was used to shield a bridge pier, and the culvert and utility pole were secondary (i.e.,incidental) hazards which happened to be shielded by the guardrail as well. Although the guardrail in ran-behind-guardrail crash no. 1 appeared to be lengthened due to secondary hazard (utility pole), the crash vehicle was a large truck. No guardrail is proven to successfully redirect a large truck impact. Guardrail length may not have been important for ran-behind-guardrail crash no. 1. As a result, the statistical analysis was believed to be conservative by over-representing the likelihood of a vehicle impacting a shielded object, and by representing a secondary hazard

4.2 Statistical Analysis of Crash Relationships

Crash data was analyzed to determine statistical relationships between the variables identified in Table 15. Crash severity and guardrail and hazard characteristics were analyzed by prescribing a binary coding of 1 for injury or fatality and 0 for PDO crash. Four different binary logit models were used with the independent variables: guardrail length; guardrail lateral offset; hazard lateral offset, and left- or right-side guardrail location. The p-values obtained by comparing guardrail length, guardrail lateral offset, hazard lateral offset, and guardrail location with crash severity were 0.71, 0.23, 0.27, and 0.77, respectively. None of these factors had a statistically significant impact on crash severity.

Hazard lateral offset was plotted against guardrail lengths, as shown in Figure 16. The correlation coefficient of 0.35 was highly significant (p-value < 0.0001), which suggests that guardrail length increased as the hazard was located farther from the traveled way edge. This finding was consistent with AASHTO RDG guidelines. Guardrail lengths were different for diffuse hazards, such as drop-offs at bridges, roadside slopes, and embankments, compared to point (i.e., discrete) hazards, such as signs, trees, poles, and bridge piers. Point hazards were typically associated with shorter lengths of guardrail, predominantly upstream of the hazard.

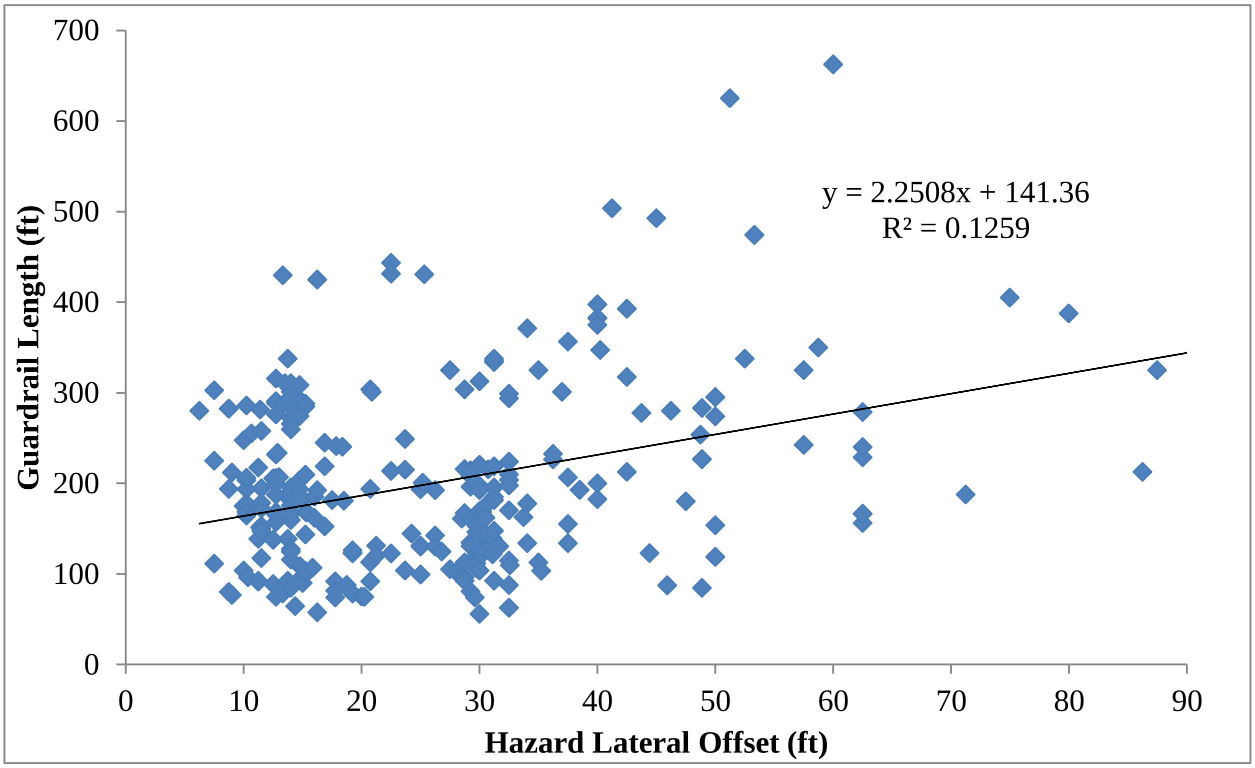


Figure 16. Guardrail Length vs. Hazard Lateral Offset

Guardrail lateral offset was also plotted against guardrail lengths, as shown in Figure 17. The correlation coefficient was 0.21 and was highly significant (p-value < 0.0001). This means that guardrail length decreased as the guardrail was located farther from the traveled way edge. A separate plot of guardrail lateral offset versus hazard lateral offset indicated that guardrail was generally located farther from the roadway whenever possible, as shown in Figure 18. The correlation coefficient was 0.24 and was highly significant (p-value < 0.0001).

Cumulative distributions of the guardrail lateral offset and guardrail length were plotted and are shown in Figures 19 and 20, respectively. In general, guardrails located on the right side of the road were located closer to the roadway and were longer than guardrails located on the left side of the road.

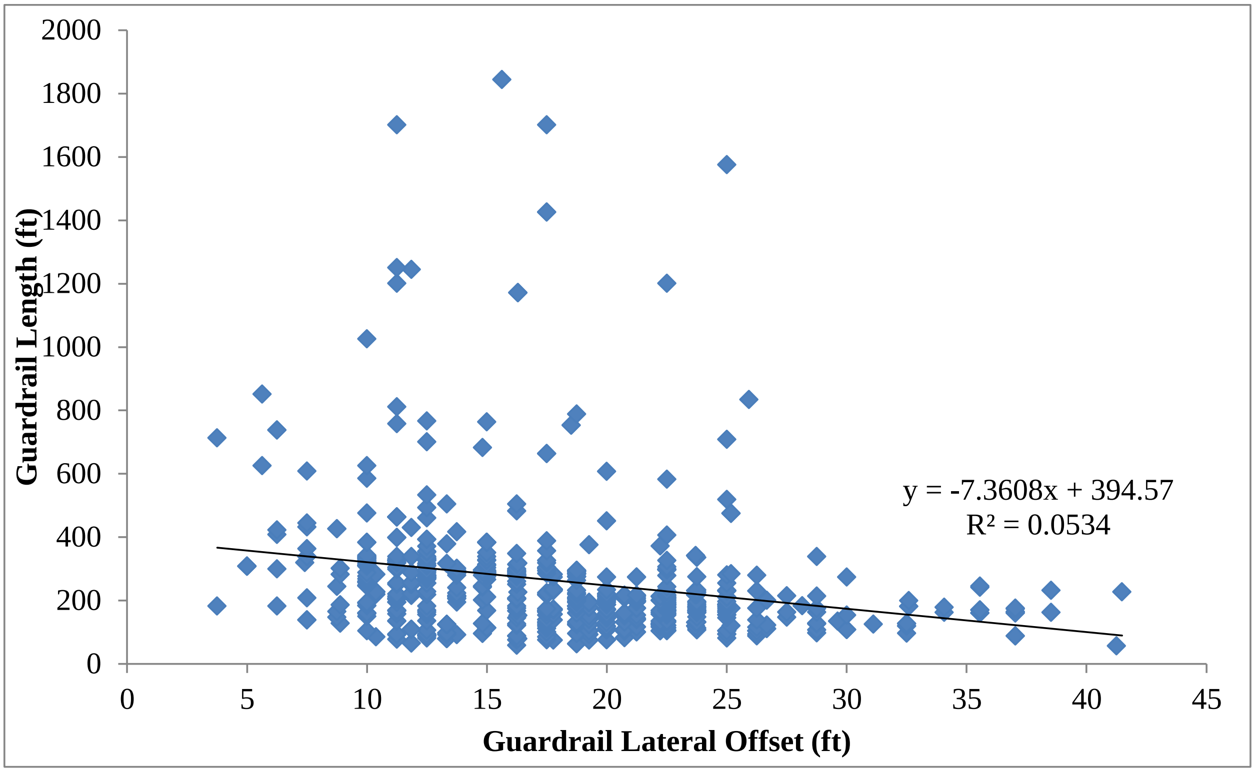


Figure 17. Guardrail Length vs. Guardrail Lateral Offset

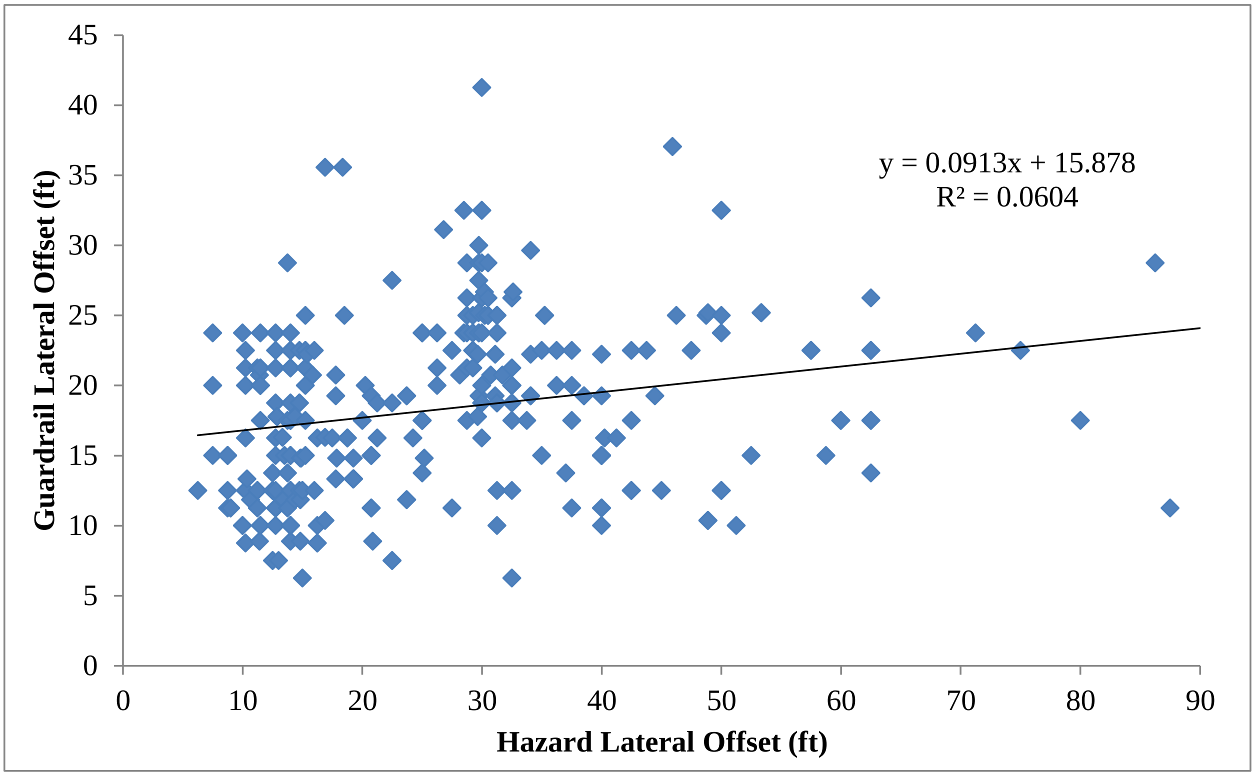


Figure 18. Guardrail Lateral Offset vs. Hazard Lateral Offset

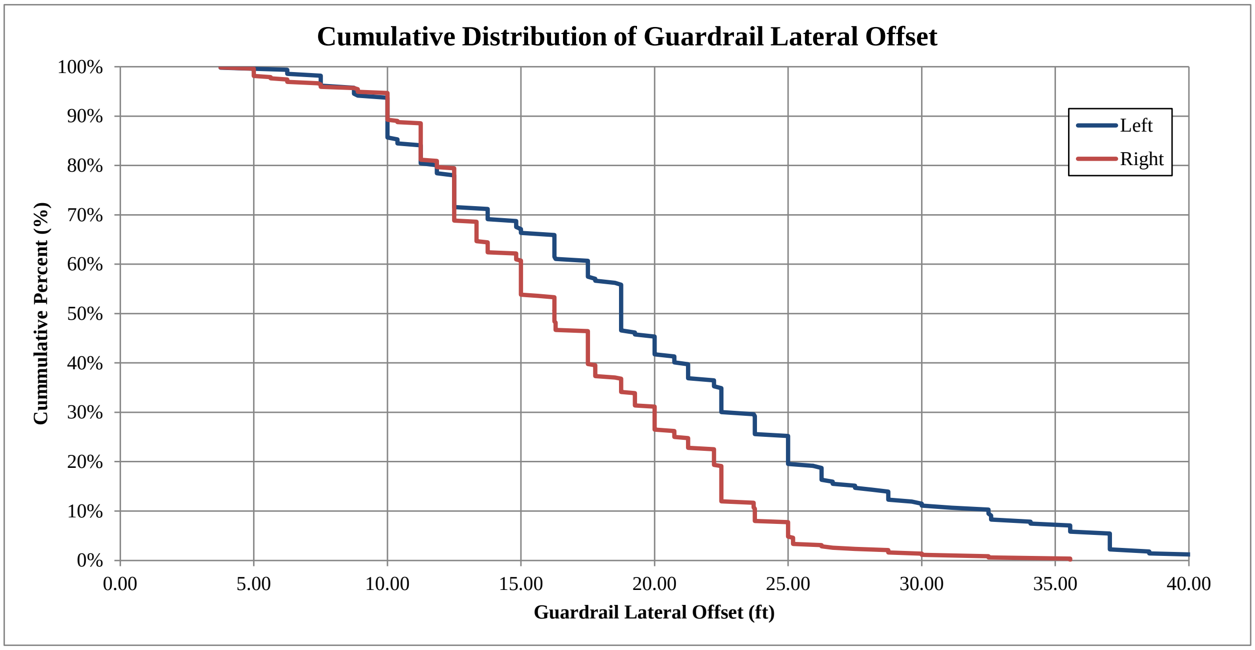


Figure 19. Guardrail Lateral Offset Distribution by Guardrail Location

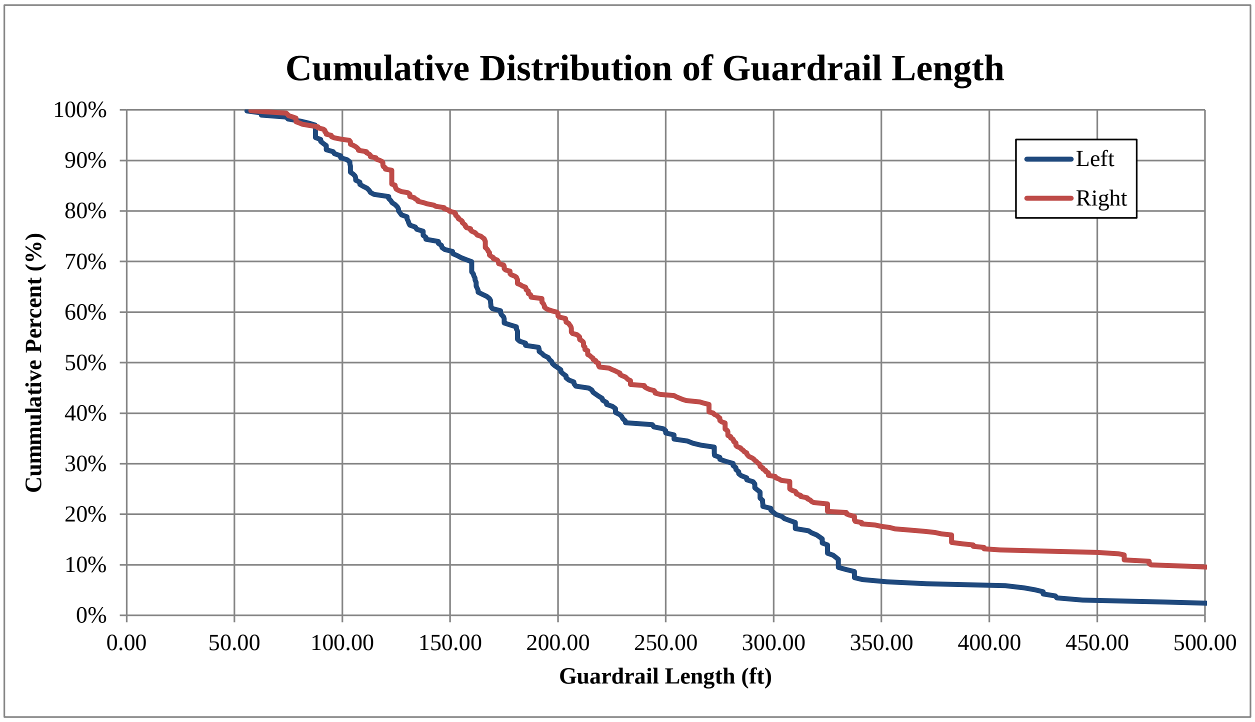


Figure 20. Guardrail Length Distribution by Guardrail Location

The hazard lateral offset cumulative distribution by guardrail location is shown in Figure 21. Median hazards were predominantly located within 30 feet (9.1 meters) from the edge of the traveled way. Over 53 percent of the left-side hazards were located between 26 and 33 ft (7.9 and

10.0 m) while 10 percent of were located between 15 and 25 ft (4.6 and 7.6 m) from the edge of the travel way. Right-side hazards were distributed throughout the roadway segments. Approximately 40 percent of the right-side hazards were located within 15 ft (4.6 m) of the roadway. Many of the hazards with large hazard lateral offsets corresponded to slope and embankment hazards.

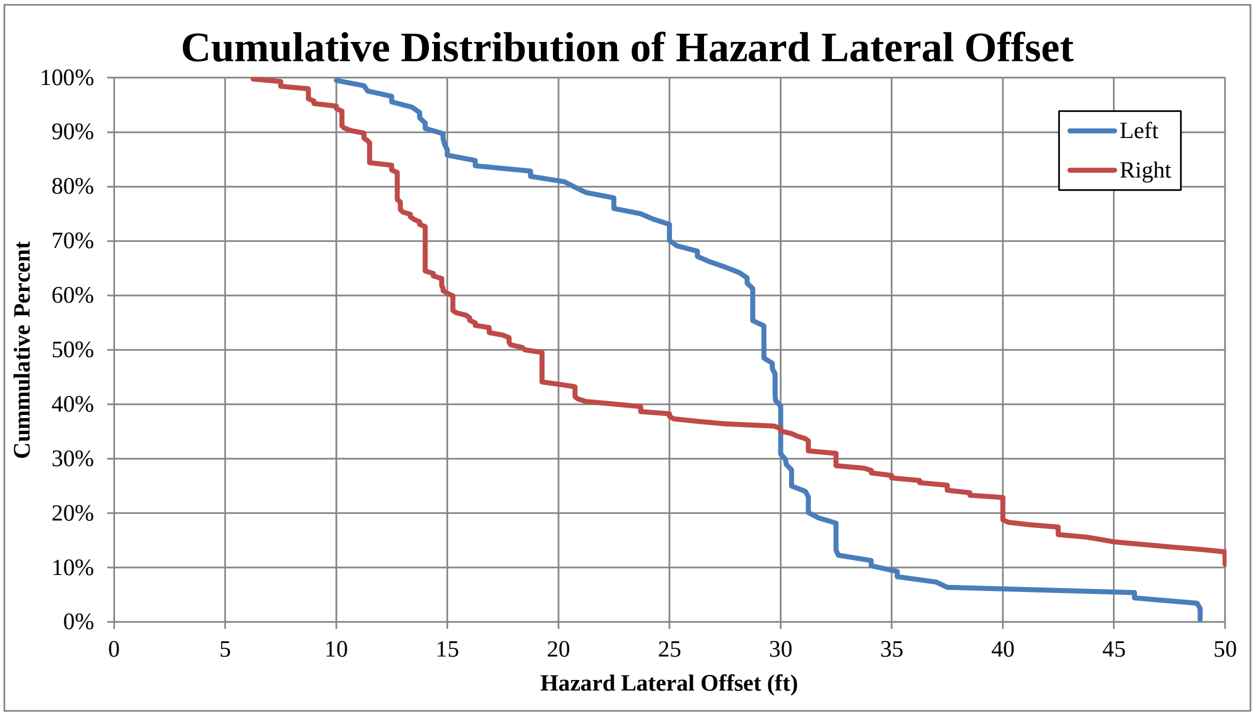


Figure 21. Hazard Lateral Offset Distribution by Guardrail Location

4.3 Crash Counts and Probabilities of Collisions

Crash outcome probability was constructed by generating a hierarchy of the 654 crash events, as shown in Figure 22. Only 2 percent ran behind the guardrail and approximately 0.3 percent, or two crashes, involved an impact with the shielded hazard.

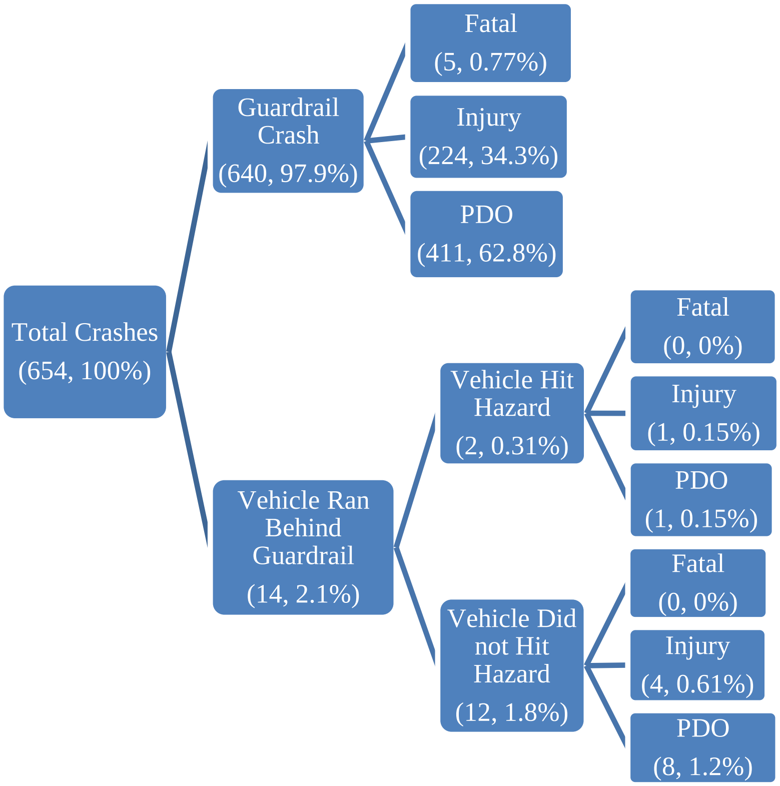


Figure 22. Tree Diagram of Crash Outcomes

The probability of each crash severity level given an event has occurred was calculated using conditional probabilities. Conditional probability is the probability of an event A occurring given some event B has occurred, and it may be denoted by P(B/A), as defined by Equation 1. The denominator indicates the probability of both events occurring.

$$\mathrm{P}(\mathrm{B}/\mathrm{A}) = \frac{\mathrm{P}(\mathrm{A}\cap\mathrm{B})}{\mathrm{P}(\mathrm{A})} \text{ if } \mathrm{P}(\mathrm{A}) > 0 \qquad \text{Equation 1}$$

A system of variables was established to determine the probabilities that certain events occur and are defined in Table 26.

Table 26. Descriptions of Variables Used in Analysis

Variable Name	Variable Description
FI	Fatal Injury
I	Non-Fatal Injury
PDO	Property-Damage Only Crash
HH	Vehicle Hit Hazard
NHH	Vehicle did Not Hit Hazard
FIGC	Fatal Injury Guardrail Crash
IGC	Injury Guardrail Crash
PDOGC	Property-Damage Only Guardrail Crash

The probability that a guardrail crash results in a fatality may be calculated using Equation 2.

$$\mathrm{P(FGC)} = \frac{\mathrm{P(F{\cap}GC)}}{\mathrm{P(GC)}} = \frac{\#(\mathrm{F \cap GC})/\#(\mathrm{total})}{\#(\mathrm{GC})/\#(\mathrm{total})} = \frac{5/654}{640/654} = 0.00782 \qquad \text{Equation 2}$$

The probability of injury given a guardrail crash has occurred is shown in Equation 3.

$$\mathrm{P(IGC)} = \frac{\mathrm{P(I{\cap}GC)}}{\mathrm{P(GC)}} = \frac{\#(\mathrm{I \cap GC})/\#(\mathrm{total})}{\#(\mathrm{GC})/\#(\mathrm{total})} = \frac{224/654}{640/654} = 0.35 \qquad \text{Equation 3}$$

The probability of PDO given a guardrail crash has occurred is shown in Equation 4.

$$\mathrm{P(PDOGC)} = \frac{\mathrm{P(PDO{\cap}GC)}}{\mathrm{P(GC)}} = \frac{\#(\mathrm{PDO \cap GC})/\#(\mathrm{total})}{\#(\mathrm{GC})/\#(\mathrm{total})} = \frac{411/654}{640/654} = 0.64219 \qquad \text{Equation 4}$$

The probability of fatality given vehicle has run behind the guardrail is shown in Equation 5.

$$\mathrm{P}(FRBG) = \frac{\mathrm{P(F{\cap}RBG)}}{\mathrm{P}(RBG)} = \frac{\#(\mathrm{F{\cap}RBG})/\#(\mathrm{total})}{\#(\mathrm{RBG})/\#(\mathrm{total})} = \frac{0/654}{11/654} = 0 \qquad \text{Equation 5}$$

The probability of injury given vehicle has run behind the guardrail is shown in Equation 6.

$$\mathrm{P(IRBG)} = \frac{\mathrm{P(I{\cap}RBG)}}{\mathrm{P}(IRBG)} = \frac{\#(\mathrm{I{\cap}RBG})/\#(\mathrm{total})}{\#(\mathrm{RBG})/\#(\mathrm{total})} = \frac{5/654}{14/654} = 0.35731 \qquad \text{Equation 6}$$

The probability of PDO given vehicle has run behind the guardrail is shown in Equation 7.

$$\mathrm{P}(PDORBG) = \frac{\mathrm{P(PDO{\cap}RBG)}}{\mathrm{P(RBG)}} = \frac{\#(\mathrm{PDO{\cap}RBG})/\#(\mathrm{total})}{\#(\mathrm{RBG})/\#(\mathrm{total})} = \frac{9/654}{14/654} = 0.64269 \qquad \text{Equation 7}$$

The probability of hitting the hazard given a vehicle has run behind the guardrail is shown in Equation 8.

$$\mathrm{P(HHRBG)} = \frac{\mathrm{P(HH \cap RBG)}}{\mathrm{P(RBG)}} = \frac{\mathrm{\#(HH \cap RBG)/\#(total)}}{\mathrm{\#(RBG)/\#(total)}} = \frac{2/654}{14/654} = 0.14286 \qquad \text{Equation 8}$$

The probability of not hitting the hazard given a vehicle has run behind the guardrail is shown in Equation 9.

$$\mathrm{P(NHHRBG)} = \frac{\mathrm{P(NHH \cap RBG)}}{\mathrm{P}(RBG)} = \frac{\mathrm{\#(NHH \cap RBG)/\#(total)}}{\mathrm{\#(RBG)/\#(total)}} = \frac{12/654}{14/654} = 0.85714 \qquad \text{Equation 9}$$

The probability of fatality given a vehicle has hit the hazard is shown in Equation 10.

$$\mathrm{P}(FHH) = \frac{\mathrm{P(F \cap HH)}}{\mathrm{P}(HH)} = \frac{\mathrm{\#(FF \cap HH)/\#(total)}}{\mathrm{\#(HH)/\#(total)}} = \frac{0/654}{2/654} = 0.0 \qquad \text{Equation 10}$$

The probability of injury given a vehicle has hit the hazard is shown in Equation 11.

$$\mathrm{P}(IHH) = \frac{\mathrm{P(I \cap HH)}}{\mathrm{P}(HH)} = \frac{\mathrm{\#(I \cap HH)/\#(total)}}{\mathrm{\#(HH)/\#(total)}} = \frac{1/654}{2/654} = 0.50 \qquad \text{Equation 11}$$

The probability of PDO given a vehicle has hit the hazard is shown in Equation 12.

$$\mathrm{P}(PDOHH) = \frac{\mathrm{P(PDO \cap HH)}}{\mathrm{P}(HH)} = \frac{\mathrm{\#(PDO \cap HH)/\#(total)}}{\mathrm{\#(HH)/\#(total)}} = \frac{1/654}{2/654} = 0.50 \qquad \text{Equation 12}$$

The probability of fatality given a vehicle did not hit the hazard is shown in Equation 13.

$$\mathrm{P}(FNHH) = \frac{\mathrm{P(F \cap NHH)}}{\mathrm{P}(NHH)} = \frac{\mathrm{\#(F \cap NHH)/\#(total)}}{\mathrm{\#(NHH)/\#(total)}} = \frac{0/654}{12/654} = 0.0 \qquad \text{Equation 13}$$

The probability of injury given a vehicle did not hit the hazard is shown in Equation 14.

$$\mathrm{P}(INHH) = \frac{\mathrm{P(I \cap NHH)}}{\mathrm{P}(NHH)} = \frac{\mathrm{\#(I \cap NHH)/\#(total)}}{\mathrm{\#(NHH)/\#(total)}} = \frac{4/654}{12/654} = 0.33333 \qquad \text{Equation 14}$$

The probability of PDO given a vehicle did not hit the hazard is shown in Equation 15.

$$\mathrm{P}(PDONHH) = \frac{\mathrm{P(PDO \cap NHH)}}{\mathrm{P}(NHH)} = \frac{\mathrm{\#(PDO \cap NHH)/\#(total)}}{\mathrm{\#(NHH)/\#(total)}} = \frac{8/654}{12/654} = 0.66667 \qquad \text{Equation 15}$$

The probability of injury was almost the same whether the vehicle struck guardrail or ran behind guardrail, as shown in Table 27. As the vehicle traversed behind guardrail, however, the probability of injury was much higher given the vehicle hit the hazard, as compared to the probability of injury given the vehicle did not hit the hazard. However, these two probabilities were calculated based on a very small sample size.

Table 27. Probability Distribution of Crash Outcome and Severity

Crash Outcome	Crash Severity		
	Fatal	**Injury**	**PDO**
Guardrail Struck	0.0078	0.35	0.6422
Ran Behind Guardrail	0.0	0.36	0.64
Vehicle Hit Hazard	0.0	0.50	0.50
Vehicle Did Not Hit Hazard	0.0	0.33	0.67

4.4 Guardrail and Hazard Crash Rates

The previous section presented the number of crashes and associated probabilities based on type of crash and injury outcome. However, this analysis only considered crash reports, which have been shown to underestimate the actual number of impacts with a guardrail system [11]. The actual number of crashes shown in Figure 22 could be significantly higher than what was reported. Likewise, since it is believed that most unreported crashes occur with low injury severities, the estimates for fatal crash probabilities may be lower than those shown in Table 27.

In order to take exposure into account, guardrail and hazard crash rates were assessed using highway mileage as well as average annual daily traffic (ADT) as exposure terms. Highway mileage provided by staff from the Kansas DOT is shown in Table 16. ADT data was collected from all highway sites containing a guardrail, and was matched up with each guardrail system using guardrails site data from all interstate highways in the state of Kansas. Crash rates were then calculated based on the number of crashes per mile as well as the total number of vehicles passing by a guardrail installation.

Guardrails were identified at 2,120 sites, and the total number of guardrails located on the left and right sides of the road at these sites totaled 2,850. The distribution of the number of guardrail structures by road is shown in Table 28. The “Reference Point” column refers to the road that crossed the interstate at that particular site. Road I-70 had the highest number of guardrails while I-635 had the fewest. Roads with higher mileage available in the database also had more guardrails. As shown in Table 28, a large portion of these roads with higher mileage were located in rural areas. In contrast, urban areas were associated with higher crash rates, likely because hazard frequency increased near urban areas. Crash rates were calculated using the equation shown in Equation 16. The average number of crashes for each roadway segment, the number of guardrails per mile of roadway considered, and the associated crash rates are shown in Table 29.

Crash Rate = (# Crashes) / (Exposure) Equation 16

Table 28. Area Type, Mileage, and Guardrail Distribution by Road

Road	Area	Mileage	# Guardrails	%
I-635	Urban	17.81	39	1.4
I-470	Urban	27.44	89	3.1
I-435	Urban	56.07	128	4.5
I-235	Urban	33.03	130	4.6
I-335	Rural	100.35	186	6.5
I-135	Rural	191.48	384	13.5
I-35	Rural	470.81	703	24.7
I-70	Rural	847.54	1,191	41.8

Table 29. Number of Crashes and Guardrails per Mile of Road and Guardrail Crash Rates per Road

Road	Area	# Guardrails/Mile	# Crashes/Mile	# Crash Rate (in # Crashes per Thousand Mile-Guardrail)
I-70	Rural	1.40	0.27	0.22
I-35	Rural	1.49	0.31	0.44
I-335	Rural	1.85	0.20	1.07
I-135	Rural	2.00	0.55	1.43
I-470	Urban	3.24	0.47	5.32
I-435	Urban	2.28	0.96	7.52
I-235	Urban	3.93	1.81	13.97
I-635	Urban	2.19	1.57	40.31

For example, when applied to I-70, the crash rate was calculated as shown in Equation 17.

Crash Rate = 1000 x (227) / (847.54 x 1,191) = Equation 17

= 0.22 crashes per thousand mile-guardrail

Interstates I-70 and I-35 had the lowest number of guardrails per mile of roadway (i.e., 1.40 and 1.49) while I-470 and I-235 had the highest number of guardrails per mile (i.e., 3.24 and 3.93). Interstates I-335 and I-70 had the lowest number of crashes per mile (i.e., 0.20 and 0.27) while I-635 and I-235 had the highest number of crashes per mile (i.e., 1.57 and 1.81). Crash rates per thousand mile-guardrail varied widely. Interstates I-70 and I-35 had the lowest guardrail crash rates (i.e., 0.22 and 0.44) while I-235 and I-635 had very high guardrail crash rates (i.e., 13.97 and 40.31). These numbers indicate that highways located on more urbanized areas tend to have more guardrails and higher guardrail crash rates, in terms of crashes per thousand mile-guardrail.

Crash rates were also calculated using traffic volume and guardrail structure as exposure instead of mileage and guardrail structure, as shown in Table 30. In this case, crash rate was given in number of crashes per trillion vehicle-guardrail per day. Exposure was included in this analysis by summing the total traffic passing by a guardrail installation between 2002 and 2006, based on ADT data provided by Kansas DOT, corresponding to the time span of the available crash data. The ADT at a particular guardrail location was defined as the number of daily opportunities for a crash to have happened. The total daily number of opportunities for all guardrails on each specific road had to be summed up in order to calculate the number of daily opportunities.

Table 30. Guardrail Crash Rates, Ran-Behind-Guardrail Crash Rates, and Hazard Crash Rates

Road Name	**I-70**	**I-35**	**I-435**	**I-135**	**I-235**	**I-470**	**I-635**	**I-335**	**All**
# Opportunities/ Day	36,020,025	32,134,365	16,154,120	14,919,440	9,986,850	5,696,090	5,619,050	3,115,475	123,645,415
# Guardrail Crashes	219	145	54	103	59	13	28	19	640
# Ran Behind Barrier	8	2	0	2	1	0	0	1	14
# Hazard Crashes	2	0	0	1	0	0	0	0	3
# Guardrails	1191	703	128	384	130	89	39	186	2,850
Guardrail Crash Rate	2.80	3.52	14.31	9.85	24.90	14.05	70.01	17.97	0.99
Ran Behind Barrier Rate	0.102	0.049	0.000	0.191	0.422	0.000	0.000	0.946	0.017
Hazard Crash Rate	0.026	0.000	0.000	0.096	0.000	0.000	0.000	0.000	0.0047

Since the ADT data corresponds to the annual average daily traffic, the ADT average for each year of the study was multiplied by 365 days, and the yearly data was summed to estimate the total number of vehicles that had passed by a particular guardrail installation during the entire period between 2002 and 2006.

The total guardrail crash rate was calculated using Equation 18. The total crash rate for crashes that involved a vehicle traveling behind a guardrail and the total hazard crash rate were calculated using Equations 19 and 20, respectively.

$$\text{Guardrail Crash Rate} = \frac{(640 \text{ x } 1{,}000{,}000{,}000{,}000)}{(123{,}645{,}415 \text{ x } 365 \text{ x } 5 \text{ x } 2{,}850)} \qquad \text{Equation 18}$$

$$= 0.99 \text{ Crash per Trillion Vehicle-Guardrail}$$

$$\text{Run-Behind-Guardrail Crash Rate} = \frac{(14 \text{ x } 1{,}000{,}000{,}000{,}000)}{(123{,}645{,}415 \text{ x } 365 \text{ x } 5 \text{ x } 2{,}850)} \qquad \text{Equation 19}$$

$$= 0.017 \text{ Crash per Trillion Vehicle-Guardrail}$$

$$\text{Hazard Crash Rate} = \frac{(2 \text{ x } 1{,}000{,}000{,}000{,}000)}{(123{,}645{,}415 \text{ x } 365 \text{ x } 5 \text{ x } 2{,}850)} \qquad \text{Equation 20}$$

$$= 0.0031 \text{ Crash per Trillion Vehicle-Guardrail}$$

Calculated guardrail and hazard crash rates were divergent. Guardrail crash rates were 319 times higher than hazard crash rates, equal to 0.99 crash per trillion vehicle-guardrail vs. 0.0031 crashes into shielded hazards per million vehicle-guardrail. Recall that injury percentages for vehicles impacting guardrail compared to shielded hazards behind guardrail were similar. Based on current guardrail lengths, the disproportionate rate of guardrail crashes compared to shielded hazard crashes likely corresponds to a significant number of nuisance crashes that could contribute to either injury or fatality. As a result, guardrail lengths may be excessively long, which could increase the frequency of crashes, including severe crashes, occurring at each location.

In addition to crashes per trillion vehicle-guardrails, crash rates were calculated in terms of number of crashes per billion vehicle-miles for each road, as shown in Table 31, and per hazard, as shown in Figures 23 and 24. Crashes occurred at a rate 40 times higher on interstate I-635, with the highest crash rate, than interstate I-70, which had the lowest crash rate. The rate of bridge rail and slope hazard crashes was greater on every urban interstate than on any rural interstate in the database. Discrete hazards with narrow hazard offsets, such as bridge piers and poles or signs, were much more commonly represented on urban highways than rural highways. In contrast, long hazards such as slopes, culverts, and hazards protected by bridge rails were more commonly protected for rural roadways.

Table 31. Crash Rates per Road in Number of Crashes per Billion Vehicle-Miles

Road	**Area**	**Mileage**	**# Crashes per 5 Years**	**Opportunities / Day**	**Crash Rate (Crashes / BVMT-day)**
I-70	Rural	847.54	227	36,020,025	0.004
I-35	Rural	470.81	147	32,134,365	0.005
I-135	Rural	191.48	105	14,919,440	0.020
I-335	Rural	100.35	20	3,115,475	0.035
All Rural		**1610.18**	**499**	**86,189,305**	**0.008***
I-435	Urban	56.07	54	16,154,120	0.033
I-470	Urban	27.44	13	5,696,090	0.046
I-235	Urban	33.03	60	9,986,850	0.100
I-635	Urban	17.81	28	5,619,050	0.153
All Urban		**134.35**	**155**	**37,456,110**	**0.071***

*Aggregate rural and urban crash rates were weighted numbers. Crash rates were calculated by multiplying the crash rate and opportunities per day of each roadway, dividing by the total opportunities per day for either rural or urban roads, respectively, then summing each roadway's weighted contribution to the total crash rate.

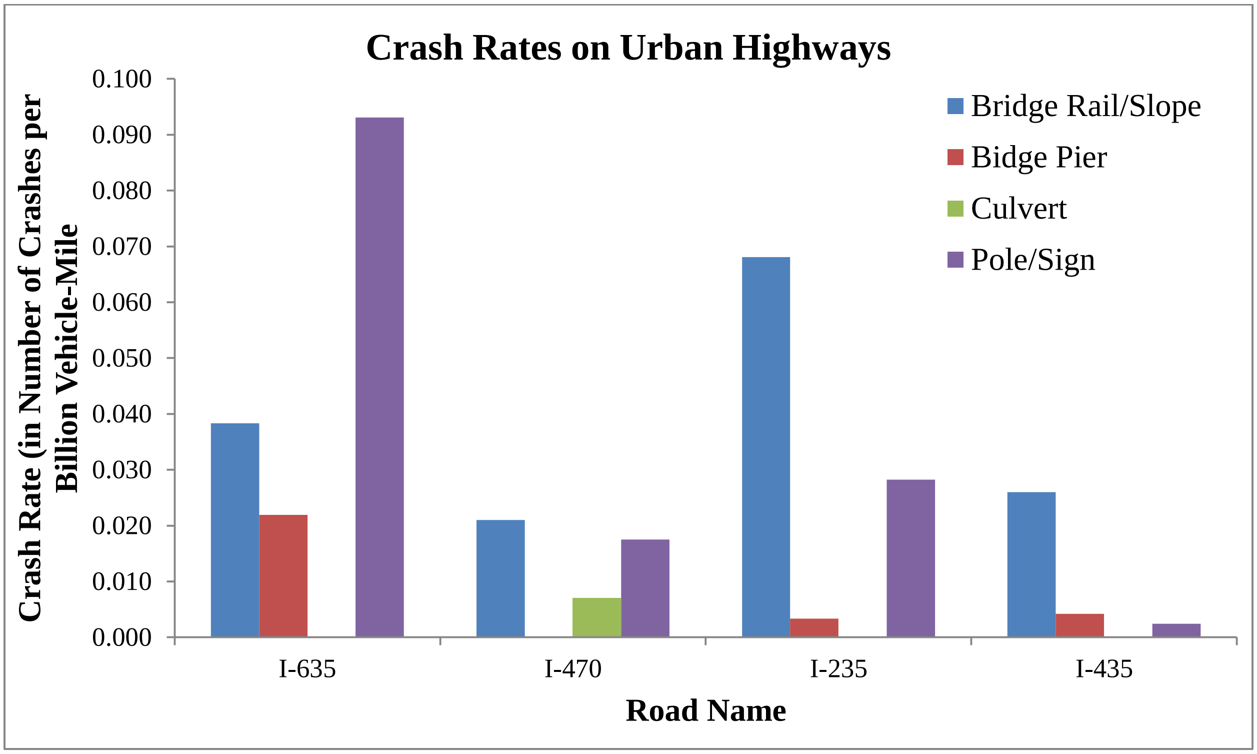


Figure 23. Urban Road Crash Rates per Shielded Hazard and Billion Vehicle-Miles

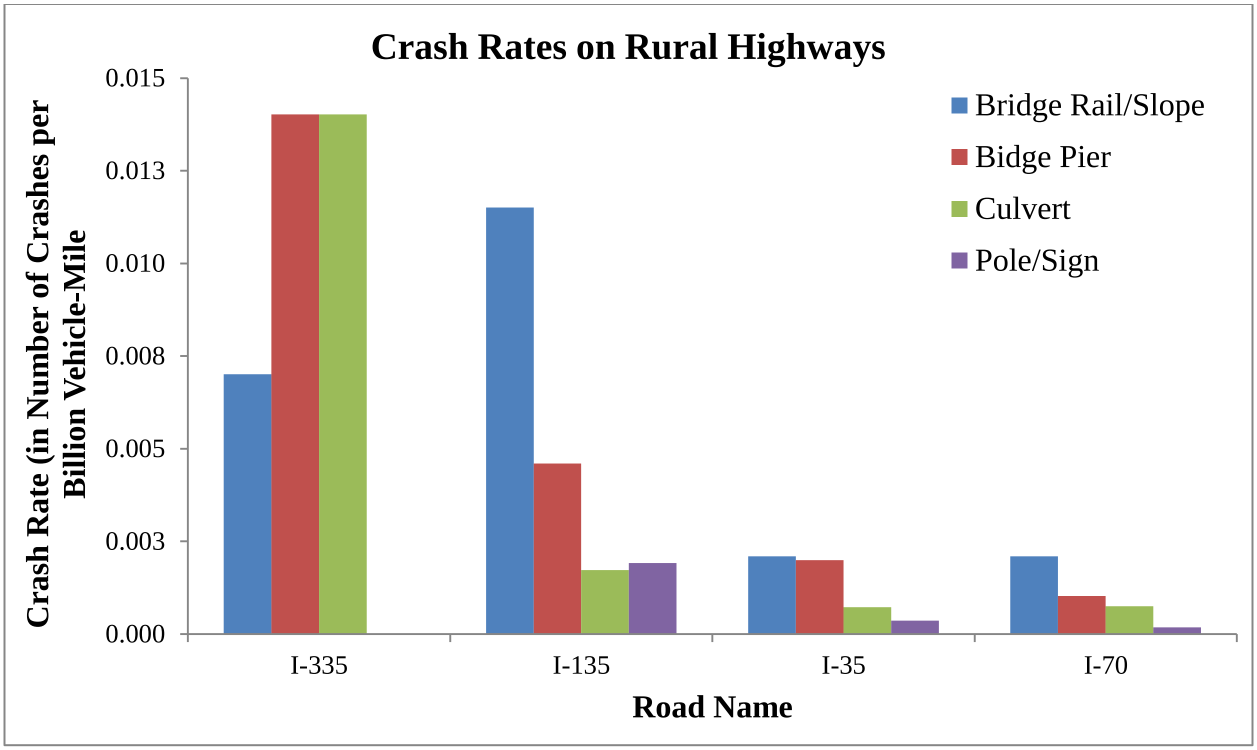


Figure 24. Rural Road Crash Rates per Shielded Hazard and Billion Vehicle-Miles

Although efforts were made to account for exposure in guardrail crash risk analysis, Kansas roadways may not be representative of freeways in all states. It may be appropriate to modify the exposure-controlled crash rates to account for variations in different states.

4.5 Risk of Collisions

For purposes of analysis, risk was defined as the potential effect of an event considering its probability and consequences. The analysis can determine risk (R) associated with event (E), which has probability (P) to occur and expected consequence (C), which is calculated using Equation 21.

$$R = P \times C \qquad \text{Equation 21}$$

The probability (P) may be estimated from failure rates whenever sufficient data is available. The risk (R) referred to the potential monetary loss associated with either a guardrail or a shielded hazard crash. Two major analyses were implemented: probability and consequence analyses. Risk Analysis procedures were applied to determine the risks associated with a vehicle striking a guardrail, traveling behind a guardrail, and impacting a shielded hazard after traveling behind a guardrail. In order to calculate the risk of a vehicle traveling behind a guardrail, three terms had to be defined and calculated.

1) P(TG) = Probability a vehicle has left the road and is traveling towards a guardrail;
2) P(BG/TG) = Probability vehicle traveled behind guardrail given it is traveling towards a guardrail; and
3) R(BG) = Risk a vehicle traveling behind a guardrail.

These quantities were calculated using Equations 22 through 24.

$$\text{P(TG)} = \frac{\text{\# Crashes}}{\text{\# Opportunities}} = \frac{654}{(123{,}645{,}415 \text{ x } 365 \text{ x } 5)} = 2.9\ x\ 10^{-9} \qquad \text{Equation 22}$$

$$\text{P(BG/TG)} = \frac{\text{\# Vehicles Traveled Behind Guardrail}}{\text{\# Crashes}} = \frac{14}{654} = 0.02141 \qquad \text{Equation 23}$$

$$\text{R(BG)} = \text{P(TG) x P(BG/TG)} = 2.9x10^{-9}\ x\ 0.02141 = 6.2\ x\ 10^{-11} \qquad \text{Equation 24}$$

In order to calculate the risk of a vehicle hitting a shielded hazard, P(BG/TG) and R(BG) were modified to P(HH/TG) and R(HH). These two terms are defined as follows:

4) P(HH/TG) = Probability a hazard is impacted given vehicle left the road given it is traveling towards a guardrail; and
5) R(HH) = Risk a vehicle impacting a shielded hazard.

$$\text{P(HH/TG)} = \frac{\text{\# Vehicles Hit Hazard}}{\text{\# Crashes}} = \frac{2}{654} = 0.00306 \qquad \text{Equation 25}$$

$$\text{R(HH)} = \text{P(HH/TG) x P(TG)} = 2.9x10^{-9}\ x\ 0.00306 = 8.87\ x\ 10^{-12} \qquad \text{Equation 26}$$

In order to calculate the risk of a vehicle hitting a guardrail, P(BG/TG) and R(HH) were modified to P(HG/TG) and R(HG). These two terms are defined as follows.

6) P(HG/TG) = Probability a guardrail is impacted given vehicle left the road given it is traveling towards a guardrail; and
7) R(HG) = Risk a vehicle impacting a guardrail.

$$\text{P(HG/TG)} = \frac{\text{\# Vehicles Hit Guardrail}}{\text{\# Crashes}} = \frac{640}{654} = 0.97859 \qquad \text{Equation 27}$$

$$R(HG) = R(HG/TG) \text{ x } P(TG) = 2.9x10^{-9}\ x\ 0.97859 = 2.84\ x\ 10^{-9} \qquad \text{Equation 28}$$

As can be seen, the risk associated with a vehicle traveling on Kansas interstate highways to crash a guardrail, R(HG), is much higher than the risk associated with traveling behind a guardrail, R(BH). The risk associated with a vehicle hitting a shielded hazard, R(HH), is lower than the risk of traveling behind the guardrail. These imply that the risks associated with a vehicle to travel behind a guardrail and, subsequently, hit the shielded hazard is very low. This reinforces the findings presented from calculated crash rates. Equivalently, the probability of a vehicle impacting a hazard which is shielded by a guardrail that was designed based on the 2006 RDG runout lengths is extremely low.

It is important to stress that the risks calculated above were assumed to be the same for all vehicles, and applies specifically to Kansas roadways. This implies that factors such as different driving behavior or vehicle type were not taken in consideration. However, this methodology can be repeated for a specific highway or data that only include, for example, a certain group of vehicles or drivers, or a different location.

A consequence analysis to evaluate the monetary loss equivalent due to safety hazards was also conducted. The crash severity distributions for both guardrail and non-guardrail crashes was utilized and which are shown in Tables 32 through 33. Costs for injuries shown in Table 34 are obtained from the Statistical Cost of a Life concept, and were obtained from FHWA for year 2012 [23].

Table 32. Crash Severity Distribution for Guardrail Crashes

	Year 2002		**Year 2003**		**Year 2004**		**Year 2005**		**Year 2006**		**Total**	
SEVERITY	#	%	#	%	#	%	#	%	#	%	#	%
Fatal	1	0.78	1	0.76	3	1.82	0	0	0	0	5	0.78
Incapacitating	7	5.47	7	5.30	7	4.24	2	2.04	5	4.24	28	4.38
Non-incapacitating	20	15.63	26	19.70	31	18.79	16	16.33	31	26.27	124	19.38
Possible	15	11.72	20	15.15	16	9.70	8	8.16	13	11.02	72	11.25
PDO	85	66.41	78	59.09	108	65.45	72	73.47	69	58.47	412	64.38

Table 33. Crash Severity Distribution for Non-Guardrail Crashes

	Year 2002		Year 2003		Year 2004		Year 2005		Year 2006		Total	
SEVERITY	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**
Fatal	0	0	0	0	0	0	0	0	0	0	0	0
Incapacitating	1	33.33	1	12.50	0	0	0	0	0	0	2	14.29
Non-incapacitating	1	33.33	1	12.50	0	0	0	0	0	0	2	14.29
Possible	0	0	1	12.50	0	0	0	0	0	0	1	7.14
PDO	1	33.33	5	62.50	2	100	0	0	1	100	9	64.29

Table 34. 2012 Crash Costs [23]

CRASH SEVERITY	US$
Fatal	6,749,184
Incapacitating	467,251
Non-Incapacitating	93,450
Possible	49,321
PDO	5,192

Guardrail and non-guardrail crash injury distributions were not significantly different. However, guardrail collisions resulted in five fatal crashes which resulted in seven fatalities. Therefore, the expected crash cost for each guardrail and non-guardrail crashes can be calculated using the following equations:

Crash Cost (Guardrail Crash) = 0.0078 x (Fatal Crash Cost) +

+ 0.0438 x (Incapacitating Crash Cost) + 0.1938 x (Non-Incapacitating Crash Cost) +

+ 0.1125 x (Possible Injury Crash Cost) + 0.6438 x (PDO Crash Cost) Equation 29

Crash Cost (Non-Guardrail Crash) = 0.3571 x (Injury Crash Cost) +

+ 0.6429 x (PDO Crash) Equation 30

The costs shown in Table 34 were used in combination with Equations 29 and 30, and the average guardrail crash cost was estimated to be $100,111.05, while the estimated non-guardrail crash cost was estimated to be $86,983.63. The associated risk of each crash outcome was estimated using Equation 21, using these dollar amounts as costs (C) in Equation 21 and the crash probabilities (P) calculated using Equations 24 and 28. Therefore, the risk associated with a guardrail crash was estimated to be $0.0002, while the risk associated with a non-guardrail crash was estimated to be $0.000005, which is 40 times less expensive. The risk associated with guardrail crashes is much higher than the risk associated with a vehicle traveling behind a guardrail.

4.6 Summary

A total of 654 real-world vehicle crashes which occurred on urban and rural Kansas interstate highways from years 2002 to 2006 were analyzed. Almost three-fourths (i.e., 479 crashes) of all these crashes occurred on interstates I-70, I-35, and I-135. Interstate I-70 was predominantly rural, was the longest facility with 847 miles (1,363 km) of roadway, with the largest number of guardrails installed (i.e., 1,191) and the highest number of crashes, 227 (i.e., 34 percent).

Approximately 64 percent of the crashes resulted in no injury, 35 percent resulted in possible, non-incapacitating, or disabling injury crashes, and less than 1 percent resulted in fatal injury crashes. The fewest number of injury crashes were recorded on interstate I-35 with 27 percent of crashes involving at least one injury, while interstate I-635 had the highest injury percentage with 57 percent of crashes resulting in injury.

Roadways with the longest and shortest guardrail lengths were interstates I-70 and I-635, respectively. Bridge rails, slopes, culverts, and embankments were correlated with the longest guardrail lengths, and the shortest lengths were observed with discrete hazards such as poles and signs. The widest and narrowest guardrail lateral offsets were observed on Interstates I-435 and I-470, respectively, whereas the narrowest hazard lateral offsets were observed on Interstate I-135. Hazard lateral offsets were narrowest when guardrails shielded bridge piers.

Guardrail crashes at roadside culverts had the lowest overall severity. No fatalities were recorded and less than 30 percent of the crashes resulting in injury. It was also determined that of the crashes in which an errant vehicle impacted a guardrail, approximately 60 percent impacted the first upstream quarter of the guardrail installation. Thus, upstream end anchorages and terminals must be adequately designed to develop the full capacity.

Statistical models suggested that crash severity tended to be lower as guardrail and hazard lateral offsets increased. However, these findings were not statistically significant at a confidence level lower than 23 percent. These findings may indicate the importance of wider clear roadside areas which could be used by errant drivers to take corrective maneuvers, such as breaking and steering, to minimize crash consequences.

Cumulative probability distributions indicated that left-side guardrails were located farther from the travel way edge, and right-side guardrails were longer. Hazard lateral offsets tended to be wider on the right side than on the left side of the roadway. Approximately 70 percent of all median hazards were located less than or equal to 30 feet (9.1 m) from the traveled way on which the crash occurred.

Only 2 percent, or 14 crashes, involved a vehicle departing the road and traversing behind the guardrail. Most of run-off-the-road crashes involving a vehicle running behind a guardrail occurred on Interstate I-70, for a total of 8 crashes or 3.52 percent of all I-70 crashes. Five injury crashes and no fatalities related to traversing behind the guardrail were recorded. Less than 1 percent, or 2 crashes, impacted the shielded hazard. One of these crashes resulted in an injury.

The probability analyses revealed that based on the sampled guardrail crash data, the probability of a crash resulting in no injury is the same for guardrail and non-guardrail crashes. The probability of an injury for guardrail and non-guardrail crashes is also similar. Although the likelihood of a fatality to occur given a guardrail crash has happened was found to be almost 1 percent, and no fatalities occurred in non-guardrail crash events. This analysis was based on a very small number of vehicles running behind a guardrail. Therefore, results are considered inconclusive.

Crash rates showed that guardrail, run-behind-guardrail, and hazard crash rates were 0.99, 0.017, and 0.0047 crashes per trillion vehicle-guardrail. This indicates that the guardrail crash rates are 58 times higher than run-behind-guardrail crash rates and 210 times higher than hazard crash rates. The risk of a hazard collision was also estimated. A Risk Analysis indicated that a vehicle traveling on Kansas interstate highways to run off the road and hit a guardrail equated to \$0.0002, while the cost-based risk of running behind a guardrail was \$0.000005.

The results of the Risk Analysis and statistical descriptions indicate a statistical imbalance between optimal and existing guardrail length. Severe and injury crashes may be minimized by shortening guardrail lengths to reduce exposure. This could reduce the rate of severe and moderate crashes and also reduce installation and repair costs. An analysis was conducted to evaluate the optimum length of the guardrail and is shown in Chapter 5.

5 RSAP ANALYSIS

Optimizing guardrail length depends on two factors. First, decreases in guardrail length may contribute to more vehicles traversing behind the guardrail and impacting the shielded hazard. For roadside safety design, guardrail crashes should be less severe than crashes involving the shielded hazard or the guardrail may not be cost-beneficial. Therefore, an increase in impact frequency between the vehicle and hazard may increase the rate of severe and non-severe injury crashes, compared to PDO crashes. Alternatively, the increase in crash severity of more vehicles impacting the shielded hazard may be offset by the larger reduction in crashes involving the guardrail system, which is itself a roadside hazard which may be involved in severe crashes. If the benefit associated with reducing the guardrail length is greater than the cost, then a shorter guardrail length may be warranted. It should also be noted that savings in direct and indirect costs with shorter guardrail lengths could be used to make further safety improvements for other features, which could amplify the benefit-to-cost ratio of the same total amount of safety improvement funds.

Unfortunately, it is impractical to conduct controlled experiments where the analyst would have control over all roadside, roadway, and traffic characteristics to optimize guardrail length. Researchers relied on the Roadside Safety Analysis Program (RSAP), a roadside safety cost-benefit estimation tool which has received widespread acceptance [24]. The program utilizes real-world crash trajectories, severities, and departure statistics to estimate probabilities of crashes and their associated costs while controlling factors which could not normally be controlled in real-world applications. The current version of RSAP (RSAPv3) was used in this study. A brief summary of features is provided in the following sections. For more details about RSAPv3, readers are referred to Roadside Safety Analysis Program Update [25].

5.1 Overview of RSAP

The first version of RSAP was released in 2003 as a cost-effectiveness procedure developed by Mak and Sicking [24]. Details of the program were described in NCHRP Report 492. The program utilized severity indices which had linear correlations with vehicle impact energies and used distributions of roadside departure trajectories and speeds, vehicle fleet descriptions, and roadway functional class relationships to run-off-road crash rates to estimate benefits and costs of safety improvements on roadways. The program allowed user controls over functional class, speed limit, hazard offset, shielding options, and could incorporate a broad spectrum of hazard types and shielding options to suit the user's needs. Despite the significant benefit of this tool, the program required constant tuning to match real-world data, which was sometimes not available for particular research efforts.

In 2012, RSAPv3 was released. The purpose of this newer version was to overcome some of the limitations that the previous version had, in particular by updating the representation of trajectories using real-world data. The RSAPv3 program bases its analyses on four modules (i.e., Encroachment Probability Module, Crash Prediction Module, Severity Prediction Module, and Benefit/Cost Module), similar to the original version. Each of the modules was modified to improve accuracy and reliability.

5.1.1 Encroachment Probability Module

The encroachment probability module calculates the encroachment rate on a specified road segment. Traditionally, encroachment probabilities have been based on data obtained by Cooper [18]. However, the Cooper data has been criticized for underrepresenting narrow-distance departures, such as roadway departures in which the vehicle does not exit the shoulder and may return to the travel lane. RSAPv3 also uses the Cooper encroachment data, but the data was re-analyzed to attempt to resolve some of these issues. The re-analyzed data was then used as the default encroachment rate in RSAPv3. This re-analyzed Cooper data was called the Miaou-Cooper data.

The results from the re-analysis produced baseline encroachment frequencies for three highway types: four-lane and multi-lane divided highways and two-lane undivided highways. The baseline conditions for the encroachment frequencies are: posted speed limit of 65 mph (104.6 km/h), flat ground, relatively straight segment, lane width greater or equal to 12 feet, and zero major access points per mile. Whenever road conditions deviate from these conditions, adjustment factors can be used to calibrate the encroachment rate to the specific road characteristics.

For the prediction model of run-off-road trajectories, the Miaou-Cooper data was compared to the data utilized in earlier versions of RSAP. The historical data did not differentiate between roadways with different speed limits, access densities, terrain types or posted speeds. As a result, the calculated distribution of crashes from the module were treated compositely. The Miaou-Cooper data normalized the data based on roadway and utilized different encroachment models for each scenario.

5.1.2 Crash Prediction Module

The crash prediction module calculates the probability of a fixed-object collision or rollover once a vehicle has left the traveled way by performing a series of analyses. Initially, trajectories collected under a crash reconstruction project described in NCHRP Project 17-22 [26] are projected from the roadway throughout the designated roadway segment. A database of impact angles and speeds associated with these trajectories are consulted in the analysis.

After selecting and mapping trajectories and determining their potential impact conditions, RSAPv3 then determines whether these trajectories will intersect any roadside or median hazard. Hazards are classified as: point hazards (e.g., trees, signs, and utility poles); line hazards (e.g. longitudinal barriers); or area hazards (e.g. slopes and ditches). The modeled vehicle interaction with the feature is then extrapolated from the impact conditions and type of object impacted or traversed. For example, RSAPv3 will predict a higher rollover propensity whenever steeper roadsides are defined, as well as whenever a vehicle trajectory will intersect a line or point hazard that tends to cause vehicle instability.

Once a collision is detected, RSAPv3 will calculate the probability of a rollover occurring before hazard collision, probability of hazard penetration, and probability of redirection. Hazard penetration means that the vehicle traverses to the back side of the obstacle. This may occur due to structural failure of the hazard, underride, vaulting, or rolling over the top of the hazard. RSAPv3 only considers vehicle redirection for impacts with longitudinal barriers.

Once a vehicle has been redirected or penetrated through a hazard, RSAPv3 will define the vehicle's trajectory after the first event and determine whether the vehicle will encounter any other hazard, resulting in additional collisions. Alternatively, RSAPv3 may also predict no crash or rollover whatsoever. This happens when the selected and mapped vehicle trajectories do not intersect any hazard. In these cases, encroaching vehicles will simply come to a safe stop on the roadside.

5.1.3 Severity Prediction Module

The severity prediction module estimates the severity of a crash once the probabilities of an encroachment and crash have been estimated. In the previous version of RSAP, the Severity Index (SI) estimate for crash severity was linearly correlated with impact speed. However, the slope values for these curves were based on engineering judgment instead of crash data. This procedure was updated in RSAPv3 using dimensionless, adjustable severity indices which could be based on impact speed. In addition, severity index data was based on the results of an analysis of real-world crashes and also accounted for unreported crash estimates.

5.1.4 Benefit/Cost Module

The Benefit/Cost (B/C) module conducts the benefit-cost analyses needed to determine the most cost-effective alternative. For roadside safety analyses, the "costs" are calculated as the sum of installation, maintenance, and repair costs. Repair costs may be a function of crash severity and rate and are calculated based on findings from the previous modules. Other costs, including purchasing right-of-way, environmental costs, and other indirect costs can be included in the analysis, but calculation of these costs is more rigorous and is not completed automatically by the program.

The benefits are calculated in terms of reduction in crash costs or crash severity. Historically, methods for calculating the benefit have relied on either the AASHTO "Red Book" [27], which purportedly reflects only costs that directly impact the user, or FHWA Comprehensive costs, which are based on the willingness-to-pay concept. Both of these approaches lead to different results and may alter the expected cost-effectiveness of a solution. To accommodate these concerns, RSAPv3 utilized the FHWA Comprehensive Costs from the current year as a baseline but allowed the calculation of alternative costs if the user desires [25]. These costs may be updated based on more recent information. Although baseline costs were not used in this study, they are shown in Table 35 for comparison. The FHWA Comprehensive Costs from 2012 used in this study were previously shown in Table 34.

Table 35. 2009 FHWA Comprehensive Crash Costs

Crash Severity	**Crash Cost**
Fatal	$6,000,000
Serious Injury	$415,385
Moderate Injury	$83,077
Possible/Minor Injury	$43,486
PDO	$4,615

The calculated benefits and costs are then utilized to determine the cost-effectiveness of using one roadside safety treatment in comparison with another, as shown in Equation 31. If the ratio is greater than 1, the reduction in crash costs (benefit) is larger than the cost to install the system. However, transportation agencies usually have adopted a minimum B/C ratio of 2, and prefer a ratio greater than 4, when investigating the economic feasibility of a highway safety improvement alternative.

$$B/C_{2-1} = \frac{AC_1 - AC_2}{DC_2 - DC_1} \qquad \text{Equation 31}$$

Where:

B/C_{2-1} = Benefit-to-Cost ratio of alternative 2 with respect to alternative 1
AC_1 = Crash costs associated with alternative 1;
AC_2 = Crash costs associated with alternative 2;
DC_1 = Direct costs associated with alternative 1; and
DC_1 = Direct costs associated with alternative 2.

5.2 Benefit-to-Cost Modeling and Analysis Methods

5.2.1 Road Segment Modeling

This research project sought to identify the optimal guardrail length based on benefit-to-cost analysis derived from freeway crash data, and to evaluate which guardrail length provides the optimum safety improvement for the cost incurred. The baseline guardrail lengths were calculated using the runout length, L_R, recommended by AASHTO in the 2006 and 2011 RDGs [2,3]. Other variations were also considered. Roadway geometries and real-world run-off-road crash trajectories were modeled in RSAPv3 to reproduce traffic conditions at guardrail crash sites using data obtained from Kansas DOT.

Much of the obtained data included rural 4-lane interstate highways divided by a grass median with rumble strips at the shoulders. Many medians were at least 60 feet (18.2 m) wide with shallow cross-slopes. The typical lane width was 12 feet (3.6 m), while the typical right and left shoulder widths were 12 and 8 feet (3.6 and 2.4 m), respectively. Traffic growth factor was assumed to be 1 percent. Therefore, all these parameter values were specified in every highway scenario modeled in RSAPv3.

As discussed in Chapter 4, the most commonly shielded hazards were features spanned by bridges as well as bridge piers. Due to the diverse array of possible hazards shielded by bridge rails, for analysis purposes, all hazards protected by bridge rails were grouped under the category "Bridge Rail". Approach slope length, steepness, width, and height varied widely between bridge locations. Therefore, modeling bridge rail scenarios could be too extensive and beyond the scope of this study. In contrast, visual estimates from applications such as Google StreetView indicated roadside terrains were mostly flat whenever a bridge pier was present. However, researchers did not have exact slope measurements. As a result, left-side (or median) slopes were assumed to be 10:1, and right-side slopes were assumed to be flat. Note that 10:1 slopes are the shallowest non-flat slope features available to be modeled in RSAPv3. A typical highway cross-section of a crash site containing bridge piers which are being shielded by guardrails on the left and right sides is shown in Figure 25.

Several variables were investigated in this modeling effort and included: average annual daily traffic (ADT); hazard lateral offset; guardrail length; and guardrail lateral offset. The values chosen for guardrail and hazard lateral offsets were based on the values contained in the Kansas crash dataset used in the data analysis described in Chapter 4. The guardrail and hazard lateral offset distribution from the dataset are shown in Table 36.

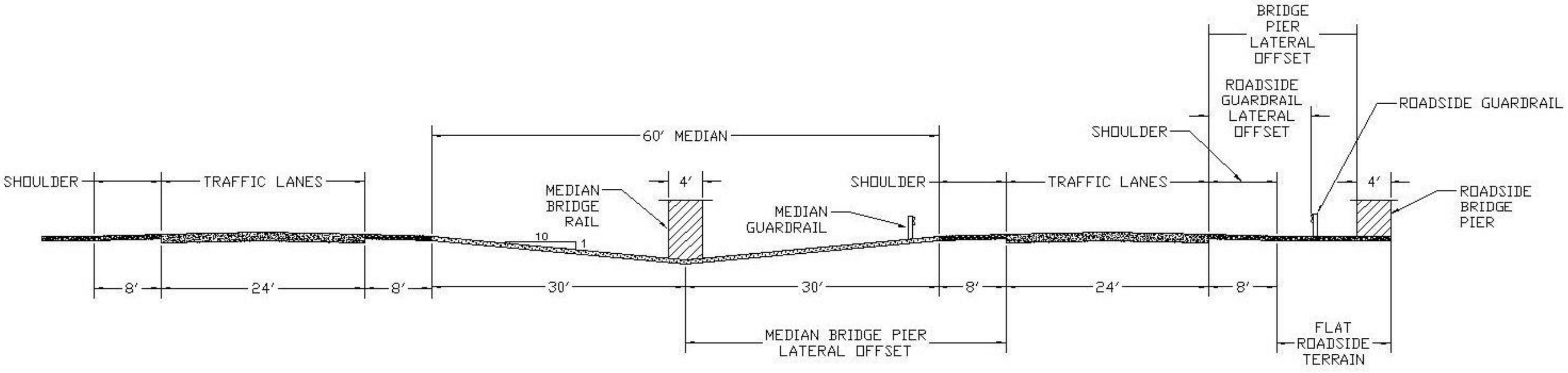


Figure 25. Highway Cross-Section View

Table 36. Parameter Values Used

	Lateral Offset (ft)	Guardrail		Bridge Pier	
		#	%	#	%
Right Side	Up to 11.99	23	23	30	30
	12 - 15.99	23	23	52	52
	16 - 19.99	19	19	8	8
	20 - 23.99	29	29	4	4
	24 – 30	4	6	5	5
	> 30	2	2	1	1
Left Side	Up to 11.99	3	5.26	1	1.75
	12 - 15.99	4	7.02	3	5.26
	16 - 19.99	7	12.28	0	0.00
	20 - 23.99	18	31.58	4	7.02
	24 – 30	19	33.53	33	57.89
	> 30	6	10.53	16	28.07

Many bridge piers and guardrail installations were within 30 feet (9.1 m) from the traveled way edge. Recall guardrail lateral offset was measured from the traveled way edge to the front face of the rail at the upstream end of the system. Thus, guardrail flares, which were common, also had higher recorded lateral offsets than some bridge pier hazards. Flares were included in the lateral offset analysis because over 60 percent of guardrail crashes occur in the first upstream quarter of the guardrail, as shown in Table 22, and flared guardrail can capture more low-angle impacts. As shown in Figure 26, the last three quarters (i.e., second, third, and fourth quarters) of the roadside guardrail may be exposed to a smaller number of encroachments as compared to the first quarter, which also included terminal impacts. The rate and severity of terminal impacts was assumed to be constant, independent of guardrail length. The guardrail and bridge pier lateral offset values adopted in the RSAPv3 analysis are shown in Table 37.

Guardrail runout lengths are used to determine the minimum length of guardrail upstream of the hazard, and are is configured to prevent a vehicle from encroaching on the roadside and impacting the farthest lateral extent of the hazard within the clear zone, as shown in Figure 1.The minimum guardrail length upstream of a hazard is often defined as the longitudinal length-of-need (LON). For this study, guardrail LON values were calculated using guardrail runout lengths recommended by the 2006 and 2011 AASHTO RDG. In addition, LONs were also calculated based on 90, 70, and 40 percent for values in the 2006 and 2011 RDGs. The 2006 and 2011 RDG runout lengths were shown in Tables 12 and 14, respectively.

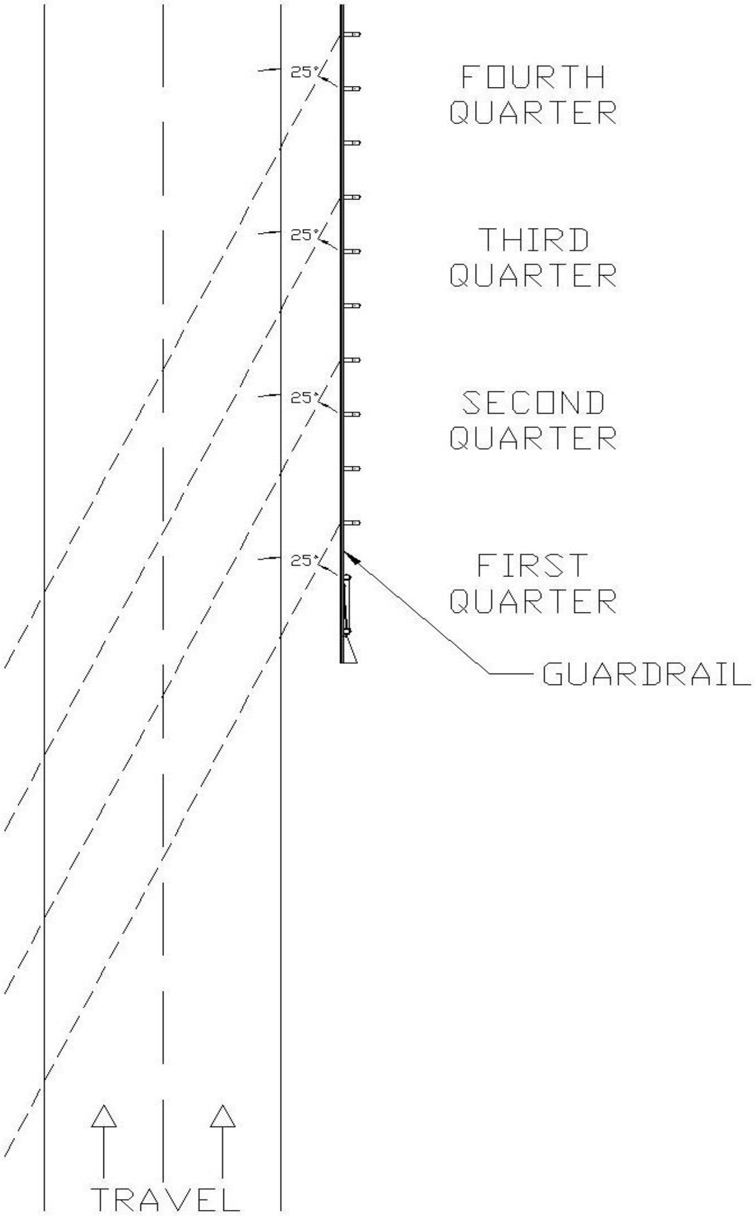


Figure 26. Guardrail Exposure per Guardrail Quarter

Table 37. Parameter Values Used in Median Bridge Pier Analysis

Right Side	**ADT (veh./day)**	6,000, 12,000, 30,000
	Guardrail Lateral Offset, ft (m)	6 (1.8), 12 (3.6), 16 (4.9), 20 (6.1), 24 (7.3)
	Bridge Pier Lateral Offset, ft (m)	12 (3.6), 18 (5.5), 26 (7.9), 32 (9.8)
	Guardrail Length, L_R	2006 and 2011 RDG, 90%, 70%, 40%
Left Side	**ADT (veh./day)**	6,000, 12,000, 30,000
	Guardrail Lateral Offset, ft (m)	8 (2.4), 12 (3.6), 18 (5.5), 24 (7.3)
	Bridge Pier Lateral Offset, ft (m)	12 (3.6), 18 (5.5), 24 (7.3), 28 (8.5)
	Guardrail Length	2006 and 2011 RDG, 90%, 70%, 40%

The runout lengths vary according to the traffic volume and design speed of the road segment, as shown previously in Tables 12 and 14. Most of the crashes used in this study occurred on road segments which had posted speed limits of 65 or 70 mph (104.6 or 112.6 km/h) as most of the data correlated with rural interstates. Crashes sometimes occurred on urban interstates with posted speed limits of 55 or 60 mph (88.5 or 96.5 km/h). Highway scenarios were modeled with 60 and 70 mph (96.5 and 112.6 km/h) speed limits to reduce computational time, because cost-effectiveness analysis using RSAPv3 can be very time consuming.

In order to select traffic volume values to be used in the RSAPv3 analyses, traffic volumes from the crash sites were evaluated. The traffic volume distribution for all 654 crash sites used in the study is shown in Figure 27. Approximately 80 percent of crashes occurred on roadways with ADTs less than or equal to 30,000, which were predominantly rural roadways. Three traffic volumess were used in the RSAPv3 analysis: 25th; 50th; and 85th percentile ADTs, which corresponded to ADTs of approximately 6,000, 12,000, and 30,000, respectively.

Lastly, all road segments were modeled as being 1,000 feet (304.8 m) long, and the bridge pier center was located 998 ft (304.2 m) from the beginning of the segment. A typical highway segment of a crash site containing bridge piers shielded by guardrails on both median and roadside is shown in Figure 28.

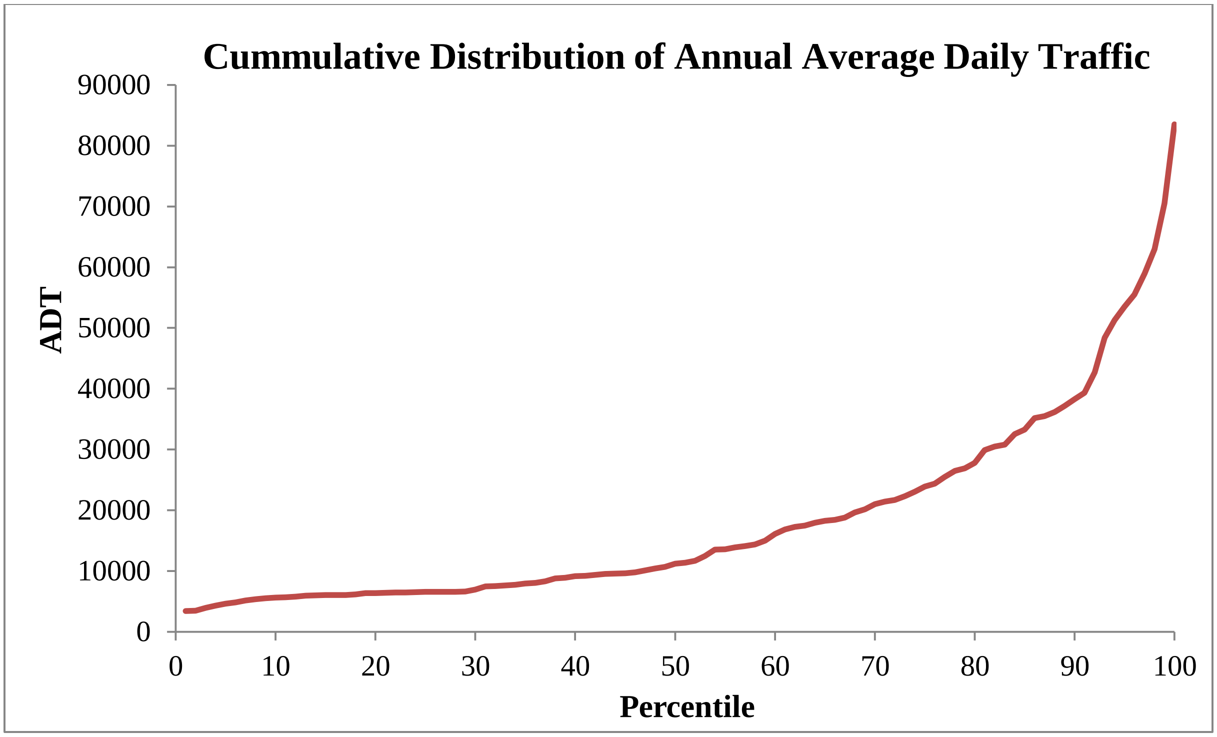


Figure 27. ADT Distribution from Crash Sites

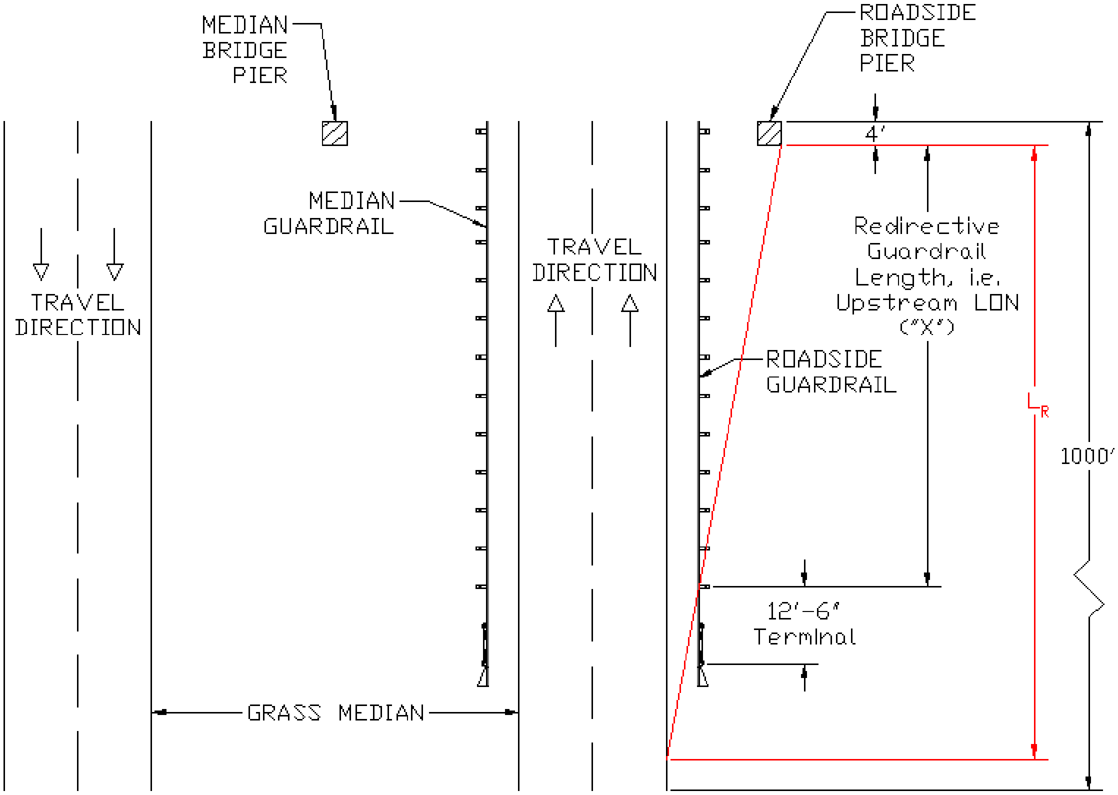


Figure 28. 1,000-ft (304.8-m) Highway Segment Plan View

5.2.2 Safety Alternatives

For RSAPv3 analyses performed in this study, the baseline condition corresponded to a no-guardrail option (i.e., Do Nothing). Four safety treatment alternatives included guardrail install with lengths corresponding to 40, 70, 90, and 100 percent of the values calculated using the 2006 and 2011 AAHSTO RDG guardrail LONs, which are defined in Equation 32.

$$Redirective\ Guardrail\ Length, X' = \mathrm{LON} * (P_L) = \left(\frac{L_A - L_2}{L_A/L_R}\right)(P_L) \qquad \text{Equation 32}$$

where

L_A = lateral distance from travel way to back of hazard
L_2 = lateral distance from edge of travel way to front face of barrier
L_R = runout length; longitudinal distance vehicle would have to travel to impact hazard, measured parallel with road (obtained from table in RDG)
P_L = decimal percentage of RDG guardrail length (i.e., 1.00, 0.90, 0.70, or 0.40)

The upstream guardrail LON (“X”) was rounded up to the nearest 10-ft (3.0-m) increment for simplicity. In addition, no guardrail was modeled downstream from the hazard. For each guardrail length, at least 6 post spans, or 37 ft – 6 in. (11.4 m) of downstream trailing end guardrail was assumed, but not modeled, because the contribution from that guardrail length did not change for different upstream guardrail LON (“X”) values.

Many guardrail systems installed near freeways have upstream ends within the clear zone, and must be terminated with a crashworthy end terminal. Many guardrail terminals in use begin to redirect the vehicle at and downstream from the third post, and are non-redirecting upstream from the third post. However, no non-redirecting guardrail option was available in RSAPv3, and modeling the terminal as a 12.5-ft (3.8-m) long feature also over-estimated the redirective capacity of the system by estimating a significant energy loss associated with oblique impacts. It was believed that the most conservative approach to modeling the terminal was to approximate the head as a point hazard located at the upstream end of the guardrail LON (“X”).

This method should overestimate an errant vehicle's likelihood of impacting the shielded hazard by ignoring energy losses due to impacts with the non-redirecting portion of the end terminal.

Direct costs associated with different guardrail lengths were estimated using average costs of guardrail bidding, normalized per unit length. Average guardrail installation costs in Kansas were $29.06 per ft ($95.34 per m) for the first quarter of 2012, and $30.48 per ft ($100.00 per m) for the second quarter of 2012. These two estimates were averaged for a resultant cost of $29.77 per ft ($97.67 per m), which was used for all safety treatment direct cost analyses. In addition, the average bid awarded for end terminal construction was $1,988.16 per unit. A 25-year project life was selected, with a discount rate of 4%.

5.2.3 Example Guardrail Length Calculation

A scenario involving a 4-ft (1.2-m) diameter bridge pier located 26 ft (7.9 m) away from the roadway edge was used to demonstrate the guardrail LON options. The distance to the back side of the hazard, L_A, was equal to 30 ft (9.1 m). The 2006 and 2011 RDG runout lengths, or L_R, were approximately 394 and 330 ft (120 and 101 m), respectively, for a roadway with 6,000 ADT. A guardrail located 12 ft (3.6 m) from the travel way, or 14 ft (4.3 m) in front of the hazard, would then have upstream LONs ("X" values) equal to those shown in .

Table 38. Guardrail Upstream LON ("X") Options for Example Scenario

	2006 RDG	2011 RDG
RDG Upstream LON	236 ft (72.1 m)	198 ft (60.4 m)
90% Upstream LON	213 ft (64.8 m)	178 ft (54.3 m)
70% Upstream LON	165 ft (50.4 m)	139 ft (42.2 m)
40% Upstream LON	95 ft (28.8 m)	79 ft (24.1 m)

5.2.4 Lowest Crash Cost Guardrail Length

The lowest crash cost guardrail system was selected as the length which minimized the estimated injury crash costs. No benefit-to-cost analysis was performed with this approach so that the alternative with the largest safety benefit could be identified. Crash costs declined after guardrail installation for every guardrail and hazard offset scenario analyzed.

An example of the analysis used to determine the lowest-crash cost guardrail system is shown in Figure 29. The analysis utilized a traffic volume of 30,000 vehicles per day, guardrail located 12 ft (3.7 m) from the side of the road, and a speed limit of 60 mph (97 km/h). Hazards located far from the roadway edge had crash costs minimized with guardrail lengths much smaller than those recommended by the 2011 AASHTO RDG.

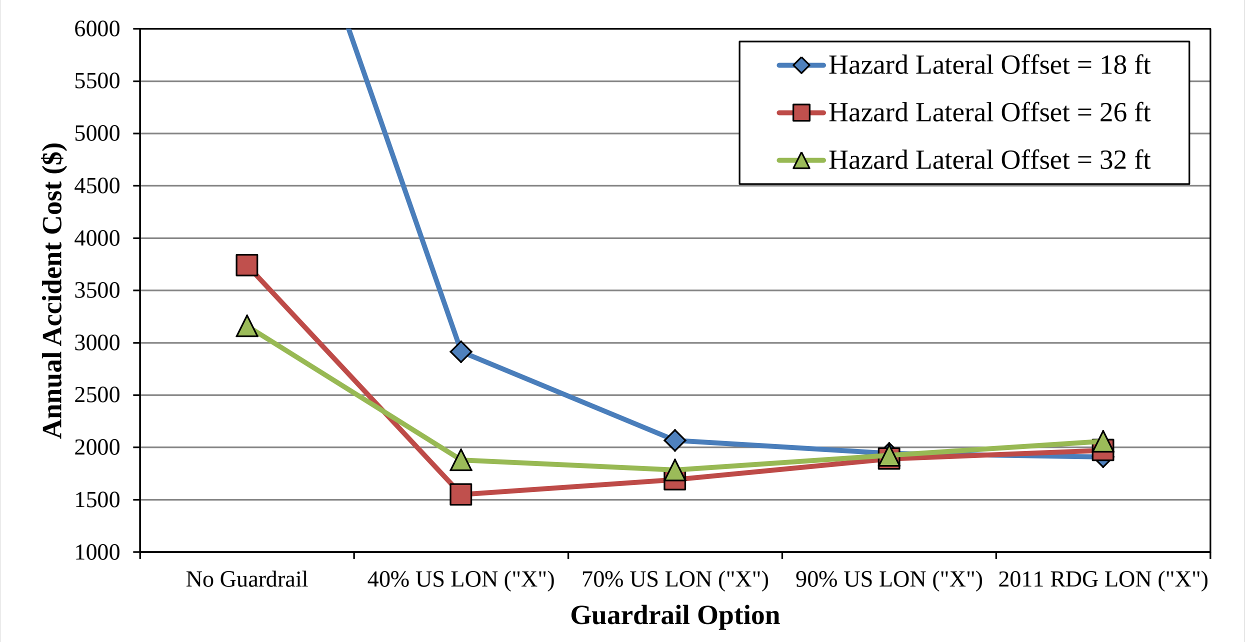


Figure 29. Crash Costs, Bridge Pier Shielded with 12 ft (3.7 m) Guardrail Offset

Guardrail upstream LON (“X”) options were considered in greater detail, as shown in Figure 30. Crash costs for all three hazard offsets converged due to the crash cost contribution from guardrail impacts at guardrail upstream LONs (“X”) over 140 ft (42.7 m). The lowest-cost option for each scenario would be a guardrail 100 percent, 40 percent, and 70 percent of the 2011 RDG upstream LONs (“X”) for hazards located 18 ft (5.5 m), 26 ft (7.9 m), and 32 ft (9.8 m) from the roadway edge, respectively.

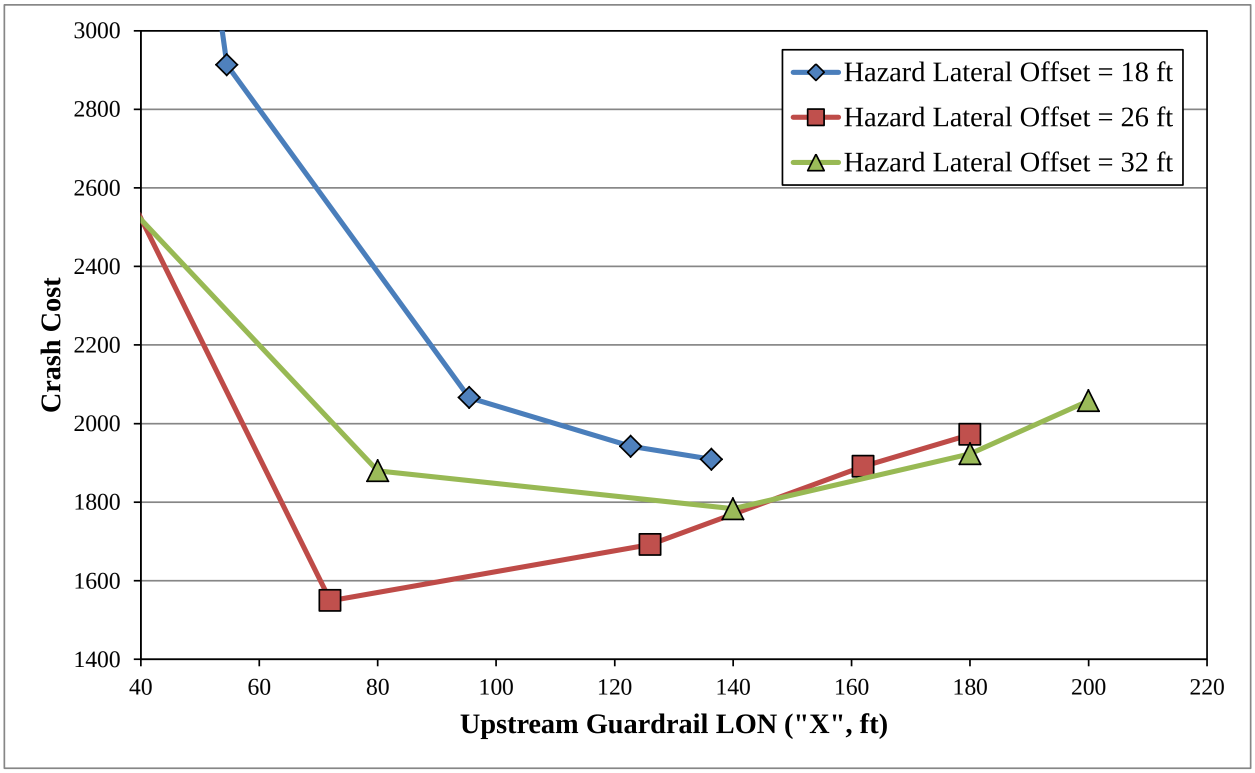


Figure 30. Crash Costs, Bridge Pier Shielded with 12-ft (3.7 m) Guardrail Offset

Recall that real-world crash trajectories were used to simulate vehicle trajectories into or near hazard locations. Curvilinear or redirecting vehicle trajectories interacted with hazards located closer to the roadway, particularly for shorter lengths of guardrail, as shown in Figure 31. Only vehicles with larger lateral encroachments interacted with hazards located farther from the roadway. These vehicles were also typically associated with larger CG trajectory angles at departure from the roadway, which made shorter guardrail lengths more favorable.

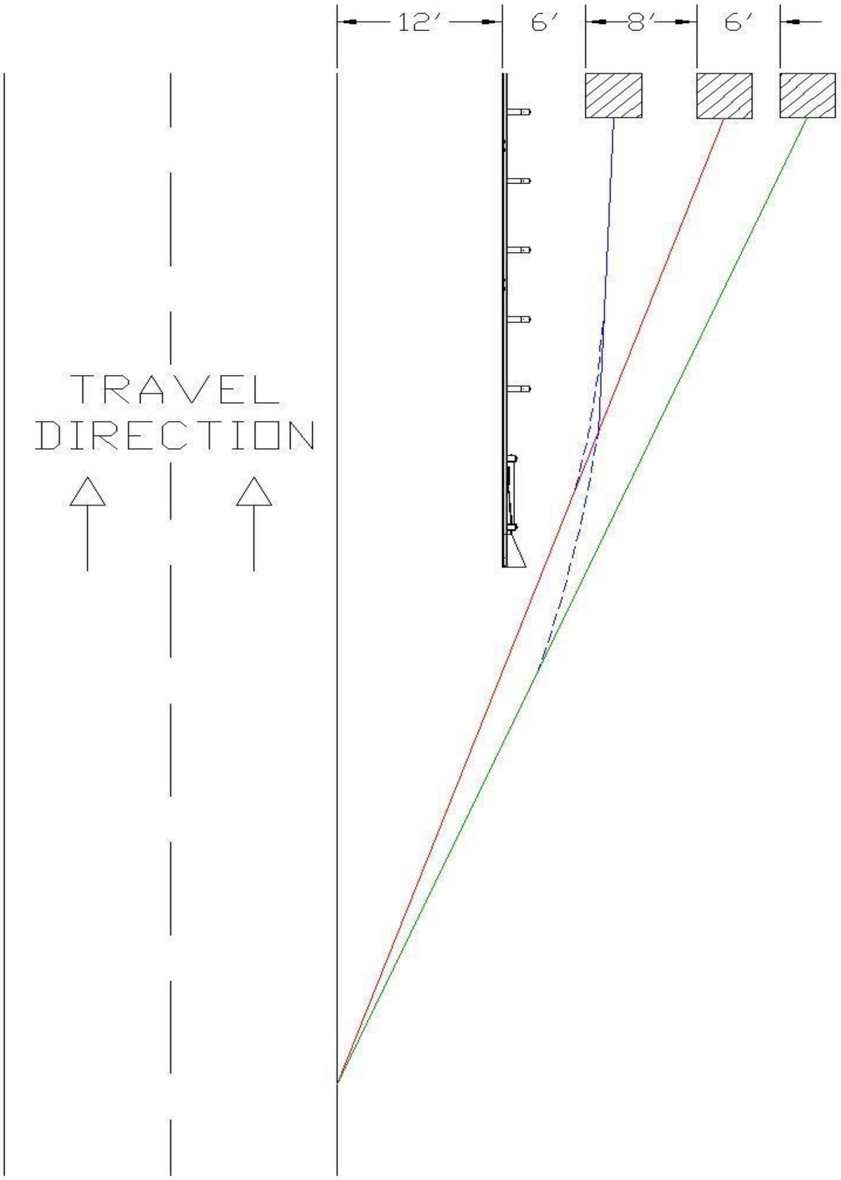


Figure 31. Trajectories of Vehicles Running Behind a Guardrail

Direct costs were not analyzed using the lowest-severity crash risk approach. Thus, total annualized crash costs were recorded and analyzed, and benefit-to-cost ratios were calculated. Results from this study were very similar for lowest crash cost and highest cost-effectiveness guardrail lengths, so whenever feasible or reasonable to do so, the lowest crash cost guardrail length should be used.

5.2.5 Most Cost-Effective Guardrail Length

Benefit-to-cost analyses were used to determine the most cost-effective guardrail length. The cost-effectiveness analysis normalized the approximate monetary benefits, or crash cost reductions, of the safety treatments based on annualized installation costs and recurring repair costs. Many state DOTs utilize a cost-effectiveness approach to assist with the implementation of guardrail systems based on maximizing the safety benefits for the least expenditures due to limited available funds.

The "Do Nothing" scenario was not associated with any direct costs. For the other safety treatment options, repair costs per impact were neglected. By ignoring repair costs, direct costs would be minimized, which would bias results toward using guardrail with sufficient length to minimize ran-behind guardrail crash risk.

5.2.6 Selection of Optimal Guardrail Length

After conducting an analysis on hazard treatment alternatives using the 2006 and 2011 AASHTO RDG upstream LONs ("X"), it was observed that the results of RSAP were singularly deterministic, or that one answer was predicted for one prescribed combination of hazard and guardrail offsets. Based on this observation, crash costs and direct costs were collected and summarized. The combined simulation of guardrail lengths provided a total of 8 unique guardrail lengths for any scenario, which is summarized in Table 38. Because guardrail lengths were rounded to increments of 10 ft (3.0 m) for analysis purposes, guardrail lengths sometimes overlapped, but each distinct increment was segregated by not less than 10 ft (3.0 m) of guardrail length. For some simulations, the safest and/or most beneficial guardrail lengths required greater discretization, and limited analyses were conducted with guardrail lengths different from the standard 40, 70, and 90th percentile numbers for either 2006 or 2011 RDGs.

Table 39. Simulated Guardrail Length Categories and Relationship to 2006 and 2011 RDGs

Categorical Description	**Approximate Relationship to 2006 RDG**	**Approximate Relationship to 2011 RDG**
2006 RDG	100%	120-130%
90% 2006 RDG	90%	110-120%
2011 RDG	70-80%	100%
70% 2006 RDG	70%	80-100%
90% 2011 RDG	60-70%	90%
70% 2011 RDG	40-60%	70%
40% 2006 RDG	40%	50-70%
40% 2011 RDG	20-30%	40%

5.3 RSAP Results

Because guardrail systems are assumed to redirect vehicles at the start of the calculated LON, new LON recommendations (i.e., X^*s) were tabulated as a percentage of the 2006 and 2011 AASHTO RDG LONs. Results were tabulated with respect to the distance between the edge of lane and front face of the hazard as well as the edge of lane and front face of the guardrail. LONs associated with the lowest crash cost are as shown in Figures 32 through 35. LONs associated with maximum cost-effectiveness are shown in Figures 36 through 39. For convenience, results were repeated based on the lateral distance from the edge of lane to front face of hazard, and front face of hazard to front face of guardrail, as shown in Figures 40 through 47. All results were color-coded by the optimum percentage of initial 2006 or 2011 RDG upstream guardrail LON (“X”). Median and roadside trajectories were markedly different, with longer roadside guardrail lengths recommended than median lengths on average for 60-mph (97-km/h) roads with similar hazard and guardrail offsets.

		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		60 (97)			70 (113)				
Front Edge of Hazard to Road, ft (m)	12 (3.7)	50	50	50	40	40	40	6 (1.8)	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	80	80	80	40	40	40	12 (3.7)	
	26 (7.9)	50	40	40	80	60	60	12 (3.7)	
		50	40	40	80	80	80	16 (4.9)	
		40	40	40	50	50	50	20 (6.1)	
	32 (9.8)	50	50	50	60	60	60	12 (3.7)	
		50	50	50	60	60	60	16 (4.9)	
		50	50	50	80	60	60	20 (6.1)	
		50	40	40	80	80	80	24 (7.3)	
Simulated ADT		6,000	12,000	30,000	6,000	12,000	30,000		
Recomended ADT Range		2,000 -6,000	6,000 - 18,000	> 18,000	2,000 -6,000	6,000 - 18,000	> 18,000		
AASHTO RDG ADT Range		2,000 -6,000	> 6000	> 6000	2,000 -6,000	> 6000	> 6000		

Figure 32. Percent of 2006 RDG Upstream LON ("X") for Minimum Crash Cost, Hazard on Right Side of Road

		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		60 (97)			70 (113)				
Front Edge of Hazard to Road, ft (m)	12 (3.7)	80	60	60	50	50	50	6 (1.8)	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	120	110	110	50	50	50	12 (3.7)	
	26 (7.9)	80	50	50	100	80	80	12 (3.7)	
		80	50	50	110	110	110	16 (4.9)	
		60	60	60	70	70	70	20 (6.1)	
	32 (9.8)	80	70	70	80	80	80	12 (3.7)	
		70	70	70	80	80	80	16 (4.9)	
		80	70	70	100	80	80	20 (6.1)	
		80	60	60	110	110	110	24 (7.3)	
Simulated ADT		6,000	12,000	30,000	6,000	12,000	30,000		
Recomended ADT Range		2,000 -6,000	6,000 - 18,000	> 18,000	2,000 -6,000	6,000 - 18,000	> 18,000		
AASHTO RDG ADT Range		5,000- 10,000	> 10,000	> 10,000	5,000- 10,000	> 10,000	> 10,000		

Figure 33. Percent of 2011 RDG Upstream LON ("X") for Minimum Crash Cost, Hazard on Right Side of Road

		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**40**	**30**	**30**	**30**	**30**	**30**	**8 (2.4)**	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	**30**	**30**	**30**	**50**	**40**	**40**	**8 (2.4)**	
		30	**30**	**30**	**50**	**50**	**50**	**12 (3.7)**	
	24 (7.3)	**30**	**30**	**30**	**60**	**60**	**60**	**8 (2.4)**	
		30	**30**	**30**	**80**	**80**	**80**	**12 (3.7)**	
		40	**30**	**30**	**50**	**50**	**50**	**18 (5.5)**	
	28 (8.5)	**30**	**30**	**30**	**60**	**60**	**60**	**8 (2.4)**	
		30	**30**	**30**	**60**	**60**	**60**	**12 (3.7)**	
		30	**30**	**30**	**100**	**80**	**80**	**18 (5.5)**	
		40	**40**	**40**	**120**	**120**	**120**	**24 (7.3)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**> 6000**	**> 6000**	**2,000 -6,000**	**> 6000**	**> 6000**		
AASHTO RDG ADT Range		**2,000 -6,000**	**> 6000**	**> 6000**	**2,000 -6,000**	**> 6000**	**> 6000**		

Figure 34. Percent of 2006 RDG Upstream LON ("X") for Minimum Crash Cost, Hazard on Left Side of Road (Median)

		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**60**	**50**	**50**	**40**	**40**	**40**	**8 (2.4)**	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	**50**	**40**	**40**	**60**	**60**	**60**	**8 (2.4)**	
		50	**40**	**40**	**70**	**60**	**60**	**12 (3.7)**	
	24 (7.3)	**50**	**40**	**40**	**80**	**80**	**80**	**8 (2.4)**	
		50	**40**	**40**	**100**	**100**	**100**	**12 (3.7)**	
		60	**50**	**50**	**70**	**60**	**60**	**18 (5.5)**	
	28 (8.5)	**50**	**40**	**40**	**80**	**70**	**70**	**8 (2.4)**	
		50	**40**	**40**	**80**	**80**	**80**	**12 (3.7)**	
		50	**50**	**50**	**130**	**100**	**100**	**18 (5.5)**	
		60	**50**	**50**	**160**	**160**	**160**	**24 (7.3)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**> 6000**	**> 6000**	**2,000 -6,000**	**> 6000**	**> 6000**		
AASHTO RDG ADT Range		**5,000-10,000**	**> 10,000**	**> 10,000**	**5,000-10,000**	**> 10,000**	**> 10,000**		

Figure 35. Percent of 2011 RDG Upstream LON ("X") for Minimum Crash Cost, Hazard on Left Side of Road (Median)

		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		60 (97)			70 (113)				
Front Edge of Hazard to Road, ft (m)	12 (3.7)	50	50	50	40	40	40	6 (1.8)	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	70	60	80	40	40	40	12 (3.7)	
	26 (7.9)	30	40	40	60	60	60	12 (3.7)	
		30	40	40	80	80	80	16 (4.9)	
		40	40	40	40	40	40	20 (6.1)	
	32 (9.8)	40	50	50	60	60	60	12 (3.7)	
		50	50	50	60	60	60	16 (4.9)	
		50	40	50	60	60	60	20 (6.1)	
		40	40	40	80	60	60	24 (7.3)	
Simulated ADT		6,000	12,000	30,000	6,000	12,000	30,000		
Recomended ADT Range		2,000 -6,000	6,000 - 18,000	> 18,000	2,000 -6,000	6,000 - 18,000	> 18,000		
AASHTO RDG ADT Range		2,000 -6,000	> 6000	> 6000	2,000 -6,000	> 6000	> 6000		

Figure 36. Percent of 2006 RDG Upstream LON (“X”) for Maximum Cost-Effectiveness, Hazard on Right Side of Road

		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		60 (97)			70 (113)				
Front Edge of Hazard to Road, ft (m)	12 (3.7)	80	60	60	50	50	50	6 (1.8)	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	110	80	110	50	50	50	12 (3.7)	
	26 (7.9)	50	50	50	80	80	80	12 (3.7)	
		50	50	50	100	100	100	16 (4.9)	
		60	60	60	50	50	50	20 (6.1)	
	32 (9.8)	70	70	70	80	80	80	12 (3.7)	
		70	70	70	80	80	80	16 (4.9)	
		80	50	70	80	80	80	20 (6.1)	
		60	60	60	110	80	80	24 (7.3)	
Simulated ADT		6,000	12,000	30,000	6,000	12,000	30,000		
Recomended ADT Range		2,000 -6,000	6,000 - 18,000	> 18,000	2,000 -6,000	6,000 - 18,000	> 18,000		
AASHTO RDG ADT Range		5,000- 10,000	> 10,000	> 10,000	5,000- 10,000	> 10,000	> 10,000		

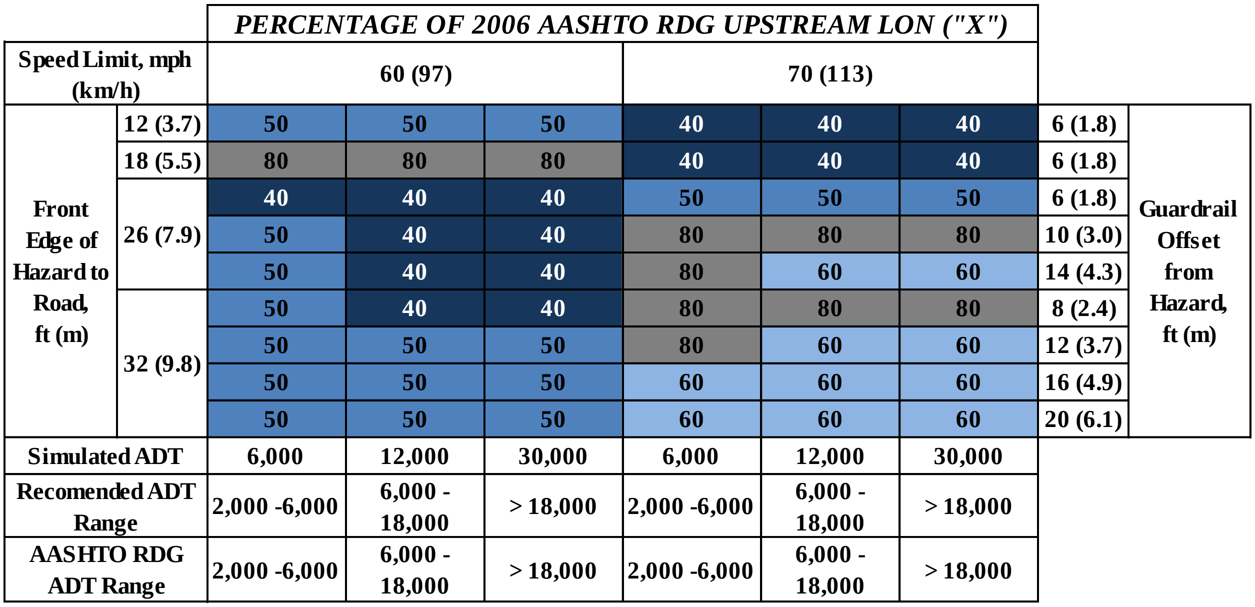
Figure 37. Percent of 2011 RDG Upstream LON (“X”) for Maximum Cost-Effectiveness, Hazard on Right Side of Road

		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**40**	**30**	**30**	**30**	**30**	**30**	**8 (2.4)**	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	**30**	**30**	**30**	**50**	**40**	**40**	**8 (2.4)**	
		30	**30**	**30**	**50**	**30**	**30**	**12 (3.7)**	
	24 (7.3)	**30**	**30**	**30**	**60**	**60**	**60**	**8 (2.4)**	
		30	**30**	**30**	**60**	**60**	**60**	**12 (3.7)**	
		40	**30**	**30**	**30**	**50**	**50**	**18 (5.5)**	
	28 (8.5)	**30**	**30**	**30**	**60**	**60**	**60**	**8 (2.4)**	
		30	**30**	**30**	**60**	**60**	**60**	**12 (3.7)**	
		30	**30**	**30**	**70**	**80**	**80**	**18 (5.5)**	
		40	**40**	**40**	**40**	**30**	**30**	**24 (7.3)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**> 6000**	**> 6000**	**2,000 -6,000**	**> 6000**	**> 6000**		
AASHTO RDG ADT Range		**2,000 -6,000**	**> 6000**	**> 6000**	**2,000 -6,000**	**> 6000**	**> 6000**		

Figure 38. Percent of 2006 RDG Upstream LON ("X") for Maximum Cost-Effectiveness, Hazard on Left Side of Road (Median)

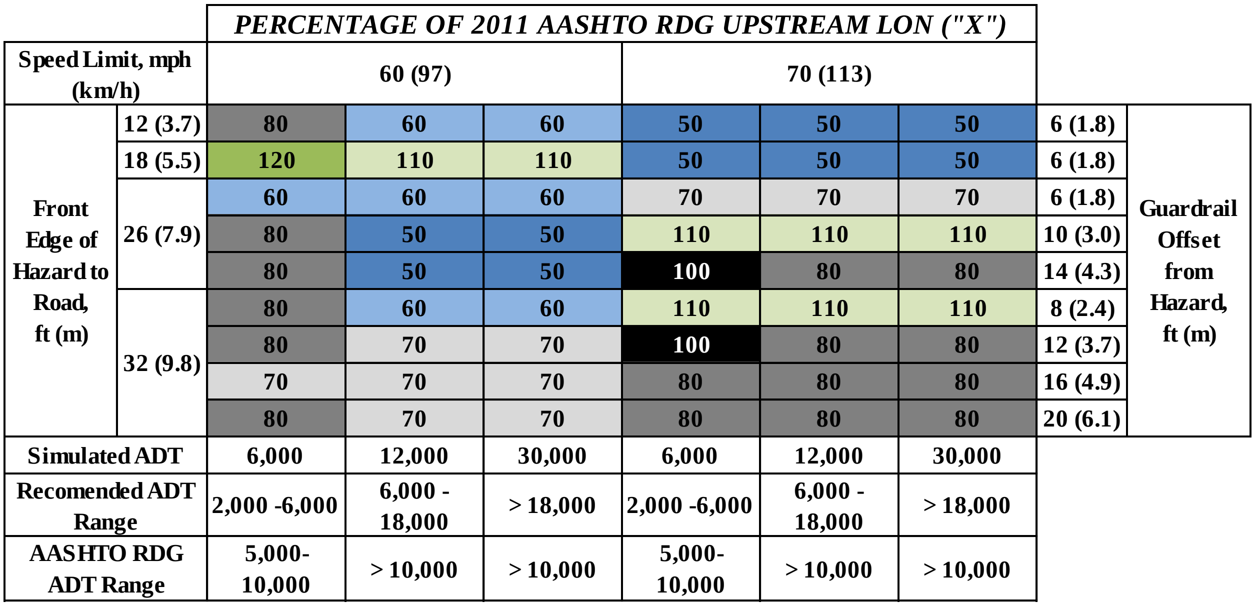
		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**60**	**50**	**50**	**40**	**40**	**40**	**8 (2.4)**	**Guardrail Offset from Road, ft (m)**
	18 (5.5)	**50**	**40**	**40**	**60**	**60**	**60**	**8 (2.4)**	
		50	**40**	**40**	**70**	**40**	**40**	**12 (3.7)**	
	24 (7.3)	**50**	**40**	**40**	**80**	**80**	**80**	**8 (2.4)**	
		50	**40**	**40**	**80**	**80**	**80**	**12 (3.7)**	
		60	**50**	**50**	**40**	**60**	**60**	**18 (5.5)**	
	28 (8.5)	**50**	**40**	**40**	**80**	**70**	**70**	**8 (2.4)**	
		50	**40**	**40**	**80**	**80**	**80**	**12 (3.7)**	
		50	**50**	**50**	**90**	**100**	**100**	**18 (5.5)**	
		60	**50**	**50**	**50**	**40**	**40**	**24 (7.3)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**> 6000**	**> 6000**	**2,000 -6,000**	**> 6000**	**> 6000**		
AASHTO RDG ADT Range		**5,000-10,000**	**> 10,000**	**> 10,000**	**5,000-10,000**	**> 10,000**	**> 10,000**		

Figure 39. Percent of 2011 RDG Upstream LON ("X") for Maximum Cost-Effectiveness, Hazard on Left Side of Road (Median)



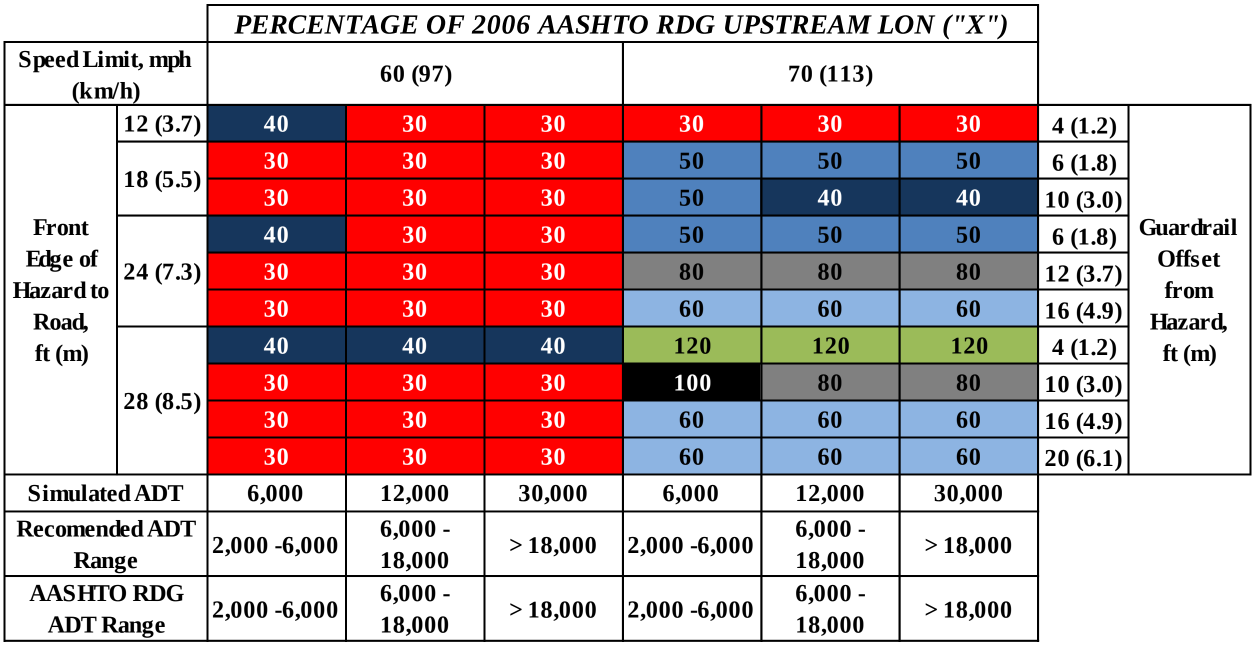
		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**50**	**50**	**50**	**40**	**40**	**40**	**6 (1.8)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**80**	**80**	**80**	**40**	**40**	**40**	**6 (1.8)**	
	26 (7.9)	**40**	**40**	**40**	**50**	**50**	**50**	**6 (1.8)**	
		50	**40**	**40**	**80**	**80**	**80**	**10 (3.0)**	
		50	**40**	**40**	**80**	**60**	**60**	**14 (4.3)**	
	32 (9.8)	**50**	**40**	**40**	**80**	**80**	**80**	**8 (2.4)**	
		50	**50**	**50**	**80**	**60**	**60**	**12 (3.7)**	
		50	**50**	**50**	**60**	**60**	**60**	**16 (4.9)**	
		50	**50**	**50**	**60**	**60**	**60**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		

Figure 40. Percent of 2006 RDG Upstream LON ("X") for Minimum Crash Cost Based on Guardrail-to-Hazard Distance, Hazard on Right Side of Road



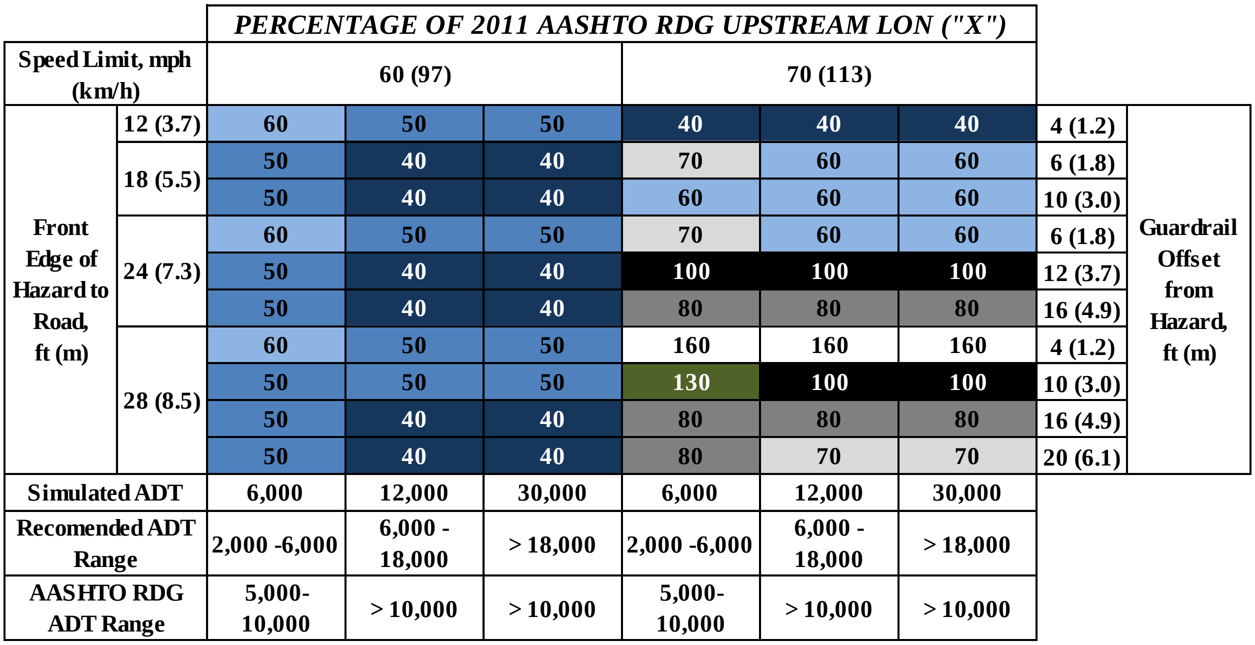
		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**80**	**60**	**60**	**50**	**50**	**50**	**6 (1.8)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**120**	**110**	**110**	**50**	**50**	**50**	**6 (1.8)**	
	26 (7.9)	**60**	**60**	**60**	**70**	**70**	**70**	**6 (1.8)**	
		80	**50**	**50**	**110**	**110**	**110**	**10 (3.0)**	
		80	**50**	**50**	**100**	**80**	**80**	**14 (4.3)**	
	32 (9.8)	**80**	**60**	**60**	**110**	**110**	**110**	**8 (2.4)**	
		80	**70**	**70**	**100**	**80**	**80**	**12 (3.7)**	
		70	**70**	**70**	**80**	**80**	**80**	**16 (4.9)**	
		80	**70**	**70**	**80**	**80**	**80**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**5,000-10,000**	**> 10,000**	**> 10,000**	**5,000-10,000**	**> 10,000**	**> 10,000**		

Figure 41. Percent of 2011 RDG Upstream LON ("X") for Minimum Crash Cost Based on Guardrail-to-Hazard Distance, Hazard on Right Side of Road



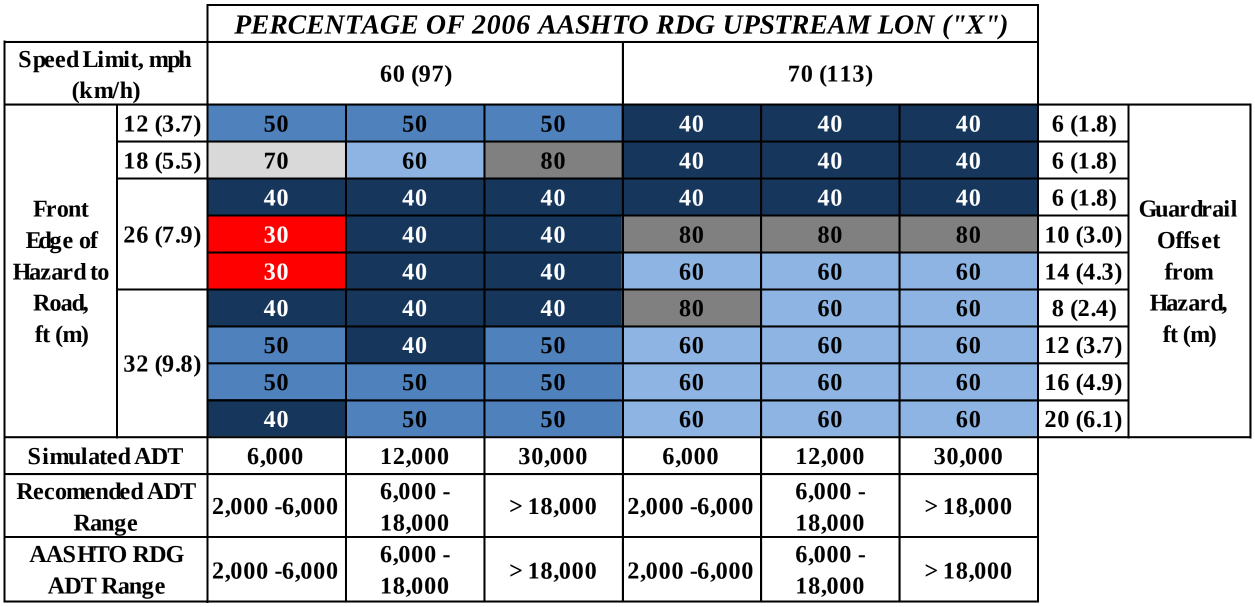
		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**40**	**30**	**30**	**30**	**30**	**30**	**4 (1.2)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**30**	**30**	**30**	**50**	**50**	**50**	**6 (1.8)**	
		30	**30**	**30**	**50**	**40**	**40**	**10 (3.0)**	
	24 (7.3)	**40**	**30**	**30**	**50**	**50**	**50**	**6 (1.8)**	
		30	**30**	**30**	**80**	**80**	**80**	**12 (3.7)**	
		30	**30**	**30**	**60**	**60**	**60**	**16 (4.9)**	
	28 (8.5)	**40**	**40**	**40**	**120**	**120**	**120**	**4 (1.2)**	
		30	**30**	**30**	**100**	**80**	**80**	**10 (3.0)**	
		30	**30**	**30**	**60**	**60**	**60**	**16 (4.9)**	
		30	**30**	**30**	**60**	**60**	**60**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		

Figure 42. Percent of 2006 RDG Upstream LON (“X”) for Minimum Crash Cost Based on Guardrail-to-Hazard Distance, Hazard on Left Side of Road (Median)



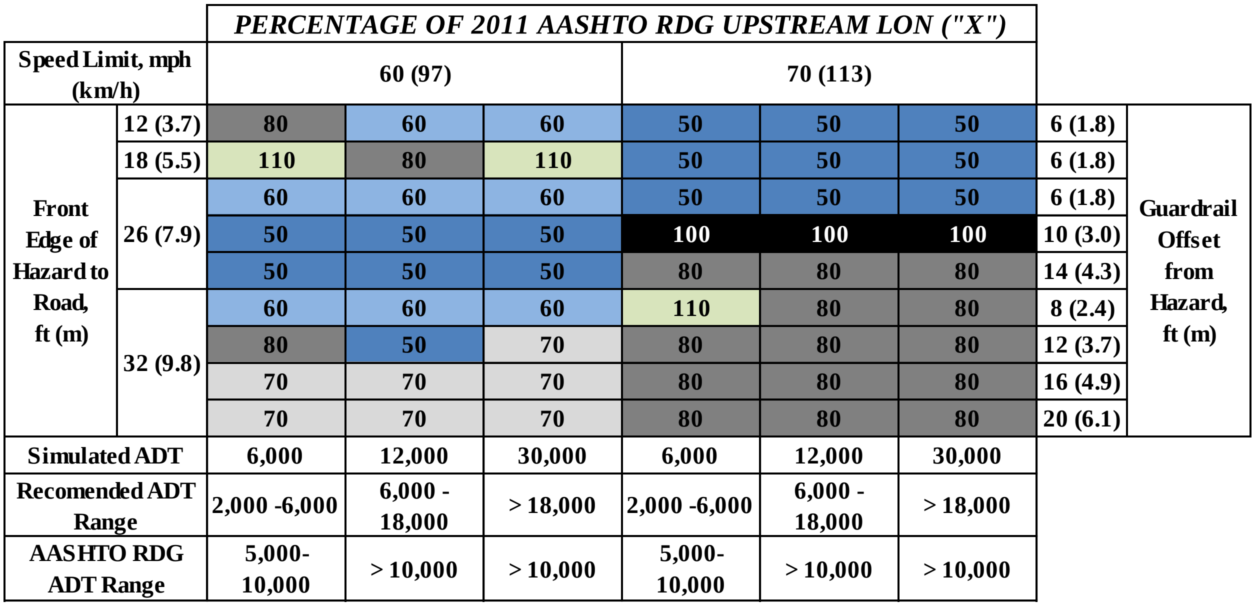
		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**60**	**50**	**50**	**40**	**40**	**40**	**4 (1.2)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**50**	**40**	**40**	**70**	**60**	**60**	**6 (1.8)**	
		50	**40**	**40**	**60**	**60**	**60**	**10 (3.0)**	
	24 (7.3)	**60**	**50**	**50**	**70**	**60**	**60**	**6 (1.8)**	
		50	**40**	**40**	**100**	**100**	**100**	**12 (3.7)**	
		50	**40**	**40**	**80**	**80**	**80**	**16 (4.9)**	
	28 (8.5)	**60**	**50**	**50**	**160**	**160**	**160**	**4 (1.2)**	
		50	**50**	**50**	**130**	**100**	**100**	**10 (3.0)**	
		50	**40**	**40**	**80**	**80**	**80**	**16 (4.9)**	
		50	**40**	**40**	**80**	**70**	**70**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**5,000- 10,000**	**> 10,000**	**> 10,000**	**5,000- 10,000**	**> 10,000**	**> 10,000**		

Figure 43. Percent of 2011 RDG Upstream LON (“X”) for Minimum Crash Cost Based on Guardrail-to-Hazard Distance, Hazard on Left Side of Road (Median)



		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**50**	**50**	**50**	**40**	**40**	**40**	**6 (1.8)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**70**	**60**	**80**	**40**	**40**	**40**	**6 (1.8)**	
	26 (7.9)	**40**	**40**	**40**	**40**	**40**	**40**	**6 (1.8)**	
		30	**40**	**40**	**80**	**80**	**80**	**10 (3.0)**	
		30	**40**	**40**	**60**	**60**	**60**	**14 (4.3)**	
	32 (9.8)	**40**	**40**	**40**	**80**	**60**	**60**	**8 (2.4)**	
		50	**40**	**50**	**60**	**60**	**60**	**12 (3.7)**	
		50	**50**	**50**	**60**	**60**	**60**	**16 (4.9)**	
		40	**50**	**50**	**60**	**60**	**60**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		

Figure 44. Percent of 2006 RDG Upstream LON ("X") for Maximum Cost-Effectiveness Based on Guardrail-to-Hazard Distance, Hazard on Right Side of Road



		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**80**	**60**	**60**	**50**	**50**	**50**	**6 (1.8)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**110**	**80**	**110**	**50**	**50**	**50**	**6 (1.8)**	
	26 (7.9)	**60**	**60**	**60**	**50**	**50**	**50**	**6 (1.8)**	
		50	**50**	**50**	**100**	**100**	**100**	**10 (3.0)**	
		50	**50**	**50**	**80**	**80**	**80**	**14 (4.3)**	
	32 (9.8)	**60**	**60**	**60**	**110**	**80**	**80**	**8 (2.4)**	
		80	**50**	**70**	**80**	**80**	**80**	**12 (3.7)**	
		70	**70**	**70**	**80**	**80**	**80**	**16 (4.9)**	
		70	**70**	**70**	**80**	**80**	**80**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**5,000- 10,000**	**> 10,000**	**> 10,000**	**5,000- 10,000**	**> 10,000**	**> 10,000**		

Figure 45. Percent of 2011 RDG Upstream LON ("X") for Maximum Cost-Effectiveness Based on Guardrail-to-Hazard Distance, Hazard on Right Side of Road

		PERCENTAGE OF 2006 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**40**	**30**	**30**	**30**	**30**	**30**	**4 (1.2)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**30**	**30**	**30**	**50**	**30**	**30**	**6 (1.8)**	
		30	**30**	**30**	**50**	**40**	**40**	**10 (3.0)**	
	24 (7.3)	**40**	**30**	**30**	**30**	**50**	**50**	**6 (1.8)**	
		30	**30**	**30**	**60**	**60**	**60**	**12 (3.7)**	
		30	**30**	**30**	**60**	**60**	**60**	**16 (4.9)**	
	28 (8.5)	**40**	**40**	**40**	**40**	**30**	**30**	**4 (1.2)**	
		30	**30**	**30**	**70**	**80**	**80**	**10 (3.0)**	
		30	**30**	**30**	**60**	**60**	**60**	**16 (4.9)**	
		30	**30**	**30**	**60**	**60**	**60**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		

Figure 46. Percent of 2006 RDG Upstream LON ("X") for Maximum Cost-Effectiveness Based on Guardrail-to-Hazard Distance, Hazard on Left Side of Road (Median)

		PERCENTAGE OF 2011 AASHTO RDG UPSTREAM LON ("X")							
Speed Limit, mph (km/h)		**60 (97)**			**70 (113)**				
Front Edge of Hazard to Road, ft (m)	**12 (3.7)**	**60**	**50**	**50**	**40**	**40**	**40**	**4 (1.2)**	**Guardrail Offset from Hazard, ft (m)**
	18 (5.5)	**50**	**40**	**40**	**70**	**40**	**40**	**6 (1.8)**	
		50	**40**	**40**	**60**	**60**	**60**	**10 (3.0)**	
	24 (7.3)	**60**	**50**	**50**	**40**	**60**	**60**	**6 (1.8)**	
		50	**40**	**40**	**80**	**80**	**80**	**12 (3.7)**	
		50	**40**	**40**	**80**	**80**	**80**	**16 (4.9)**	
	28 (8.5)	**60**	**50**	**50**	**50**	**40**	**40**	**4 (1.2)**	
		50	**50**	**50**	**90**	**100**	**100**	**10 (3.0)**	
		50	**40**	**40**	**80**	**80**	**80**	**16 (4.9)**	
		50	**40**	**40**	**80**	**70**	**70**	**20 (6.1)**	
Simulated ADT		**6,000**	**12,000**	**30,000**	**6,000**	**12,000**	**30,000**		
Recomended ADT Range		**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**	**2,000 -6,000**	**6,000 - 18,000**	**> 18,000**		
AASHTO RDG ADT Range		**5,000- 10,000**	**> 10,000**	**> 10,000**	**5,000- 10,000**	**> 10,000**	**> 10,000**		

Figure 47. Percent of 2011 RDG Upstream LON ("X") for Maximum Cost-Effectiveness Based on Guardrail-to-Hazard Distance, Hazard on Left Side of Road (Median)

Results from the minimum crash cost and highest cost-effectiveness analyses were surprising. For median applications, guardrail lengths for roads with 60 mph (97 km/h) speed limits were frequently reduced to as low as 20 percent of the 2006 RDG guidelines. This result suggested that some median guardrails in Kansas had actual LONs five times longer than the length that would minimize crash cost and maximize cost-effectiveness. Although some hazards located on the right side of the roadway had higher cost-effectiveness with lengths of approximately 30 to 40 percent of the RDG LONs, most right-side guardrail lengths were determined to be approximately twice as large as those calculated using the 2006 RDG values and between 60 and 90 percent of the guardrail lengths determined using the 2011 RDG values.

The most cost-effective upstream guardrail LON ("X") was always less than or equal to the lowest crash cost guardrail LON ("X"). The maximum cost-effectiveness guardrail upstream LON ("X") length may be associated with a higher percentage of impacts with the shielded hazard, so long as installation cost savings justify higher crash costs. Likewise, lowest crash cost guardrail lengths did not eliminate impacts with the shielded hazard, but did significantly reduce the risk of impact. Guardrail upstream LON ("X") length options associated with the lowest crash costs were also typically much shorter than 2011 recommendations. Regardless of which guardrail length option is selected, shorter guardrail lengths are frequently warranted.

5.4 New Effective Guardrail Runout Lengths

The 2006 and 2011 AASHTO RDG utilized runout lengths based on historical data from vehicles encroaching on the side of the road. However, LON recommendations obtained from RSAP results suggested that shorter LONs may provide a substantial improvement with regard to total crash cost and maximum cost-effectiveness.

Recall from Equation 32 that the guardrail length was a function of the runout length and a dimensionless relationship the lateral distance from the face of the guardrail to back edge of hazard as well as the lateral distance from the edge of lane to the front face of the guardrail. According to AASHTO LON calculation procedures, the LON is calculated using the formula shown in Equation 33.

$$X = L_R\left(\frac{L_A}{L_A - L_2}\right) = L_R\left(\frac{1}{1-{L_2}/{L_A}}\right) \qquad \text{Equation 33}$$

L_A = lateral distance from travel way to back of hazard
L_2 = lateral distance from edge of travel way to front face of barrier
X = LON
L_R = guardrail runout length

The LON equation shown in Equation 33 was rearranged to solve for L_R as a function of X. Then, new L_R^* values were calculated by replacing X with X^*, the optimized LON. The expression used to solve for L_R^* is shown in Equation 34, and a schematic illustration of the equation parameters is shown in Figure 48.

$$L_R{}^* = X^*\left(1 - {L_2}/{L_A}\right) \qquad \text{Equation 34}$$

L_A = lateral distance from travel way to back of hazard
L_2 = lateral distance from edge of travel way to front face of barrier
L_R^* = optimized runout length; longitudinal distance vehicle would have to travel to impact hazard, measured parallel with road
X^* = optimized guardrail length-of-need (based on RSAPv3 results)

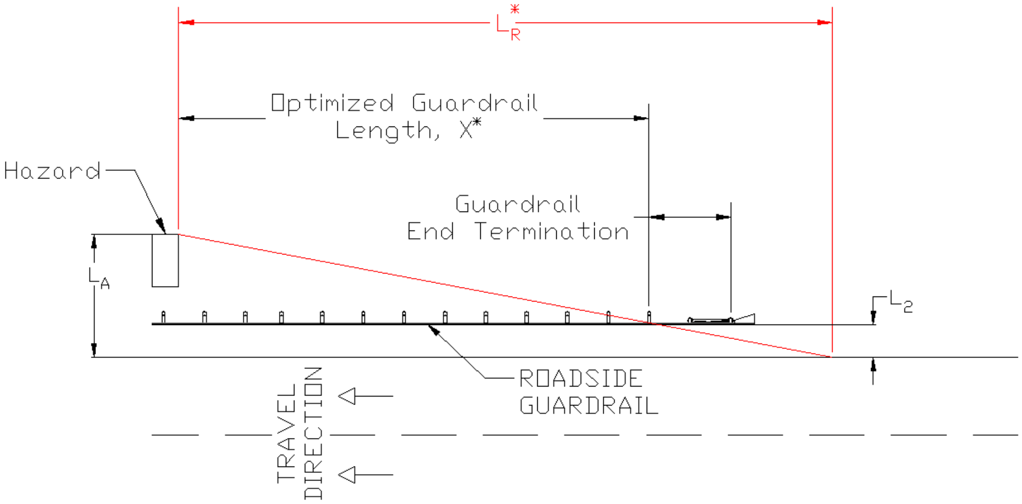


Figure 48. Re-Analysis of AASHTO Runout Length based on Optimized Guardrail Length

New LONs were plotted against the dimensionless relationship between guardrail and hazard lateral offset shown in Equation 34, as shown in Figures 49 through 56. It was observed

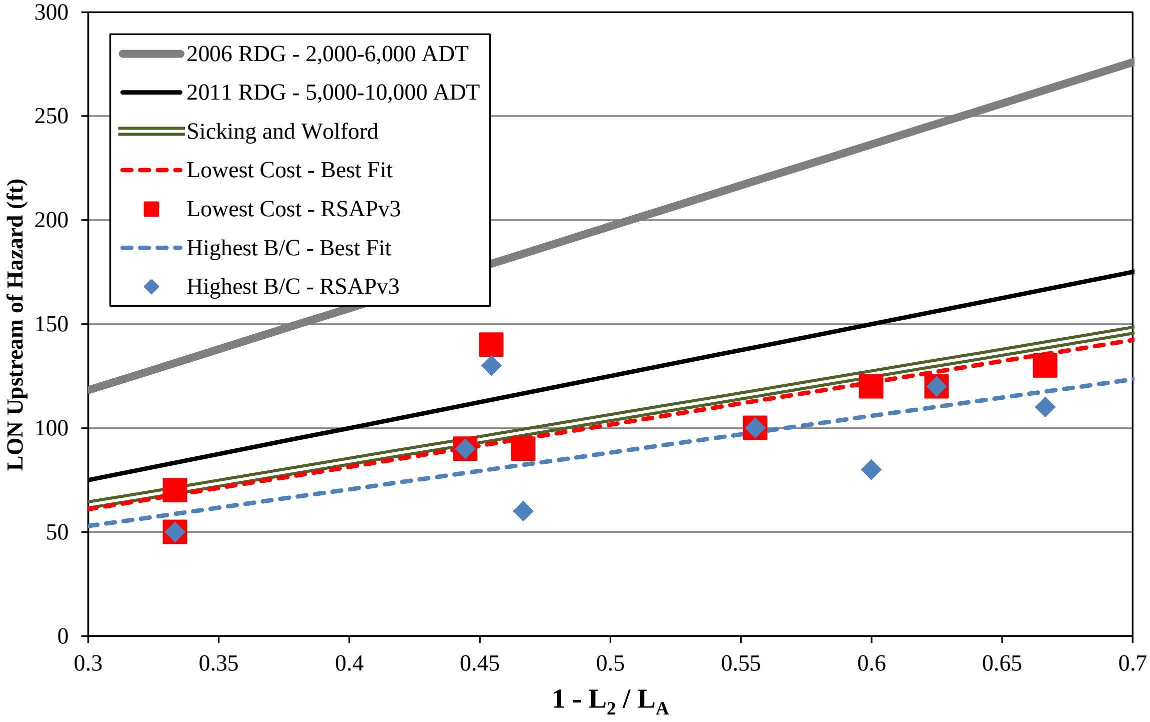


Figure 49. Recommended Guardrail Lengths for ADT < 6,000, 60 mph (97 km/h) Roadway, Right Side

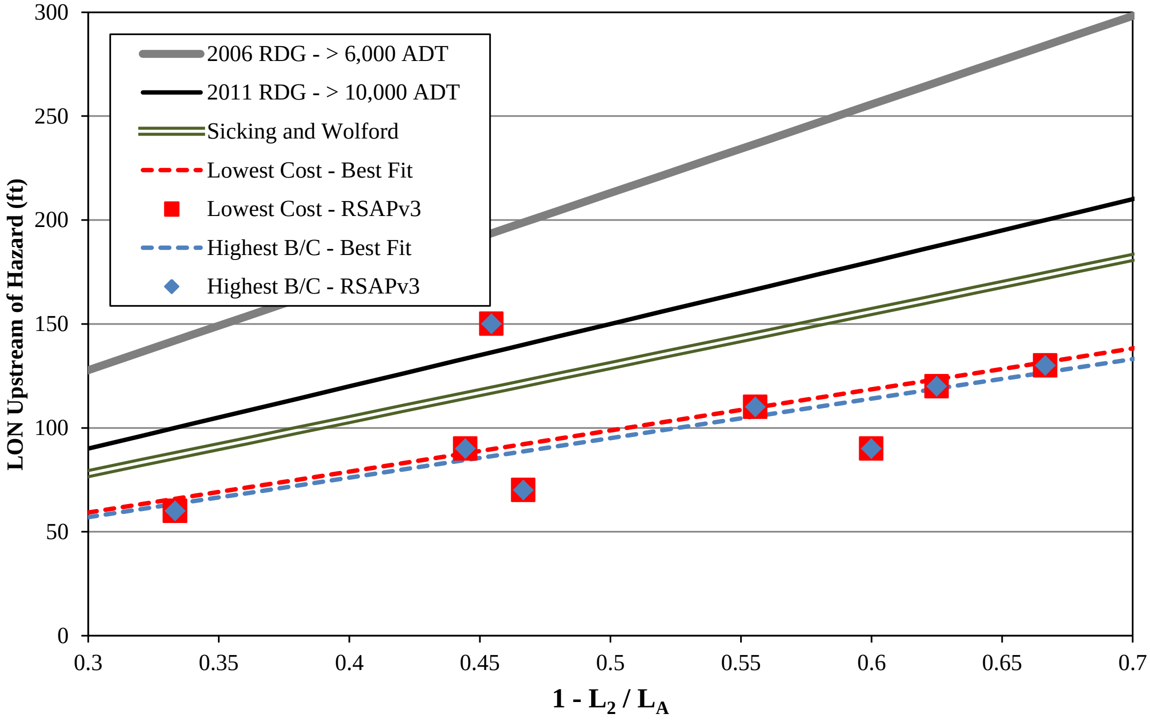


Figure 50. Recommended Guardrail Lengths for ADT > 6,000, 60 mph (97 km/h) Roadway, Right Side

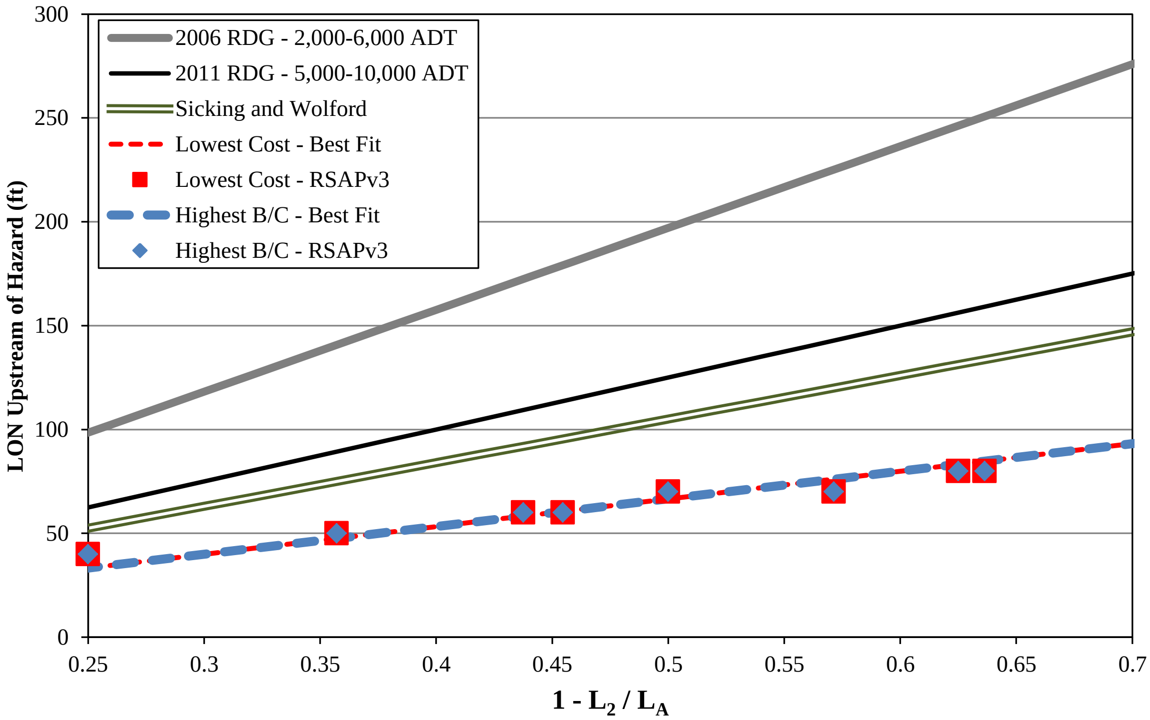


Figure 51. Recommended Guardrail Lengths for ADT < 6,000, 60 mph (97 km/h) Roadway, Left Side (Median)

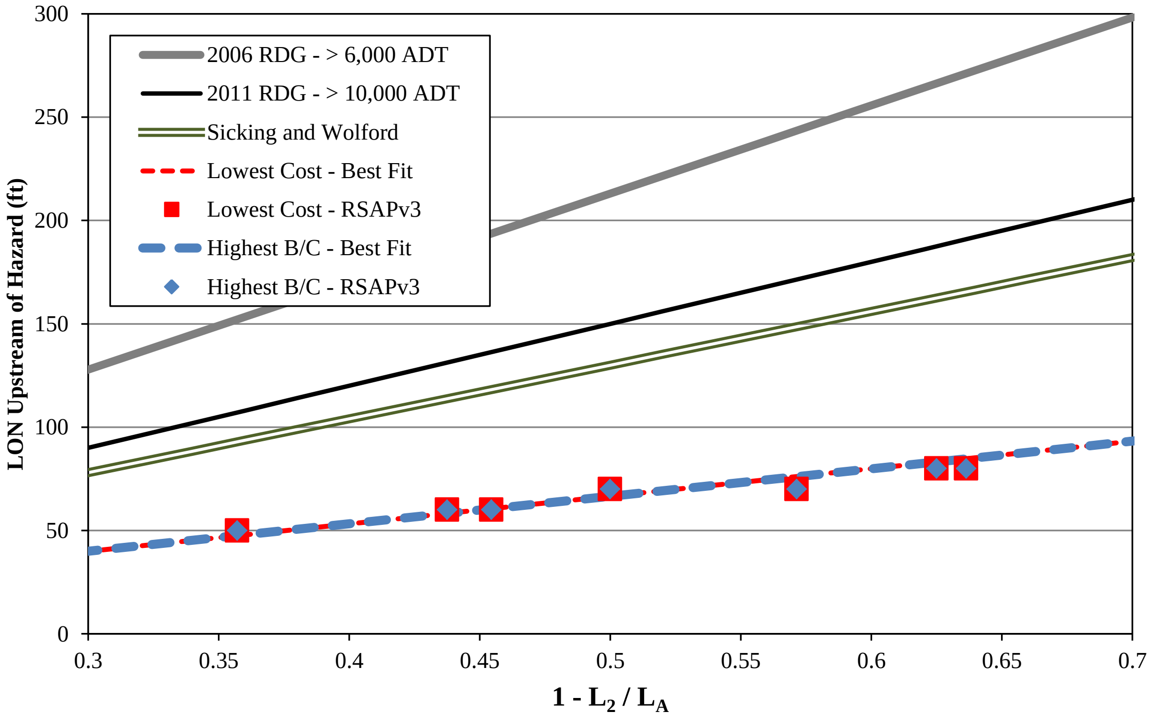


Figure 52 Recommended Guardrail Lengths for ADT > 6,000, 60 mph (97 km/h) Roadway, Left Side (Median)

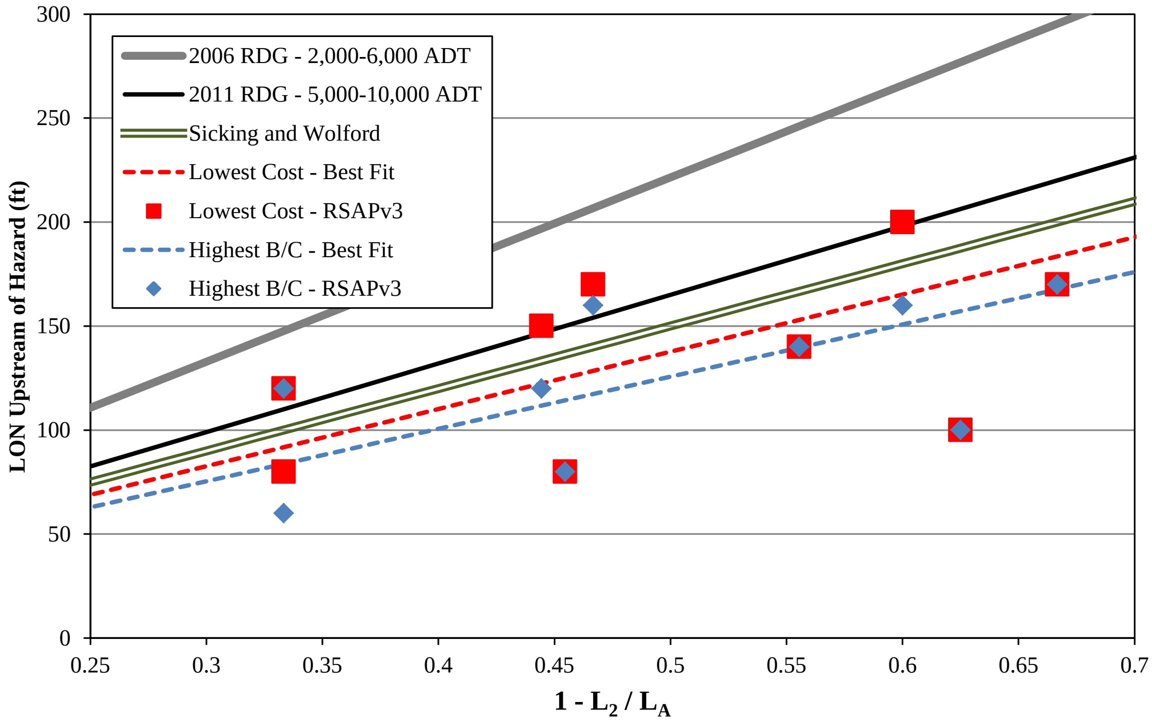


Figure 53. Recommended Guardrail Lengths for ADT < 6,000, 70 mph (113 km/h) Roadway, Right Side

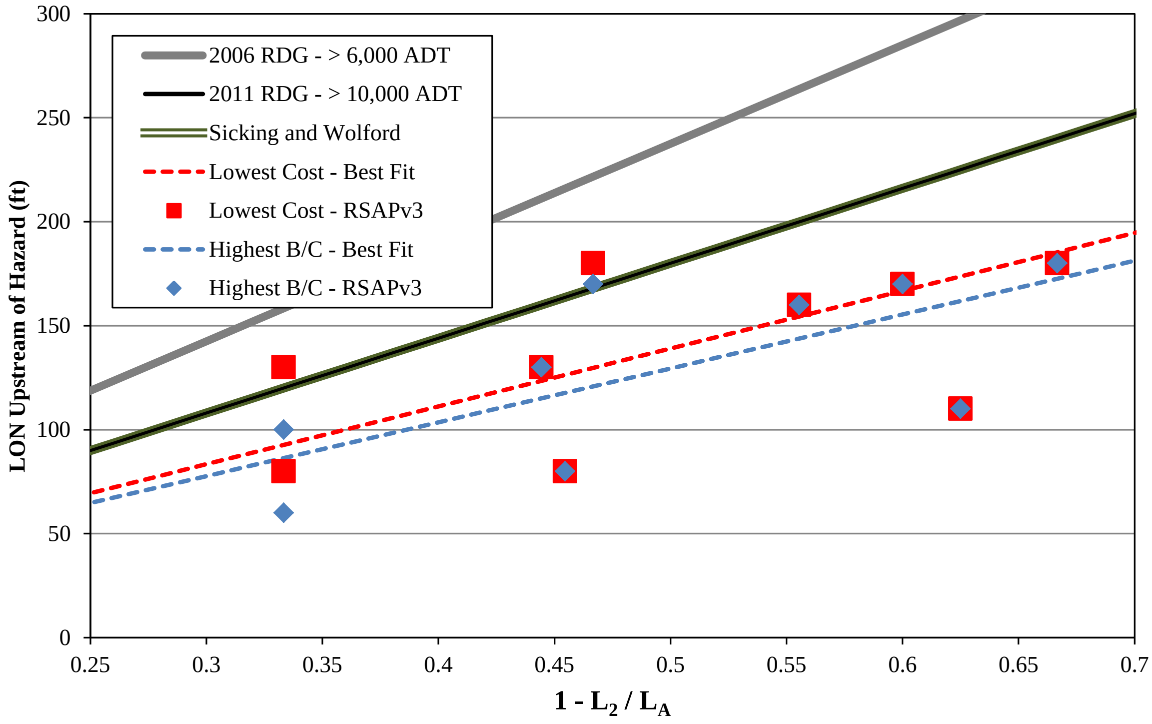


Figure 54. Recommended Guardrail Lengths for ADT > 6,000, 70 mph (113 km/h) Roadway, Right Side

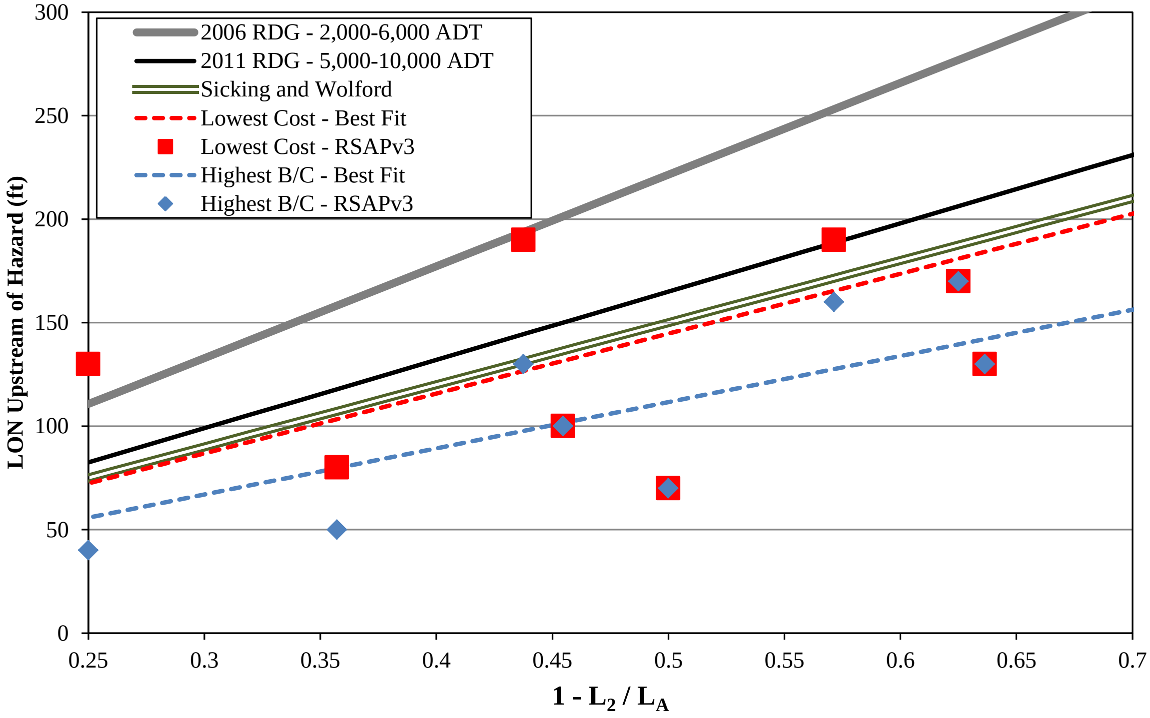


Figure 55. Recommended Guardrail Lengths for ADT < 6,000, 70 mph (113 km/h) Roadway, Left Side (Median)

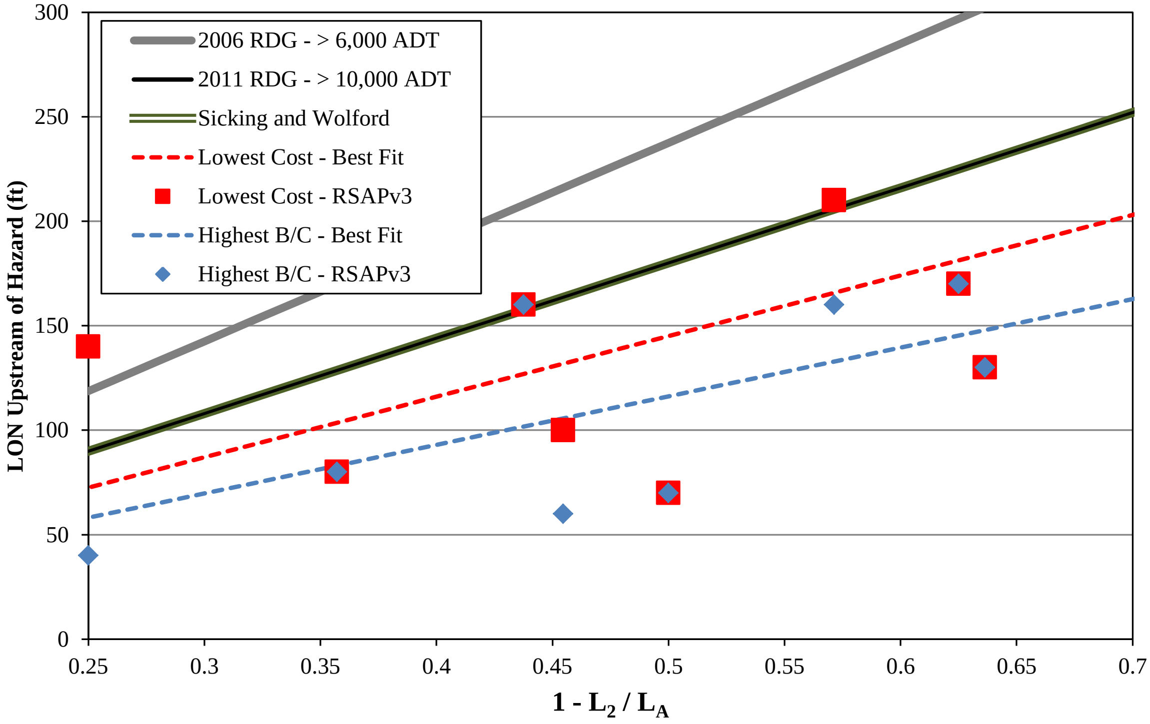


Figure 56. Recommended Guardrail Lengths for ADT > 6,000, 70 mph (113 km/h) Roadway, Left Side (Median)

that for 60-mph (97-km/h) speed limits, the optimized guardrail lengths followed an approximately linear trend. For 70-mph (113-km/h) speed limits, data was more scattered, but still generally increased as the ratio $1 - L_2/L_A$ increased. Thus, a linear best-fit line was applied to the data for both the minimum crash cost and maximum cost-effectiveness X^* guardrail LONs. Best-fit lines for each data set were also shown in Figures 49 through 56, and new best-fit L_R^*s were tabulated and compared to the L_Rs provided in the 2006 and 2011 AASHTO RDGs, as shown in Table 40.

Table 40. Recommended Runout Lengths and Comparison to Literature

ADT			**Runout Lengths, ft (m)**			
			L_R^*		**L_R**	
			Lowest Crash Cost	**Highest Cost-Effectiveness**	**2006 RDG (Table 12)**	**2011 RDG (Table 14)**
Right Side (Roadside)	60 mph	2,000-6,000	203 (62)	176 (54)	394 (120)	250 (76)
		> 6,000	198 (60)	190 (58)	426 (130)	300 (91)
	70 mph	2,000-6,000	275 (84)	251 (77)	443 (135)	330 (101)
		> 6,000	278 (85)	259 (79)	475 (145)	360 (110)
Left Side (Median)	60 mph	2,000-6,000	133 (41)	133 (41)	394 (120)	250 (76)
		> 6,000	133 (41)	133 (41)	426 (130)	300 (91)
	70 mph	2,000-6,000	289 (88)	223 (68)	443 (135)	330 (101)
		> 6,000	290 (88)	232 (71)	475 (145)	360 (110)

Remarkably, the lowest crash cost optimized guardrail runout length for 60-mph (97-km/h) roads was lower for traffic volumes of more than 6,000 vehicles / day (vpd), than for traffic volumes less than 6,000 vpd. However, those differences were very small (< 4%) and are likely the result of statistical noise. In some scenarios, particularly left-side (median) hazards with 60 mph (97 km/h) speed limits, the lowest crash cost and highest cost-effectiveness solutions were the same and thus the optimized runout lengths were also equal. When this occurred, the lowest crash cost results (red squares) overlapped the highest cost-effectiveness (blue diamonds) data points, as shown in Figures 49 through 56.

As previously mentioned, repair costs were neglected in order to bias the results towards more frequent installations of guardrail, and longer lengths when used. Thus, the only direct cost for each scenario applicable in each scenario was the installation cost of the system, which was approximately a linear function of system length. Minimization of the crash cost occurred when the total cost of all vehicle crashes, consisting of impact with the hazard and the guardrail, was limited. Generally, impacts with the hazard were more severe than all guardrail crashes combined, so crash costs were more significantly reduced when the rate of impact with the bridge pier was reduced. Even with the bias in the results toward more often installation of longer guardrail systems, optimized LONs were still much shorter on average than LONs recommended in either the 2006 or 2011 AASHTO RDGs.

In addition, impacts with the shielded hazard were never completely prevented with any upstream guardrail LON (“X”). The optimized guardrail LON was determined to be the one at which the reduction in the total crash cost due to hazard impacts was less than the increase in crash cost associated with more common guardrail impacts, which could also be severe.

6 DISCUSSION

Throughout this study, crash data was limited to Kansas roadways because of crash data availability, and road conditions were primarily flat, minimizing skewing effects due to ditches or sideslopes. These roads have a high relative volume of passenger vehicles, medians which were often at least 60 ft (18 m) wide, and relatively flat median and roadside slopes. Furthermore, the most predominant shielded point hazard was a bridge pier.

The study period extended between 2002 and 2006, and predominantly involved guardrail installed consistently with the 2006 RDG. The 2006 RDG utilized identical runout length recommendations as the 2002 and 1996 versions of the RDG.

In narrow medians, guardrail lengths may need to be longer due to concerns for cross-median crash risk. Based on ADT and cross-median crash frequencies, the analysis could be re-analyzed with an additional continuous hazard extending across the entire median to represent cross-median crash risk, and optimal guardrail risks could be re-analyzed. Similar research for hazard-free median conditions was previously conducted by Peterson and Sicking [28]. There may be other concerns relevant to median applications besides shielding hazards.

Additional reasons for selecting longer guardrail lengths could include possibility of damage to infrastructure, such as electrical equipment or utilities, large overhead sign supports which could fall on roadways, or concerns for pedestrian or other human risk factors which warrant higher protection levels. For these features, the crash costs may not be a sufficient estimate of the total costs due to run-behind-guardrail crashes, and as such could bias results toward longer guardrail lengths. Designers are urged to use discretion to accommodate these sensitive, critical locations.

The most recent version of the Roadside Safety Analysis Program (RSAPv3) was used to assess the cost-effectiveness of guardrail length alternatives, as well as the economic benefits of each alternative using the FHWA Comprehensive Cost data for 2012. Hundreds of highway scenarios were modeled using this program. Even though RSAPv3 presents significant improvements in relation to the older RSAP version (V2), it still has its limitations and cannot simulate real-world crashes with 100 percent accuracy. Some potential programing errors were also identified during the use of this program, including:

1. Initial use of the program resulted in auto-ranking alternatives incorrectly based on direct cost. This error was fixed and a newer version of the program was used.
2. With five alternative guardrail lengths considered and for hazards located on the right side of a divided roadway, the predicted rates of rollover, run-behind guardrail rate, and average crash severity were markedly different for the fifth alternative, compared to the other four. Reasons for the variation were unknown. Although the total crash costs were typically within the expected range based on longer or shorter guardrail lengths, some of the crash cost estimates were outliers. To avoid the possibility of error, results from the fifth alternative of right-side-of-road RSAPv3 analyses were neglected and only four options were considered for each scenario: “Do Nothing”, 2011 or 2006 RDG guardrail length, 40% of 2011 or 2006 RDG guardrail length, and 70% of 2011 or 2006 guardrail length.
3. The program was deterministic; thus, a singular solution was consistently found for the same ADT, speed limit, hazard, and lateral offset configuration. Nonetheless, some simulations, using identical hazard location, traffic volume, side of road, feature severity, and encroachment probability, varied between two different simulations. Although the variations were unexpected, they were not determined to be significant, and did not ultimately affect guardrail selection recommendations.

Besides the caveats of computer simulation of benefit-to-cost analyses, guardrails were simulated with arbitrarily short lengths in many of the scenarios analyzed. Actual guardrail systems have a finite redirection capacity and require sufficient guardrail length to redirect or capture an errant vehicle. Currently, the minimum guardrail length recommended for a Midwest Guardrail System (MGS) guardrail system is 75 ft (22.9 m), based on successful crash testing conducted at the Midwest Roadside Safety Facility (MwRSF) [30]. For most crashworthy end terminals, the beginning of the LON is the third post from the upstream end, or 12 ft - 6 in. (3.81 m). The downstream end of the LON of an MGS system was determined to be approximately 31 ft – 3 in. (9.5 m), or the sixth post, from the downstream end [31]. Therefore, the window of vehicle redirection for vehicles impacting at 62.1 mph (100 km/h) and 25 degrees is 31 ft – 3 in. (9.5 m) long. Impacts outside of this range could result in the guardrail gating and the vehicle encroaching on the back side of the guardrail system.

For short guardrail systems, there is some concern that compression-based, energy-absorbing guardrail terminals with extruder heads may not be able to develop the necessary compressive rail load. Guardrail may disengage prematurely from posts downstream from impact during end-on impacts. Tensile capacities of upstream anchors may also require modifications for short system lengths [30]. Another concern for shorter-length systems include the possibility for vehicles to impact fixed objects, or the hazard, after disengaging from the terminal and traversing within the 20 ft (6.1 m) wide by 70 ft (21.3 m) long clear zone behind the guardrail terminal recommended by AASHTO. Alternatively, a vehicle impacting the upstream terminal may impact a hazard while still engaged with the terminal if the hazard is located within 50 ft (15 m) of the upstream end of the guardrail.

Some states utilize a minimum length for standard guardrail of 175 ft (53 m) based on historical crash testing programs and associated safety performance. For these hazards, it is recommended that guardrail be installed with at least 31 ft – 6 in. (9.5 m) downstream from the downstream end of the hazard. Designers may be flexible with guardrail starting and ending locations if the standard length of guardrail exceeds recommendations provided in this report. Alternatively, crash cushions or sand barrel arrays may be more feasible if recommended guardrail lengths are too low and the alternative safety treatments are cost-competitive.

Underreported crashes involving Kansas guardrails could influence the recommendations. Ray examined crashes in Iowa, North Carolina, and Connecticut and determined that 50 percent of guardrail crashes were unreported [29]. Underreported crashes could potentially have two competing effects on safety and cost-effectiveness recommendations. These crashes tend to be PDO or lower-injury level crashes, which can increase guardrail repair costs and make longer guardrail lengths less desirable. Using the crash report data from Kansas, the average crash cost of guardrail crashes using the 2012 FHWA comprehensive cost was $100,111.05, which was 26 percent higher than the average non-guardrail crash cost of $86,983.63. However, non-guardrail crash costs were based on a small sample and could be subject to change with additional data.

Alternatively, underreported crashes may include low-angle roadside departures in which an errant vehicle drifts off of the side of the road. Low-angle departures could result in a higher proportion of impacts with the shielded hazard. For these scenarios, longer tangent guardrail lengths may be more advantageous. However, large hazard and guardrail offsets could reduce the frequency of these collisions to a greater extent than longer guardrail lengths, as well as placing the guardrail as close to the hazard as feasible. Although terminal impacts may be more severe than guardrail in general, the rate of terminal impacts is unlikely to be significantly different with different guardrail lengths.

Throughout this study, consideration was given to runout lengths for passenger vehicles, such as cars and pickups. Currently runout lengths for large trucks are unknown. Nonetheless, most guardrail systems are not intended to capture or redirect large trucks and may not perform as desired during those crashes, including contributing to large-vehicle rollovers. Reducing guardrail length could conversely reduce the number of large-vehicle truck crashes resulting in undesirable rollovers. Nonetheless, this relationship has not been studied.

All guardrail installations considered in this report were tangent guardrails. Flared guardrail installations were not considered in the analysis, because flares were rarely observed in the crash data. It is recommended that current AASHTO recommendations for treating flared end terminations should be applied to this research with the new guardrail runout lengths.

Urban roadways were characterized by an increased crash rate per mile and per million vehicle miles, compared to rural roadways. Drivers on urban roadways are typically exposed to significantly more hazards in terms of interchanges, overpasses or underpasses, sign supports, utility poles and other roadside features. Driver distraction and confusion may also lead to increased rates of run-off-road excursions, in addition to “driver overload”, which is a diminished sense of focus caused by diverting attention to signs, billboards, adjacent traffic, or other urban-related factors. The distributed attention to other factors may be referred to as “driver workload”.

Lastly, different roadway profiles and speed limits were not considered because they were outside of the scope of this research effort. As such, research findings are limited to freeways with wide, flat medians and relatively flat sideslopes.

7 SUMMARY AND CONCLUSIONS

7.1 Summary

A study was conducted to evaluate tangent guardrail length based on the 2006 AASHTO RDG using crash data obtained for Kansas interstates and freeways. Roadway, hazard, crash, and guardrail parameters were tabulated for each interstate roadway in Kansas, including: hazard offsets, numbers, and types; speed limits; guardrail locations, lengths, offsets, and counted installations; and whether the roads were predominantly urban or rural. Accident reports involving crashes on these roadways were analyzed, and 654 crashes were identified in which an errant vehicle either impacted or traveled behind a guardrail between 2002 and 2006.

For each crash, the guardrail length was partitioned into four segments: 1st quarter (including upstream end terminal); 2nd quarter; 3rd quarter; and 4th quarter (including downstream end terminal), and impact locations into each quarter of the guardrail on each side of the road were identified. Approximately 46 percent of all terminal crashes resulted in reported injuries as compared to 34 percent of non-terminal crashes. There was no significant difference in injury rates between median and roadside guardrail crashes.

Crashes which involved guardrails shielding culvert hazards had the lowest injury rate of 28 percent as compared to the highest rate of 41 percent for crashes involving guardrails shielding signs and poles. A larger portion of poles and signs were located on urban highways, such as I-635 and I-235. Culverts were predominantly located on rural roads.

Based on an analysis of crash data, only 2 percent or 14 crashes involved a vehicle traveling behind the guardrail, and only 0.3 percent (i.e., 2 crashes) involved a vehicle hitting a shielded hazard. Both impacts with the shielded hazards involved secondary hazards only; the primary hazard which warranted the shielding was never impacted. Injury percentages were similar for impacts in which the vehicle impacted the hazard as when the vehicle impacted the guardrail. However, the data set was too limited to make broad conclusions.

Guardrail and shielded hazard crash rates were calculated using different exposure variables. By multiplying the average ADT by the observed number of guardrails on the roadways on a per-year basis, a crash rate of 0.017 crashes per trillion vehicle-guardrail was calculated for ran-behind guardrail crashes and 0.99 crashes per trillion vehicle-guardrail for guardrail crashes. Likewise, by comparing crash costs and controlling for exposure, the risk was US$0.0002 per vehicle for guardrail crashes and US$0.000005 per vehicle for ran-behind guardrail crashes.

In order to determine the most cost-effective and lowest crash cost lengths of guardrail, rigid point hazards were analyzed in RSAP using different guardrail lengths. Both lowest crash cost and highest cost-effectiveness guardrail lengths were frequently between 40 and 70 percent of 2006 RDG guidelines. Based on the results of the RSAPv3 analysis, new runout length numbers were recommended, consistent with the corresponding guardrail lengths.

7.2 Conclusions

The study results suggested that guardrail lengths-of-need on low-grade, divided freeways with flat sideslopes, calculated using either the 2006 or 2011 RDG runout length values, are likely excessively long. Current recommendations for guardrail length are significantly greater than lengths associated with the lowest crash cost or highest cost-effectiveness.

Guardrail lengths longer than necessary to shield the hazard can pose several problems to state DOTs. First, excessively long guardrail installations are expensive to install and will incur more repair costs over the design life than shorter systems. The cost difference between shorter and longer guardrail lengths could be substantial, and cost savings may enable a state to allocate funding for additional safety treatments. Second, shorter guardrail lengths are consistent with the stated goals of the RDG. In particular, priority item no. 1 corresponds to removing a hazard. It is known that a guardrail is also considered a roadside obstacle that can incur injury or fatality to an occupant of an errant vehicle. For shorter length systems consistent with recommendations in this study, it is expected that the decreased rate of fatalities and injuries associated with eliminating unnecessary guardrail will be greater than the increased rate of fatalities and injuries resulting from impact with shielded hazards. Until a system can be constructed and tested which eliminates any risk of injury or fatality and could be installed along every roadside shoulder, guardrail length should be optimized to minimize the number of severe and fatal crashes.

During the crash data and benefit-to-cost analyses, efforts were made to accommodate the higher average crash severity of a terminal compared to the guardrail tangent length, to ensure accuracy in the estimated crash cost. The total crash cost related directly to the terminal is not believed to be a function of terminal location, but total guardrail crash cost does have a cost component associated the increased severity of a terminal impact. If the severity of an average terminal impact decreased, it is likely that the cost-effectiveness of shorter lengths of guardrail would increase, although the magnitude of that change is currently unknown.

The report analysis specifically consisted of the evaluation of W-beam system length-of-need. Results from this report are believed to be representative of other types of semi-rigid guardrail systems with similar installation costs and crash severities. If installation costs are significantly different, but crash severities are similar, then guidelines for the lowest crash cost option (i.e., safest) are expected to be unchanged. However, for systems with significantly different average crash severities, results of the length-of-need evaluation may be significantly different.

8 RECOMMENDATIONS

To validate the study findings for use on alternative roadway functional classes and speed limits, a dataset which incorporates data from other states, different sideslopes, road profiles, and hazard types should be collected and analyzed using similar methods as described in this report. The expanded dataset should also include other highway functional classes, other states, and locations where guardrails have been designed based on 2011 RDG runout lengths. Crashes occurring on roads with more variability in sideslope profiles, higher urban representation, and broader variety of hazard types would also strengthen the study findings.

Using the Kansas crash data and RSAPv3 analyses, the study results indicated that roadway traffic volume did not have a significant effect on the optimized runout lengths for freeways with wide, flat, divided medians and relatively flat roadsides. As such, it may be possible to ignore the effects of traffic volume when installing guardrail on these roadways. In contrast, significant differences were observed for left- and right-side roadway departures due to characteristics of departing vehicle trajectories. Further research is necessary to evaluate other roadway classifications, traffic volumes, hazard types, and departure side (right or left) combinations.

The 65, 75, and 80-mph (105, 121, and 129 km/h) roadway runout lengths were linearly extrapolated from the results of the 60- and 70-mph (97 and 113-km/h) freeways. Currently, the optimal guardrail length for use on 80 mph (129 km/h) roadways is unknown, and may require further analysis to estimate. Likewise, the study was not conducted for roads with speed limits less than 60 mph (97 km/h). Although absolute crash costs may be lower with shorter guardrail lengths on these lower-speed roads, it is believed that a more conservative approach would be to utilize results from the 60-mph (97-km/h) road analysis for all divided freeways with speed limits less than 60 mph (97 km/h).

Further research should be conducted to determine the recommended guardrail lengths at increased travel speeds. Many of the optimum LONs were similar to recommendations made by Sicking and Wolford [20], and many were even shorter, as shown in Figures 49 through 56. Optimized runout lengths for freeways with wide, flat divided medians are shown in Table 41.

Table 41. Recommended Guardrail Runout Lengths for Right and Left Sides of Divided Freeways

Speed Limit, mph (km/h)	Runout Length, ft (m)	
	Left Side (Median)	Right Side (Roadside)
80 (129)	415 (126)	352 (107)
75 (121)	352 (107)	315 (96)
70 (113)	289 (88)	278 (85)
65 (105)	211 (64)	241 (73)
≤ 60 (97)	133 (41)	203 (62)

*Note, results extrapolated from freeways with PSL = 60 or 70 mph (97 or 121 km/h)

There may be concerns that results of this study may not be representative of all freeways, and making guardrail lengths too short will cause a much higher rate of impact and injury or fatality with the shielded hazard than was predicted in this study. Such concerns are valid, as this study is the first to evaluate very short approach guardrail lengths. State DOTs may pursue one of the following options for implementing all, some, or none of the recommendations contained in this report:

1. Findings and recommendations from this report may be implemented exactly as specified for some or all divided freeways. This approach could provide an aggressive measure of the validity of study findings, and would warrant a follow-up performance evaluation to ensure crash data supports the use of shorter guardrails.
2. Findings and recommendations from this report could be applied to a sample of roadways, and compared in real time to similar guardrails on similar roads. This

method would limit any adverse effects from excessively short guardrail lengths, or could support the use of less guardrail if adverse effects are minimal.

3. State DOTs could pursue a modified table of recommendations for new guardrail lengths; for example, results could be applied with the caveat that the minimum guardrail length is not less than 70% of what was specified in the AASHTO 2011 RDG. This method is believed to be a conservative compromise between implementing the cost- and life-saving research contained herein without shortening guardrail lengths to the extent there is concern about the rate of ran-behind-guardrail crashes resulting in impact with the primary shielded hazard.
4. State DOTs could utilize a minimum guardrail length of 175 ft (53.3 m), which is the standard guardrail length used during crash testing and has been used in compressive terminal testing. Alternatively, states could utilize minimum guardrail lengths recommended by end terminal manufacturers to remain compliant with design guidelines.
5. State DOTs may continue to use existing guidelines or AASHTO recommendations and delay revisions to guardrail length calculations until other states have demonstrated positive benefits due to guardrail length reductions.

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10 APPENDICES

Appendix A. RSAP Results, Hazard on Right Side of Roadway

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	6000	12	68	N/A	N/A	N/A	N/A	0	996	$5,966	$0	-	120	50%	80%	120	50%	80%
				6	60	246.3	156.3	80	920	$1,499	$4,370	$280						
								120	880	$1,293	$5,561	$356						
								130	870	$1,335	$5,858	$375						
								170	830	$1,488	$7,049	$451						
								190	810	$1,562	$7,644	$489						
								260	740	$1,809	$9,728	$623						
60	6000	18	74	N/A	N/A	N/A	N/A	0	996	$5,391	$0	-	140	80%	120%	130	70%	110%
				12	66	179.1	113.6	60	940	$1,969	$3,774	$242						
								90	910	$1,525	$4,667	$299						
								100	900	$1,416	$4,965	$318						
								130	870	$1,205	$5,858	$375						
								140	860	$1,188	$6,156	$394						
								200	800	$1,299	$7,942	$508						
60	6000	26	82	N/A	N/A	N/A	N/A	0	996	$2,295	$0	-	120	50%	80%	80	30%	50%
				12	66	236.4	150.0	80	920	$1,020	$4,370	$280						
								110	890	$1,062	$5,263	$337						
								120	880	$989	$5,561	$356						
								170	830	$1,127	$7,049	$451						
								180	820	$1,179	$7,347	$470						
								250	750	$1,434	$9,431	$604						
60	6000	26	82	N/A	N/A	N/A	N/A	0	996	$2,295	$0	-	90	50%	80%	60	30%	50%
				16	70	183.9	116.7	60	940	$890	$3,774	$242						
								90	910	$823	$4,667	$299						
								100	900	$840	$4,965	$318						
								130	870	$911	$5,858	$375						
								160	840	$986	$6,751	$432						
								200	800	$1,088	$7,942	$508						
60	6000	26	82	N/A	N/A	N/A	N/A	0	996	$2,295	$0	-	50	40%	60%	50	40%	60%
				20	74	131.3	83.3	50	950	$716	$3,477	$223						
								70	930	$743	$4,072	$261						
								100	900	$828	$4,965	$318						
								110	890	$855	$5,263	$337						
								150	850	$953	$6,454	$413						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	6000	32	88	N/A	N/A	N/A	N/A	0	996	$1,940	$0	-	130	50%	80%	110	40%	70%
				12	66	262.7	166.7	80	920	$1,379	$4,370	$280						
								110	890	$1,062	$5,263	$337						
								130	870	$1,027	$5,858	$375						
								180	820	$1,148	$7,347	$470						
								190	810	$1,179	$7,644	$489						
								280	720	$1,434	$10,324	$661						
60	6000	32	88	N/A	N/A	N/A	N/A	0	996	$1,940	$0	-	100	50%	70%	100	50%	70%
				16	70	218.9	138.9	70	930	$1,140	$4,072	$261						
								100	900	$855	$4,965	$318						
								110	890	$871	$5,263	$337						
								160	840	$982	$6,751	$432						
								170	830	$1,008	$7,049	$451						
								240	760	$1,184	$9,133	$585						
60	6000	32	88	N/A	N/A	N/A	N/A	0	996	$1,940	$0	-	90	50%	80%	90	50%	80%
				20	74	175.1	111.1	60	940	$949	$3,774	$242						
								90	910	$790	$4,667	$299						
								130	870	$876	$5,858	$375						
								140	860	$899	$6,156	$394						
								190	810	$1,014	$7,644	$489						
60	6000	32	88	N/A	N/A	N/A	N/A	0	996	$1,940	$0	-	70	50%	80%	50	40%	60%
				24	78	131.3	83.3	50	950	$729	$3,477	$223						
								70	930	$677	$4,072	$261						
								100	900	$740	$4,965	$318						
								110	890	$757	$5,263	$337						
								150	850	$839	$6,454	$413						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	12000	12	68	N/A	N/A	N/A	N/A	0	996	$9,017	$0	-	120	50%	60%	120	50%	60%
				6	60	266.3	187.5	90	910	$2,116	$4,667	$299						
								120	880	$1,955	$5,561	$356						
								150	850	$2,134	$6,454	$413						
								200	800	$2,414	$7,942	$508						
								280	720	$2,839	$10,324	$661						
60	12000	18	74	N/A	N/A	N/A	N/A	0	996	$8,148	$0	-	150	80%	110%	110	60%	80%
				12	66	193.6	136.4	70	930	$2,702	$4,072	$261						
								90	910	$3,367	$4,667	$299						
								110	890	$1,916	$5,263	$337						
								150	850	$1,771	$6,454	$413						
								210	790	$2,011	$8,240	$527						
60	12000	26	82	N/A	N/A	N/A	N/A	0	996	$3,468	$0	-	90	40%	50%	90	40%	50%
				12	66	255.6	180.0	90	910	$1,437	$4,667	$299						
								120	880	$1,494	$5,561	$356						
								140	860	$1,569	$6,156	$394						
								200	800	$1,829	$7,942	$508						
								270	730	$2,135	$10,026	$642						
60	12000	26	82	N/A	N/A	N/A	N/A	0	996	$3,468	$0	-	70	40%	50%	70	40%	50%
				16	70	198.8	140.0	70	930	$1,210	$4,072	$261						
								100	900	$1,270	$4,965	$318						
								110	890	$1,300	$5,263	$337						
								160	840	$1,491	$6,751	$432						
								220	780	$1,720	$8,538	$547						
60	12000	26	82	N/A	N/A	N/A	N/A	0	996	$3,468	$0	-	60	40%	60%	60	40%	60%
				20	74	142.0	100.0	60	940	$1,103	$3,774	$242						
								70	930	$1,122	$4,072	$261						
								90	910	$1,209	$4,667	$299						
								120	880	$1,330	$5,561	$356						
								160	840	$1,475	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	12000	32	88	N/A	N/A	N/A	N/A	0	996	$2,932	$0	-	130	50%	70%	130	50%	70%
				12	66	284.0	200.0	100	900	$1,744	$4,965	$318						
								130	870	$1,552	$5,858	$375						
								160	840	$1,654	$6,751	$432						
								220	780	$1,908	$8,538	$547						
								300	700	$2,254	$10,919	$699						
60	12000	32	88	N/A	N/A	N/A	N/A	0	996	$2,932	$0	-	110	50%	70%	110	50%	70%
				16	70	236.7	166.7	80	920	$1,549	$4,370	$280						
								110	890	$1,327	$5,263	$337						
								130	870	$1,378	$5,858	$375						
								180	820	$1,560	$7,347	$470						
								250	750	$1,829	$9,431	$604						
60	12000	32	88	N/A	N/A	N/A	N/A	0	996	$2,932	$0	-	90	50%	70%	70	40%	50%
				20	74	189.3	133.3	70	930	$1,268	$4,072	$261						
								90	910	$1,195	$4,667	$299						
								110	890	$1,256	$5,263	$337						
								150	850	$1,393	$6,454	$413						
								210	790	$1,602	$8,240	$527						
60	12000	32	88	N/A	N/A	N/A	N/A	0	996	$2,932	$0	-	60	40%	60%	60	40%	60%
				24	78	142.0	100.0	60	940	$1,006	$3,774	$242						
								70	930	$1,081	$4,072	$261						
								90	910	$1,081	$4,667	$299						
								120	880	$1,181	$5,561	$356						
								160	840	$1,429	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	30000	12	68	N/A	N/A	N/A	N/A	0	996	$9,723	$0	-	120	50%	60%	120	50%	60%
				6	60	266.3	187.5	90	910	$2,282	$4,667	$299						
								120	880	$2,108	$5,561	$356						
								150	850	$2,301	$6,454	$413						
								200	800	$2,603	$7,942	$508						
								280	720	$3,061	$10,324	$661						
60	30000	18	74	N/A	N/A	N/A	N/A	0	996	$8,786	$0	-	150	80%	110%	150	80%	110%
				12	66	193.6	136.4	70	930	$2,913	$4,072	$261						
								90	910	$3,631	$4,667	$299						
								110	890	$2,066	$5,263	$337						
								150	850	$1,909	$6,454	$413						
								210	790	$2,168	$8,240	$527						
60	30000	26	82	N/A	N/A	N/A	N/A	0	996	$3,740	$0	-	90	40%	50%	90	40%	50%
				12	66	255.6	180.0	90	910	$1,549	$4,667	$299						
								120	880	$1,611	$5,561	$356						
								140	860	$1,692	$6,156	$394						
								200	800	$1,972	$7,942	$508						
								270	730	$2,302	$10,026	$642						
60	30000	26	82	N/A	N/A	N/A	N/A	0	996	$3,740	$0	-	70	40%	50%	70	40%	50%
				16	70	198.8	140.0	70	930	$1,304	$4,072	$261						
								100	900	$1,370	$4,965	$318						
								110	890	$1,401	$5,263	$337						
								160	840	$1,607	$6,751	$432						
								220	780	$1,855	$8,538	$547						
60	30000	26	82	N/A	N/A	N/A	N/A	0	996	$3,740	$0	-	60	40%	60%	60	40%	60%
				20	74	142.0	100.0	60	940	$1,189	$3,774	$242						
								70	930	$1,210	$4,072	$261						
								90	910	$1,304	$4,667	$299						
								120	880	$1,434	$5,561	$356						
								160	840	$1,591	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	30000	32	88	N/A	N/A	N/A	N/A	0	996	$3,161	$0	-	130	50%	70%	130	50%	70%
				12	66	284.0	200.0	100	900	$1,880	$4,965	$318						
								130	870	$1,674	$5,858	$375						
								160	840	$1,783	$6,751	$432						
								220	780	$2,058	$8,538	$547						
								300	700	$2,430	$10,919	$699						
60	30000	32	88	N/A	N/A	N/A	N/A	0	996	$3,161	$0	-	110	50%	70%	110	50%	70%
				16	70	236.7	166.7	80	920	$1,671	$4,370	$280						
								110	890	$1,420	$5,263	$337						
								130	870	$1,486	$5,858	$375						
								180	820	$1,683	$7,347	$470						
								250	750	$1,972	$9,431	$604						
60	30000	32	88	N/A	N/A	N/A	N/A	0	996	$3,161	$0	-	90	50%	70%	90	50%	70%
				20	74	189.3	133.3	70	930	$1,367	$4,072	$261						
								90	910	$1,288	$4,667	$299						
								110	890	$1,354	$5,263	$337						
								150	850	$1,502	$6,454	$413						
								210	790	$1,727	$8,240	$527						
60	30000	32	88	N/A	N/A	N/A	N/A	0	996	$3,161	$0	-	60	40%	60%	60	40%	60%
				24	78	142.0	100.0	60	940	$1,084	$3,774	$242						
								70	930	$1,104	$4,072	$261						
								90	910	$1,166	$4,667	$299						
								120	880	$1,274	$5,561	$356						
								160	840	$1,408	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	6000	12	68	N/A	N/A	N/A	N/A	0	996	$7,467	$0	-	100	40%	50%	100	40%	50%
				6	60	276.9	206.3	100	900	$2,175	$4,965	$318						
								130	870	$2,399	$5,858	$375						
								160	840	$2,566	$6,751	$432						
								210	790	$2,758	$8,240	$527						
								220	780	$2,797	$8,538	$547						
								290	710	$3,010	$10,621	$680						
70	6000	18	74	N/A	N/A	N/A	N/A	0	996	$5,877	$0	-	80	40%	50%	80	40%	50%
				12	66	201.4	150.0	80	920	$1,523	$4,370	$280						
								100	900	$1,683	$4,965	$318						
								120	880	$1,842	$5,561	$356						
								160	840	$2,106	$6,751	$432						
								170	830	$2,161	$7,049	$451						
								220	780	$2,392	$8,538	$547						
70	6000	26	82	N/A	N/A	N/A	N/A	0	996	$4,973	$0	-	200	80%	100%	160	60%	80%
				12	66	265.8	198.0	100	900	$2,381	$4,965	$318						
								120	880	$2,224	$5,561	$356						
								160	840	$1,933	$6,751	$432						
								200	800	$1,927	$7,942	$508						
								210	790	$1,971	$8,240	$527						
								280	720	$2,250	$10,324	$661						
70	6000	26	82	N/A	N/A	N/A	N/A	0	996	$4,973	$0	-	170	80%	110%	160	80%	100%
				16	70	206.7	154.0	80	920	$1,861	$4,370	$280						
								100	900	$1,723	$4,965	$318						
								120	880	$1,638	$5,561	$356						
								160	840	$1,482	$6,751	$432						
								170	830	$1,454	$7,049	$451						
								220	780	$1,601	$8,538	$547						
70	6000	26	82	N/A	N/A	N/A	N/A	0	996	$4,973	$0	-	80	50%	70%	60	40%	50%
				20	74	147.7	110.0	60	940	$1,526	$3,774	$242						
								80	920	$1,497	$4,370	$280						
								90	910	$1,537	$4,667	$299						
								120	880	$1,566	$5,561	$356						
								130	870	$1,547	$5,858	$375						
								160	840	$1,519	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	6000	32	88	N/A	N/A	N/A	N/A	0	996	$4,166	$0	-	170	60%	80%	170	60%	80%
				12	66	295.3	220.0	100	900	$2,595	$4,965	$318						
								130	870	$2,136	$5,858	$375						
								170	830	$1,892	$7,049	$451						
								220	780	$2,020	$8,538	$547						
								240	760	$2,090	$9,133	$585						
								310	690	$2,342	$11,217	$718						
70	6000	32	88	N/A	N/A	N/A	N/A	0	996	$4,166	$0	-	140	60%	80%	140	60%	80%
				16	70	246.1	183.3	90	910	$1,982	$4,667	$299						
								110	890	$1,722	$5,263	$337						
								140	860	$1,452	$6,156	$394						
								190	810	$1,508	$7,644	$489						
								200	800	$1,528	$7,942	$508						
								260	740	$1,733	$9,728	$623						
70	6000	32	88	N/A	N/A	N/A	N/A	0	996	$4,166	$0	-	150	80%	100%	120	60%	80%
				20	74	196.9	146.7	80	920	$1,612	$4,370	$280						
								100	900	$1,403	$4,965	$318						
								120	880	$1,264	$5,561	$356						
								150	850	$1,240	$6,454	$413						
								160	840	$1,256	$6,751	$432						
								210	790	$1,422	$8,240	$527						
70	6000	32	88	N/A	N/A	N/A	N/A	0	996	$4,166	$0	-	120	80%	110%	120	80%	110%
				24	78	147.7	110.0	60	940	$1,427	$3,774	$242						
								80	920	$1,225	$4,370	$280						
								90	910	$1,176	$4,667	$299						
								120	880	$1,055	$5,561	$356						
								130	870	$1,070	$5,858	$375						
								160	840	$1,196	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	12000	12	68	N/A	N/A	N/A	N/A	0	996	$11,285	$0	-	110	40%	50%	110	40%	50%
				6	60	296.9	225.0	110	890	$3,427	$5,263	$337						
								140	860	$3,722	$6,156	$394						
								170	830	$3,924	$7,049	$451						
								220	780	$4,227	$8,538	$547						
								240	760	$4,315	$9,133	$585						
								310	690	$4,671	$11,217	$718						
70	12000	18	74	N/A	N/A	N/A	N/A	0	996	$8,881	$0	-	80	40%	50%	80	40%	50%
				12	66	215.9	163.6	80	920	$2,301	$4,370	$280						
								100	900	$2,543	$4,965	$318						
								130	870	$2,890	$5,858	$375						
								170	830	$3,265	$7,049	$451						
								180	820	$3,346	$7,347	$470						
								230	770	$3,683	$8,835	$566						
70	12000	26	82	N/A	N/A	N/A	N/A	0	996	$7,516	$0	-	170	60%	80%	170	60%	80%
				12	66	285.0	216.0	100	900	$3,599	$4,965	$318						
								130	870	$3,223	$5,858	$375						
								170	830	$2,886	$7,049	$451						
								220	780	$3,045	$8,538	$547						
								230	770	$3,112	$8,835	$566						
								300	700	$3,506	$10,919	$699						
70	12000	26	82	N/A	N/A	N/A	N/A	0	996	$7,516	$0	-	180	80%	110%	170	80%	100%
				16	70	221.7	168.0	80	920	$2,812	$4,370	$280						
								110	890	$2,544	$5,263	$337						
								130	870	$2,381	$5,858	$375						
								170	830	$2,198	$7,049	$451						
								180	820	$2,194	$7,347	$470						
								240	760	$2,526	$9,133	$585						
70	12000	26	82	N/A	N/A	N/A	N/A	0	996	$7,516	$0	-	80	50%	70%	60	40%	50%
				20	74	158.3	120.0	60	940	$2,306	$3,774	$242						
								80	920	$2,262	$4,370	$280						
								100	900	$2,359	$4,965	$318						
								130	870	$2,338	$5,858	$375						
								140	860	$2,337	$6,156	$394						
								170	830	$2,305	$7,049	$451						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	12000	32	88	N/A	N/A	N/A	N/A	0	996	$6,296	$0	-	180	60%	80%	180	60%	80%
				12	66	316.7	240.0	110	890	$3,628	$5,263	$337						
								140	860	$3,077	$6,156	$394						
								180	820	$2,880	$7,347	$470						
								240	760	$3,159	$9,133	$585						
								260	740	$3,277	$9,728	$623						
								330	670	$3,628	$11,812	$756						
70	12000	32	88	N/A	N/A	N/A	N/A	0	996	$6,296	$0	-	160	60%	80%	160	60%	80%
				16	70	263.9	200.0	100	900	$2,755	$4,965	$318						
								120	880	$2,449	$5,561	$356						
								160	840	$2,171	$6,751	$432						
								200	800	$2,309	$7,942	$508						
								220	780	$2,404	$8,538	$547						
								280	720	$2,725	$10,324	$661						
70	12000	32	88	N/A	N/A	N/A	N/A	0	996	$6,296	$0	-	130	60%	80%	130	60%	80%
				20	74	211.1	160.0	80	920	$2,437	$4,370	$280						
								100	900	$2,121	$4,965	$318						
								130	870	$1,835	$5,858	$375						
								160	840	$1,898	$6,751	$432						
								180	820	$1,988	$7,347	$470						
								230	770	$2,252	$8,835	$566						
70	12000	32	88	N/A	N/A	N/A	N/A	0	996	$6,296	$0	-	130	80%	110%	100	60%	80%
				24	78	158.3	120.0	60	940	$2,156	$3,774	$242						
								80	920	$1,852	$4,370	$280						
								100	900	$1,695	$4,965	$318						
								130	870	$1,617	$5,858	$375						
								140	860	$1,691	$6,156	$394						
								170	830	$1,851	$7,049	$451						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	30000	12	68	N/A	N/A	N/A	N/A	0	996	$12,169	$0	-	110	40%	50%	110	40%	50%
				6	60	296.9	225.0	110	890	$3,695	$5,263	$337						
								140	860	$4,013	$6,156	$394						
								170	830	$4,231	$7,049	$451						
								220	780	$4,558	$8,538	$547						
								240	760	$4,652	$9,133	$585						
								310	690	$5,036	$11,217	$718						
70	30000	18	74	N/A	N/A	N/A	N/A	0	996	$9,577	$0	-	80	40%	50%	80	40%	50%
				12	66	215.9	163.6	80	920	$2,481	$4,370	$280						
								100	900	$2,743	$4,965	$318						
								130	870	$3,116	$5,858	$375						
								170	830	$3,521	$7,049	$451						
								180	820	$3,608	$7,347	$470						
								230	770	$3,971	$8,835	$566						
70	30000	26	82	N/A	N/A	N/A	N/A	0	996	$8,105	$0	-	170	60%	80%	170	60%	80%
				12	66	285.0	216.0	100	900	$3,881	$4,965	$318						
								130	870	$3,476	$5,858	$375						
								170	830	$3,112	$7,049	$451						
								220	780	$3,284	$8,538	$547						
								230	770	$3,355	$8,835	$566						
								300	700	$3,780	$10,919	$699						
70	30000	26	82	N/A	N/A	N/A	N/A	0	996	$8,105	$0	-	180	80%	110%	170	80%	100%
				16	70	221.7	168.0	80	920	$3,033	$4,370	$280						
								110	890	$2,743	$5,263	$337						
								130	870	$2,568	$5,858	$375						
								170	830	$2,370	$7,049	$451						
								180	820	$2,366	$7,347	$470						
								240	760	$2,724	$9,133	$585						
70	30000	26	82	N/A	N/A	N/A	N/A	0	996	$8,105	$0	-	80	50%	70%	60	40%	50%
				20	74	158.3	120.0	60	940	$2,487	$3,774	$242						
								80	920	$2,439	$4,370	$280						
								100	900	$2,543	$4,965	$318						
								130	870	$2,521	$5,858	$375						
								140	860	$2,520	$6,156	$394						
								170	830	$2,485	$7,049	$451						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	30000	32	88	N/A	N/A	N/A	N/A	0	996	$6,789	$0	-	180	60%	80%	180	60%	80%
				12	66	316.7	240.0	110	890	$3,912	$5,263	$337						
								140	860	$3,318	$6,156	$394						
								180	820	$3,106	$7,347	$470						
								240	760	$3,406	$9,133	$585						
								260	740	$3,533	$9,728	$623						
								330	670	$3,912	$11,812	$756						
70	30000	32	88	N/A	N/A	N/A	N/A	0	996	$6,789	$0	-	160	60%	80%	160	60%	80%
				16	70	263.9	200.0	100	900	$2,971	$4,965	$318						
								120	880	$2,641	$5,561	$356						
								160	840	$2,341	$6,751	$432						
								200	800	$2,490	$7,942	$508						
								220	780	$2,592	$8,538	$547						
								280	720	$2,939	$10,324	$661						
70	30000	32	88	N/A	N/A	N/A	N/A	0	996	$6,789	$0	-	130	60%	80%	130	60%	80%
				20	74	211.1	160.0	80	920	$2,627	$4,370	$280						
								100	900	$2,287	$4,965	$318						
								130	870	$1,978	$5,858	$375						
								160	840	$2,046	$6,751	$432						
								180	820	$2,144	$7,347	$470						
								230	770	$2,429	$8,835	$566						
70	30000	32	88	N/A	N/A	N/A	N/A	0	996	$6,789	$0	-	130	80%	110%	100	60%	80%
				24	78	158.3	120.0	60	940	$2,325	$3,774	$242						
								80	920	$1,997	$4,370	$280						
								100	900	$1,828	$4,965	$318						
								130	870	$1,744	$5,858	$375						
								140	860	$1,824	$6,156	$394						
								170	830	$1,996	$7,049	$451						

Appendix B. RSAP Results, Hazard on Left Side of Roadway

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	6,000	12	16	N/A	N/A	N/A	N/A	0	996	$3,252	$0	-	70	40%	60%	70	40%	60%
				8	22	197.0	125.0	70	930	$1,130	$4,072	$261						
								100	900	$1,316	$4,965	$318						
								130	870	$1,461	$5,858	$375						
								140	860	$1,501	$6,156	$394						
								150	850	$1,540	$6,454	$413						
								190	810	$1,675	$7,644	$489						
								210	790	$1,733	$8,240	$527						
60	6000	18	10	N/A	N/A	N/A	N/A	0	996	$2,638	$0	-	80	30%	50%	80	30%	50%
				8	22	250.7	159.1	80	920	$810	$4,370	$280						
								120	880	$893	$5,561	$356						
								130	870	$919	$5,858	$375						
								160	840	$993	$6,751	$432						
								180	820	$1,047	$7,347	$470						
								190	810	$1,079	$7,644	$489						
								240	760	$1,200	$9,133	$585						
								270	730	$1,280	$10,026	$642						
60	6000	18	10	N/A	N/A	N/A	N/A	0	996	$2,638	$0	-	60	30%	50%	60	30%	50%
				12	18	179.1	113.6	60	940	$606	$3,774	$242						
								90	910	$749	$4,667	$299						
								100	900	$799	$4,965	$318						
								120	880	$884	$5,561	$356						
								130	870	$923	$5,858	$375						
								140	860	$959	$6,156	$394						
								180	820	$1,078	$7,347	$470						
								200	800	$1,115	$7,942	$508						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	6000	24	4	N/A	N/A	N/A	N/A	0	996	$2,306	$0	-	90	30%	50%	90	30%	50%
				8	22	281.4	178.6	90	910	$946	$4,667	$299						
								130	870	$1,026	$5,858	$375						
								140	860	$1,047	$6,156	$394						
								180	820	$1,067	$7,347	$470						
								200	800	$1,087	$7,942	$508						
								210	790	$1,116	$8,240	$527						
								270	730	$1,279	$10,026	$642						
								300	700	$1,351	$10,919	$699						
60	6000	24	4	N/A	N/A	N/A	N/A	0	996	$2,306	$0	-	70	30%	50%	70	30%	50%
				12	18	225.1	142.9	70	930	$739	$4,072	$261						
								110	890	$813	$5,263	$337						
								120	880	$832	$5,561	$356						
								150	850	$857	$6,454	$413						
								160	840	$861	$6,751	$432						
								170	830	$862	$7,049	$451						
								220	780	$952	$8,538	$547						
								240	760	$998	$9,133	$585						
60	6000	24	4	N/A	N/A	N/A	N/A	0	996	$2,306	$0	-	50	40%	60%	50	40%	60%
				18	12	140.7	89.3	50	950	$606	$3,477	$223						
								70	930	$658	$4,072	$261						
								80	920	$703	$4,370	$280						
								100	900	$789	$4,965	$318						
								110	890	$833	$5,263	$337						
								120	880	$850	$5,561	$356						
								140	860	$873	$6,156	$394						
								160	840	$892	$6,751	$432						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	6000	28	0	N/A	N/A	N/A	N/A	0	996	$2,230	$0	-	90	30%	50%	90	30%	50%
				8	22	295.5	187.5	90	910	$1,024	$4,667	$299						
								130	870	$1,052	$5,858	$375						
								150	850	$1,057	$6,454	$413						
								190	810	$1,081	$7,644	$489						
								200	800	$1,088	$7,942	$508						
								220	780	$1,139	$8,538	$547						
								280	720	$1,302	$10,324	$661						
								310	690	$1,378	$11,217	$718						
60	6000	28	0	N/A	N/A	N/A	N/A	0	996	$2,230	$0	-	80	30%	50%	80	30%	50%
				12	18	246.3	156.3	80	920	$835	$4,370	$280						
								120	880	$858	$5,561	$356						
								130	870	$855	$5,858	$375						
								160	840	$862	$6,751	$432						
								170	830	$863	$7,049	$451						
								190	810	$879	$7,644	$489						
								240	760	$999	$9,133	$585						
								260	740	$1,044	$9,728	$623						
60	6000	28	0	N/A	N/A	N/A	N/A	0	996	$2,230	$0	-	60	30%	50%	60	30%	50%
				18	12	172.4	109.4	60	940	$702	$3,774	$242						
								90	910	$736	$4,667	$299						
								110	890	$730	$5,263	$337						
								130	870	$731	$5,858	$375						
								140	860	$728	$6,156	$394						
								170	830	$738	$7,049	$451						
								190	810	$781	$7,644	$489						
60	6000	28	0	N/A	N/A	N/A	N/A	0	996	$2,230	$0	-	40	40%	60%	40	40%	60%
				24	6	98.5	62.5	40	960	$746	$3,179	$203						
								60	940	$883	$3,774	$242						
								70	930	$915	$4,072	$261						
								80	920	$951	$4,370	$280						
								90	910	$973	$4,667	$299						
								110	890	$1,007	$5,263	$337						
								120	880	$1,027	$5,561	$356						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	12000	12	16	N/A	N/A	N/A	N/A	0	996	$4,915	$0	-	70	30%	50%	70	30%	50%
				8	22	213.0	150.0	70	930	$1,708	$4,072	$261						
								100	900	$1,988	$4,965	$318						
								130	870	$2,208	$5,858	$375						
								140	860	$2,268	$6,156	$394						
								170	830	$2,433	$7,049	$451						
								210	790	$2,621	$8,240	$527						
								230	770	$2,702	$8,835	$566						
60	12000	18	10	N/A	N/A	N/A	N/A	0	996	$3,987	$0	-	80	30%	40%	80	30%	40%
				8	22	271.1	190.9	80	920	$1,225	$4,370	$280						
								120	880	$1,349	$5,561	$356						
								130	870	$1,388	$5,858	$375						
								160	840	$1,500	$6,751	$432						
								180	820	$1,583	$7,347	$470						
								210	790	$1,691	$8,240	$527						
								260	740	$1,895	$9,728	$623						
								290	710	$2,014	$10,621	$680						
60	12000	18	10	N/A	N/A	N/A	N/A	0	996	$3,987	$0	-	60	30%	40%	60	30%	40%
				12	18	193.6	136.4	60	940	$916	$3,774	$242						
								90	910	$1,132	$4,667	$299						
								100	900	$1,207	$4,965	$318						
								120	880	$1,336	$5,561	$356						
								130	870	$1,394	$5,858	$375						
								150	850	$1,498	$6,454	$413						
								190	810	$1,649	$7,644	$489						
								210	790	$1,726	$8,240	$527						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	12000	24	4	N/A	N/A	N/A	N/A	0	996	$3,485	$0	-	90	30%	40%	90	30%	40%
				8	22	304.3	214.3	90	910	$1,430	$4,667	$299						
								140	860	$1,583	$6,156	$394						
								180	820	$1,613	$7,347	$470						
								200	800	$1,643	$7,942	$508						
								230	770	$1,767	$8,835	$566						
								290	710	$2,013	$10,621	$680						
								320	680	$2,117	$11,515	$737						
60	12000	24	4	N/A	N/A	N/A	N/A	0	996	$3,485	$0	-	70	30%	40%	70	30%	40%
				12	18	243.4	171.4	70	930	$1,117	$4,072	$261						
								110	890	$1,229	$5,263	$337						
								120	880	$1,257	$5,561	$356						
								150	850	$1,295	$6,454	$413						
								160	840	$1,302	$6,751	$432						
								190	810	$1,329	$7,644	$489						
								240	760	$1,511	$9,133	$585						
								260	740	$1,579	$9,728	$623						
60	12000	24	4	N/A	N/A	N/A	N/A	0	996	$3,485	$0	-	50	30%	50%	50	30%	50%
				18	12	152.1	107.1	50	950	$915	$3,477	$223						
								80	920	$1,062	$4,370	$280						
								100	900	$1,193	$4,965	$318						
								110	890	$1,259	$5,263	$337						
								120	880	$1,284	$5,561	$356						
								150	850	$1,343	$6,454	$413						
								170	830	$1,367	$7,049	$451						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	12000	28	0	N/A	N/A	N/A	N/A	0	996	$3,370	$0	-	90	30%	40%	90	30%	40%
				8	22	319.5	225.0	90	910	$1,548	$4,667	$299						
								140	860	$1,583	$6,156	$394						
								150	850	$1,598	$6,454	$413						
								190	810	$1,633	$7,644	$489						
								200	800	$1,644	$7,942	$508						
								240	760	$1,882	$9,133	$585						
								300	700	$2,047	$10,919	$699						
								340	660	$2,186	$12,110	$775						
60	12000	28	0	N/A	N/A	N/A	N/A	0	996	$3,370	$0	-	80	30%	40%	80	30%	40%
				12	18	266.3	187.5	80	920	$1,262	$4,370	$280						
								120	880	$1,297	$5,561	$356						
								130	870	$1,293	$5,858	$375						
								160	840	$1,302	$6,751	$432						
								170	830	$1,304	$7,049	$451						
								200	800	$1,362	$7,942	$508						
								260	740	$1,581	$9,728	$623						
								280	720	$1,648	$10,324	$661						
60	12000	28	0	N/A	N/A	N/A	N/A	0	996	$3,370	$0	-	60	30%	50%	60	30%	50%
				18	12	186.4	131.3	60	940	$1,061	$3,774	$242						
								90	910	$1,112	$4,667	$299						
								110	890	$1,103	$5,263	$337						
								130	870	$1,105	$5,858	$375						
								150	850	$1,109	$6,454	$413						
								180	820	$1,146	$7,347	$470						
								200	800	$1,211	$7,942	$508						
60	12000	28	0	N/A	N/A	N/A	N/A	0	996	$3,370	$0	-	40	40%	50%	40	40%	50%
				24	6	106.5	75.0	40	960	$1,127	$3,179	$203						
								60	940	$1,334	$3,774	$242						
								70	930	$1,383	$4,072	$261						
								80	920	$1,437	$4,370	$280						
								90	910	$1,471	$4,667	$299						
								110	890	$1,522	$5,263	$337						
								120	880	$1,553	$5,561	$356						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	30000	12	16	N/A	N/A	N/A	N/A	0	996	$5,299	$0	-	70	30%	50%	70	30%	50%
				8	22	213.0	150.0	70	930	$1,842	$4,072	$261						
								100	900	$2,144	$4,965	$318						
								130	870	$2,381	$5,858	$375						
								140	860	$2,446	$6,156	$394						
								170	830	$2,624	$7,049	$451						
								210	790	$2,826	$8,240	$527						
								230	770	$2,913	$8,835	$566						
60	30000	18	10	N/A	N/A	N/A	N/A	0	996	$4,300	$0	-	80	30%	40%	80	30%	40%
				8	22	271.1	190.9	80	920	$1,321	$4,370	$280						
								120	880	$1,455	$5,561	$356						
								130	870	$1,497	$5,858	$375						
								160	840	$1,618	$6,751	$432						
								180	820	$1,707	$7,347	$470						
								210	790	$1,824	$8,240	$527						
								260	740	$2,043	$9,728	$623						
								290	710	$2,172	$10,621	$680						
60	30000	18	10	N/A	N/A	N/A	N/A	0	996	$4,300	$0	-	60	30%	40%	60	30%	40%
				12	18	193.6	136.4	60	940	$988	$3,774	$242						
								90	910	$1,221	$4,667	$299						
								100	900	$1,302	$4,965	$318						
								120	880	$1,440	$5,561	$356						
								130	870	$1,503	$5,858	$375						
								150	850	$1,615	$6,454	$413						
								190	810	$1,778	$7,644	$489						
								210	790	$1,861	$8,240	$527						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	30000	24	4	N/A	N/A	N/A	N/A	0	996	$3,758	$0	-	90	30%	40%	90	30%	40%
				8	22	304.3	214.3	90	910	$1,542	$4,667	$299						
								140	860	$1,707	$6,156	$394						
								180	820	$1,739	$7,347	$470						
								200	800	$1,772	$7,942	$508						
								230	770	$1,905	$8,835	$566						
								290	710	$2,171	$10,621	$680						
								320	680	$2,283	$11,515	$737						
60	30000	24	4	N/A	N/A	N/A	N/A	0	996	$3,758	$0	-	70	30%	40%	70	30%	40%
				12	18	243.4	171.4	70	930	$1,204	$4,072	$261						
								110	890	$1,326	$5,263	$337						
								120	880	$1,356	$5,561	$356						
								150	850	$1,396	$6,454	$413						
								160	840	$1,404	$6,751	$432						
								190	810	$1,433	$7,644	$489						
								240	760	$1,629	$9,133	$585						
								260	740	$1,703	$9,728	$623						
60	30000	24	4	N/A	N/A	N/A	N/A	0	996	$3,758	$0	-	50	30%	50%	50	30%	50%
				18	12	152.1	107.1	50	950	$987	$3,477	$223						
								80	920	$1,145	$4,370	$280						
								100	900	$1,286	$4,965	$318						
								110	890	$1,357	$5,263	$337						
								120	880	$1,384	$5,561	$356						
								150	850	$1,448	$6,454	$413						
								170	830	$1,474	$7,049	$451						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
60	30000	28	0	N/A	N/A	N/A	N/A	0	996	$3,634	$0	-	90	30%	40%	90	30%	40%
				8	22	319.5	225.0	90	910	$1,669	$4,667	$299						
								140	860	$1,707	$6,156	$394						
								150	850	$1,723	$6,454	$413						
								190	810	$1,761	$7,644	$489						
								200	800	$1,773	$7,942	$508						
								240	760	$1,942	$9,133	$585						
								300	700	$2,207	$10,919	$699						
								340	660	$2,357	$12,110	$775						
60	30000	28	0	N/A	N/A	N/A	N/A	0	996	$3,634	$0	-	80	30%	40%	80	30%	40%
				12	18	266.3	187.5	80	920	$1,360	$4,370	$280						
								120	880	$1,398	$5,561	$356						
								130	870	$1,394	$5,858	$375						
								160	840	$1,404	$6,751	$432						
								170	830	$1,406	$7,049	$451						
								200	800	$1,469	$7,942	$508						
								260	740	$1,705	$9,728	$623						
								280	720	$1,777	$10,324	$661						
60	30000	28	0	N/A	N/A	N/A	N/A	0	996	$3,634	$0	-	60	30%	50%	60	30%	50%
				18	12	186.4	131.3	60	940	$1,144	$3,774	$242						
								90	910	$1,199	$4,667	$299						
								110	890	$1,190	$5,263	$337						
								130	870	$1,192	$5,858	$375						
								150	850	$1,196	$6,454	$413						
								180	820	$1,236	$7,347	$470						
								200	800	$1,306	$7,942	$508						
60	30000	28	0	N/A	N/A	N/A	N/A	0	996	$3,634	$0	-	40	40%	50%	40	40%	50%
				24	6	106.5	75.0	40	960	$1,215	$3,179	$203						
								60	940	$1,439	$3,774	$242						
								70	930	$1,491	$4,072	$261						
								80	920	$1,550	$4,370	$280						
								90	910	$1,586	$4,667	$299						
								110	890	$1,641	$5,263	$337						
								120	880	$1,674	$5,561	$356						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	6000	12	16	N/A	N/A	N/A	N/A	0	996	$5,502	$0	-	70	30%	40%	70	30%	40%
				8	22	221.5	165.0	70	930	$1,649	$4,072	$261						
								100	900	$1,837	$4,965	$318						
								110	890	$1,850	$5,263	$337						
								130	870	$1,885	$5,858	$375						
								140	860	$1,898	$6,156	$394						
								170	830	$2,018	$7,049	$451						
								220	780	$2,199	$8,538	$547						
								240	760	$2,262	$9,133	$585						
70	6000	18	10	N/A	N/A	N/A	N/A	0	996	$3,920	$0	-	130	50%	60%	130	50%	60%
				8	22	281.9	210.0	80	920	$1,476	$4,370	$280						
								130	870	$1,250	$5,858	$375						
								160	840	$1,305	$6,751	$432						
								180	820	$1,355	$7,347	$470						
								210	790	$1,451	$8,240	$527						
								270	730	$1,522	$10,026	$642						
								300	700	$1,740	$10,919	$699						
70	6000	18	10	N/A	N/A	N/A	N/A	0	996	$3,920	$0	-	100	50%	70%	100	50%	70%
				12	18	201.4	150.0	60	940	$1,346	$3,774	$242						
								100	900	$1,123	$4,965	$318						
								120	880	$1,226	$5,561	$356						
								130	870	$1,277	$5,858	$375						
								160	840	$1,398	$6,751	$432						
								200	800	$1,529	$7,942	$508						
								220	780	$1,582	$8,538	$547						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	6000	24	4	N/A	N/A	N/A	N/A	0	996	$3,507	$0	-	200	60%	80%	180	60%	80%
				8	22	316.4	235.7	90	910	$2,094	$4,667	$299						
								140	860	$1,803	$6,156	$394						
								180	820	$1,492	$7,347	$470						
								200	800	$1,422	$7,942	$508						
								240	760	$1,538	$9,133	$585						
								300	700	$1,741	$10,919	$699						
								330	670	$1,825	$11,812	$756						
70	6000	24	4	N/A	N/A	N/A	N/A	0	996	$3,507	$0	-	190	80%	100%	160	60%	80%
				12	18	253.1	188.6	70	930	$1,801	$4,072	$261						
								120	880	$1,493	$5,561	$356						
								150	850	$1,378	$6,454	$413						
								160	840	$1,325	$6,751	$432						
								190	810	$1,255	$7,644	$489						
								240	760	$1,410	$9,133	$585						
								270	730	$1,490	$10,026	$642						
70	6000	24	4	N/A	N/A	N/A	N/A	0	996	3507	0	-	80	50%	70%	50	30%	40%
				18	12	158.2	117.9	50	950	1196	3476.66	$223						
								80	920	1091	4369.76	$280						
								100	900	1147	4965.16	$318						
								110	890	1179	5262.86	$337						
								130	870	1211	5858.26	$375						
								160	840	1131	6751.36	$432						
								170	830	1105	7049.06	$451						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	6000	28	0	N/A	N/A	N/A	N/A	0	996	$3,314	$0	-	200	60%	80%	200	60%	80%
				8	22	332.3	247.5	90	910	$2,196	$4,667	$299						
								150	850	$1,857	$6,454	$413						
								190	810	$1,516	$7,644	$489						
								200	800	$1,459	$7,942	$508						
								250	750	$1,573	$9,431	$604						
								320	680	$1,799	$11,515	$737						
								350	650	$1,877	$12,408	$794						
70	6000	28	0	N/A	N/A	N/A	N/A	0	996	$3,314	$0	-	170	60%	80%	170	60%	80%
				12	18	276.9	206.3	80	920	$1,988	$4,370	$280						
								130	870	$1,627	$5,858	$375						
								160	840	$1,359	$6,751	$432						
								170	830	$1,306	$7,049	$451						
								210	790	$1,314	$8,240	$527						
								270	730	$1,499	$10,026	$642						
								290	710	$1,544	$10,621	$680						
70	6000	28	0	N/A	N/A	N/A	N/A	0	996	$3,314	$0	-	190	100%	130%	130	70%	90%
				18	12	193.8	144.4	60	940	$1,483	$3,774	$242						
								90	910	$1,333	$4,667	$299						
								110	890	$1,174	$5,263	$337						
								130	870	$1,068	$5,858	$375						
								150	850	$993	$6,454	$413						
								190	810	$992	$7,644	$489						
								210	790	$1,034	$8,240	$527						
70	6000	28	0	N/A	N/A	N/A	N/A	0	996	$3,314	$0	-	130	120%	160%	40	40%	50%
				24	6	110.8	82.5	40	960	$1,256	$3,179	$203						
								60	940	$1,306	$3,774	$242						
								70	930	$1,337	$4,072	$261						
								80	920	$1,334	$4,370	$280						
								90	910	$1,322	$4,667	$299						
								120	880	$1,260	$5,561	$356						
								130	870	$1,231	$5,858	$375						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	12000	12	16	N/A	N/A	N/A	N/A	0	996	$7,635	$0	-	70	30%	40%	70	30%	40%
				8	22	237.5	180.0	70	930	$2,493	$4,072	$261						
								100	900	$2,776	$4,965	$318						
								110	890	$2,796	$5,263	$337						
								130	870	$2,850	$5,858	$375						
								140	860	$2,868	$6,156	$394						
								180	820	$3,104	$7,347	$470						
								230	770	$3,383	$8,835	$566						
								250	750	$3,476	$9,431	$604						
70	12000	18	10	N/A	N/A	N/A	N/A	0	996	$5,924	$0	-	130	40%	60%	130	40%	60%
				8	22	302.3	229.1	80	920	$2,231	$4,370	$280						
								130	870	$1,889	$5,858	$375						
								140	860	$1,909	$6,156	$394						
								160	840	$1,973	$6,751	$432						
								180	820	$2,048	$7,347	$470						
								230	770	$2,293	$8,835	$566						
								290	710	$2,601	$10,621	$680						
								320	680	$2,719	$11,515	$737						
70	12000	18	10	N/A	N/A	N/A	N/A	0	996	$5,924	$0	-	100	50%	60%	60	30%	40%
				12	18	215.9	163.6	60	940	$1,717	$3,774	$242						
								100	900	$1,697	$4,965	$318						
								120	880	$1,854	$5,561	$356						
								130	870	$1,929	$5,858	$375						
								170	830	$2,173	$7,049	$451						
								210	790	$2,363	$8,240	$527						
								230	770	$2,442	$8,835	$566						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	12000	24	4	N/A	N/A	N/A	N/A	0	996	$5,300	$0	-	200	60%	80%	200	60%	80%
				8	22	339.3	257.1	90	910	$3,165	$4,667	$299						
								140	860	$2,725	$6,156	$394						
								150	850	$2,622	$6,454	$413						
								180	820	$2,255	$7,347	$470						
								200	800	$2,149	$7,942	$508						
								250	750	$2,381	$9,431	$604						
								320	680	$2,723	$11,515	$737						
								360	640	$2,872	$12,705	$813						
70	12000	24	4	N/A	N/A	N/A	N/A	0	996	$5,300	$0	-	210	80%	100%	160	60%	80%
				12	18	271.4	205.7	70	930	$2,722	$4,072	$261						
								120	880	$2,256	$5,561	$356						
								130	870	$2,196	$5,858	$375						
								150	850	$2,083	$6,454	$413						
								160	840	$2,003	$6,751	$432						
								210	790	$1,991	$8,240	$527						
								260	740	$2,220	$9,728	$623						
								290	710	$2,337	$10,621	$680						
70	12000	24	4	N/A	N/A	N/A	N/A	0	996	$5,300	$0	-	80	50%	60%	80	50%	60%
				18	12	169.6	128.6	50	950	$1,807	$3,477	$223						
								80	920	$1,648	$4,370	$280						
								100	900	$1,734	$4,965	$318						
								110	890	$1,782	$5,263	$337						
								140	860	$1,777	$6,156	$394						
								170	830	$1,682	$7,049	$451						
								190	810	$1,731	$7,644	$489						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	12000	28	0	N/A	N/A	N/A	N/A	0	996	$5,008	$0	-	200	60%	70%	200	60%	70%
				8	22	356.3	270.0	90	910	$3,319	$4,667	$299						
								150	850	$2,806	$6,454	$413						
								160	840	$2,649	$6,751	$432						
								190	810	$2,291	$7,644	$489						
								200	800	$2,205	$7,942	$508						
								270	730	$2,476	$10,026	$642						
								340	660	$2,807	$12,110	$775						
								370	630	$2,914	$13,003	$832						
70	12000	28	0	N/A	N/A	N/A	N/A	0	996	$5,008	$0	-	170	60%	80%	170	60%	80%
				12	18	296.9	225.0	80	920	$3,005	$4,370	$280						
								130	870	$2,458	$5,858	$375						
								140	860	$2,305	$6,156	$394						
								160	840	$2,058	$6,751	$432						
								170	830	$1,974	$7,049	$451						
								220	780	$2,024	$8,538	$547						
								280	720	$2,303	$10,324	$661						
								310	690	$2,418	$11,217	$718						
70	12000	28	0	N/A	N/A	N/A	N/A	0	996	$5,008	$0	-	160	80%	100%	160	80%	100%
				18	12	207.8	157.5	60	940	$2,241	$3,774	$242						
								90	910	$2,014	$4,667	$299						
								100	900	$1,873	$4,965	$318						
								110	890	$1,775	$5,263	$337						
								130	870	$1,614	$5,858	$375						
								160	840	$1,441	$6,751	$432						
								200	800	$1,546	$7,942	$508						
								220	780	$1,606	$8,538	$547						
70	12000	28	0	N/A	N/A	N/A	N/A	0	996	$5,008	$0	-	140	120%	160%	40	30%	40%
				24	6	118.8	90.0	40	960	$1,899	$3,179	$203						
								60	940	$1,973	$3,774	$242						
								70	930	$2,020	$4,072	$261						
								80	920	$2,017	$4,370	$280						
								100	900	$1,963	$4,965	$318						
								120	880	$1,904	$5,561	$356						
								140	860	$1,818	$6,156	$394						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	30000	12	16	N/A	N/A	N/A	N/A	0	996	$8,233	$0	-	70	30%	40%	70	30%	40%
				8	22	237.5	180.0	70	930	$2,688	$4,072	$261						
								100	900	$2,994	$4,965	$318						
								110	890	$3,015	$5,263	$337						
								130	870	$3,073	$5,858	$375						
								140	860	$3,093	$6,156	$394						
								180	820	$3,346	$7,347	$470						
								230	770	$3,648	$8,835	$566						
								250	750	$3,748	$9,431	$604						
70	30000	18	10	N/A	N/A	N/A	N/A	0	996	$6,388	$0	-	130	40%	60%	130	40%	60%
				8	22	302.3	229.1	80	920	$2,406	$4,370	$280						
								130	870	$2,036	$5,858	$375						
								140	860	$2,059	$6,156	$394						
								160	840	$2,127	$6,751	$432						
								180	820	$2,209	$7,347	$470						
								230	770	$2,472	$8,835	$566						
								290	710	$2,804	$10,621	$680						
								320	680	$2,932	$11,515	$737						
70	30000	18	10	N/A	N/A	N/A	N/A	0	996	$6,388	$0	-	100	50%	60%	60	30%	40%
				12	18	215.9	163.6	60	940	$1,852	$3,774	$242						
								100	900	$1,829	$4,965	$318						
								120	880	$1,999	$5,561	$356						
								130	870	$2,080	$5,858	$375						
								170	830	$2,343	$7,049	$451						
								210	790	$2,548	$8,240	$527						
								230	770	$2,633	$8,835	$566						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	30000	24	4	N/A	N/A	N/A	N/A	0	996	$5,715	$0	-	200	60%	80%	200	60%	80%
				8	22	339.3	257.1	90	910	$3,413	$4,667	$299						
								140	860	$2,938	$6,156	$394						
								150	850	$2,827	$6,454	$413						
								180	820	$2,431	$7,347	$470						
								200	800	$2,318	$7,942	$508						
								250	750	$2,567	$9,431	$604						
								320	680	$2,936	$11,515	$737						
								360	640	$3,096	$12,705	$813						
70	30000	24	4	N/A	N/A	N/A	N/A	0	996	$5,715	$0	-	210	80%	100%	160	60%	80%
				12	18	271.4	205.7	70	930	$2,935	$4,072	$261						
								120	880	$2,433	$5,561	$356						
								130	870	$2,367	$5,858	$375						
								150	850	$2,246	$6,454	$413						
								160	840	$2,160	$6,751	$432						
								210	790	$2,147	$8,240	$527						
								260	740	$2,394	$9,728	$623						
								290	710	$2,520	$10,621	$680						
70	30000	24	4	N/A	N/A	N/A	N/A	0	996	$5,715	$0	-	80	50%	60%	80	50%	60%
				18	12	169.6	128.6	50	950	$1,949	$3,477	$223						
								80	920	$1,777	$4,370	$280						
								100	900	$1,869	$4,965	$318						
								110	890	$1,921	$5,263	$337						
								140	860	$1,916	$6,156	$394						
								170	830	$1,814	$7,049	$451						
								190	810	$1,867	$7,644	$489						

Posted Speed Limit (mph)	ADT	Hazard Offset (ft)	RSAP Hazard Offset (ft)	Guardrail Offset (ft)	RSAP Guardrail Offset (ft)	2006 RDG LON (ft)	2011 RDG LON (ft)	Modeled LON (ft)	Start Station (ft)	Annual Crash Cost	Construction Cost	Annualized Construction Cost	Lowest Crash Cost			Highest Cost-Effectiveness		
													Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG	Guardrail Length, X* (ft)	% 2006 RDG	% 2011 RDG
70	30000	28	0	N/A	N/A	N/A	N/A	0	996	$5,400	$0	-	200	60%	70%	200	60%	70%
				8	22	356.3	270.0	90	910	$3,579	$4,667	$299						
								150	850	$3,026	$6,454	$413						
								160	840	$2,856	$6,751	$432						
								190	810	$2,470	$7,644	$489						
								200	800	$2,377	$7,942	$508						
								270	730	$2,670	$10,026	$642						
								340	660	$3,027	$12,110	$775						
								370	630	$3,142	$13,003	$832						
70	30000	28	0	N/A	N/A	N/A	N/A	0	996	$5,400	$0	-	170	60%	80%	170	60%	80%
				12	18	296.9	225.0	80	920	$3,240	$4,370	$280						
								130	870	$2,651	$5,858	$375						
								140	860	$2,486	$6,156	$394						
								160	840	$2,215	$6,751	$432						
								170	830	$2,128	$7,049	$451						
								220	780	$2,182	$8,538	$547						
								280	720	$2,484	$10,324	$661						
								310	690	$2,607	$11,217	$718						
70	30000	28	0	N/A	N/A	N/A	N/A	0	996	$5,400	$0	-	160	80%	100%	160	80%	100%
				18	12	207.8	157.5	60	940	$2,416	$3,774	$242						
								90	910	$2,172	$4,667	$299						
								100	900	$2,019	$4,965	$318						
								110	890	$1,914	$5,263	$337						
								130	870	$1,740	$5,858	$375						
								160	840	$1,554	$6,751	$432						
								200	800	$1,667	$7,942	$508						
								220	780	$1,731	$8,538	$547						
70	30000	28	0	N/A	N/A	N/A	N/A	0	996	$5,400	$0	-	140	120%	160%	40	30%	40%
				24	6	118.8	90.0	40	960	$2,047	$3,179	$203						
								60	940	$2,128	$3,774	$242						
								70	930	$2,178	$4,072	$261						
								80	920	$2,175	$4,370	$280						
								100	900	$2,116	$4,965	$318						
								120	880	$2,053	$5,561	$356						
								140	860	$1,960	$6,156	$394						

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