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COST-EFFECTIVE SAFETY TREATMENTS FOR LOW-VOLUME ROADS

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16. Abstract (Limit: 200 words)

The majority of roadside safety guidance pertains to high-volume roads. Very little guidance exists to assist engineers in treating common obstacles found alongside low-volume roads. In general, it is assumed that low traffic volumes can effectively mitigate the risks associated with vehicle impacts into fixed objects and other geometric features to a point where they do not significantly increase the accident costs relative to high-volume roads. However, a single crash on a low-volume road may result in a fatality or a severe injury, effectively making low-volume roads competitive in severity scale with high-volume roads. As a result, the possibility of a fatal or severe injury crash needs to be mitigated on low-volume roads.

Common roadside features were observed in a field study and included culverts, trees, slopes, ditches, and bridges. A probability-based encroachment tool, known as the Roadside Safety Analysis Program (RSAP), was used to determine impact frequencies and severities for each feature. Treatment options, like removing the fixed object or installing W-beam guardrail, were considered for each feature. Finally, acceptable ranges in traffic volume were recommended for each safety treatment option. In these recommendations, the "do nothing" option was often considered to be the most cost-effective safety treatment for the existing configuration. However, this was not always the case.

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1 INTRODUCTION

1.1 Problem Statement

In the U.S., there are many local roads, and streets, and even rural roads and highways, with low traffic volumes, which are overrepresented in the total number of fatal and injury accidents when considering the proportion of our nation's traffic traveling on these facilities. The American Association of State Highway Transportation Officials (AASHTO) *Roadside Design Guide* (RDG) is focused primarily on high-speed and high-volume roads and streets, providing limited guidance for low-volume local roads and streets [1]. Much of the guidance provided for low-volume roads was extrapolated from higher-speed and higher-volume guidelines. As a result, these guidelines for the local roads are only loosely based on actual research results. In addition, much of the guidance is not practical for local road applications due to right-of-way and financial constraints [1].

Current methods of determining the cost effectiveness of roadside safety improvement measures are of minimal use in low-volume locations. Typically, no improvement is cost effective on these roads due to the limited opportunities for a crash (i.e., low exposure). Although prior analysis has shown that improvements in general are not cost effective, some low-cost measures should be considered either during maintenance operations or as part of improvement projects that can reduce the consequences of a vehicle leaving the roadway. The AASHTO *Guidelines for Geometric Design of Very Low Volume Local Roads* gives cursory coverage to roadside safety for roads with ADTs less than 400 vehicles per day. In essence, improvements are only recommended where a documentable accident history exists. The very low volumes produce sparsely populated accident histories. As a result, a single serious accident can dramatically affect the apparent need for safety treatment [2].

1.2 Background

In order to address the disproportionately high number of fatalities on traditionally low-volume roadways, transportation agencies need guidelines and recommendations to treat common roadway obstacles. However, very little effort has been directed toward documenting the frequency and nature of roadside obstacles found along very low-volume roads. Without this type of basic data collection, it is impossible to identify the need for safety improvements along these highways and roadways. Treatment options for the low-volume roadway features traditionally have been limited to the installation of guardrail. Other treatment options have included installing delineators, leveling terrain, and adding culvert grates. These options require benefit-to-cost analyses to determine the efficacy of the solutions. This type of analysis may show that, at some locations, it is more cost-effective to eliminate existing protection systems, including guardrail, thus allowing vehicles to traverse the terrain and potentially impact the noted fixed object or geometric feature.

1.3 Objective

The objective of this research study was to develop recommendations for the safety treatment of common features found on roadways with traffic volumes less than 500 vehicles per day (vpd) and posted speed limits of 55 mph (88.5 km/h) or greater with the use of benefit-to-cost analyses for the treatment options.

1.4 Scope

The research objective was achieved by performing several tasks. First, a field investigation was conducted in Kansas and Nebraska to identify common roadside fixed objects and geometric features located along very low-volume roadways. Next, the obstacles, roadside geometries, and potential safety treatment options were tabulated. Utilizing the tabulated data, a benefit-to-cost analysis with the Roadside Safety Analysis Program (RSAP) was conducted to determine the efficacy of each alternative. Finally, conclusions and recommendations were presented based on the results of the benefit-to-cost analyses.

A field investigation was conducted to determine common roadside features, and the results are given in Chapter 2. The process of identifying features to be analyzed for treatment is presented in Chapter 3. A general description of the analysis using RSAP is given in Chapter 4. Analyses for individual safety treatments, procedures for implementing RSAP, and development of road-specific guidelines for each fixed object and geometric feature are presented in Chapters 5 through 9. Methods for identifying conditions meriting further analysis, a summary, and conclusions for each feature are presented at the end of each analysis chapter. Chapter 10 presents conclusions and recommendations.

2 FIELD INVESTIGATION

2.1 Locations

To determine the common fixed objects and geometric features found along very low-volume roadways, two field surveys were undertaken. The first field study was conducted in Marshall County, Kansas. The Kansas Department of Transportation (KDOT) and Marshall County officials identified two continuous stretches of very low-volume roadways. One stretch was 8 miles (12.9 km) long, and the other segment was 13 miles (20.9 km) long. The second field study was conducted in Saunders and Butler counties in Nebraska. Local road officials identified 55 miles (88.5 km) of very low-volume roadways in these counties.

2.2 Field Observations

Numerous roadside obstacles were found during the field investigation, including culverts, bridges, driveways, trees, ditches, slopes, utility poles, and public broadcast service routing stations. These hazards are described in greater detail in the following sections.

2.2.1 Culvert Structures

When roadways span creeks or streams, concrete box culverts are often used to facilitate drainage. During the field investigation, the width of a culvert was measured perpendicular to the roadway, and the length was measured parallel to the roadway. Culvert lengths varied from 9.3 to 20.5 ft (2.8 to 6.2 m). Culverts were typically less than 20 ft (6.1 m) long. Lateral widths of the culverts ranged from 8.25 to 15 in. (210 to 381 mm). Culvert heights ranged from 39.5 to 70 in. (1,003 to 1,778 mm). Measurements of all culverts observed in the field investigation are shown in Table 1. A graphical depiction of the dimensions is given in Figure 1.

Typical culverts were constructed with a concrete headwall extending 3 to 8 in. (76 to 203 mm) above the road surface. Concrete post-and-beam structures were constructed on these headwalls. The concrete posts were typically 6 to 9 in. (152 to 229 mm) wide, 9 to 15 in. (229 to 381 mm) deep, and 20 to 36 in. (508 to 914 mm) tall. The posts were spaced approximately 36 in. (914 mm) on center, with one or two rectangular beams between the posts, as shown in Figure 1. Depths were measured perpendicular to the rail, and widths were measured parallel to the rail. Several of the posts had depths in excess of 12 in. (305 mm), and one set of posts had widths of 15 in. (381 mm). It should be noted that two of the culverts had been damaged. One concrete post fractured and separated from the concrete rail. It was observed that very little reinforcement was utilized between the post and rail connection. Further, the fractured posts had six rectangular-shaped vertical reinforcements.

Some culverts observed in the field study had barriers consisting of wood beams measuring 2-in. x-2-in. (51-mm x 51-mm) on 2-in. x 2-in. by 36-in. (51-mm x 51-mm by 914-mm) wood posts, spaced approximately 4 ft (1.2 m) on center. Other treatments included various sizes of angle-iron and channel sections, typically less than 3 in. (76 mm) in width.

Table 1. Culvert Dimensions Measured During Field Investigation

Culvert Description						Road Profile									
Length		Width		Object Height		Hazard Offset			Shoulder Width		Traveled Width		Road Width	
in	mm	in	mm	in	mm	ft	m	Side (NSEW)	ft	m	ft	m	ft	m
228	5791	8.25	210	64	1626	4.1	1.3	West	4.3	1.3	12	3.7	20.5	6.2
246	6248	9.25	235	70	1778	4.3	1.3	East	4.3	1.3	12	3.7	20.5	6.2
114	2896	15	381	57	1448	5.4	1.7	West	5.4	1.7	10	2.9	24.1	7.3
114	2896	15	381	57	1448	8.9	2.7	East	5.4	1.7	10	2.9	24.1	7.3
111.5	2832	12	305	39.5	1003	5.8	1.8	Both N/S	5.5	1.7	17	5.0	29.3	8.9

2.2.2 Bridges Railings

Several different bridge configurations were observed during the field investigation. Bridge rail systems varied widely from region to region. Three common bridge railing types consisted of the following: (1) an angle-post and rail design; (2) a variation of W-beam guardrail; and (3) a through-truss bridge with steel sections for beams and posts.

The angle-post bridge rail design utilized 3-in. x 3-in. by 20-ft (76-mm x 76-mm by 6.1-m) long steel angles for rails supported by 3-in. x 3-in. by 6-ft (76-mm x 76-mm by 1.8-m) long steel angles for posts. The post spacing measured 3 ft (0.91 m) on center.

The W-beam bridge rail system consisted of rectangular concrete sections with 6-in. wide by 6-in. long by 12-in. tall (152-mm x 152-mm by 305-mm) wooden blockouts. Round head bolts with steel plate washers, measuring 2-in. long x 1-in. wide by 12-gauge thick (51-mm x 25-mm x 2.67-mm) were used to attach the W-beam guardrail to the concrete posts. Resurfacing has caused a reduction in the top rail mounting height for the W-beam bridge rail. A reduction in top rail mounting height has been shown to result in reduced performance of W-beam guardrail systems [3]. In addition, thick grass and shrub growth in front of the approach guardrail prevented effective delineation of the bridge. The bridge dimensions observed in the field study are shown in Table 2. Common bridge rail types are shown in Figure 2.

Table 2. Bridge Dimensions Measured During Field Investigation

Bridge Hazard Description								Road Profile					
Bridge Height		Length		Width		Rail Height		Hazard Offset		Traveled Width		Road Width	
in	mm	in	mm	in	mm	in	mm	ft	m	ft	m	ft	m
204	5182	864	21946	290	7366	N/A	N/A	6.9	2.1	11	3.4	24.2	7.4
139	3531	1698	43129	384	9753.6	N/A	N/A	7.8	2.4	14	4.3	32.0	9.8

2.2.3 Driveways

Driveways are another common obstacle located on very low-volume roadways and are a combination of two features. Parallel drainage was found at the ends of driveways where it connects to the roadway to allow water to drain through the ditch. The complex slope geometries, especially intersecting slopes that form the slope of the driveway, pose a potential concern to motorists. The distance from the road surface to the bottom of the parallel drainage ranged from 3 to 6 ft (0.9 to 1.8 m). Many driveways were lined with decorative rocks, railroad ties, concrete blocks, or support beams. The driveways were usually perpendicular to the travel way, and the embankments on the sides of the driveways were often steep. The driveway dimensions observed during the field study are shown in Table 3. Several driveways observed during the field investigation are shown in Figure 3. Unlike culverts, the length of the driveway was measured perpendicular to the road, whereas, the width was measured parallel to the road.

Table 3. Driveway Dimensions Measured During Field Investigation

Driveway Description						Road Profile								
Length		Width		Ditch Depth		Hazard Offset			Shoulder Width		Traveled Width		Road Width	
in	mm	in	mm	in	mm	ft	m	Side (NSEW)	ft	m	ft	m	ft	m
309	7849	120	3048	-53	-1346	10.0	3.0	North	5.0	1.5	15	4.6	25.8	7.8
372	9449	206	5232	-54	-1372	16.0	4.9	South	7.0	2.1	12	3.7	35.0	10.7

2.2.4 Trees

Trees were also documented during the field investigation. A typical tree had a diameter of 42 in. (1,067 mm). Another common configuration was a cluster of trees, which could be as large as 84 in. long x 54 in. wide (2,134 mm by 1,372 mm). Two examples of tree measurements observed in the field investigation are provided in Table 4 for a discrete and continuous fixed object. Examples of trees observed in the field study are shown in Figure 4.

Table 4. Tree Dimensions Measured During Field Investigation

Tree Description						Road Profile								
Length		Width		Diameter		Hazard Offset			Shoulder Width		Traveled Width		Road Width	
in	mm	in	mm	in	mm	ft	m	Side (NSEW)	ft	m	ft	m	ft	m
N/A	N/A	N/A	N/A	42	1067	8.5	2.6	West	4.3	1.3	12	3.7	20.5	6.2
54	1372	84	2134	N/A	N/A	16.5	5.0	East	5.4	1.7	10	3.0	24.1	7.3

2.2.5 Slopes and Ditches

Another commonly-observed geometric feature found along very low-volume roads was sloped terrain. A total of 13 slopes were measured in the field study. Slope rates varied from 0.8H:1V to 2H:1V. Slopes flatter than 2H:1V were not recorded nor measured. Depths of the slopes ranged from 7 to 10 ft (2.1 to 3.0 m), and many slopes were often more than 100 ft (30.5 m) long. Slope measurements gathered in the field study are shown in Table 5. Photographs and typical roadside slope configurations are shown in Figure 5.

2.2.6 Utility Poles

Utility poles are another fixed object located along very low-volume roads. Typical utility poles had an 8 in. (203 mm) diameter and were located 17 ft (5.3 m) laterally away from the traveled way. Dimensions observed in the field study are shown in Table 6 for a typical roadside utility pole. Examples of utility poles observed in the field study are shown in Figure 6.

2.2.7 Public Broadcast Service Routing Stations

Public broadcast service routing stations were also located near the roadway on low-volume roads. A typical routing station measured 6 ft-6 in. long x 6 ft wide by 5 ft tall (2.0 m x

1.8 m x 1.5 m) and was located 19 ft (5.9 m) from the edge of the roadway. The stations were also surrounded by steel pipe frame fences. Dimensions observed in the field study are shown in Table 7 for a typical public broadcast service routing station. Examples of the routing stations observed in the field study are shown in Figure 7.

2.3 Additional Obstacles

Additional obstacles were observed in the field investigation, including road signs, advertising signs, mailboxes, tree stumps, bushes, rock walls, boulders, and bodies of water. However, these obstacles were either infrequently observed or posed little risk to motorists.

Table 5. Slope Cross-Section Dimensions Measured During Field Investigation

Dimensions									Road Profile			
Length		Width		Height		Slope Rate			Lane Width at Hazard		Hazard Offset	
ft	m	in	mm	in	mm	Control Length	Control Height	Resulting Slope Rate	ft	m	ft	m
200	61	128	3251	63	1600	48	24	2.0 : 1	16.0	4.9	4.5	1.4
600	183	420	10668	360	9144	92	48	1.9 : 1	21.1	6.4	5.3	1.6
120	37	206	5232	110	2791	90	48	1.9 : 1	30.0	9.1	10.8	3.3
100	30	158	4013	90	2293	84	48	1.8 : 1	20.0	6.1	7.0	2.1
500	152	104	2642	59	1509	84	48	1.8 : 1	21.7	6.6	30.1	9.2
50	15	146	3708	91	2312	77	48	1.6 : 1	19.2	5.8	8.3	2.5
75	23	132	3353	82	2090	77	48	1.6 : 1	21.7	6.6	30.1	9.2
85	26	182	4623	156	3962	76	48	1.6 : 1	16.9	5.2	23.2	7.1
150	46	360	9144	237	6012	73	48	1.5 : 1	30.0	9.1	0.0	0.0
150	46	168	4267	112	2845	72	48	1.5 : 1	22.7	6.9	4.8	1.4
75	23	156	3962	115	2926	65	48	1.4 : 1	21.0	6.4	6.3	1.9
200	61	120	3048	91	2322	63	48	1.3 : 1	19.3	5.9	6.5	2.0
150	46	231	5867	185	4694	60	48	1.3 : 1	22.7	6.9	4.0	1.2
50	15	300	7620	360	9144	40	48	0.8 : 1	21.0	6.4	0.0	0.0

Table 6. Typical Utility Pole Dimensions Measured During Field Investigation

Utility Pole Description				Road Profile								
Diameter		Object Height		Hazard Offset			Shoulder Width		Traveled Width		Road Width	
in	mm	in	mm	ft	m	Side (NSEW)	ft	m	ft	m	ft	m
8	203	Unk	Unk	17.3	5.3	West	3.7	1.1	15	4.7	25.0	7.6

Table 7. Typical Public Broadcast Service Routing Station Dimensions

Routing Station Description						Road Profile								
Length		Width		Object Height		Hazard Offset			Shoulder Width		Traveled Width		Road Width	
in	mm	in	mm	in	mm	ft	m	Side (NSEW)	ft	m	ft	m	ft	m
77	1956	72	1829	60	1524	19.4	5.9	West	3.9	1.2	15	4.5	24.0	7.3

Figure 1. Concrete Box Culvert Examples

Figure 2. Bridge Railing Examples

Figure 3 Driveway Examples

Figure 4. Tree Layout Examples

Figure 5. Roadside Slope Examples

Figure 6. Utility Pole Examples

Figure 7. Public Broadcast Service Routing Station Examples

3 OBSTACLE SELECTION

The obstacles were ranked by their number of observations in the field investigation, lateral offset from the roadway, and their estimated severity. Recall the common obstacles were culverts, trees, slopes, ditches, bridges, mailboxes, driveways, utility poles, and public communication centers. By this ranking method, the obstacle with the greatest opportunity for safety improvement involved a culvert structure. The next three common features in ranking order were (1) trees, (2) slopes and ditches, and (3) bridges.

Culverts varied in size, shape, and type of culvert opening. For example, one culvert was a small pipe set in the center of a rock wall, and another was a box culvert with a concrete post-and-rail system. Severity of these obstacles may be largely influenced by impacts with the concrete post-and-rail barrier. Due to their common occurrence and their potential to impart injury to occupants in errant vehicles, culverts were selected as one of the fixed objects to be included in the benefit-to-cost analysis.

Trees also vary in size and were observed with high frequency in the field investigation. Tree rigidity poses undue risk to errant motorists. Unlike culverts, trees can be found almost anywhere along the road, which effectively increases their severity by increasing exposure. Since trees increase in size over time, they may not pose a risk to errant motorists early in their life but may become a risk to an errant motorist once they've grown to an appreciable size. Furthermore, data collected by the Fatality Accident Reporting System (FARS) from years 1990 through 1999 indicated that impacts with trees were responsible for nearly 30 percent of the fatalities occurring on very low-volume roads [4]. Therefore, trees were also selected as one of the obstacles to be included in the benefit-to-cost analysis.

The variety in drop heights and slope rates make roadside slopes another common geometric roadside feature located on low-volume roads [5]. Since the observed slopes typically did not have rigid or hazardous obstacles, the greatest risk to motorists was rollover down a steep incline. The risk increased when the roadways were curved and/or not properly illuminated or delineated. Therefore, slopes were selected as one of the obstacles to be included in the benefit-to-cost analysis. Ditches were also included due to the risks associated with vehicle impacts into backslopes.

Many bridges on low-volume roads are old, and safety treatments typically do not satisfy safety performance criteria of the National Cooperative Highway Research Program (NCHRP) Report No. 350 [6]. Furthermore, due to the cost of replacing a bridge rail system, it is often preferred to wait until the rail is damaged. Since an impact with the bridge rail and the possibility of vehicle override or underride poses undue risk to an errant vehicle, bridges require analysis for implementing a safety improvement. Therefore, bridges were selected to be included in the benefit-to-cost analysis.

Safety treatments for mailboxes found on the roadside has been discussed in detail in previous reports [6]. Driveways were commonly observed in the field study; however, previous research on driveway treatments indicated that it is unfeasible to alter the driveway geometry to protect motorists. [7-9]. Utility poles and public communication centers were often located outside of the clear zone of low-volume roadways. Thus, and according to the 2003 AASHTO RDG [1], safety treatment is not necessary unless shown through the analysis of crash history. Therefore, mailboxes, driveways, utility poles, and public communication centers were not included in the benefit-to-cost analyses.

4 RSAP ANALYSIS

4.1 Overview of the Approach

The research described herein attempted to utilize a benefit-to-cost analysis procedure to develop general guidelines for the safety treatment of common obstacles found along low-volume roads. The primary goal of this research was to identify the most appropriate safety treatment option based on roadway and obstacle geometry and traffic characteristics. The first step involved choosing the obstacles to be analyzed and determining typical obstacle geometries that would reflect a large number of obstacles found along low-volume roadways. Next, safety treatment options were identified as well as the relevant treatment option parameters, such as safety treatment layout, construction costs, and accident severities. Next, the roadway, roadside, and traffic characteristics for very low-volume roadways were identified. A set of detailed highway scenarios for each hazard were configured for the benefit-to-cost analyses.

RSAP was used to analyze each highway scenario under a variety of roadway and traffic characteristics. These RSAP runs were then tabulated to determine specific locations and obstacle geometries, which required various safety treatment options. Recommendations for obstacle treatment on very low-volume roadways were developed as a function of road width.

4.2 Discrepancy in RSAP

The original analyses concluded that nearly every scenario required treatment of some form, regardless of the traffic volume, lateral offset, or any other characterizing parameter. This was contrary to logic, which holds that on low-volume roads, with large lateral offsets, the small probability of a crash event reduces the benefit-to-cost ratio for any treatment option below a pre-determined threshold. After verifying that all roadway parameters were correctly entered through the RSAP user interface, a deeper investigation was carried out. The interface was added to RSAP after the initial program was released. This interface conveniently creates the data files needed to run the RSAP executable program. Therefore, the interface was bypassed, and the data files were inspected in combination with the fixed-format FORTRAN code. It was discovered that functional class codes were incorrect. The original analyses were modeled with a freeway, which utilizes a significantly different speed and angle distribution when estimating the severity index of any given fixed object or geometric feature.

4.3 Modified and Re-simulated Results

The original analyses incorrectly used a freeway classification instead of a rural local highway classification in the models. As a result, the severity indexes were higher than they should have been. One solution to this problem would have been to replace the incorrect functional class codes with the code that corresponds to rural local highways. However, the effort to re-simulate all of the scenarios would have required a great deal of time and would have been superfluous because many of the severity indexes were much larger than 2 or 4 (e.g., some ratios for trees exceeded 100).

Instead, a small simulation matrix was created and run for each of the commonly-observed roadside features contained in this report. From that re-simulation effort, an estimated reduction in benefit-to-cost ratios was determined. Then, the original ratios were reduced accordingly. For scenarios where the benefit-to-cost ratio fell below the threshold (either 2 or 4), that scenario was flagged. Each flagged scenario was re-simulated with the correct functional class code. This process lead to logical recommendations for each of the studied features.

4.4 Required Changes to RSAP

The original analyses used a freeway classification to model rural local highways due to an error in the computer code of the RSAP user interface. This user interface conveniently generates all of the data files that are necessary for RSAP to run. One of these files is called "road.dat," which contains parameters to model the roadway, such as functional class, number of lanes, lane width, speed limit, segment length, as well as curve and grade information. The functional class was determined by a two-digit number, which was then used by the computer program to determine the speed and angle of the vehicle encroachment. The speed and angle distributions for the freeway and rural local highway classifications are given in Table 8.

Table 8. Speed-Angle Distributions Used by RSAP – (a) Freeway and (b) Rural Local

	Freeway		Speed (km/h)						
			8	24	40	56	72	88	115
(a)	Angle (Degrees)	2.5	0.0002	0.0049	0.0151	0.0215	0.0205	0.0152	0.02
		7.5	0.0005	0.0119	0.0364	0.0519	0.0494	0.0367	0.0484
		12.5	0.0005	0.0118	0.0359	0.0513	0.0488	0.0362	0.0478
		17.5	0.0003	0.0088	0.0268	0.0382	0.0364	0.027	0.0356
		22.5	0.0002	0.0057	0.0174	0.0248	0.0236	0.0176	0.0231
		27.5	0.0001	0.0034	0.0104	0.0149	0.0142	0.0105	0.0139
		32.5	0.0002	0.0042	0.0127	0.0181	0.0173	0.0128	0.0169

	Rural Local		Speed (km/h)						
			8	24	40	56	72	88	115
(b)	Angle (Degrees)	2.5	0.007	0.0364	0.0446	0.0315	0.0169	0.0077	0.005
		7.5	0.0109	0.0568	0.0696	0.0493	0.0265	0.0121	0.0078
		12.5	0.0094	0.049	0.0601	0.0425	0.0228	0.0104	0.0067
		17.5	0.0069	0.036	0.0441	0.0312	0.0168	0.0077	0.0049
		22.5	0.0047	0.0245	0.03	0.0212	0.0114	0.0052	0.0034
		27.5	0.003	0.0159	0.0195	0.0138	0.0074	0.0034	0.0022
		32.5	0.0049	0.0253	0.031	0.0219	0.0118	0.0054	0.0035

The values in the preceding table represented probabilities of a vehicle experiencing the given speed and angle combination. For example, the probability was 0.0169 at 71.5 mph (115 km/h) and 32.5 degrees for a freeway. In contrast, the probability was only 0.0035 for a rural local highway. These probabilities were highlighted in Table 8. The difference between these two probabilities is an order of magnitude. However, the original analyses used the higher probabilities from the freeway classification to model rural local highways, which from Table 8 should be significantly lower.

To fix this problem, the functional class code in the “road.dat” file may need to be adjusted. For completeness, the old codes generated by the user interface are shown in column 2 of Table 9 for five common functional class/land usage combinations. The new or correct codes are shown in column 3. In particular, the old code for a rural local highway corresponds to the correct code for a freeway, which if not corrected, could produce false results. From Table 9, the user interface correctly models the rural arterial highway classification, but incorrectly models all other functional classifications. Therefore, it is recommended that for any future RSAP projects using version 2003.04.01 (or any version that may utilize the user interface), the functional class codes should be checked and adjusted according to the information presented in Table 9.

Table 9. Functional Class Codes for "road.dat"

Functional Class	Old Code	New Code
Freeway	22	21
Urban Arterial	25	12
Urban Local	24	15
Rural Arterial	22	22
Rural Local	21	25

5 CULVERT TREATMENTS

5.1 Introduction

Culverts are one of the most common roadside fixed objects located along low-volume roads. Safety treatments for culverts and any other drainage feature (e.g., drainage channels, pipes, and drop inlets) found along low-volume roads have traditionally consisted of field-constructed barriers or hazard indicators, such as delineators and object markers. Historical barriers constructed on top of culvert headwalls have varied greatly and include wood post-and-beam designs, angle-iron systems, and concrete post-and-beam configurations. However, many of the barrier designs are not crashworthy and pose a greater risk to errant vehicles than the culvert opening which the barrier was intended to shield. Smaller rails, constructed from wood or small angle-iron sections, are too weak to prevent vehicles from passing over or penetrating through the barriers, and thus are essentially no safer than omitting the culvert rail completely. In fact, the potential for those rails to penetrate the vehicle compartment may make them even more severe than the unprotected culvert opening and vertical drop off.

Many box-type culvert systems have also incorporated a rigid, concrete post-and-beam protection systems attached to the headwall, as shown in Figure 1. Therefore, benefit-to-cost analyses was undertaken to determine what safety treatment, if any, would pose a significant improvement over the concrete post-and-beam barrier systems used on box culverts.

5.2 Modeling Procedure

For the RSAP modeling effort, culvert shapes and sizes were determined from the field investigation. Following the development of the culvert geometry, hazardous features on the culvert were identified and matched to the corresponding features available in RSAP.

5.2.1 Culvert Details

Culverts with concrete posts attached to the top of the headwall varied between 9.3 ft and 20.5 ft (2.8 m and 6.2 m) long. The depths of the culverts, as measured from the top mid-point of the headwall to the ground below the travel way, varied between 3.3 ft (0.99 m) and 5.8 ft (1.78 m) deep. Additional culverts observed in the Nebraska field study had depths greater than 10 ft (3.0 m). It was also found that the bottom of the creeks and streams in the culverts were located more than 15 ft (4.6 m) below the road surface.

It was necessary to simulate the culvert with a vertical drop-off behind the culvert headwall, as was prevalent in the field investigation. The pre-defined object classification of a type-C culvert, as shown in Figure 8, had a severity that was only slightly higher than the severity of a slope with a vertical drop-off. Since the culverts were to be evaluated on road geometries with side slopes, inclusion of slopes in the culvert analysis was desired. Because the severity index (SI) values were close for vertical drop offs, the error associated with using vertical drop offs was negligible.

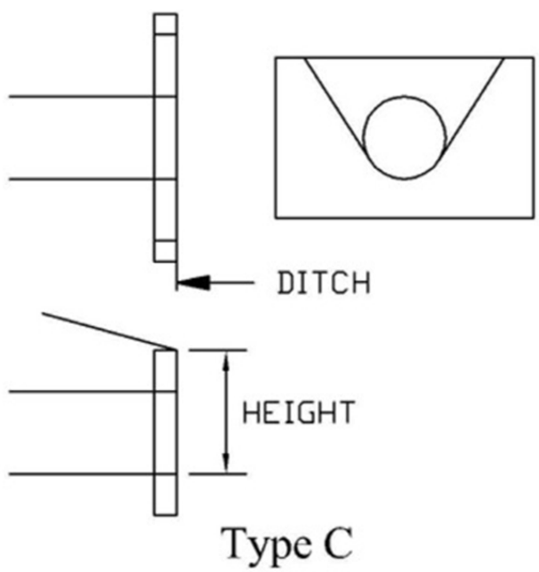


Figure 8. Type-C Culvert Used in RSAP

In RSAP, culverts and vertical foreslope drops are modeled by specifying a lateral offset from the edge of the travel way to the obstacle. Essentially, the fixed object was a line running parallel to the roadway. The probability of a vehicular crash would be almost zero because it would require a steep approach angle. Due to the narrow profile of the road, a steep impact angle was unlikely. Instead of using RSAP's default culvert or vertical foreslope models, intersecting slopes were chosen. Within the intersecting slopes category, vertical drop-offs were used to model the ground or creek for which the culvert was spanned. Steep foreslopes were also common on low-volume roads. As a result, the land adjacent to the road leading up to the modeled culvert was configured with a 2H:1V or 1.5H:1V foreslope extending laterally from the closest offset of the intersecting slope to the farthest edge. This model was continued on the upstream side of the intersecting slopes as well. A backslope was included beyond the foreslope to replicate a common ditch configuration found along low-volume roads.

The selected predefined culvert depths for drop-offs were 1, 3, 7, and 13 ft, (0.3, 1, 2, and 3 m) deep, which were the smallest four drop heights available in RSAP. Although it was desired to have results at the 5 and 10 ft (1.5 and 3.0 m) heights, it would have required interpolation between the provided heights to generate representative impact severities. Since the actual severities of these larger drop heights are unknown, the predefined heights provided in the RSAP module were utilized.

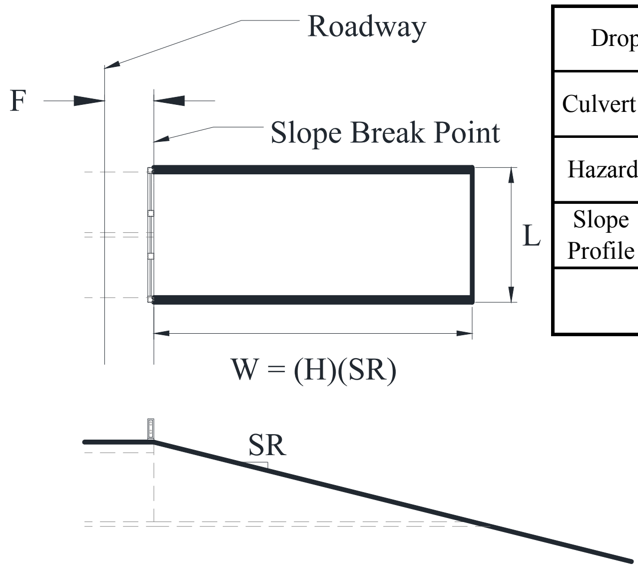
A critical aspect of the culvert modeling was the concrete posts attached to the top of the concrete headwall. The concrete posts were very rigid and were typically larger than 6 in. by 9 in. (152 mm by 229 mm). The post was oriented such that the shorter side was parallel with the roadway. Small concrete rails, measuring 3 in. tall x 2 in. deep (76 mm x 51 mm) and 2 to 3 ft (0.6 to 0.9 m) in length, spanned between the posts. Since these small concrete rails lack the ability to redirect impacting vehicles, the simulated fixed object essentially consisted of a series of 3-ft (0.9-m) tall rigid concrete posts attached to the edge of the culvert. Low-angle impacts on the barrier system were believed to be more severe than high-angle impacts due to propensity for rails to spear into the occupant compartment and longitudinally stiffen and strengthen multiple posts placed in a row. Therefore, a conservative approximation was used to model the concrete support posts.

RSAP's predefined rigid rectangular object was used to model a rectangular concrete post. The representative post size was selected to be a 1.5-ft wide by 3-ft tall (0.5-m by 1-m) fixed object. Even though this predefined post had dimensions greater than most of the posts observed during the field investigation, it was the smallest available predefined rectangular object. As a result, the severities were based on a larger object which would overestimate the post severity by a small amount. This conservative approach would place a small emphasis on using more crashworthy designs or doing away with the existing configurations.

Culverts were modeled using the dimensions observed in the field investigation. Five culvert lengths and four culvert heights (drop-offs) were chosen for the analysis. A representative culvert with primary dimensions used in the analysis is shown in Figure 9.

5.2.2 Road Simulation

As stated previously, road dimensions were documented at each culvert location during the field investigation. Typical road widths were 24 ft (8.3 m). However, some roadways had widths less than 20 ft (6.1 m), and in Nebraska, several roads were only 15 ft (4.6 m) wide. Roads less than 24 ft (8.3 m) wide did not have clearly defined lane widths. The tire tracks overlapped in the center of the roadway, indicating vehicles tend to drive closer to the center of the road than the shoulder. Due to low traffic volumes on these roads over the course of a day, driving in the center of the road often occurs for long distances. When two vehicles approach from opposite directions, the drivers are forced to enter what is effectively the true lane width of the roadway. Therefore, the lane width feature in RSAP was defined by taking the documented road width and dividing by 2.



Drop-Off		ft (m)	H	1, 3, 7, 13 (0.3, 1, 2, 4)
Culvert Length		ft (m)	L	4, 6, 8, 10, 12 (1.2, 1.8, 2.4, 3.0, 3.7)
Hazard Offset		ft (m)	F	2, 3, 4, 5, 6 (0.6, 0.9, 1.2, 1.5, 1.8)
Slope Profile	Long Slope		SR	Flat, 8:1, 6:1, 4:1, 3:1, 2:1, 1.5:1
	Ditch			1.5:1 and -1.5:1, 2:1 and -2:1
ADT				50, 100, 150, 200, 250, 300, 350, 400, 450, 500

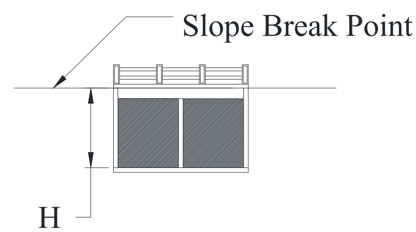


Figure 9. Representative Culvert and Primary Dimensions

It was important to have realistic road geometry. However, the RSAP module was based on data derived from accidents on roadways with typical lane widths of 12 ft (3.7 m) or greater. Therefore, for roadways with widths greater than 24 ft (8.3 m), the road geometry was approximated by holding the lane width constant at 12 ft (4.2 m) and offsetting the culvert and slopes. The offset values were determined based on the actual road width, as shown in Equation 1.

$$\text{lateral offset} = \frac{\text{road width}}{2} - \text{lane width} \tag{1}$$

The use of lateral offsets to separate the road and the culvert had realistic implications. Roadside impact frequency decreases with increased lateral offsets. By increasing the lateral offset, the potential impact with the culvert was reduced. This correlates with physical observations of tire tracks near culverts, which were observed to steer away from steeper drop-offs. When road widths were greater, the culvert bottlenecking effect was reduced, indicating a reduced perception of the culvert. When two vehicles approach a culvert, the drivers may slow down to safely traverse the feature. This further reduces the severity at culvert locations. Furthermore, increased lateral distance between the vehicle and the culverts increased the reaction time for errant motorists. Therefore, this modification was believed to be the most accurate method of simulating larger lane widths.

Most roadways included in the field study had a gravel or crushed limestone surface. The shoulders of the roadways occasionally had vegetation growth and/or gravel piles caused by road graders. Furthermore, the shoulders of the roadways were generally sloped at a rate of 6H:1V to 4H:1V. The shoulder slope was believed to have an effect on errant drivers. However, in order to minimize the number of iterations required to complete the culvert analysis, variations in culvert approach slopes were not added to the model. Shoulder slopes were set at 6H:1V in all RSAP simulations.

5.2.3 Side Slope Details

An important consideration when modeling culverts was the definition of side slopes, commonly referred to as fill slopes or foreslopes. The severity of the side slope varied based on slope rates, which may increase rollover propensity. Side slopes may have slope rates steeper than 1.5H:1V and may have widths greater than 50 ft (15.2 m). Although evaluations of roadside slopes were not the objective of the culvert treatment analysis, it was important to consider the slopes and how each slope may contribute to the culvert safety.

A total of seven different slopes were considered, including 1.5H:1V, 2H:1V, 3H:1V, 4H:1V, 6H:1V, and 8H:1V as well as flat terrain. Since only culvert treatments were addressed in this phase of the study, no safety treatments were considered to shield the vehicle from the side slopes. To further prevent the analysis matrix from becoming too large, an effort was made to be consistent in modeling slopes. To ensure consistency, a constant slope width was evaluated to ensure that the severity of each slope was based on roadside geometry. Therefore, only the depth of the vertical drop was adjusted within each segment length.

In order to determine the most appropriate slope width, the various slopes were plotted against culvert drop heights, as shown in Figure 10. Based on the maximum culvert depth of 13 ft (4.0 m), the slope width was chosen such that a 4H:1V slope was analyzed. The intersection of a 6H:1V slope with the maximum culvert depth was well beyond the lateral distance that could be possible for some right-of-way widths observed in the field investigation. Therefore, the slope widths for all slopes was set to 52 ft (15.9 m) to capture the longest option but to minimize the excessive distance behind the clear zone. In addition, RSAP used a cubic polynomial to determine the probability of lateral extent. The coefficients used in the polynomial provided positive probabilities at lateral offsets less than 18 ft (5.5 m). Beyond this offset, the calculated probability was negative, and the program adjusted that probability to zero. Therefore, even though the slopes were extended out to 52 ft (15.9 m), only the first 18 ft (5.5 m) were useful in the analysis. This range still fell within the clear zone of the roadway, which was generally between 12 and 18 ft (3.7 and 5.5 m). The fact that the probability of lateral extent was governed by the same algorithm permits consistency between all of the scenarios. The slopes and culvert depths are shown in Figure 10.

Culvert depths were treated as intersecting slopes with constant depth. As a result, the intersecting slope depths were incrementally stepped down to match the approximate depth from the sloped ground to the bottom of the culvert at a lateral location away from the roadway, as shown in Figure 10. Three steps were used to accurately capture the behavior of the sloped terrain as the distance from the road increased. This decision was based on the assumption that culverts are built up to span the body of water, rather than spanning a small canyon, which would maintain a constant depth away from the road. Drop-off dimensions for the constant slope configurations are shown in Figure 10 and Table 10.

Culverts with ditches were addressed differently than culverts with constant slopes, as shown in Figure 11. Many ditches observed in the field study were narrower than 10 ft (3.0 m) and did not require special consideration for culvert treatment options. After conducting a preliminary benefit-to-cost analyses on the culverts with shallow depths, it was determined that minimal consideration should be given to ditches with depths less than 3 ft (0.9 m). Ditches were evaluated with slopes of 1.5H:1V and 2H:1V and at depths of 7 ft and 13 ft (2 m and 4 m).

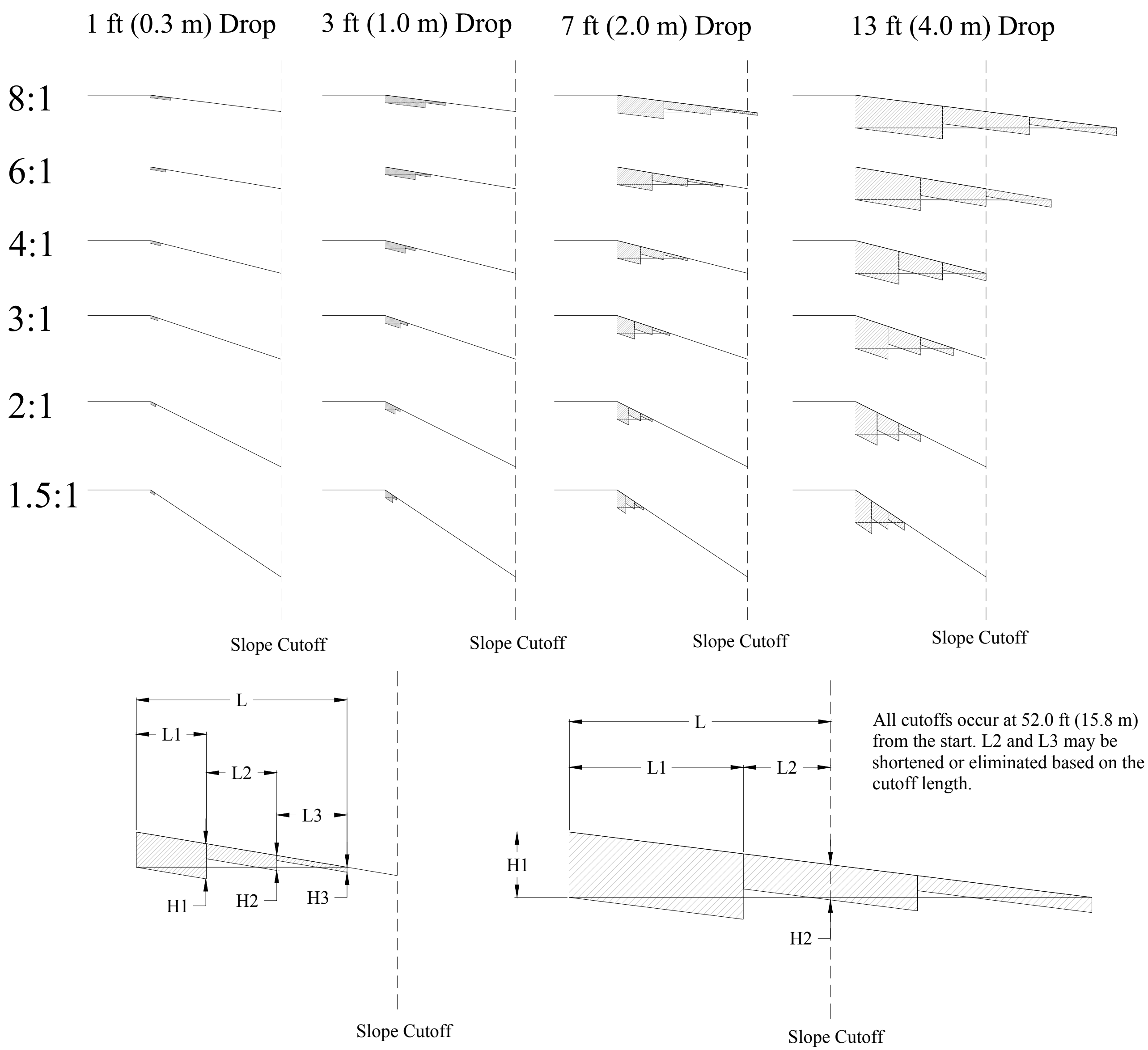


Figure 10. Long Slope Modeling Dimensions and Drop-Off Heights Simulated

Table 10. Drop-Off Stage Dimensions for Culverts Located on Constant Slopes

Drop-Off (H1)		Slope Profile	Slope Width (L)		First Stage Width (L1)		Second Stage Start		Second Stage Width (L2)		Third Stage Start		Third Stage Width (L3)	
ft	m	(L/H1)	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m
1	0.3	None	52	15.8	52	15.8	-	-	-	-	-	-	-	-
1	0.3	8	8.0	2.4	8.0	2.4	-	-	-	-	-	-	-	-
1	0.3	6	6.0	1.8	6.0	1.8	-	-	-	-	-	-	-	-
1	0.3	4	4.0	1.2	4.0	1.2	-	-	-	-	-	-	-	-
1	0.3	3	3.0	0.9	3.0	0.9	-	-	-	-	-	-	-	-
1	0.3	2	2.0	0.6	2.0	0.6	-	-	-	-	-	-	-	-
1	0.3	1.5	1.5	0.5	1.5	0.5	-	-	-	-	-	-	-	-
3	0.9	None	52	15.8	52	15.8	-	-	-	-	-	-	-	-
3	0.9	8	24.0	7.3	16.0	4.9	16.0	4.9	8.0	2.4	-	-	-	-
3	0.9	6	18.0	5.5	12.0	3.7	12.0	3.7	6.0	1.8	-	-	-	-
3	0.9	4	12.0	3.7	8.0	2.4	8.0	2.4	4.0	1.2	-	-	-	-
3	0.9	3	9.0	2.7	6.0	1.8	6.0	1.8	3.0	0.9	-	-	-	-
3	0.9	2	6.0	1.8	4.0	1.2	4.0	1.2	2.0	0.6	-	-	-	-
3	0.9	1.5	4.5	1.4	3.0	0.9	3.0	0.9	1.5	0.5	-	-	-	-
7	2.1	None	52	15.8	52	15.8	-	-	-	-	-	-	-	-
7	2.1	8	52.0	15.8	18.7	5.7	18.7	5.7	18.7	5.7	37.3	11.4	14.7	4.5
7	2.1	6	42.0	12.8	14.0	4.3	14.0	4.3	14.0	4.3	28.0	8.5	14.0	4.3
7	2.1	4	28.0	8.5	9.3	2.8	9.3	2.8	9.3	2.8	18.7	5.7	9.3	2.8
7	2.1	3	21.0	6.4	7.0	2.1	7.0	2.1	7.0	2.1	14.0	4.3	7.0	2.1
7	2.1	2	14.0	4.3	4.7	1.4	4.7	1.4	4.7	1.4	9.3	2.8	4.7	1.4
7	2.1	1.5	10.5	3.2	3.5	1.1	3.5	1.1	3.5	1.1	7.0	2.1	3.5	1.1
13	4.0	None	52	15.8	52	15.8	-	-	-	-	-	-	-	
13	4.0	8	52.0	15.8	34.7	10.6	34.7	10.6	17.3	5.3	-	-	-	
13	4.0	6	52.0	15.8	26.0	7.9	26.0	7.9	26.0	7.9	52.0	15.8	0.0	0.0
13	4.0	4	52.0	15.8	17.3	5.3	17.3	5.3	17.3	5.3	34.7	10.6	17.3	5.3
13	4.0	3	39.0	11.9	13.0	4.0	13.0	4.0	13.0	4.0	26.0	7.9	13.0	4.0
13	4.0	2	26.0	7.9	8.7	2.6	8.7	2.6	8.7	2.6	17.3	5.3	8.7	2.6
13	4.0	1.5	19.5	5.9	6.5	2.0	6.5	2.0	6.5	2.0	13.0	4.0	6.5	2.0

Note, stage starting locations must be added to the hazard offset for the lateral distance to edge of road.

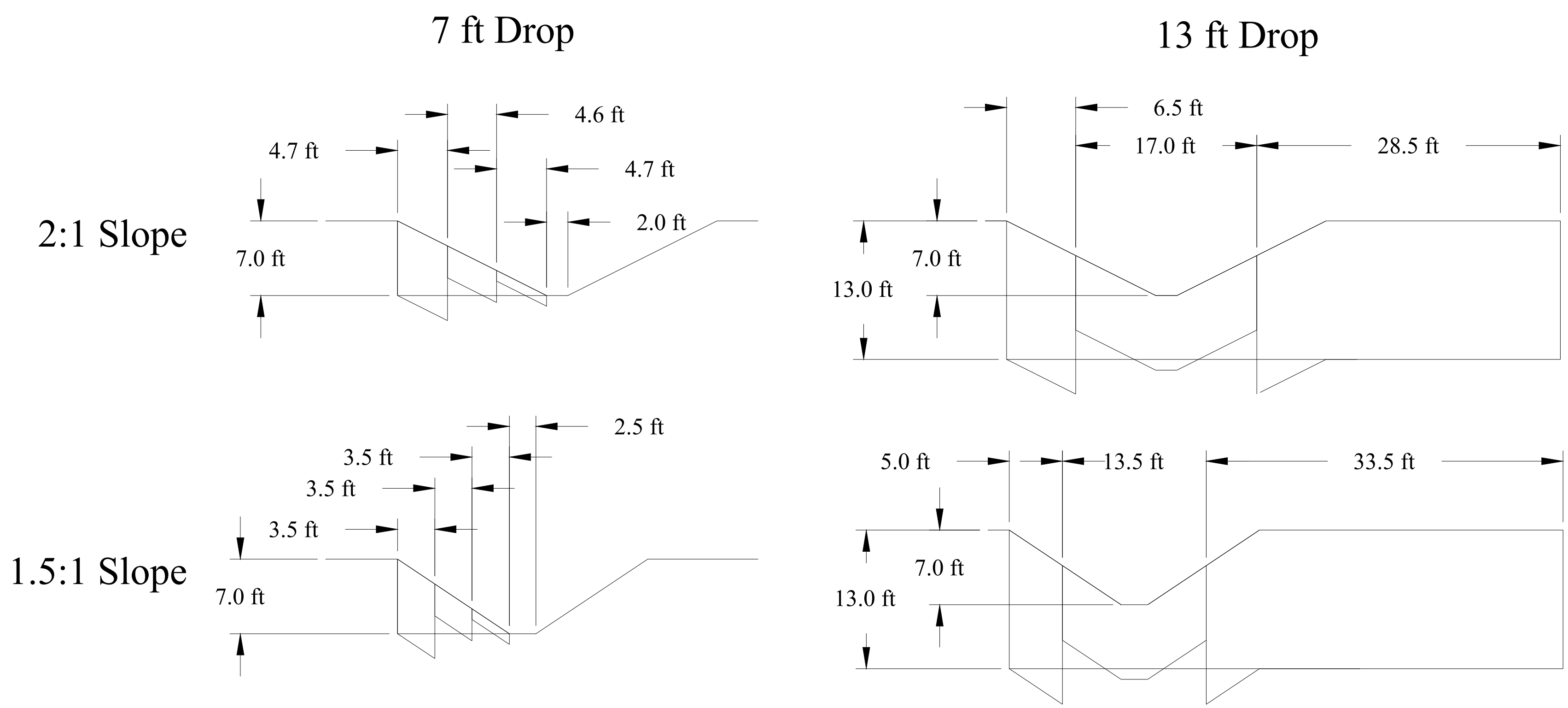


Figure 11. Cross-Sectional Ditch Modeling Dimensions and Drop-Off Heights

5.2.4 Road Geometry

The culvert analysis was conducted on a straight section of road with no vertical grade. Most often, culverts were constructed in valley regions or on flat planes due to water channelization. It is possible that culverts located at the bottom of a hill will have a higher frequency of impact than culverts located on a flat plane due to the effects of vertical curvature and increased speeds that result from downward acceleration. However, historical analyses of these effects on crash rates have shown this effect to be small [10].

It should be noted that the analyses conducted in this report did not include intersecting roadways or driveways, including near concrete box culverts.

5.2.5 Road Modeling

The modeled road was 1,000 ft (304.8 m) long. This road length permitted a longitudinal provision for the clear zone of more than 250 ft (76.2 m) on either side of the downstream and upstream guardrail terminals. The culvert was centered in the section at 500 ft (152.4 m). The roadway was modeled as a rural local road with two lanes of travel and an undivided median. A lane width of 12 ft (3.7 m) and a shoulder width of 2 ft (0.6 m) were used. The nominal percent of trucks was set to two percent, and the speed limit was 55 mph (89 km/h). The traffic growth factor was zero, and the encroachment rate adjustment factor was left unchanged at the default value of 1.

5.3 Treatment Options

Several treatments options were evaluated during the analyses, including the do nothing option, removing concrete posts and rail, installing guardrail, and installing culvert grates. These treatment options are discussed in greater detail in the following sections.

5.3.1 Do Nothing

The baseline condition was to do nothing to the culvert system. The baseline condition included rectangular posts attached to the culvert deck 1 ft (0.30 m) laterally away from the edge of the roadway, as measured to the traffic-side face of the posts. The end posts were modeled with the center of each post 1 ft (0.30 m) longitudinally from the corresponding end of the culvert in order to simulate the posts located near the culvert drop-off location. Culvert posts were spaced 3 ft (0.9 m) on center.

5.3.2 Remove Concrete Posts and Rail

The second treatment option was to remove the concrete posts and rail, or any existing system that does not meet crashworthy standards. The focus of this analysis was on removing posts. However, the results found herein can apply to any substandard system. KDOT indicated that the likely method of removing the posts would be by using a ball hammer on a crane, knocking the posts off of the culvert, and dumping them at a disposal location. The cost of removing one post from the headwall was estimated by KDOT officials to be approximately $1,000 for travel to and from the site and renting a dump truck and a ball hammer attachment for a crane bucket. For each additional post, crew and equipment use costs were estimated at $100. The $1,000 charge essentially represents a mobilization cost, and the post removal costs were dependent on the number of posts at a given culvert.

Since RSAP was designed to primarily address the risk of running off the road on the right side, symmetry of the culvert was used to determine the total cost of removing the posts. The fixed cost for traveling to the culvert was the same if treating one side or both sides, and it was anticipated that both sides would be treated at the same time. Thus, the fixed cost was determined to be $500 for the symmetrical culvert analysis. The costs per post were not changed since posts were located on both sides of the culvert.

When culverts span less than 10 ft (3.0 m), three posts were often installed on the culvert headwall. Longer spans typically had four or five posts installed across the culvert headwall. Thus, three concrete posts were used on culvert lengths less than 10 ft (3.0 m), and four posts were used on longer culverts. Five-post culverts were not considered in the analysis since the post spacing was very small. Small changes in post spacing will not increase nor decrease the propensity for impact if the analysis length remains constant. Furthermore, adding extra concrete posts only increased the cost of the alternative without significantly increasing the risk of injury.

Post-removal costs per side of the roadway were estimated at $800 for culvert lengths less than 10 ft and $900 for culverts with spans greater than or equal to 10 ft (3.0 m). The cost estimates were $50 greater than the estimate provided by KDOT. By overestimating the cost, the benefit-to-cost ratios were reduced for the post removal option. However, additional costs, which may be incurred during the process and not included in KDOT estimates, are then accounted for in the analysis.

The removal option was necessary if any other treatment option was considered. Therefore, the removal option was treated as the new baseline when analyzing the remaining treatment options.

5.3.3 Install Longitudinal Barrier

The third treatment option was to shield traffic from the culvert with the use of a barrier system. Test level two (TL-2) guardrail and end terminal systems were used in the RSAP model for this longitudinal barrier. Many culverts are low-fill box culverts with simple spans, which may allow for the use of a long-span W-beam guardrail with an unsupported length placed across the culvert. The guardrail installation was configured with the front face of the rail positioned 2 ft (0.61 m) in front of the culvert drop-off location. This guardrail position was evaluated based on current recommendations for unsupported W-beam and long-span Midwest Guardrail System (MGS) [11-13]. A long-span guardrail installation represents the most economical alternative for shielding culverts that are less than 25 ft (7.62 m) wide. Hence, this alternative would provide the most economical alternative for guardrail treatment.

As stated previously and for this option, it was necessary to remove the concrete posts and rails from the culvert headwall. As a result, the cost estimation for installing guardrail included the cost of removing the concrete posts and rails. W-Beam guardrail costs from the State Highway Agencies in Colorado, Kansas, Montana, Nebraska, Oregon, and Tennessee were averaged to obtain cost estimates for the RSAP analysis. The average cost was found to be $18.16 per linear foot ($59.58 per linear meter). A minimum guardrail length of 137.5 ft (41.91 m) was recommended based on estimated guardrail runout lengths developed by Wolford and Sicking [14-15].

It should be noted that the minimum guardrail length was determined as the sum of two guardrail sections: (1) the length of the crashworthy guardrail end terminal that is not capable of redirecting the vehicle, which is typically the last 12.5 ft (3.8 m) of the terminal; and (2) the guardrail segment length from the hazard to the beginning of the length-of-need (LON), which often includes a portion of the crashworthy end terminal system. When a vehicle strikes the terminal at a distance far enough downstream of the terminal end, the severity of the impact with the terminal is the same as for guardrail. Thus, the location at which the terminal redirects a vehicle may be used as the location of the start of the LON. This was modeled in RSAP by designating the length of the guardrail in the terminal downstream from the redirection point as part of the LON, and incorporating the remaining length of the terminal as an end terminal meeting the TL-2 performance criteria recommended in NCHRP Report No. 350 [5]. Then, the length of guardrail required between the terminals may be multiplied by a linearized cost to determine the total system cost.

For further guidance in selecting a longitudinal barrier, refer to the AASHTO RDG [1] for general guidelines or to the FHWA Barrier Guide for Low Volume and Low Speed Roads [16] for specific and extended guidelines.

5.3.4 Culvert Grate Installation

The fourth and fifth alternatives consisted of installing a culvert grate onto the existing side slopes. It was assumed that the culvert was in good condition and was capable of handling the loads imparted to it by the culvert grate during impact events. Culvert grate construction and installation costs were difficult to estimate. It was important to determine a model for the culvert grate costs that could be used to evaluate the three slopes (3H:1V, 4H:1V, and 6H:1V). KDOT supplied estimated costs for culvert grate construction and equipment based on steel weight, concrete volume, and reinforcement, which included labor costs associated with each material. When applicable, the cost to remove an existing substandard system was included in the total cost of the grate installation. Additionally, mobilization and extra equipment costs were estimated to be approximately 30 percent of the direct cost associated with culvert grate installation.

To determine appropriate costs for the different culverts, several methods were used to develop a “universal” culvert grate cost formula. Many of the culverts that were evaluated in the benefit-to-cost analyses were sized differently than culverts constructed with grates in Kansas. The culvert grate costs provided by KDOT were divided into four groups. The groups consisted of: (1) culvert grates installed with flared wingwalls and constructed on 3H:1V slopes; (2) culvert grates installed with straight wingwalls and located on 3H:1V slopes; (3) culvert grates installed with straight wingwalls and located on 6H:1V slopes; and (4) culvert grates installed on pre-existing wingwalls located on 3H:1V slopes. The cost associated with installing only a culvert grate is significantly less than when wingwall construction is required and formed the basis for breaking culvert grate costs down into four groups.

5.3.4.1 Wingwalls Constructed in the Field

The cost of each culvert type was plotted against different variables including length of culvert, width of culvert, drop height, and projected culvert area to horizontal and vertical planes. The strongest correlation was observed when the culvert grate area was projected parallel with the roadway and in a vertical plane. The projected vertical area was based on the total length of the culvert multiplied by the culvert depth. The length of the culvert was determined by the outer dimensions of the culvert wingwalls at the longest extent of the culvert.

Costs of grates on culverts installed on 3H:1V and 6H:1V slopes were very linear with respect to the vertical projected area, as shown in Figure 12. Construction costs for flared and straight wingwalls on 3H:1V slopes were collinear when based on the area of calculation, as shown in Figure 12. This finding indicates insensitivity to the type of wingwall (flared or straight) constructed. The correlation of grate costs installed on pre-existing culverts was the weakest, but it also had the least number of data points. It should be noted that culvert sizes with pre-existing wingwalls were very small, and realistic culvert grates installed in the field would likely be larger than those provided.

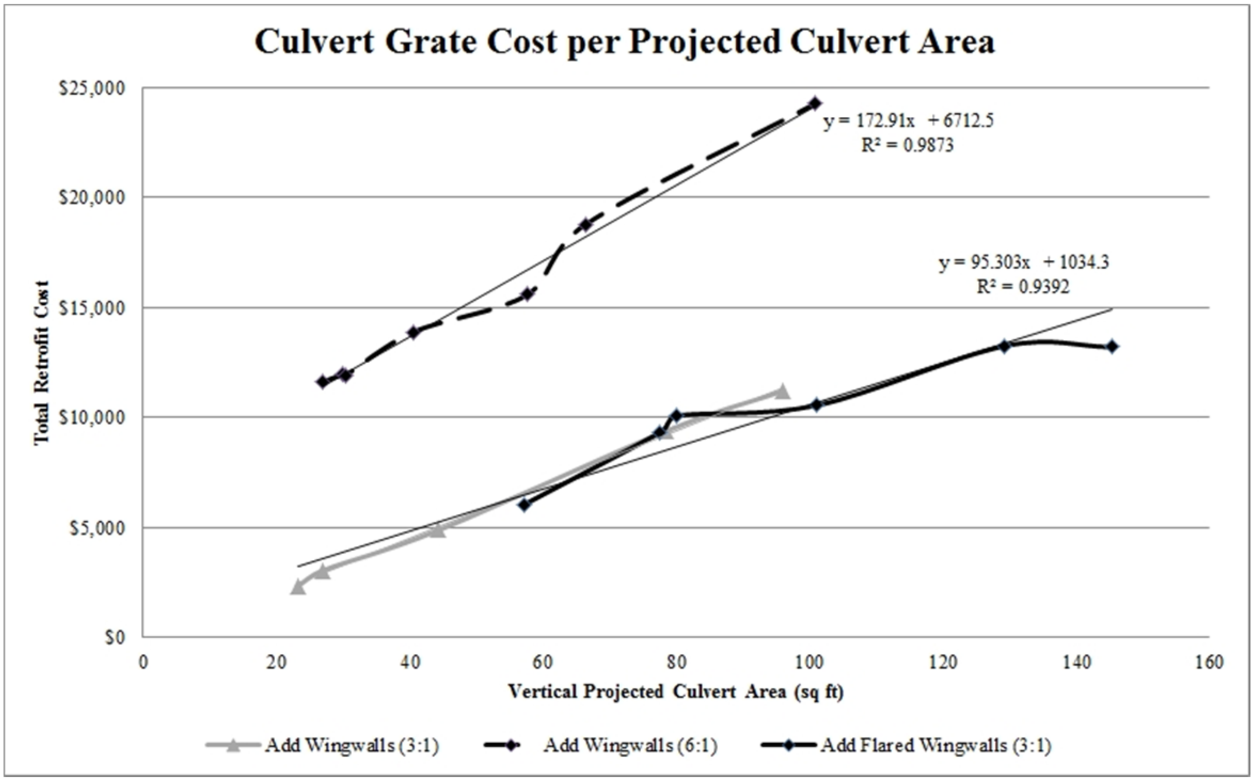


Figure 12. Culvert Grate Cost per Projected Area (KDOT Data and Approximation)

The costs of the culvert grates installed on 4H:1V slopes with wingwalls constructed in the field was determined by interpolation of findings for 6H:1V and 3H:1V slopes, as shown in Figure 13. The virtual intersection point of the 3H:1V and 6H:1V culvert grate cost lines was determined, and the 4H:1V slope installation cost approximation was linearly interpolated between the 3H:1V and 6H:1V costs per unit slope rate.

In addition, the costs were increased by 30 percent, as recommended by KDOT, to account for mobilization and traffic control efforts, as well as equipment costs. Cost estimates for culvert grates on slopes of 3H:1V, 4H:1V, and 6H:1V are shown in Tables 11 through 13, respectively.

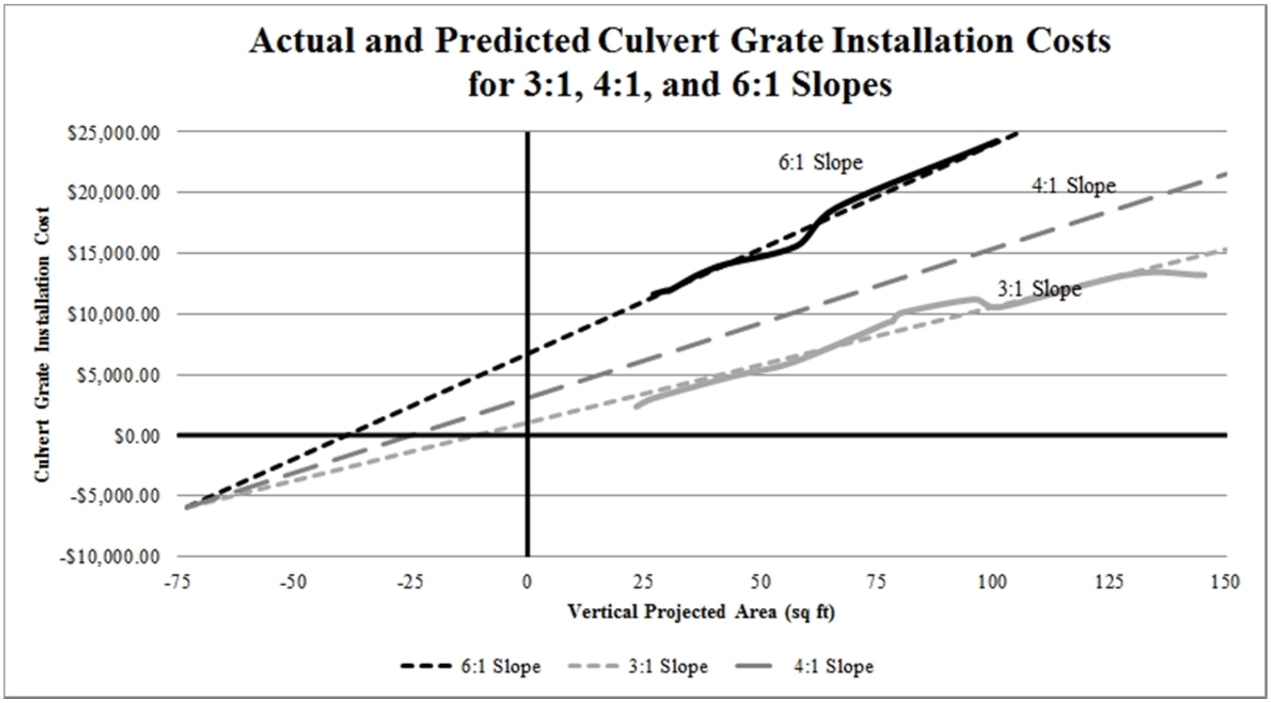


Figure 13. Interpolated Estimate for 4H:1V Culvert Grate Cost with Wingwall Construction

Table 11. Culvert Grate Costs by Simulated Culvert Size – Slope Rate 3H:1V

Culvert Length		Culvert Drop		Vertical Area		Wingwalls Added		Wingwalls Pre-Existing	
						Culvert Grate Predicted Cost	Cost Including Post Removal	Culvert Grate Predicted Cost	Cost Including Post Removal
ft	m	ft	m	ft^2	m^2				
4	1.2	3	0.9	12	1.11	$2,177.94	$3,650.00	$1,568.11	$2,850.00
4	1.2	7	2.1	28	2.60	$3,702.78	$5,625.00	$2,666.00	$4,275.00
4	1.2	13	4.0	52	4.83	$5,990.06	$8,600.00	$4,312.84	$6,425.00
6	1.8	3	0.9	18	1.67	$2,749.75	$4,375.00	$1,979.82	$3,375.00
6	1.8	7	2.1	42	3.90	$5,037.03	$7,350.00	$3,626.66	$5,525.00
6	1.8	13	4.0	78	7.25	$8,467.93	$11,825.00	$6,096.91	$8,750.00
8	2.4	3	0.9	24	2.23	$3,321.57	$5,125.00	$2,391.53	$3,925.00
8	2.4	7	2.1	56	5.20	$6,371.27	$9,100.00	$4,587.31	$6,775.00
8	2.4	13	4.0	104	9.66	$10,945.81	$15,050.00	$7,880.98	$11,050.00
10	3.0	3	0.9	30	2.79	$3,893.39	$5,975.00	$2,803.24	$4,550.00
10	3.0	7	2.1	70	6.50	$7,705.51	$10,925.00	$5,547.97	$8,125.00
10	3.0	13	4.0	130	12.08	$13,423.69	$18,350.00	$9,665.06	$13,475.00
12	3.7	3	0.9	36	3.34	$4,465.21	$6,700.00	$3,214.95	$5,100.00
12	3.7	7	2.1	84	7.80	$9,039.75	$12,650.00	$6,508.62	$9,375.00
12	3.7	13	4.0	156	14.49	$15,901.57	$21,575.00	$11,449.13	$15,800.00

Table 12. Culvert Grate Costs by Simulated Culvert Size – Slope Rate 4H:1V

Culvert Length		Culvert Drop		Vertical Area		Wingwalls Added		Wingwalls Pre-Existing	
						Culvert Grate Predicted Cost	Cost Including Post Removal	Culvert Grate Predicted Cost	Cost Including Post Removal
ft	m	ft	m	ft^2	m^2				
4	1.2	3	0.9	12	1.11	$4,548.55	$6,725.00	$3,274.96	$5,075.00
4	1.2	7	2.1	28	2.60	$6,518.76	$9,275.00	$4,693.51	$6,900.00
4	1.2	13	4.0	52	4.83	$9,474.08	$13,125.00	$6,821.34	$9,675.00
6	1.8	3	0.9	18	1.67	$5,287.38	$7,675.00	$3,806.92	$5,750.00
6	1.8	7	2.1	42	3.90	$8,242.70	$11,525.00	$5,934.74	$8,525.00
6	1.8	13	4.0	78	7.25	$12,675.68	$17,300.00	$9,126.49	$12,675.00
8	2.4	3	0.9	24	2.23	$6,026.21	$8,650.00	$4,338.87	$6,450.00
8	2.4	7	2.1	56	5.20	$9,966.63	$13,775.00	$7,175.98	$10,150.00
8	2.4	13	4.0	104	9.66	$15,877.27	$21,450.00	$11,431.63	$15,675.00
10	3.0	3	0.9	30	2.79	$6,765.04	$9,700.00	$4,870.83	$7,250.00
10	3.0	7	2.1	70	6.50	$11,690.57	$16,100.00	$8,417.21	$11,850.00
10	3.0	13	4.0	130	12.08	$19,078.86	$25,700.00	$13,736.78	$18,775.00
12	3.7	3	0.9	36	3.34	$7,503.87	$10,675.00	$5,402.79	$7,925.00
12	3.7	7	2.1	84	7.80	$13,414.50	$18,350.00	$9,658.44	$13,475.00
12	3.7	13	4.0	156	14.49	$22,280.46	$29,875.00	$16,041.93	$21,750.00

Table 13 Culvert Grate Costs by Simulated Culvert Size – Slope Rate 6H:1V

Culvert Length		Culvert Drop		Vertical Area		Wingwalls Added		Wingwalls Pre-Existing	
						Culvert Grate Predicted Cost	Cost Including Post Removal	Culvert Grate Predicted Cost	Cost Including Post Removal
ft	m	ft	m	ft^2	m^2				
4	1.2	3	0.9	12	1.11	$8,787.42	$12,225.00	$6,326.94	$9,050.00
4	1.2	7	2.1	28	2.60	$11,553.98	$15,825.00	$8,318.87	$11,625.00
4	*1.2*	*13*	*4.0*	*52*	*4.83*	*$15,703.82*	*$21,225.00*	*$11,306.75*	*$15,500.00*
6	1.8	3	0.9	18	1.67	$9,824.88	$13,575.00	$7,073.91	$10,000.00
6	1.8	7	2.1	42	3.90	$13,974.72	$18,975.00	$10,061.80	$13,900.00
6	*1.8*	*13*	*4.0*	*78*	*7.25*	*$20,199.48*	*$27,075.00*	*$14,543.63*	*$19,725.00*
8	2.4	3	0.9	24	2.23	$10,862.34	$14,925.00	$7,820.88	$10,975.00
8	2.4	7	2.1	56	5.20	$16,395.46	$22,125.00	$11,804.73	$16,150.00
8	*2.4*	*13*	*4.0*	*104*	*9.66*	*$24,695.14*	*$32,900.00*	*$17,780.50*	*$23,925.00*
10	3.0	3	0.9	30	2.79	$11,899.80	$16,375.00	$8,567.86	$12,050.00
10	3.0	7	2.1	70	6.50	$18,816.20	$25,375.00	$13,547.66	$18,525.00
10	*3.0*	*13*	*4.0*	*130*	*12.08*	*$29,190.80*	*$38,850.00*	*$21,017.38*	*$28,225.00*
12	3.7	3	0.9	36	3.34	$12,937.26	$17,725.00	$9,314.83	$13,025.00
12	3.7	7	2.1	84	7.80	$21,236.94	$28,525.00	$15,290.60	$20,800.00
12	*3.7*	*13*	*4.0*	*156*	*14.49*	*$33,686.46*	*$44,700.00*	*$24,254.25*	*$32,450.00*

*Note, highlighted cells indicate scenarios not evaluated

5.3.4.1 Pre-Existing Wingwalls

Data for pre-existing culverts was too small to be very useful. A best-fit linear curve for pre-existing wingwall installation costs extrapolated to culvert grates with 7 ft (2.1 m) drops was higher than anticipated. An alternative approach was used to determine the cost of installing a culvert grate on pre-existing wingwalls. As noted by KDOT, the culvert grate material and labor costs were estimated by multiplying the steel weight by a cost per unit weight for structural steel. Since the culvert grates installed on pre-existing wingwalls would only use structural steel for the construction of the grates and not concrete or reinforcing steel, the percentage of structural steel cost was isolated from the total cost of each culvert. The percent of structural steel cost varied from 61 percent for culvert grates on 3H:1V slopes with straight wingwalls to 72 percent for culvert grates on 6H:1V slopes with straight wingwalls. The culvert grates on 3H:1V slopes with flared wingwalls was approximately 71 percent structural steel, by cost.

It should be noted that the cost of the grate and any additional wingwall hardware was included with the frames and concrete. Thus, the additional labor required to set the culvert grate on the pre-existing wingwalls would need to be included. Furthermore, additional costs for potential repair work were not accounted for in the initial cost estimates. Therefore, to minimize the effect of unknown costs, the maximum percentage cost of 72 percent was chosen to be representative of the typical installation cost for a culvert grate on pre-existing wingwalls, as shown in Figure 14. It should be noted that this estimate may be higher than the actual cost of installing a culvert grate, which may imply that the benefit of a culvert grate is greater than estimated. If the cost is significantly less for a particular scenario, further analysis may be necessary.

Culvert grates installed on a 6H:1V slope over a 13 ft (4.0 m) drop were not considered feasible at this time. Due to right-of-way limitations and the intersection of private property, it was determined that the indicated culvert grate size would have to extend 78 ft (23.8 m) laterally away from the edge of the road. This would require land purchases from private owners and

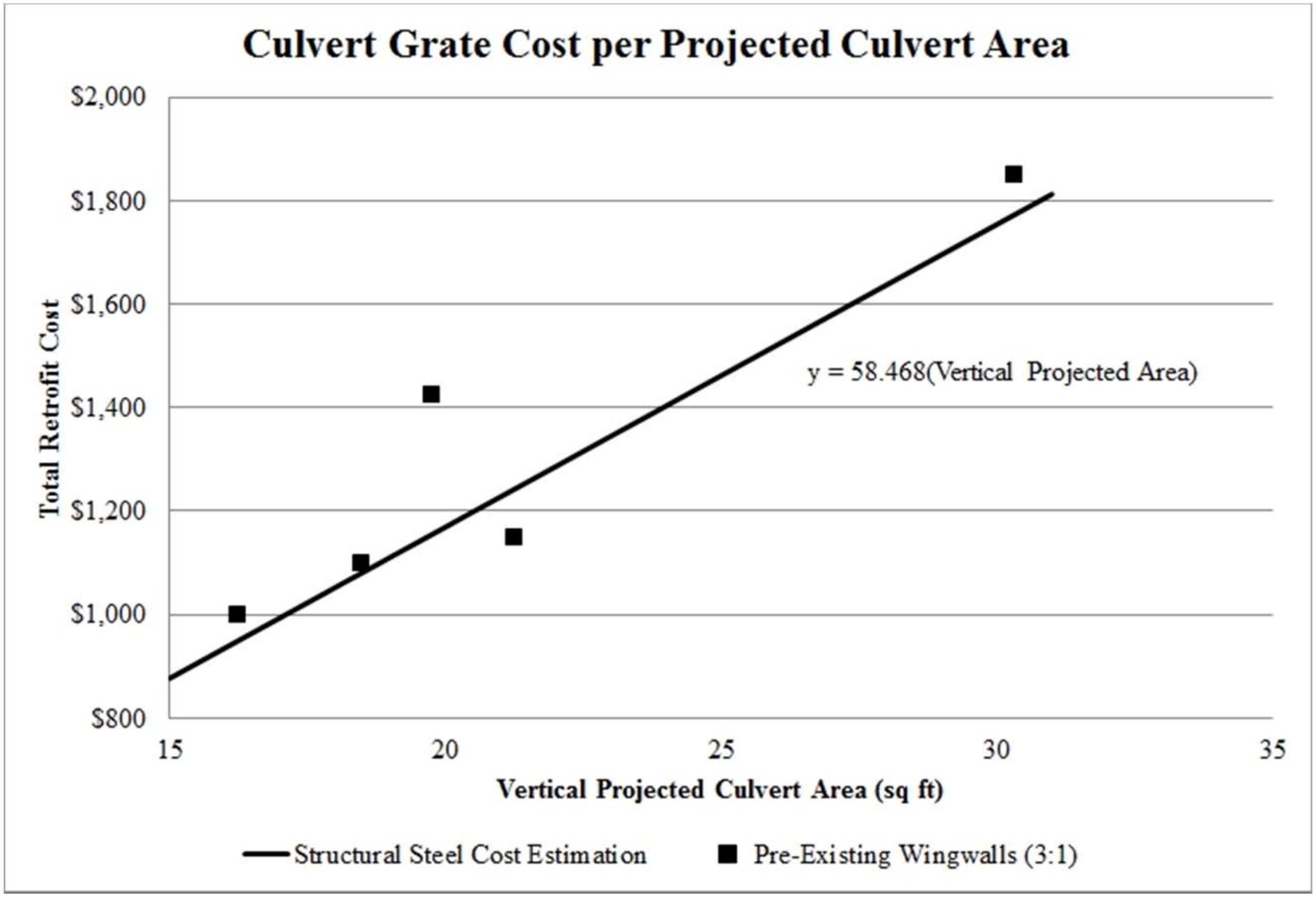


Figure 14. Pre-Existing Culvert Approximation and Provided Data

earthwork. Furthermore, it is not believed that many of these slopes are in existence. Therefore, culvert grates were not evaluated on 6H:1V slope rates spanning 13 ft (4.0 m) drop-offs.

5.4 Simulation Results

The results from the benefit-to-cost analyses of culverts installed on constant slopes and in ditch cross-sections are shown in Tables 14 through 22. The results of the culvert analyses are shown in an extended graphical form in Appendix A. The benefit-to-cost analyses indicated that it was beneficial to remove the substandard system for a majority of the scenarios analyzed.

The existence of wingwalls was found to have a significant effect on the benefit-to-cost ratios for the installation of culvert grates. Hence, Tables 14 through 19 have three categories for culvert grate treatment. The first category covers culverts with existing wingwalls and identifies when grates are more beneficial than merely removing the existing system. The second category also covers culverts with existing wingwalls, but it applies to the traffic volumes and roadway configurations where guardrail was cost beneficial when grates are not used. The final category applies to situations where wingwalls must be constructed.

Using a minimum benefit-to-cost ratio of 2.0 in combination with culvert drop heights of 1 to 3 ft (0.3 to 0.9 m) as well as fill slopes 3H:1V or shallower, removal of the existing system was cost-effective at an ADT as low as 50 vpd for all road widths. For a benefit-to-cost ratio of 4.0, the “do nothing” alternative was recommended only for ADT less than 100 vpd and was not recommended for an ADT greater than 250 vpd on most roadways. Additionally, the recommendation to install guardrail was generally restricted to roads with fill slope of 1.5H:1V or steeper. As road widths increased, the recommendation to install guardrail decreased.

Culvert grate recommendations were strongly dependent on the culvert dimensions. For longer culverts, the benefit of the culvert grate did not increase as rapidly as the cost of installation. Culvert length did not have a significant effect on culvert treatment recommendations except for grate treatments.

On culverts with 4H:1V fill slopes, the most common recommendation was the installation of culvert grates. Culverts with steeper slopes were more often treated with guardrail to prevent the vehicle from traversing the non-recoverable slopes. However, culvert grates were recommended for 3H:1V slopes that had drop heights greater than 8 ft (2.4 m), even though AASHTO classifies 3H:1V slopes as non-recoverable slopes, which means that vehicles are not expected to return to the roadway after a departure [1]. Additionally, rollovers are more likely to occur on 3H:1V slopes than 4H:1V or 6H:1V slopes, thus indicating a lower risk to errant motorists by placing culvert grates on 4H:1V slopes than on 3H:1V slopes. Therefore, culvert grates were recommended for 3H:1V fill slopes or flatter and favored minimal heights.

The analyses were not set up to compare slope flattening options in this report. However, previous work has been done focusing on this alternative [17] and was reviewed in this report in Section 7.3.4.

Table 14. Culvert Recommendations by ADT, Road Width < 30 ft (9.14 m), Foreslope Cross-Section, B/C = 2

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 2 ft	< 5 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-249	250-500			
		≥ 3:1		0-500				
	5 - 10.9 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-299	300-500			
		≥ 3:1		0-500				
	≥ 11 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-299	300-500			
		≥ 3:1		0-500				
2 - 3.9 ft	< 5 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-249	250-500			
		3:1		0-449	450-500			
		4:1		0-349		350-449		450-500
		≥ 6:1		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-299	300-500			
		3:1		0-449	450-500			
		4:1		0-399		400-500		
		≥ 6:1		0-500				
	7 - 8.9 ft	1.5:1	0-149		150-500			
		2:1		0-299	300-500			
		3:1		0-449	450-500			
		4:1		0-449		450-500		
		≥ 6:1		0-449				
	≥ 9 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-249	250-500			
		3:1		0-399	400-500			
		≥ 4:1		0-500				
4 - 7.9 ft	< 5 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-299		300-399	400-449	450-500
		6:1		0-449			450-500	
		≥ 8:1		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-399			400-500	
		6:1		0-449	450-500			

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
4 - 7.9 ft	5 - 6.9 ft	≥ 8:1		0-500				
	7 - 10.9 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-399	400-500			
		6:1		0-449	450-500			
		≥ 8:1		0-500				
	≥ 11 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-249	250-500			
		3:1		0-399	400-500			
		≥ 4:1		0-500				
≥ 8 ft	< 5 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-249	250-500			
		3:1	0-49	50-199		200-249	250-349	350-500
		4:1	0-49	50-199	200-299			300-500
		6:1	0-49	50-449	450-500			
		≥ 8:1	0-49	50-500				
	5 - 6.9 ft	1.5:1	0-49	50-249	250-500			
		2:1	0-49	50-249	250-500			
		3:1	0-49	50-249	250-349		350-500	
		4:1	0-49	50-299		300-349	350-399	400-500
		6:1	0-49	50-299		300-349	350-399	400-500
		8:1	0-49	50-299		300-349	350-399	400-500
		Flat	0-49	50-500				
	7 - 10.9 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-249	250-500			
		4:1		0-299	300-399		400-500	
		6:1		0-449	450-500			
		8:1		0-449	450-500			
		Flat		0-500				
	≥ 11 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-249	250-500			
		4:1		0-299	300-500			
		6:1		0-399	400-500			
		8:1		0-449	450-500			
		Flat		0-500				

Table 15. Culvert Recommendations by ADT, Road Width 30 – 31.9 ft (9.14 - 9.72 m), Foreslope Cross-Section, B/C = 2

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 2 ft	< 7 ft	1.5:1	0-49	50-199	200-500			
		2:1	0-49	50-299	300-500			
		3:1		0-500				
		≥ 4:1		0-500				
	7 - 8.9 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-349	350-500			
		3:1		0-500				
		4:1		0-500				
		6:1		0-500				
		8:1		0-500				
		Flat		0-500				
	8.9 - 10.9 ft	1.5:1	0-99		100-500			
		2:1		0-299	300-500			
		≥ 3:1		0-500				
	≥ 11 ft	1.5:1	0-49	50-199	200-500			
		2:1	0-49	50-299	300-500			
		≥ 3:1		0-500				
2 - 3.9 ft	< 5 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-249	250-500			
		3:1		0-449	450-500			
		4:1		0-349		350-449		450-500
		≥ 6:1		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-299	300-500			
		3:1		0-449	450-500			
		4:1		0-399		400-500		
		≥ 6:1		0-500				
	7 - 8.9 ft	1.5:1	0-99		100-500			
		2:1		0-299	300-500			
		3:1		0-449	450-500			
		4:1		0-449		450-500		
		≥ 6:1		0-500				
	9 - 10.9 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-249	250-500			
		3:1		0-399	400-500			
		≥ 4:1		0-500				
	≥ 11 ft	1.5:1	0-49	50-99	100-500			
		2:1		0-249	250-500			
		3:1		0-399	400-500			
		≥ 4:1		0-500				
4 - 7.9 ft	< 5 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-299		300-399	400-449	450-500
		6:1		0-449			450-500	
		≥ 8:1		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-99	100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-399			400-500	
		6:1		0-449	450-500			
		≥ 8:1		0-500				
	≥ 7 ft	1.5:1	0-49	50-199	200-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-349	350-500			
		6:1		0-399	400-500			
		≥ 8:1		0-500				
≥ 8 ft	< 5 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-199		200-299	300-399	400-500
		4:1	0-249			250-349		350-500
		6:1		0-500				
		≥ 8:1		0-500				
	5 - 6.9 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-349		350-500	
		4:1		0-299		300-349	350-449	450-500
		≥ 6:1		0-500				
	7 - 10.9 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-349	350-399		400-500	
		6:1		0-449	450-500			
		≥ 8:1		0-500				
	≥ 11 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-349	350-500			
		6:1		0-449	450-500			
		8:1		0-449	450-500			
		Flat		0-500				

Table 16. Culvert Recommendations by ADT, Road Width 32 – 35.9 ft (9.75 – 10.94 m), Foreslope Cross-Section, B/C = 2

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 2 ft	< 5 ft	1.5:1	0-99	100-199	200-500			
		2:1	0-49	50-349	350-500			
		≥ 3:1		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-149	150-500			
		2:1	0-49	50-249	250-500			
		≥ 3:1		0-500				
	7 - 8.9 ft	1.5:1	0-49	50-149	150-500			
		2:1	0-49	50-349	350-500			
		≥ 3:1		0-500				
	9 - 10.9 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-500				
		≥ 3:1		0-500				
	≥ 11 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-299	300-500			
		≥ 3:1		0-500				
2 - 3.9 ft	< 5 ft	1.5:1	0-49	50-199	200-500			
		2:1	0-49	50-249	250-500			
		3:1		0-449	450-500			
		4:1		0-399		400-500		
		≥ 6:1		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-199	200-500			
		2:1	0-49	50-249	250-500			
		3:1		0-449	450-500			
		4:1		0-449		450-500		
		≥ 6:1		0-500				
	≥ 7 ft	1.5:1	0-49	50-199	200-500			
		2:1	0-49	50-249	250-500			
		3:1		0-449	450-500			
		≥ 4:1		0-500				
4 - 7.9 ft	< 5 ft	1.5:1	0-99	100-199	200-500			
		2:1	0-49	50-299	300-500			
		3:1		0-349	350-500			
		4:1		0-349		350-449	450-500	
		6:1		0-449			450-500	
		≥ 8:1		0-500				
4 - 7.9 ft	≥ 5 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-299	300-500			
		3:1		0-349	350-500			
		4:1		0-399	400-500			
		≥ 6:1		0-500				
≥ 8 ft	< 5 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-249	250-500			
		3:1		0-199		200-299	300-399	400-500
		4:1		0-249		250-349		350-500
		≥ 6:1		0-500				
	5 - 6.9 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-199	200-500			
		3:1		0-249	250-449		450-500	
		4:1		0-349			350-500	
		6:1		0-500				
		8:1		0-500				
		Flat		0-500				
	7 - 8.9 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-249	250-500			
		3:1		0-349	350-500			
		4:1		0-349	350-449		450-500	
		≥ 6:1		0-500				
	9 - 10.9 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-349	350-500			
		≥ 6:1		0-500				
	≥ 11 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-249	250-500			
		3:1		0-299	300-500			
		4:1		0-349	350-500			
		6:1		0-449	450-500			
		≥ 8:1		0-500				

Table 17. Culvert Recommendations by ADT, Road Width ≥ 36 ft (10.97 m), Foreslope Cross-Section, B/C = 2

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 2 ft	all	1.5:1	0-49	50-149	150-500			
		2:1	0-49	50-349	350-500			
		≥ 3:1		0-500				
2 - 3.9 ft	< 5 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-349	350-500			
		3:1		0-500				
		4:1		0-449		450-500		
		6:1		0-500				
		8:1		0-500				
		Flat		0-500				
	≥ 5 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-349	350-500			
		≥ 3:1		0-500				
4 - 7.9 ft	< 5 ft	1.5:1	0-99	100-249	250-500			
		2:1	0-49	50-349	350-500			
		3:1		0-399	400-500			
		4:1		0-349		350-449	450-500	
		6:1		0-500				
		8:1		0-500				
		Flat		0-500				
	5 - 6.9 ft	1.5:1	0-49	50-249	250-500			
		2:1	0-49	50-349	350-500			
		3:1		0-399	400-500			
4 - 7.9 ft	5 - 6.9 ft	4:1		0-449			450-500	
		6:1		0-500				
		8:1		0-500				
		Flat		0-500				
	≥ 7 ft	1.5:1	0-49	50-349	350-500			
		2:1	0-49	50-349	350-500			
		3:1		0-399	400-500			
		4:1		0-449	450-500			
		≥ 6:1		0-500				
≥ 8 ft	< 5 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-299	300-500			
		3:1	0-49	50-249		250-349	350-449	450-500
		4:1	0-49	50-349		350-399	400-500	
		≥ 6:1	0-49	50-500				
	5 - 6.9 ft	1.5:1	0-99		100-500			
		2:1	0-49	50-299	300-500			
		3:1	0-49	50-299	300-500			
		4:1	0-49	50-399			400-500	
		≥ 6:1	0-49	50-500				
	≥ 7 ft	1.5:1	0-99	100-149	150-500			
		2:1	0-49	50-299	300-500			
		3:1		0-299	300-500			
		4:1		0-399	400-500			
		≥ 6:1		0-500				

Table 18. Culvert Recommendations by ADT, Road Width ≤ 30 ft (9.14 m), Foreslope Cross-Section, B/C = 4

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 4 ft	all	1.5:1	0-149	150-299	300-500			
		≥ 2:1	0-49	50-500				
4 - 7.9 ft	< 5 ft	1.5:1	0-149	150-249	250-500			
		2:1	0-99	100-449	450-500			
		3:1	0-49	50-449	450-500			
		≥ 4:1	0-49	50-500				
	≥ 5 ft	1.5:1	0-149	150-249	250-500			
		2:1	0-99	100-449	450-500			
		≥ 3:1	0-49	50-500				
≥ 8 ft	< 5 ft	1.5:1	0-199	200-299	300-500			
		2:1	0-99	100-449	450-500			
		3:1	0-49	50-349		350-449	450-500	
		4:1	0-49	50-399		400-500		
		≥ 6:1	0-49	50-500				
	≥ 5 ft	1.5:1	0-199	200-299	300-500			
		2:1	0-99	100-399	400-500			
		3:1	0-49	50-449	450-500			
		≥ 4:1	0-49	50-500				

Table 19. Culvert Recommendations by ADT, Road Width 30 – 31.9 ft (9.14 – 9.72 m), Foreslope Cross-Section, B/C = 4

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 4 ft	all	1.5:1	0-149	150-349	350-500			
		2:1	0-99	100-500				
		≥ 3:1	0-49	50-500				
4 - 7.9 ft	all	1.5:1	0-149	150-249	250-500			
		2:1	0-99	100-449	450-500			
		≥ 3:1	0-49	50-500				
≥ 8 ft	< 5 ft	1.5:1	0-199	200-249	250-500			
		2:1	0-99	100-399	400-500			
		3:1	0-49	50-399		400-449		450-500
		4:1	0-49	50-449		450-500		
		≥ 6:1	0-49	50-500				
	≥ 5 ft	1.5:1	0-199	200-249	250-500			
		2:1	0-99	100-399	400-500			
		≥ 3:1	0-49	50-500				

Table 20. Culvert Recommendations by ADT, Road Width 32 – 35.9 ft (9.75 – 10.94 m), Foreslope Cross-Section, B/C = 4

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 2 ft	all	1.5:1	0-149	150-349	350-500			
		2:1	0-99	100-500				
		≥ 3:1	0-49	50-500				
2 - 3.9 ft	all	1.5:1	0-99	100-249	250-500			
		2:1	0-49	50-399	400-500			
		≥ 3:1	0-49	50-500				
4 - 7.9 ft	all	1.5:1	0-199	200-349	350-500			
		2:1	0-99	100-500				
		≥ 3:1	0-49	50-500				
≥ 8 ft	< 5 ft	1.5:1	0-199	200-349	350-500			
		2:1	0-149	150-449	450-500			
		3:1	0-99	100-399		400-500		
		4:1	0-49	50-449		450-500		
		≥ 6:1	0-49	50-500				
	≥ 5 ft	1.5:1	0-199	200-349	350-500			
		2:1	0-99	100-449	450-500			
		≥ 3:1	0-49	50-500				

Table 21. Culvert Recommendations by ADT, Road Width ≥ 36 ft (10.97 m), Foreslope Cross-Section, B/C = 4

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 8 ft	all	1.5:1	0-199	200-399	400-500			
		2:1	0-99	100-500				
		≥ 3:1	0-49	50-500				
≥ 8 ft	< 5 ft	1.5:1	0-249	250-399	400-500			
		2:1	0-149	150-500				
		3:1	0-99	100-449		450-500		
		≥ 4:1	0-99	100-500				
	≥ 5 ft	1.5:1	0-249	250-399	400-500			
		2:1	0-149	150-500				
		≥ 3:1	0-99	100-500				

Table 22. Culvert Recommendations by ADT, Road Width ≥ 36 ft (10.97 m), Foreslope Cross-Section, B/C = 4

Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail	Culvert Grate if wingwalls, else Remove Posts	Culvert Grate if wingwalls, else Install Guardrail	Culvert Grate
< 8 ft	all	1.5:1	0-199	200-399	400-500			
		2:1	0-99	100-500				
		≥ 3:1	0-49	50-500				
≥ 8 ft	< 5 ft	1.5:1	0-249	250-399	400-500			
		2:1	0-149	150-500				
		3:1	0-99	100-449		450-500		
		≥ 4:1	0-99	100-500				
	≥ 5 ft	1.5:1	0-249	250-399	400-500			
		2:1	0-149	150-500				
		≥ 3:1	0-99	100-500				

Table 23. Culvert Recommendations by ADT, Ditch Cross-Section, B/C = 2

Road Width W	Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail
< 32 ft	< 4 ft	all	1.5:1		0-249	250-500
			2:1		0-299	300-500
	4 - 7.9 ft	all	1.5:1	0-49	50-249	250-500
			2:1		0-349	350-500
	≥ 8 ft	all	1.5:1	0-49	50-249	250-500
			2:1	0-49	50-299	300-500
≥ 32 ft	< 4 ft	all	1.5:1	0-49	50-299	300-500
			2:1		0-399	400-500
	4 - 7.9 ft	all	1.5:1	0-49	50-199	200-500
			2:1	0-49	50-249	250-500
	≥ 8 ft	all	1.5:1	0-49	50-249	250-500
			2:1	0-49	50-299	300-500

Table 24. Culvert Recommendations by ADT, Ditch Cross-Section, B/C = 4

Road Width W	Drop Height H	Culvert Length L	Slope Rate SR	Do Nothing	Remove Posts	Install Guardrail
< 32 ft	< 4 ft	all	1.5:1	0-99	100-500	
			2:1	0-49	50-500	
	4 - 7.9 ft	all	1.5:1	0-99	100-500	
			2:1	0-49	50-500	
	≥ 8 ft	all	1.5:1	0-99	100-399	400-500
			2:1	0-99	100-449	450-500
≥ 32 ft	< 4 ft	all	1.5:1	0-99	100-500	
			2:1	0-99	100-500	
	4 - 7.9 ft	all	1.5:1	0-99	100-500	
			2:1	0-99	100-500	
	≥ 8 ft	all	1.5:1	0-149	150-500	
			2:1	0-99	100-500	

5.5 Discussion

The culvert grate costs were derived from a small data set. As a result, interpolation was required to determine the costs of installing culvert grates on a variety of culvert and roadside geometries. Since cost estimates for culvert grate installation were based on culverts with different lengths, care should be taken to note the actual costs for culvert grate installations. If it is determined that the cost of installing and repairing the culvert grate is significantly different than what was used in this study, additional analysis may be required to determine the appropriate safety treatment for culvert grate recommendations.

Initially, and based on culvert grate crash testing, impacts with the culvert grate wingwalls were modeled with a small, rectangular object placed at the end of the culvert [18-19]. However, the small, rectangular rigid objects available in RSAP had a very small severity such that the inclusion did not significantly affect the outcome of the results. Upon further investigation, it was determined that RSAP calculates a vehicle trajectory line and evaluates the most significant object based on a severity index and vehicle speed at that location to determine what accident cost to assign to the object. Since the slopes of the culvert wingwalls were more severe than the small, rectangular rigid object used to model the culvert wingwall, impacts with the object were masked. Since fixed objects on slopes should be cumulative and not exclusive, it is recommended that further development in the RSAP program focus on rectifying fixed objects located on slopes.

Culvert grates can potentially cause risk to errant motorists. Although culvert grates were analyzed as being equivalent to the slope of the wingwalls, non-tracking vehicle impacts with the culvert grates may result in vehicle instability and rollover. Furthermore, as discussed in the culvert grate analysis section, errant vehicles may contact the wingwalls on the culvert grates, resulting in vehicle instability. RSAP does not adjust the severity of an impact based on vehicle yaw angle, nor does it analyze the potential for rollover. Therefore, additional research may be needed to evaluate the effects of non-tracking impacts on culvert grates. Nonetheless, since the culvert grate minimizes the number of nuisance hits at a culvert location, the culvert grate option is believed to be the most significant safety improvement of the choices analyzed.

Many of the box culverts observed in the field investigation had concrete posts and rails attached to the top of the headwall. However, some culverts observed in Nebraska had wood post-and-beam or steel angle post-and-beam sections. Even though these rails differ significantly, the rail configurations found in Nebraska are less likely to redirect or capture an errant vehicle than the concrete posts and rails found in Kansas. However, end-on impacts with these rails may result in occupant compartment penetration. Since these rails serve more as a delineator than anything else and pose a risk to errant motorists, the wood or steel post-and-rail designs should be treated like the concrete post-and-beam design. All recommendations applicable to the concrete post-and-beam culverts are applicable to culverts with a post-and-beam attachment. It should be noted that potentially less equipment, labor, and personnel might be required to remove these alternative structures, thus potentially reducing the overall cost.

Delineation is a cost-effective method of reducing the frequency of run-off-road accidents and may contribute to a reduction in accident severity by alerting drivers of a risk. Delineation has proven to successfully reduce impact events with obstacles by as much as 30 percent [20]. While the net hazard reduction factor is unknown and is based on visibility, vegetation growth, grade, and other factors, delineation may be an effective safety improvement over the “do nothing” recommendation. Further analysis of the delineation option is recommended to explore its use in mitigating crashes with the obstacle. Nonetheless, it should be noted that delineation does not reduce the severity of an object, it only increases driver awareness of it. Therefore, delineation should not be used in lieu of other recommended safety treatments.

Straight wingwalls were analyzed for all culverts with wingwalls present. This selection resulted from the fact that few culverts were observed in the field investigation with flared wingwalls. Culverts constructed with flared wingwalls are longer in length due to the flare and potentially pose a higher risk than culverts with straight wingwalls. However, culvert treatment options were largely insensitive to culvert length for concrete post-and-beam removal and guardrail installation. Furthermore, the culvert grate costs were estimated based on the total length of the culvert at the edges of the wingwalls, which included flared and straight wingwall configurations. Therefore, if treatment for culverts with flared wingwalls is considered, it is recommended that the length of the culvert be determined by measuring from the outermost dimension of both wingwalls and use that length to recommend treatments for that culvert. If no wingwalls are present, the length of the culvert at the road level should be used to determine the effective culvert length.

Several modeling attempts were made to gain a broader understanding of RSAP's capabilities of evaluating safety treatments for culverts. In the field investigation, road widths were as narrow as 16 ft (4.9 m) and could be wider than 30 ft (9.1 m). Lane widths were believed to have an effect on the results of the benefit-to-cost analyses. Thus, lane widths measuring 8 ft, 9 ft, 10 ft, 11 ft, and 12 ft (2.4 m, 2.7 m, 3.0 m, 3.4 m, and 3.7 m) were analyzed and evaluated by changing the parameter in RSAP. To investigate the effects of lane widths, culverts were placed at the edge of the roadway, at the minimum permitted lateral offset of 0.01 ft (0.003 m) to simulate the edge of the culvert at the edge of the road.

The modeling results indicated very little difference between the 8-ft and 12-ft (2.4-m and 3.7-m) wide lanes for a given ADT and culvert configuration. It was determined that the RSAP program was based on departure data from roads with 12-ft (3.7-m) wide lanes. Thus, departure statistics were estimated for roadways with varying lane widths. In future studies, it is recommended that lane width remain constant, and that individual studies be conducted for differing lane width roadways.

Evaluation of various ditch cross sections at several heights as observed in the field study was desired for this study. However, RSAP's predefined slopes did not produce equivalent slope severities for 3 to 5 ft (0.9 to 1.5 m) deep V-ditches with 1.5H:1V and 2H:1V fill slopes. Initial attempts to model the slopes with severities approximately equal to those corresponding to 1-ft (0.3-m) deep slopes resulted in no differentiation from those with flat ground due to the very low severity of a 1-ft (0.3-m) drop. In addition, slope severities do not adjust when the width or length of the slope is changed. As a result, it was impossible to model the 5-ft (1.5-m) ditch depths with 1.5H:1V slopes without approximating it according to available roadside geometry severity data. It is recommended that future studies considering treatment of ditch cross-sections derive accurate roadside geometry severity values for ditch depths ranging between 3 and 5 ft (0.9 and 1.5 m).

It is important to note that guardrail was recommended on culverts with 1.5H:1V and 2H:1V constant slopes for culvert depths less than 2 ft (0.6 m). This choice was based on an assumption of a constant slope extending beyond the clear zone of low-volume roadways. Since severe slopes present a risk to errant vehicles, the slopes dominate the analysis for any slope height greater than 13 ft (4.0 m). Additional analyses were conducted to evaluate 1.5H:1V and 2H:1V slopes with heights of 7 and 13 ft (2.1 and 4.0 m). However, the results of the analyses were identical to the results for culverts with ditch cross-sections. For culverts located on roadways adjacent to 1.5H:1V and 2H:1V fill slopes with depths ranging between 5 and 13 ft (1.5 and 4.0 m), safety treatment recommendations for culverts with ditch cross-sections should be used instead of the constant slope recommendations (i.e., use Tables 23 and 24).

The RSAP program does not have severities for slopes with shallow heights. Therefore, slopes with heights between 2 and 5 ft (0.6 and 1.5 m) were not considered in this study. Because of this, a “gray zone” exists where no analysis was conducted, and it is recommended that evaluations be conducted on a case-by-case basis to consider safety treatment options. If advancements are made in the slope features in RSAP, additional study may be needed to address slopes with shallow heights.

Finally, based on the results of the analysis, it was determined that the small increments between road widths, culvert lengths, and slopes were unnecessary. The RSAP program is relatively insensitive to small changes in roadway and roadside geometry. Although the small increments were necessary for the culvert grate option analysis, it is not likely required for safety treatments in which the relationship between size and cost is less critical. Furthermore, the benefit-to-cost ratios were linearly proportional to the ADT for a given roadway and roadside configuration. To reduce the number of required analysis runs while obtaining reliable results, it is recommended that culvert offset increments range from 2 to 4 ft (0.6 to 1.2 m) and that the critical ADT be determined. If the safety treatment with the maximum cost and benefit-to-cost ratio reaches the required limit, which is often 2.0 or 4.0, the analysis can be stopped at the current ADT, since a linear relationship exists between ADT and the benefit-to-cost ratio. Lastly, while object width has a significant effect on the benefit-to-cost analysis, object length does not.

Incremental changes in feature length may be large if the analysis indicates little change in the benefit-to-cost with smaller length changes.

5.6 Conclusions and Recommendations

Treatments for various culvert configurations were considered and analyzed to determine the most cost-effective treatment for such structures. Treatment options included doing nothing, removing concrete post-and-beam structures or equivalent non-crashworthy features from the culvert headwall, installing long-span guardrail across the culvert, and installing a culvert grate. Culvert grate recommendations considered either installing only the culvert grate on existing wingwalls or constructing wingwalls before installing the culvert grate.

Benefit-to-cost ratios were generated through the use of RSAP and were used to determine the most cost-effective safety treatment for culverts in various configurations of length, depth, and side slope. Recommendations indicated that if non-crashworthy features existed on the culvert headwall, it was often cost-effective to remove those features.

For benefit-to-cost ratios of 2.0, long-span W-beam guardrail was recommended for traffic volumes as low as 100 vpd. The tendency to recommend this treatment option increased as the drop height and culvert length increased. However, the recommendation tendency decreased as the approaching slope flattened. Road width also affected the recommendations, such that, as the width increased, traffic ranges recommended for guardrail installation increased from 100 vpd on 30-ft (9.1-m) roads to 150 vpd on 36-ft (11.0-m) roads with drop heights of 2 ft (0.6 m). As drop height increased, traffic volume ranges expanded for the guardrail option.

Culvert grates were also considered. This option was not viable on drop heights of 2 ft (0.6 m) or less. It was only sparsely viable for drop heights of less than 8 ft (2.4 m), but it became viable for drop heights greater than 8 ft (2.4 m) and for culvert lengths less than 10 ft

(3.0 m). If a wingwall had to be installed, and if recommendations were made to support this alternative, they were only made in the upper traffic volume ranges, such as 450 vpd or more. These treatment options were less sensitive to road width, except when paired with slopes. As road widths increased and slopes flattened, the propensity for using culvert grates was reduced.

Culvert grates were typically recommended for culverts less than 8 ft (2.4 m) long and more than 4 ft (1.2 m) deep and with foreslopes of 3H:1V and 4H:1V. Some 10-ft (3.0-m) long culverts and some culverts with 2 ft (0.6 m) depths were also recommended for culvert grate treatment. Installation of guardrail was typically recommended for ADT greater than 100 vpd for roads with a side slope of 1.5H:1V and for ADTs greater than 250 vpd for roads with side slopes of 2H:1V.

For benefit-to-cost ratios of 4.0, long-span W-beam traffic volume recommendations increased to 300 vpd on 30-ft (9.1-m) wide roads and drop heights of 4 ft (1.2 m). As the width increased to 36 ft (11.0 m), that volume increased to 400 vpd. As before, and as drop height increased, the propensity to recommend culvert grate installation increased but only when drop heights exceeded 8 ft (2.4 m). Additionally, culvert grate installation which required the construction of wingwalls was only recommended for one scenario: road widths between 30 and 32 ft (9.1 and 9.8 m), drop heights greater than 8 ft (2.4 m), culvert lengths less than 4 ft (1.2 m), and slopes of 3H:1V.

6 ANALYSIS OF ROADSIDE TREES

6.1 Introduction

Trees are naturally occurring roadside fixed objects and have been responsible for many fatalities and serious injuries during run-off-road crashes. Trees account for more than 8 percent of all traffic-related fatalities, and 90 percent of all fatalities which result from tree impacts occur on two-lane roadways [4]. Furthermore, 65 percent of all tree-related fatalities occur on roads classified as rural major collector, rural minor collector, and rural local roadways. Recommendations for tree treatment have been provided for many roadways, but treatment of trees on low-volume roadways has not received the same attention due to the perception that few cost-effective treatments are available for a reasonable severity reduction. Therefore, typical tree arrangements along low-volume roadways were analyzed to determine cost-effective treatments.

6.2 Modeling Procedure

6.2.1 Tree Details

During the field investigation, various tree configurations were observed near the roadside, which posed numerous risks to motorists. First, their proximity to the travel way increases the likelihood of being struck. Second, their configuration and structure often make them virtually rigid under vehicular impact events. Third, branches of foliage near and over the roadway can reduce visibility.

Trees near the roadway were observed in different arrangements and sizes. Some trees were spaced far apart from other trees and were considered to be individual trees for the purpose of fixed object definition. These trees tended to be larger in diameter.

Further, trees were also found to be located in clusters or groups. Tree clusters had three general forms: (1) small groups; (2) long and widely-spaced groups; and (3) long and tightly-spaced groups. Small groups of trees were representative of seemingly random tree growth with some located near the edges of fields where farm tilling machinery may not remove the saplings from the fertile soils. Longer and widely-spaced groups of trees were common near houses and property lines, particularly in the plains region, to serve as a wind break or acreage enhancement. Long and tightly-spaced groups of trees were more common when streams and/or ponds were located near the roadway.

Tree sizes were variable and depended on the age, type, and pruning of the tree. Trees near houses tend to be well-pruned with one or two large trunks at ground level. Trees dispersed randomly were more variable and were found to have as many as six identifiable trunks extending out of the same root structure. Larger trees generally had single trunks, whereas trees with multiple trunks generally had smaller and more branching trunks. Tree diameters in excess of 36 in. (914 mm) were observed in the field investigation.

6.2.2 Tree Profiles

The first step in modeling the tree scenarios was to determine what tree sizes should be investigated. RSAP's predefined tree sizes included diameters of 2 in., 4 in., 6 in., 8 in., 10 in., 12 in., and 12+ in. (51 mm, 102 mm, 152 mm, 203 mm, 254 mm, 305 mm, and 305+ mm). According to the AASHTO RDG, a tree with a diameter greater than 4 in. (102 mm) is a fixed object [1]. Lower fracture energies may correspond with 4-in. (102-mm) diameter trees. The probability of small-diameter trees causing a fatality may also be lower as compared to larger diameter trees. Likewise, 2-in. (51-mm) diameter trees are easily removed and do not require further analysis. Because of the redundancy in analyzing trees with larger diameters, only a few diameters were chosen to be representative of trees present near the roadside. Trees with diameters larger than 12 in. (305 mm) would likely be associated with high risks of injury or fatality and thus have high impact severities, so they may be considered rigid with little loss of accuracy.

A previous study was performed which attempted to estimate the breakaway energy of trees impacted by vehicles and resulted in an exponential relationship between diameter and breakaway energy [21]. Even though the RSAP severities do not reflect the recommended breakaway energies provided by Labra and Mak, the RSAP severity indices were not adjusted since the values had the same order of magnitude. Furthermore, large variations were present in the breakaway energy study. Thus, precise values for these energies—particularly due to variations in species, water availability, and climate—were not easily determined, and changes to RSAP severities were not justifiable.

6.2.3 Road Geometry

The tree analysis was conducted on a straight section of road with no vertical grade. Vertical grades are common on low-volume roadways and are expected to influence the number of accidents that occur on these roadways. Thus, areas on hills or at crests will likely recommend more stringent treatment of trees near the roadside. However, preliminary results on straight, level road sections indicated a high cost-effectiveness with removing all types of trees, regardless of size. Since the treatment of trees on level, straight roads was recommended for most tree configurations and hills are believed to be more critical than level road sections, a conservative approach for treating trees was recommended. Analyzing trees on slopes was not conducted due to limitations in RSAP for treating fixed objects located on slopes, as discussed previously.

The roadway was modeled as a rural local road, with two lanes of travel and an undivided median. Shoulder width, which has been demonstrated to have little effect on the results [22], was set to 2 ft (0.61 m). Tree modeling parameters are documented in Table 25 and are shown schematically in Figure 15.

Table 25. Tree Modeling Parameters

Offset, L	ft	0, 3, 7, 10
	m	0, 0.9, 2.1, 3.0
Diameter, D	in.	6, 10, 12+
	mm	152, 254, 305+
Spacing, S	ft	4, 15, 30
	m	1.5, 4.6, 9.1
ADT	vpd	50, 100, 150, 200, 250,
		300, 350, 400, 450, 500
Number of Trees		1, 4, 10, 25

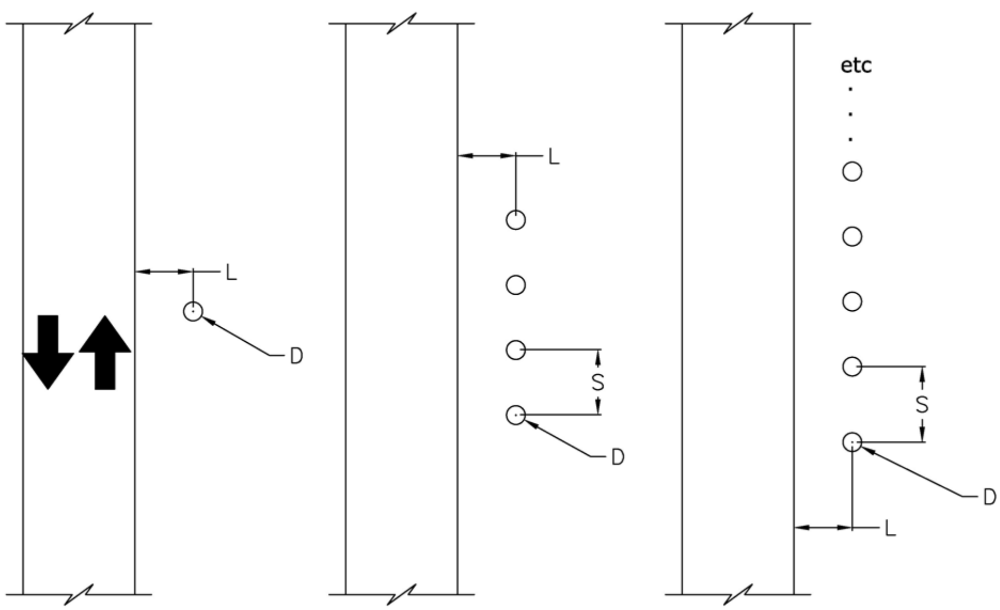


Figure 15. Tree Modeling Parameters and Locations

6.2.4 Tree Offset

Lateral tree offset from the roadway was also a critical factor in the determination of the treatment of trees. Since a low-volume roadway has a clear zone of 12 to 14 ft (3.7 to 4.3 m) for 6H:1V or flatter slopes based on recommendations provided in the RDG [1], county and local governments are not responsible for treatment of trees outside of this window. However, the treatment of trees outside of the clear zone may be considered based on other geometric factors, such as steeper foreslopes. Moreover, trees may be planted and maintained by property owners when they occur outside of the clear zone. Many residents who care for trees are unwilling to permit local governments to treat or remove trees on private properties. Legal proceedings may have to occur in order to remove high risk trees. Furthermore, tree treatment recommendations are difficult to enforce and defend in litigation lawsuits when trees occur outside of the clear zone and beyond the required bounds of local governments and authorities.

Nonetheless, trees located more than 13 ft (3.96 m) from the roadside pose a significant risk to errant motorists, and these trees are often responsible for motor-vehicle fatalities. Due to the potential legal issues associated with the treatment of trees outside of the clear zone, it is recommended that agencies conduct a site-specific benefit-to-cost analysis on the tree(s) in question to determine which treatment option to implement.

6.2.5 Tree Spacing

Vehicle run-off-road trajectories were considered in order to determine the maximum tree spacing at which multiple trees could be considered a single line of trees. For a 30-ft (9.1-m) tree spacing, vehicles measuring 6.5 ft (2.0 m) wide were able to pass between the trees at departure angles less than 13 degrees. Any tree spacing greater than 30 ft (9.1 m) was believed to be more representative of individual trees.

Three typical tree spacings were chosen, consisting of 4 ft, 15 ft, and 30 ft (1.2 m, 4.6 m, and 9.1 m). Most vehicles traveling on low-volume roads are likely pickups or passenger cars which are between 12 and 19 ft (3.7 and 5.8 m) long and 5 and 7 ft (1.5 and 2.1 m) wide. Thus, tree spacings of 15 ft (4.6 m) are difficult to penetrate between for run-off-road vehicles. Based on an average vehicle width of 6.5 ft (2.0 m), the minimum departure angle required to allow a vehicle to pass between 6-in. (152-mm) diameter trees at a 15-ft (4.6-m) spacing without contact is 24.1 degrees. This angle was calculated using the assumption that trees are perfect cylinders, vehicles are rectangular objects, and vehicles were free-wheeling after departing the roadway. A 4-ft (1.2-m) spacing will typically consist of smaller diameter trees located close to one another. This configuration is a good representation of trees found near water sources. It also represents a worst-case scenario in terms of tree densities and the potential restrictive geometric designs and narrow, off-road recovery areas.

6.2.6 Road Modeling

The length of the modeled road was 1,000 ft (304.8 m) long. The trees were centered in the section at 500 ft (152.4 m). The roadway was modeled as a rural local road, with two lanes of travel and an undivided median. A lane width of 12 ft (3.7 m) and a shoulder width of 2 ft (0.6 m) were used. The nominal percent of trucks was set to two percent, and the speed limit was 55 mph (89 km/h). The traffic growth factor was zero, and the encroachment rate adjustment factor was left unchanged at the default value of 1.

6.3 Obstacle Treatment Alternatives

Roadside trees are unique in that only a few widely-accepted treatments exist. Unlike similar fixed objects, such as utility poles, trees cannot simply be moved outside the clear zone. Instead, a tree can be removed, delineated, or shielded by a longitudinal barrier. These treatment options are discussed in greater detail in the following sections.

6.3.1 Do Nothing

The baseline condition was to allow the trees to remain in place in their current configuration. To model the baseline condition, trees were placed at the analyzed position from the roadway. The tree position was taken to be the lateral offset to the traffic-side face of the tree trunk. Trees were located a minimum of 350 ft (107 m) from the start of the road section.

6.3.2 Tree Removal

The safest treatment method was tree removal. This treatment alternative often requires hired workers to travel to the indicated site with rented chainsaws, dump trucks, and stump grinders. Tree removal will often require trees to be cut into reasonably-sized sections for disposal or resale and will often involve stump grinding to prevent tree regrowth and provide for a smooth landscape area.

Based on conversations with tree removal experts, county forestry commissioners, and county engineers, the cost of removing a single 6-in. (152-mm) diameter tree should not exceed $160 and would consist of two workers with a combined labor rate of $60/hour for one and one-half hour plus the cost of renting a chainsaw, dump truck, and stump grinder for one day. For smaller trees, the time required to complete the work would be less, effectively reducing the cost. This overestimation, however, was insignificant on small trees.

Larger diameter trees were expected to have higher costs, but not greater than an additional one-half hour of work per increase in tree size. Therefore, 10-in. (254-mm) diameter trees were believed to cost no more than $190 to remove, and the 12+ in. (305+ mm) diameter trees would cost no more than $220 per tree removal (assuming a 14-in. (356-mm) diameter tree was representative of this class). Tree removal prices were based on the indicated costs for equipment and labor provided by a Highway Superintendent in Saunders County, Nebraska, and verified by averaging previous account charges for tree removal from landscapers in Lincoln, Nebraska. Tree removal costs are provided in Tables 26 and 27.

Table 26. Estimated Tree Removal Costs Based on Cost Components

Rental Costs	
Dump Truck	$31.00 /hr
Chainsaw	
Unit	$1.50 /hr
Pole Attachment	$1.65 /hr
Stump Removal	$50.00 /stump
Labor	$60.00 /hr

* Included cost of travel, equipment, and labor

Table 27. Tree Removal Prices Based on Tree Size

Tree Size	Scenario Cost by Hazard Size*			
	1 Tree	4 Trees	10 Trees	25 Trees
6 in. (152 mm)	$160	$640	$1,600	$4,000
10 in. (254 mm)	$190	$760	$1,900	$4,750
12+ in. (305+ mm)	$220	$880	$2,200	$5,500

*Included cost of travel, equipment, and labor

Since tree groups were also evaluated, a reliable method for estimating tree removal costs was necessary for large-scale removal efforts. However, based on the size and diameter of the trees, the proximity to other trees, worker safety concerns, and the possibility of having to dump and reload a dump truck with tree debris, it was decided that a high estimate for tree removal prices per additional tree should be equal to the price of removing a single tree. It was believed that this approximation significantly over-estimates tree removal prices, as it is likely that four or more trees may be cut down and removed at a single time by two workers in less than two hours. If this is true, the cost of removing five trees would be closer to $300 than the $800 estimated by multiplying the number of trees removed by the single tree price estimate. As a result, a very significant margin of error is included for multiple trees removed at one time.

6.3.3 Install Longitudinal Barrier

Another treatment method for trees included the installation of a crashworthy guardrail system. As with delineation, a guardrail system denotes that a fixed object or geometric feature is located beyond the traveled way. A guardrail system also prevents vehicular impacts with trees by capturing or redirecting vehicles prior to contact. However, the high price of guardrail makes it cost-effective only for very long sections of closely-spaced trees or when tree removal is difficult due to tree size and location relative to other objects. In the scenarios simulated for low-volume roadways, longitudinal barriers were not more cost-effective than the do nothing or tree removal option for any scenario. Therefore, the results given in this report do not include this safety treatment option. However, other safety constraints may require the use of these barrier systems, and the engineer should use conservatively safe judgment in determining the treatment of tree configurations.

Guardrail systems can also pose risks to errant motorists, and impacts with barriers often result in vehicle damage. Guardrail systems require maintenance and repair after impacts. Consequently, tree removal requires limited effort on behalf of the transportation agencies, and many types of delineators are impact-resistant. Due to the vast number of situations associated with guardrail placement in front of trees, it was determined that the guardrail treatment option was not feasible for most tree configurations. Thus, guardrail installations for shielding trees should be approached on a case-by-case basis to determine when and where guardrail should be placed.

For further guidance in selecting a longitudinal barrier refer to the AASHTO RDG for general guidelines or the Barrier Guide for Low Volume and Low Speed Roads for specific and extended guidelines [1, 16].

6.3.4 Delineation

The final tree treatment method was to warn motorists of tree hazards located near the roadway with delineating devices. Based on various state departments of transportation surveys, delineators are credited with a 30 percent and 15 percent reduction in roadside departures and run-off-road crashes on curves and straight road sections, respectively [1, 20-21]. Benefits of delineator placement on low-volume roadways may be greater due to the reduced visibility in many areas and the lack of adequate warning devices or edge markings.

Delineation costs are difficult to accurately estimate. Delineator devices range in cost from $15 to $50 per delineator. Though installation of delineation devices may be accomplished rapidly, often in less than 10 minutes, travel time and labor costs will increase the overall installation cost. Labor costs may dominate the total cost of installing delineators. Delineation may reduce the number of run-off-road excursions that occur on low-volume roadways, but they do not shield the fixed object. Thus, delineators will be expected to be cost-effective only in densely-forested areas where tree removal of all surrounding trees is not cost-effective.

6.4 Simulation Results

The results of the tree analysis are shown in Tables 28 through 35. The results of the tree analyses are shown in an extended graphical form in Appendix B. The only cost-effective treatment option was tree removal. Therefore, any mention of treatment in this section refers to tree removal. For a benefit-to-cost ratio of 4, tree removal was recommended for all roads with an ADT greater than 400 vpd. For a benefit-to-cost ratio of 2, tree removal was recommended on all roadways with ADT greater than 300 vpd. In many scenarios, tree removal was cost-effective for all ADTs.

Tree spacing was considered an important parameter in the analysis. However, the analysis indicated that it was cost-effective to remove trees near the roadways for most scenarios, including a very close tree spacing of 4 ft (1.2 m) and a minimum ADT of 50 vpd. As the lateral tree offset away from the road increased, the analysis resulted in a recommended treatment for minimum ADTs of 100 and 150 vpd for 7-ft (2.1-m) and 10-ft (3.0-m) lateral offsets, respectively. Since the effective obstacle length, or longitudinal distance by which errant vehicles may impact at least one of the trees, is doubled, a 9-ft (2.7-m) tree spacing also indicated that tree removal was cost-effective at low ADTs. The difference between lateral offsets of 15 and 30 ft (4.6 and 9.1 m) was minimal, and both spacings indicated that it was cost-effective to remove trees of any size in all configurations and for all lateral offsets.

Table 28. Recommendations for Single Tree Treatment, B/C = 2

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
1	all	-	all		0-500

Table 29. Recommendations for Treatment of 2 to 10 Trees, B/C = 2

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
2-10	< 6 in.	< 4 ft	< 10 ft	0-49	50-500
2-10	< 6 in.	< 4 ft	≥ 10 ft	0-99	100-500
2-10	< 6 in.	4 - 15 ft	< 7 ft		0-500
2-10	< 6 in.	4 - 15 ft	≥ 7 ft	0-49	50-500
2-10	< 6 in.	> 15 ft	< 3 ft		0-500
2-10	< 6 in.	> 15 ft	≥ 3 ft	0-49	50-500
2-10	6 - 11.9 in.	< 4 ft	< 10 ft		0-500
2-10	6 - 11.9 in.	< 4 ft	≥ 10 ft	0-49	50-500
2-10	6 - 11.9 in.	4 - 15 ft	< 7 ft		0-500
2-10	6 - 11.9 in.	4 - 15 ft	≥ 7 ft	0-49	50-500
2-10	6 - 11.9 in.	> 15 ft	all		0-500
2-10	≥ 12 in.	< 4 ft	< 7 ft		0-500
2-10	≥ 12 in.	< 4 ft	≥ 7 ft	0-49	50-500
2-10	≥ 12 in.	4 - 15 ft	< 10 ft		0-500
2-10	≥ 12 in.	4 - 15 ft	≥ 10 ft	0-99	100-500
2-10	≥ 12 in.	> 15 ft	< 7 ft		0-500
2-10	≥ 12 in.	> 15 ft	≥ 7 ft	0-49	50-500

Table 30. Recommendations for Treatment of 11 to 25 Trees, B/C = 2

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
11-25	< 6 in.	< 4 ft	< 7 ft	0-99	100-500
11-25	< 6 in.	< 4 ft	7 - 10 ft	0-149	150-500
11-25	< 6 in.	< 4 ft	> 10 ft	0-199	200-500
11-25	< 6 in.	4 - 15 ft	< 10 ft	0-49	50-500
11-25	< 6 in.	4 - 15 ft	≥ 10 ft	0-99	100-500
11-25	< 6 in.	> 15 ft	< 7 ft		0-500
11-25	< 6 in.	> 15 ft	≥ 7 ft	0-49	50-500
11-25	6 - 11.9 in.	< 4 ft	< 10 ft	0-49	50-500
11-25	6 - 11.9 in.	< 4 ft	≥ 10 ft	0-99	100-500
11-25	6 - 11.9 in.	4 - 15 ft	< 7 ft		0-500
11-25	6 - 11.9 in.	4 - 15 ft	≥ 7 ft	0-49	50-500
11-25	6 - 11.9 in.	> 15 ft	all		0-500
11-25	≥ 12 in.	< 4 ft	< 7 ft		0-500
11-25	≥ 12 in.	< 4 ft	≥ 7 ft	0-99	100-500
11-25	≥ 12 in.	4 - 15 ft	< 7 ft		0-500
11-25	≥ 12 in.	4 - 15 ft	≥ 7 ft	0-49	50-500
11-25	≥ 12 in.	> 15 ft	< 10 ft		0-500
11-25	≥ 12 in.	> 15 ft	≥ 10 ft	0-99	100-500

Table 31. Recommendations for Treatment of More than 25 Trees, B/C = 2

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
> 25	< 6 in.	< 4 ft	< 3 ft	0-149	150-500
> 25	< 6 in.	< 4 ft	3 - 7.9 ft	0-199	200-500
> 25	< 6 in.	< 4 ft	8 - 10 ft	0-249	250-500
> 25	< 6 in.	< 4 ft	> 10 ft	0-299	300-500
> 25	< 6 in.	4 - 15 ft	< 7 ft	0-49	50-500
> 25	< 6 in.	4 - 15 ft	≥ 7 ft	0-99	100-500
> 25	< 6 in.	> 15 ft	< 7 ft		0-500
> 25	< 6 in.	> 15 ft	≥ 7 ft	0-49	50-500
> 25	6 - 11.9 in.	< 4 ft	< 3 ft	0-49	50-500
> 25	6 - 11.9 in.	< 4 ft	3 - 10 ft	0-99	100-500
> 25	6 - 11.9 in.	< 4 ft	> 10 ft	0-149	150-500
> 25	6 - 11.9 in.	4 - 15 ft	< 7 ft		0-500
> 25	6 - 11.9 in.	4 - 15 ft	7 - 10 ft	0-49	50-500
> 25	6 - 11.9 in.	4 - 15 ft	> 10 ft	0-99	100-500
> 25	6 - 11.9 in.	> 15 ft	< 7 ft		0-500
> 25	6 - 11.9 in.	> 15 ft	≥ 7 ft	0-49	50-500
> 25	≥ 12 in.	< 4 ft	< 3 ft	0-99	100-500
> 25	≥ 12 in.	< 4 ft	≥ 3 ft	0-149	150-500
> 25	≥ 12 in.	4 - 15 ft	< 3 ft		0-500
> 25	≥ 12 in.	4 - 15 ft	3 - 7 ft	0-49	50-500
> 25	≥ 12 in.	4 - 15 ft	> 7 ft	0-99	100-500
> 25	≥ 12 in.	> 15 ft	< 7 ft		0-500
> 25	≥ 12 in.	> 15 ft	≥ 7 ft	0-49	50-500

Table 32. Recommendations for Single Tree Treatment, B/C = 4

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
1	all	-	all		0-500

Table 33. Recommendations for Treatment of 2 to 10 Trees, B/C = 4

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
2-10	< 6 in.	< 4 ft	< 3 ft	0-49	50-500
2-10	< 6 in.	< 4 ft	3 - 7.9 ft	0-99	100-500
2-10	< 6 in.	< 4 ft	8 - 10 ft	0-149	150-500
2-10	< 6 in.	< 4 ft	> 10 ft	0-199	200-500
2-10	< 6 in.	4 - 15 ft	< 7 ft	0-49	50-500
2-10	< 6 in.	4 - 15 ft	7 - 10 ft	0-99	100-500
2-10	< 6 in.	4 - 15 ft	> 10 ft	0-149	150-500
2-10	< 6 in.	> 15 ft	< 10 ft	0-49	50-500
2-10	< 6 in.	> 15 ft	≥ 10 ft	0-99	100-500
2-10	6 - 11.9 in.	< 4 ft	< 10 ft	0-49	50-500
2-10	6 - 11.9 in.	< 4 ft	≥ 10 ft	0-99	100-500
2-10	6 - 11.9 in.	4 - 15 ft	< 3 ft		0-500
2-10	6 - 11.9 in.	4 - 15 ft	≥ 3 ft	0-49	50-500
2-10	6 - 11.9 in.	> 15 ft	< 7 ft		0-500
2-10	6 - 11.9 in.	> 15 ft	≥ 7 ft	0-49	50-500
2-10	≥ 12 in.	< 4 ft	< 7 ft		0-500
2-10	≥ 12 in.	< 4 ft	7 - 10 ft	0-49	50-500
2-10	≥ 12 in.	< 4 ft	> 10 ft	0-99	100-500
2-10	≥ 12 in.	4 - 15 ft	< 3 ft		0-500
2-10	≥ 12 in.	4 - 15 ft	3 - 7 ft	0-49	50-500
2-10	≥ 12 in.	4 - 15 ft	> 7 ft	0-99	100-500
2-10	≥ 12 in.	> 15 ft	< 7 ft		0-500
2-10	≥ 12 in.	> 15 ft	≥ 7 ft	0-49	50-500

Table 34. Recommendations for Treatment of 11 to 25 Trees, B/C = 4

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
11-25	< 6 in.	< 4 ft	< 3 ft	0-149	150-500
11-25	< 6 in.	< 4 ft	3 - 7.9 ft	0-199	200-500
11-25	< 6 in.	< 4 ft	8 - 10 ft	0-249	250-500
11-25	< 6 in.	< 4 ft	> 10 ft	0-299	300-500
11-25	< 6 in.	4 - 15 ft	< 7 ft	0-99	100-500
11-25	< 6 in.	4 - 15 ft	7 - 10 ft	0-149	150-500
11-25	< 6 in.	4 - 15 ft	> 10 ft	0-199	200-500
11-25	< 6 in.	> 15 ft	< 7 ft	0-49	50-500
11-25	< 6 in.	> 15 ft	≥ 7 ft	0-99	100-500
11-25	6 - 11.9 in.	< 4 ft	< 7 ft	0-49	50-500
11-25	6 - 11.9 in.	< 4 ft	≥ 7 ft	0-199	200-500
11-25	6 - 11.9 in.	4 - 15 ft	< 7 ft		0-500
11-25	6 - 11.9 in.	4 - 15 ft	≥ 7 ft	0-99	100-500
11-25	6 - 11.9 in.	> 15 ft	all		0-500
11-25	≥ 12 in.	< 4 ft	< 3 ft	0-49	50-500
11-25	≥ 12 in.	< 4 ft	3 - 7.9 ft	0-149	150-500
11-25	≥ 12 in.	< 4 ft	8 - 10 ft	0-199	200-500
11-25	≥ 12 in.	< 4 ft	> 10 ft	0-249	250-500
11-25	≥ 12 in.	4 - 15 ft	< 7 ft		0-500
11-25	≥ 12 in.	4 - 15 ft	7 - 10 ft	0-99	100-500
11-25	≥ 12 in.	4 - 15 ft	> 10 ft	0-149	150-500
11-25	≥ 12 in.	> 15 ft	< 3 ft		0-500
11-25	≥ 12 in.	> 15 ft	3 - 7 ft	0-49	50-500
11-25	≥ 12 in.	> 15 ft	> 7 ft	0-99	100-500

Table 35. Recommendations for Treatment of More than 25 Trees, B/C = 4

Number of Trees	Tree Diameter	Tree Spacing	Offset from Roadway	Do Nothing (ADT)	Remove Tree (ADT)
> 25	< 6 in.	< 4 ft	< 7 ft	0-199	200-500
> 25	< 6 in.	< 4 ft	7-10 ft	0-299	300-500
> 25	< 6 in.	< 4 ft	> 10 ft	0-349	350-500
> 25	< 6 in.	4 - 15 ft	< 3 ft	0-99	100-500
> 25	< 6 in.	4 - 15 ft	3 - 7 ft	0-149	150-500
> 25	< 6 in.	4 - 15 ft	> 7 ft	0-199	200-500
> 25	< 6 in.	> 15 ft	< 7 ft	0-49	50-500
> 25	< 6 in.	> 15 ft	≥ 7 ft	0-99	100-500
> 25	6 - 11.9 in.	< 4 ft	< 3 ft	0-149	150-500
> 25	6 - 11.9 in.	< 4 ft	3 - 7 ft	0-199	200-500
> 25	6 - 11.9 in.	< 4 ft	8 - 10 ft	0-249	250-500
> 25	6 - 11.9 in.	< 4 ft	> 10 ft	0-299	300-500
> 25	6 - 11.9 in.	4 - 15 ft	< 7 ft		0-500
> 25	6 - 11.9 in.	4 - 15 ft	≥ 7 ft	0-99	100-500
> 25	6 - 11.9 in.	> 15 ft	< 3 ft		0-500
> 25	6 - 11.9 in.	> 15 ft	≥ 3 ft	0-49	50-500
> 25	≥ 12 in.	< 4 ft	< 3 ft	0-199	200-500
> 25	≥ 12 in.	< 4 ft	3 - 7 ft	0-249	250-500
> 25	≥ 12 in.	< 4 ft	8 - 10 ft	0-299	300-500
> 25	≥ 12 in.	< 4 ft	> 10 ft	0-399	400-500
> 25	≥ 12 in.	4 - 15 ft	< 3 ft		0-500
> 25	≥ 12 in.	4 - 15 ft	3 - 10 ft	0-99	100-500
> 25	≥ 12 in.	4 - 15 ft	> 10 ft	0-149	150-500
> 25	≥ 12 in.	> 15 ft	< 10 ft	0-49	50-500
> 25	≥ 12 in.	> 15 ft	≥ 10 ft	0-99	100-500

6.5 Discussion

Tree removal may be one of the most cost-effective safety treatments for transportation agencies to consider along low-volume roadways. In 2009, trees accounted for nearly 2,697 fatalities out of a reported 10,555 fixed-object collision fatalities [23]. Therefore, tree removal would be a significant safety improvement wherever trees exist near a roadway.

It should be noted that the benefit-to-cost ratios of tree removal were never less than 1.00. This outcome was due to the high accident cost associated with one tree crash event. Trees are essentially rigid objects and may result in fatalities for even moderate-speed crash events. Further, the rigidity of a tree is largely dependent on the species and may contribute to additional risks not accounted for in the RSAP estimates.

The tree analysis was based on three assumptions: (1) trees were located along flat road sections or were within or behind shallow ditches, such that the ditch may be ignored; (2) the cost of removing groups of trees was equal to the number of trees to be removed multiplied by the removal price for one tree; and (3) no additional obstacles were located behind the trees.

Trees may be located at the bottom of a ditch or on its backslope with the ditch measuring more than 3 ft (0.9 m) deep. However, trees located on slopes or in ditches were not evaluated because the number of configurations of trees, slopes, and road geometries was too numerous. In addition, the scope of the analyses only considered roadside trees. An RSAP analysis was not believed to provide accurate benefit-to-cost ratio results for trees on slopes or within ditches. Since RSAP evaluates fixed objects based on predefined scenarios, tree placement in the bottom of a ditch or up a backslope would not likely reflect the actual vehicle tendency to strike a tree. If further advancements are made with respect to slope effects on vehicle stability or improved slope-object interactions, further studies may be beneficial to investigate trees in alternative configurations or locations, especially on or at the bottom of slopes.

The relationship between the number of trees removed and the total expected cost was assumed to be linear. This relationship might overestimate tree removal costs for more than one tree. The cost of tree removal was estimated based on personnel travel time, equipment rental, and labor costs, and the cost of removing multiple trees is potentially less than assumed by the linear relationship. One tree removal company indicated that up to fifteen 6-in. (152-mm) diameter trees may be removed in one hour for less than $600. However, tree removal prices are dependent on terrain, required equipment, worker and other safety, and additional care required. Tree removal near power lines or houses will likely be more expensive than at locations away from any obstacles. Due to the difficulty in estimating tree removal prices, an overestimate was used which should encompass any additional expenses that might be incurred for a particular tree removal scenario. Thus, these guidelines should represent a worst-case scenario. If the cost of tree removal is less than was assumed in this study, and treatment is not recommended on a roadway with a tree configuration, an individual benefit-to-cost analysis is recommended to determine whether tree removal is a cost-effective treatment option.

Since it was assumed that there were no objects located behind the trees, it was not certain what effect surrounding features may have on the tree analyses. If other trees are located in the clear zone or if additional fixed objects are present, the cost-effectiveness of tree removal may be reduced. However, tree removal remains a cost-effective measure for reducing the roadside accident severity unless the obstacle behind the tree is a greater risk than the tree itself. For situations in which the fixed objects behind the tree pose even greater risk, guardrail placement may be a cost-effective treatment to shield the entire region. Therefore, it is recommended that further benefit-to-cost analyses and evaluations be conducted in locations with different types of obstacles, including trees, in order to consider all safety treatment options.

Delineation was considered to be a possible treatment alternative, but quantitative guidelines for determining the effectiveness of delineation were not provided. Delineation may prove to be effective to inattentive or impaired drivers by alerting motorists of an obstacle. This effect may reduce the number and speed of tree impacts due to heightened awareness. However, many crashes are the result of avoidance maneuvers, traffic violations, and mechanical failures [24]. Delineation will not result in a reduction in the severity of a tree impact event if the departure is caused by weather, vehicle component malfunction, or avoidance maneuvers on the roadway. For this reason, delineators should not be used in lieu of other noted tree treatment guidelines. Instead, additional investigation may be desired to evaluate how delineation may affect speed distribution and encroachments on very low-volume roadways where obstacle treatment guidelines indicated that tree removal was not a cost-effective solution. Individual analysis may be needed based on clearly-defined and quantifiable safety improvements for delineation.

Finally, it should be noted that trees near the roadway are an unnecessary safety risk. Wherever it proves cost-effective, tree removal should occur since trees pose significant risk to errant motorists. Additional measures to prevent future growth or encroachment of trees into the clear zone may be very cost-effective and save lives as well. Removal of small saplings by trimming or mowing operations is a cost-effective, preventative measure. Although the aesthetic quality of trees is often promoted, aesthetics should be satisfied in such a way as to not pose undue safety risks to errant motorists.

6.6 Conclusions and Recommendations

Analyses were performed to evaluate the cost-effectiveness of various treatment options for trees found within a clear zone. The investigation was conducted based on a modified road geometry that was used in the culvert study and on field observations of tree growth patterns. Four tree-treatment methods were considered during the cost-effectiveness evaluation.

The first treatment alternative consisted of the "do nothing" option, which represented the baseline condition. The second treatment alternative consisted of tree removal. Tree removal prices were estimated based on conversations with tree removal and forestry experts, county engineers, and companies. Tree removal was considered the safest and primary alternative if the trees were located away from other obstacles. The third treatment alternative incorporated guardrail installation to shield errant motorists from a configuration of trees. It was determined that guardrail installation was not a cost-effective solution for reducing the risk associated with trees due to the high initial cost, small object size, and added risk of striking a guardrail system. The final treatment alternative was tree delineation. Due to the difficulties in quantifying the benefits of delineation, this treatment option was not considered in the RSAP analyses. Thus, an in-service performance evaluation of the delineation alternative could be used to investigate its effectiveness in a variety of low-volume roadway conditions.

Tree removal was recommended on all roadways with an ADT greater than 300 and 400 vpd for a benefit-to-cost ratio of 2.0 and 4.0, respectively. Many roadways with trees spaced moderately close together, i.e., 10 to 15 ft (3.0 to 4.6 m), had tree removal recommended for all ADTs. Furthermore, recommendations for tree removal generally indicated a higher cost-effectiveness for removing larger diameter trees as compared to smaller trees. Nonetheless, removal of saplings may represent the most cost-effective solution for risk mitigation by eliminating future fixed objects. Otherwise, recommendations were made based on the number of trees being considered.

For a benefit-to-cost ratio of 2.0 and for a single tree, tree removal was recommended in every scenario. For 2 to 10 trees, the "do-nothing" alternative became cost-effective up to 50 vpd, but only for minimal lateral offsets and larger tree spacings. The diameter of the tree did not significantly influence these recommendations. For 11 to 25 trees, the "do-nothing" alternative became cost-effective as traffic volumes increased to 150 vpd but was not recommended for large lateral offsets and large tree spacing. In this case, tree diameter was influential. As tree diameter increased, the range in traffic volumes had decreased over which the "do nothing" option was permitted. In many scenarios, tree removal was the only recommended option. For more than 25 trees, the traffic volumes at which the "do nothing" option was permitted increased again. As before, only for large lateral offsets and larger spacings was it recommended to "do nothing."

For a benefit-to-cost ratio of 4.0, the required benefit of tree removal was increased. As a result, the "do nothing" option was generally more attractive. For only a single tree, tree removal was still recommended in all scenarios. However, as the number of trees increased, tree removal became less cost-effective, in part due to the increased benefit-cost threshold.

7 ANALYSIS OF ROADSIDE SLOPES

7.1 Introduction

Roadside slopes are common geometric roadside features found along low-volume roads. In general, three types of slopes can be found along a roadway—foreslopes, backslopes, and transverse slopes. During the field investigation, foreslopes were primarily found and documented. Therefore, only foreslopes will be considered in this investigation. The AASHTO Roadside Design Guide identifies three types of foreslopes—recoverable, non-recoverable, and critical [1]. Recoverable foreslopes are generally 4H:1V or flatter, while non-recoverable slopes are steeper than 4H:1V but equal to or flatter than 3H:1V. Non-recoverable slopes are defined as slopes that are traversable, but a vehicle cannot easily stop or return to the roadway. Critical slopes are steeper than 3H:1V. On these slopes, the vehicle may be inclined to roll over. Critical slopes were evaluated within this study.

7.2 Modeling Procedure

7.2.1 Slope Details

Upon completion of the field investigation, the most common and critical slopes were 1.5H:1V, 2H:1V, and 3H:1V. Barriers are usually recommended for most slopes steeper than 3H:1V with the exception of low fill heights, such as 4 ft (1.2 m) and smaller [1]. However, the noted barrier recommendation may disappear on low-volume roads with embankment heights less than 50 ft (15 m) according to an example design chart in the RDG [1]. The slope lengths were determined based on typical ranges found on low-volume roads. A summary of the RSAP parameters is shown in Table 36.

Table 36. Summary of RSAP Parameters for Slopes

Slope Profile		3H:1V, 2H:1V, 1.5H:1V
Foreslope Drop Height	ft (m)	7, 13, 20, 26 (2, 4, 6, 8)
Length	ft (m)	50, 100, 250, 500, 1000 (15, 30.5, 76, 152, 305)
Lateral Offset	ft (m)	0, 3, 7, 10 (0, 0.9, 2.1, 3)
ADT	vpd	50, 100, 150, 200, 250, 300, 350, 400, 450, 500

The fill heights were defined by the feature parameters that are available in RSAP. Lateral offsets can be user-defined, which were chosen to represent typical situations found along low-volume roads. A graphical example of the setup used in RSAP is shown in Figure 16.

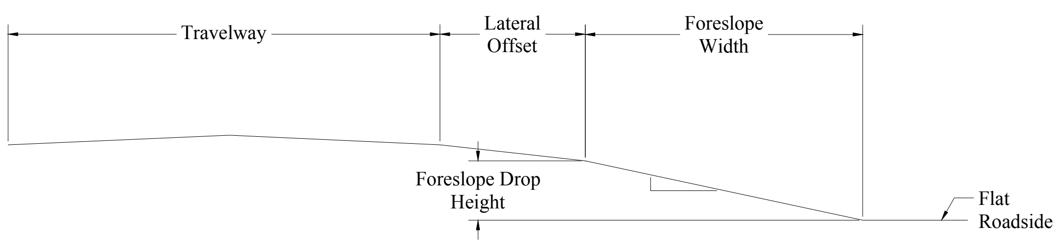


Figure 16. Schematic of Slopes in RSAP

The transition from the travelway to the slope and from the slope back to flat roadside was modeled as a series of foreslopes. These foreslopes run perpendicular to the roadway and were chosen to replicate those found in real-world applications. Several models were configured using these typical slope scenarios and are shown in Figure 17. The gradual decline toward the main slope was configured as 6H:1V along the roadway. Therefore, the length of the sloped transition was determined by the drop height of the slope. The transition slopes were then broken into sections, using no more than three for the top two largest drop heights. The lengths of these sloped transition sections were equally divided before and after the main slope. Several drop heights were used as well to transition from level ground down to the desired drop height. The transition slopes were all equal in length, as shown in Figure 17.

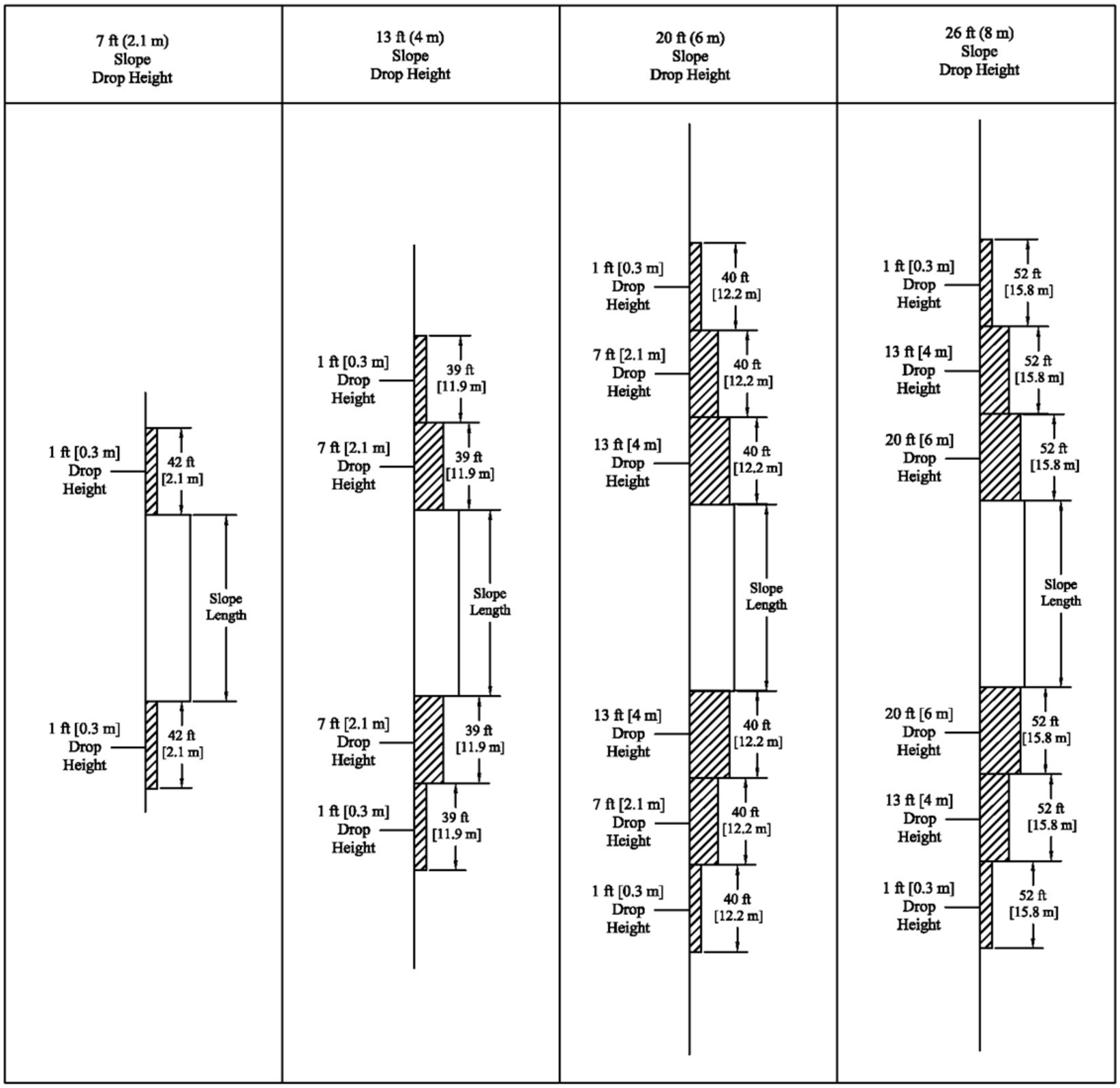


Figure 17. Schematic of Foreslopes in RSAP

7.2.2 Road Modeling

The slope analysis was conducted on a straight section of road with no vertical grade. The road segment was 1,500 ft (457.2 m) long in order to accommodate the longest slope of 1,000 ft (304.8 m). The slopes were centered in the road geometry, and starting distances varied depending on length of the slope parallel to the road. The roadway was modeled as a rural local road with two lanes of travel and an undivided median. A lane width of 12 ft (3.7 m) and a shoulder width of 2 ft (0.6 m) were used. The nominal percent of trucks was set to 2 percent, and the speed limit was 55 mph (89 km/h). The traffic growth factor was zero, and the encroachment rate adjustment factor was left unchanged at the default value of 1.

7.3 Treatment Options

Several different treatment alternatives were evaluated during the simulation effort. These alternatives included doing nothing, installing W-beam guardrail, and installing cable guardrail. Additionally, slope flattening may be used to treat critical slopes. These treatment alternatives are discussed in greater detail in the following sections.

7.3.1 Do Nothing

Most slopes found on the roadside were not protected by an existing barrier. The baseline option for RSAP was a model of the slopes with the parameters discussed previously.

7.3.2 Install W-beam Guardrail

The second alternative was to install W-beam guardrail along the slope. The length of the guardrail and its terminals were dependent on the slope length and width. Due to the critical slopes, guardrail lengths were selected to shield the entire intersecting slope using the method presented in Wolford and Sicking's report, *Development of Guardrail Runout Length Calculation Procedures* [14]. A schematic of the procedure is shown in Figure 18.

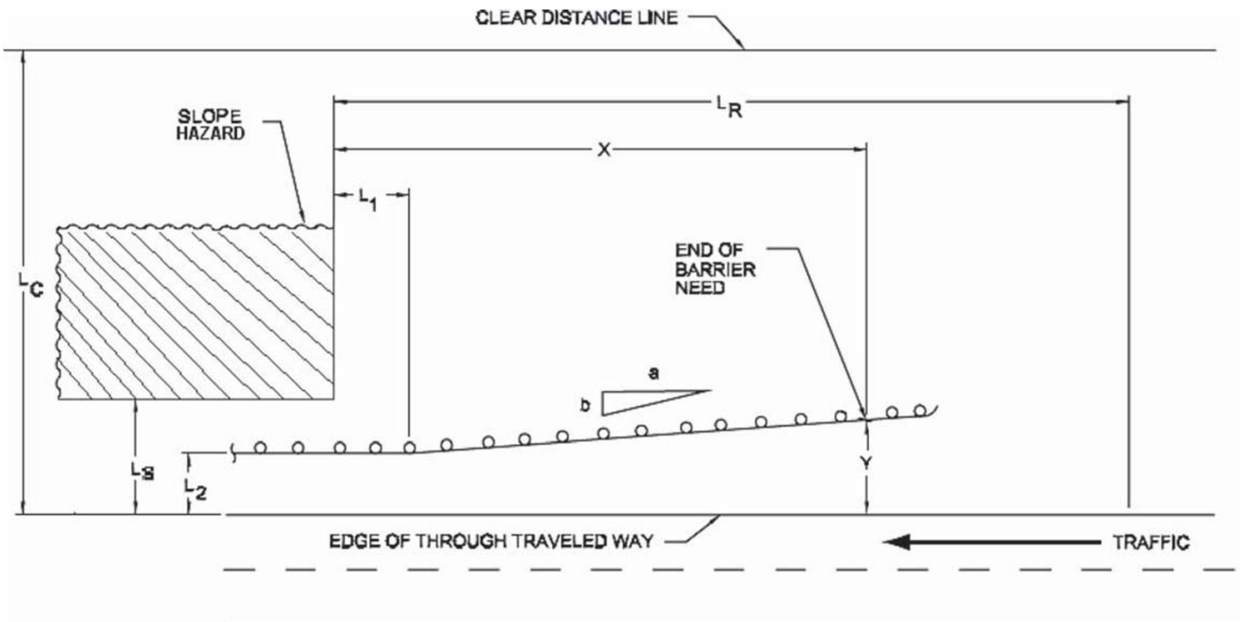


Figure 18. Guardrail Runout Length Schematic

A FLEAT terminal was used for cost and length parameters. For cost purposes, the actual length of the terminal was 37.5 ft (11.4 m). However, it was decided that the modeled terminal length would be defined as 12.5 ft (3.8 m) for the study. After that point, the FLEAT terminal is capable of redirecting a vehicle. The extra 25 ft (7.6 m) was included in the total guardrail length, but it was subtracted from the same W-beam guardrail length for cost calculations.

The upstream and downstream guardrail runout lengths were determined from Figure 19. For this RSAP analysis, the ADT ranged from 50 to 500. In Figure 19, the ADT line of 400 was used to obtain guardrail runout length approximations. For the downstream guardrail runout length, a constant 50 ft (15.2 m) was used. For the upstream guardrail runout length, a line equation was derived in Equation 2.

$$x = 1.55(L_{OD}) + 50 \tag{2}$$

where L_{OD} was the distance from the barrier terminal to the back of the hazard area, as shown in Figure 18. A spreadsheet was created to simplify the process of the RSAP analysis. The spreadsheet contains starting distances and lengths of each guardrail section, depending on the width, height, and slope. This spreadsheet is shown in Table 37. The total guardrail length is the sum of the slope length and the upstream and downstream runout lengths. If the length was an odd number, it was rounded to the next increment of 12.5 ft (3.8 m) in order to use a whole number of W-beam sections. The total barrier length includes an additional 25 ft (7.6 m) due to two 12.5-ft (3.8-m) terminals. The W-beam guardrail was modeled as Test Level 3 (TL-3) guardrail in RSAP, and an SI multiplier of 0.7 was used. The W-beam option was used for 0-, 3-, 7-, and 10-ft (0-, 0.9-, 2.1-, 3-m) lateral offsets.

Several costs for this alternative were provided by KDOT. Also, costs from several states' DOT websites were averaged in order to obtain an accurate cost for installing a W-beam guardrail. These states were Colorado, Montana, Nebraska, Oregon, and Tennessee. There were three cost components for this alternative: (1) traffic control, mobilization, and contingency; (2) TL-3 W-beam guardrail installation; and (3) end terminals. The cost for traffic control and mobilization was 10 percent and 7.5 percent of the total cost, respectively. The traffic control cost was not to exceed $2,000. Contingency was included as 15 percent of the total cost, and it covers anything that might not be covered in the other costs. Cost for the installation of TL-3 W-beam guardrail was $18.16 per linear foot ($59.58 per linear meter), and the terminal cost was $2,100 per 37.5 ft (11.4 m) terminal. The terminals were modeled as 12.5 ft (3.8 m) long, and the extra 25 ft (7.6 m) on each terminal was subtracted from the cost of the TL-3 guardrail cost. The guardrail costs are also shown in Table 37.

A second cost for installation of W-beam guardrail was also given by KDOT. This cost was $45 per linear foot ($147.64 per linear meter). Because this cost was significantly higher than the other averaged states, a second analysis of the same scenarios was considered using these costs. The cost table is shown in Table 38 and the results of this analysis will be discussed later.

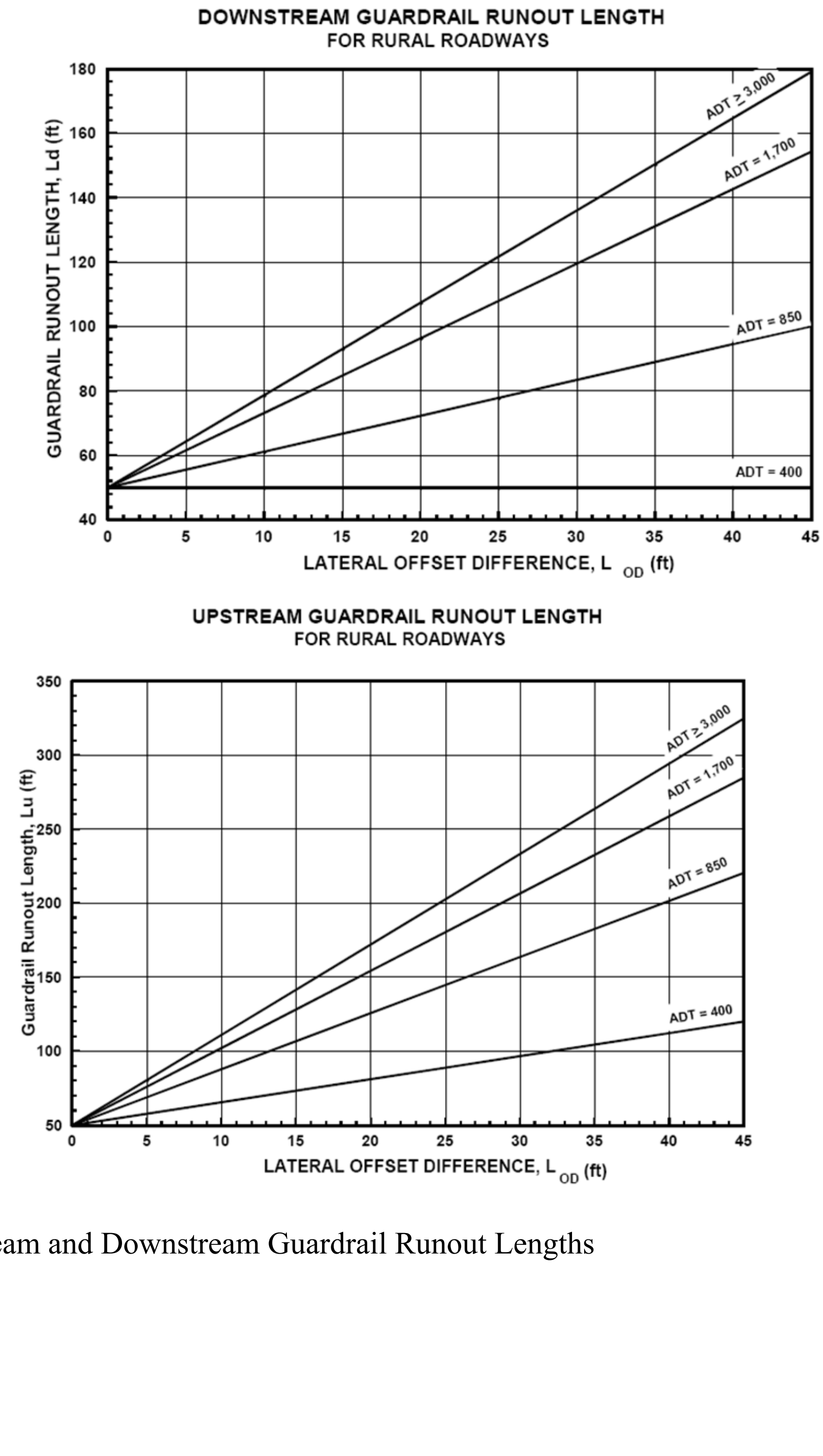


Figure 19. Upstream and Downstream Guardrail Runout Lengths

Table 37. W-Beam Guardrail Placement and Costs, $18.16 per lf

Drop Height [ft]	Slope Rate	Width of Slope [ft]	Length of Slope [ft]	Upstream Terminal Start [ft]	Upstream Guardrail Start [ft]	Guardrail Length [ft]	Downstream Terminal Start [ft]	Total Length [ft]	Cost
7	1.5	10.5	50	650	662.5	162.5	825	187.5	$8,271.98
7	1.5	10.5	100	625	637.5	212.5	850	237.5	$9,475.08
7	1.5	10.5	250	550	562.5	362.5	925	387.5	$13,084.38
7	1.5	10.5	500	425	437.5	612.5	1050	637.5	$19,099.88
7	1.5	10.5	1000	175	187.5	1112.5	1300	1137.5	$30,781.38
7	2	14	50	637.5	650	175	825	200	$8,572.75
7	2	14	100	612.5	625	225	850	250	$9,775.85
7	2	14	250	537.5	550	375	925	400	$13,385.15
7	2	14	500	412.5	425	625	1050	650	$19,400.65
7	2	14	1000	162.5	175	1125	1300	1150	$31,059.45
7	3	21	50	625	637.5	187.5	825	212.5	$8,873.53
7	3	21	100	600	612.5	237.5	850	262.5	$10,076.63
7	3	21	250	525	537.5	387.5	925	412.5	$13,685.93
7	3	21	500	400	412.5	637.5	1050	662.5	$19,701.43
7	3	21	1000	150	162.5	1137.5	1300	1162.5	$31,337.53
13	1.5	19.5	50	637.5	650	175	825	200	$8,572.75
13	1.5	19.5	100	612.5	625	225	850	250	$9,775.85
13	1.5	19.5	250	537.5	550	375	925	400	$13,385.15
13	1.5	19.5	500	412.5	425	625	1050	650	$19,400.65
13	1.5	19.5	1000	162.5	175	1125	1300	1150	$31,059.45
13	2	26	50	625	637.5	187.5	825	212.5	$8,873.53
13	2	26	100	600	612.5	237.5	850	262.5	$10,076.63
13	2	26	250	525	537.5	387.5	925	412.5	$13,685.93
13	2	26	500	400	412.5	637.5	1050	662.5	$19,701.43
13	2	26	1000	150	162.5	1137.5	1300	1162.5	$31,337.53
13	3	39	50	600	612.5	212.5	825	237.5	$9,475.08
13	3	39	100	575	587.5	262.5	850	287.5	$10,678.18
13	3	39	250	500	512.5	412.5	925	437.5	$14,287.48
13	3	39	500	375	387.5	662.5	1050	687.5	$20,302.98
13	3	39	1000	125	137.5	1162.5	1300	1187.5	$31,893.68
20	1.5	30	50	612.5	625	200	825	225	$9,174.30
20	1.5	30	100	587.5	600	250	850	275	$10,377.40
20	1.5	30	250	512.5	525	400	925	425	$13,986.70
20	1.5	30	500	387.5	400	650	1050	675	$20,002.20
20	1.5	30	1000	137.5	150	1150	1300	1175	$31,615.60
20	2	40	50	600	612.5	212.5	825	237.5	$9,475.08
20	2	40	100	575	587.5	262.5	850	287.5	$10,678.18
20	2	40	250	500	512.5	412.5	925	437.5	$14,287.48
20	2	40	500	375	387.5	662.5	1050	687.5	$20,302.98
20	2	40	1000	125	137.5	1162.5	1300	1187.5	$31,893.68
20	3	60	50	575	587.5	237.5	825	262.5	$10,076.63
20	3	60	100	550	562.5	287.5	850	312.5	$11,279.73
20	3	60	250	475	487.5	437.5	925	462.5	$14,889.03
20	3	60	500	350	362.5	687.5	1050	712.5	$20,904.53
20	3	60	1000	100	112.5	1187.5	1300	1212.5	$32,449.83
26	1.5	39	50	600	612.5	212.5	825	237.5	$9,475.08
26	1.5	39	100	575	587.5	262.5	850	287.5	$10,678.18
26	1.5	39	250	500	512.5	412.5	925	437.5	$14,287.48
26	1.5	39	500	375	387.5	662.5	1050	687.5	$20,302.98
26	1.5	39	1000	125	137.5	1162.5	1300	1187.5	$31,893.68
26	2	52	50	587.5	600	225	825	250	$9,775.85
26	2	52	100	562.5	575	275	850	300	$10,978.95
26	2	52	250	487.5	500	425	925	450	$14,588.25
26	2	52	500	362.5	375	675	1050	700	$20,603.75
26	2	52	1000	112.5	125	1175	1300	1200	$32,171.75
26	3	78	50	537.5	550	275	825	300	$10,978.95
26	3	78	100	512.5	525	325	850	350	$12,182.05
26	3	78	250	437.5	450	475	925	500	$15,791.35
26	3	78	500	312.5	325	725	1050	750	$21,806.85
26	3	78	1000	62.5	75	1225	1300	1250	$33,284.05

Table 38. W-Beam Guardrail Placement and Costs, $45 per lf

Drop Height [ft]	Slope Rate	Width of Slope [ft]	Length of Slope [ft]	Upstream Terminal Start [ft]	Upstream Guardrail Start [ft]	Guardrail Length [ft]	Downstream Terminal Start [ft]	Total Length [ft]	Cost
7	1.5	10.5	50	650	662.5	162.5	825	187.5	$12,272.81
7	1.5	10.5	100	625	637.5	212.5	850	237.5	$15,254.06
7	1.5	10.5	250	550	562.5	362.5	925	387.5	$24,197.81
7	1.5	10.5	500	425	437.5	612.5	1050	637.5	$38,152.81
7	1.5	10.5	1000	175	187.5	1112.5	1300	1137.5	$65,715.31
7	2	14	50	637.5	650	175	825	200	$13,018.13
7	2	14	100	612.5	625	225	850	250	$15,999.38
7	2	14	250	537.5	550	375	925	400	$24,943.13
7	2	14	500	412.5	425	625	1050	650	$38,841.88
7	2	14	1000	162.5	175	1125	1300	1150	$66,404.38
7	3	21	50	625	637.5	187.5	825	212.5	$13,763.44
7	3	21	100	600	612.5	237.5	850	262.5	$16,744.69
7	3	21	250	525	537.5	387.5	925	412.5	$25,688.44
7	3	21	500	400	412.5	637.5	1050	662.5	$39,530.94
7	3	21	1000	150	162.5	1137.5	1300	1162.5	$67,093.44
13	1.5	19.5	50	637.5	650	175	825	200	$13,018.13
13	1.5	19.5	100	612.5	625	225	850	250	$15,999.38
13	1.5	19.5	250	537.5	550	375	925	400	$24,943.13
13	1.5	19.5	500	412.5	425	625	1050	650	$38,841.88
13	1.5	19.5	1000	162.5	175	1125	1300	1150	$66,404.38
13	2	26	50	625	637.5	187.5	825	212.5	$13,763.44
13	2	26	100	600	612.5	237.5	850	262.5	$16,744.69
13	2	26	250	525	537.5	387.5	925	412.5	$25,688.44
13	2	26	500	400	412.5	637.5	1050	662.5	$39,530.94
13	2	26	1000	150	162.5	1137.5	1300	1162.5	$67,093.44
13	3	39	50	600	612.5	212.5	825	237.5	$15,254.06
13	3	39	100	575	587.5	262.5	850	287.5	$18,235.31
13	3	39	250	500	512.5	412.5	925	437.5	$27,127.81
13	3	39	500	375	387.5	662.5	1050	687.5	$40,909.06
13	3	39	1000	125	137.5	1162.5	1300	1187.5	$68,471.56
20	1.5	30	50	612.5	625	200	825	225	$14,508.75
20	1.5	30	100	587.5	600	250	850	275	$17,490.00
20	1.5	30	250	512.5	525	400	925	425	$26,433.75
20	1.5	30	500	387.5	400	650	1050	675	$40,220.00
20	1.5	30	1000	137.5	150	1150	1300	1175	$67,782.50
20	2	40	50	600	612.5	212.5	825	237.5	$15,254.06
20	2	40	100	575	587.5	262.5	850	287.5	$18,235.31
20	2	40	250	500	512.5	412.5	925	437.5	$27,127.81
20	2	40	500	375	387.5	662.5	1050	687.5	$40,909.06
20	2	40	1000	125	137.5	1162.5	1300	1187.5	$68,471.56
20	3	60	50	575	587.5	237.5	825	262.5	$16,744.69
20	3	60	100	550	562.5	287.5	850	312.5	$19,725.94
20	3	60	250	475	487.5	437.5	925	462.5	$28,505.94
20	3	60	500	350	362.5	687.5	1050	712.5	$42,287.19
20	3	60	1000	100	112.5	1187.5	1300	1212.5	$69,849.69
26	1.5	39	50	600	612.5	212.5	825	237.5	$15,254.06
26	1.5	39	100	575	587.5	262.5	850	287.5	$18,235.31
26	1.5	39	250	500	512.5	412.5	925	437.5	$27,127.81
26	1.5	39	500	375	387.5	662.5	1050	687.5	$40,909.06
26	1.5	39	1000	125	137.5	1162.5	1300	1187.5	$68,471.56
26	2	52	50	587.5	600	225	825	250	$15,999.38
26	2	52	100	562.5	575	275	850	300	$18,980.63
26	2	52	250	487.5	500	425	925	450	$27,816.88
26	2	52	500	362.5	375	675	1050	700	$41,598.13
26	2	52	1000	112.5	125	1175	1300	1200	$69,160.63
26	3	78	50	537.5	550	275	825	300	$18,980.63
26	3	78	100	512.5	525	325	850	350	$21,961.88
26	3	78	250	437.5	450	475	925	500	$30,573.13
26	3	78	500	312.5	325	725	1050	750	$44,354.38
26	3	78	1000	62.5	75	1225	1300	1250	$71,916.88

7.3.3 Install Cable Guardrail

The third alternative was to install cable guardrail along the slope. This option was not used on the zero offset due to the fact that cable guardrails must be placed 4 ft (1.2 m) laterally away from the slope break point. The same method was used to determine the cable barrier length as was used for the W-beam guardrail. In this case, the end terminals for cable barriers were 16 ft (4.9 m) long. The diagram shown in Figure 19 was used to determine the upstream and downstream runout lengths. These lengths were added to the slope length to determine the total length of the barrier section, and the length of the two end terminals, totaling 32 ft (9.8 m), was added to obtain the entire barrier length. Terminal and guardrail starting distances were calculated, along with costs based on length and are shown in Table 39. The cable barrier option was only considered for lateral offsets of 3, 7, and 10 ft (1, 2.1, and 3 m).

The cable guardrail was modeled as a TL-3 guardrail in RSAP, and the end terminals were modeled as cable guardrail terminals. The SI values for the TL-3 guardrail were updated to match the average cost of a cable median barrier crash as determined in a study of 640 cable median barrier crashes between 2002 and 2006 along Missouri roadways [22]. The average cost was given as $28,894, which resulted in an SI multiplier of 0.82 for the TL-3 guardrail.

The installation costs for the cable guardrail were broken up into three components: (1) traffic control and mobilization; (2) TL-3 low tension cable guardrail; and (3) end terminals. The costs for traffic control, mobilization, and contingency are defined in the previous section. Costs for the cable guardrail and terminals are $22.91 per linear foot ($75.16 per linear meter) and $2,080.13 per 16-ft (4.9-m) long terminal, respectively. These costs were provided by the Missouri Department of Transportation (MoDOT). The guardrail costs are also shown in Table 39.

Table 39. Cable Barrier Placement and Costs

Drop Height [ft]	Slope Rate	Width of Slope [ft]	Length of Slope [ft]	Upstream Terminal Start [ft]	Upstream Guardrail Start [ft]	Guardrail Length [ft]	Downstream Terminal Start [ft]	Total Length [ft]	Cost
7	1.5	10.5	50	636	652	173	825	205	$10,763.89
7	1.5	10.5	100	611	627	223	850	255	$12,281.68
7	1.5	10.5	250	536	552	373	925	405	$16,835.04
7	1.5	10.5	500	411	427	623	1050	655	$24,423.98
7	1.5	10.5	1000	161	177	1123	1300	1155	$38,613.03
7	2	14	50	631	647	178	825	210	$10,915.67
7	2	14	100	606	622	228	850	260	$12,433.46
7	2	14	250	531	547	378	925	410	$16,986.82
7	2	14	500	406	422	628	1050	660	$24,575.76
7	2	14	1000	156	172	1128	1300	1160	$38,753.36
7	3	21	50	620	636	189	825	221	$11,249.58
7	3	21	100	595	611	239	850	271	$12,767.37
7	3	21	250	520	536	389	925	421	$17,320.73
7	3	21	500	395	411	639	1050	671	$24,909.67
7	3	21	1000	145	161	1139	1300	1171	$39,062.07
13	1.5	19.5	50	622	638	187	825	219	$11,188.87
13	1.5	19.5	100	597	613	237	850	269	$12,706.66
13	1.5	19.5	250	522	538	387	925	419	$17,260.02
13	1.5	19.5	500	397	413	637	1050	669	$24,848.96
13	1.5	19.5	1000	147	163	1137	1300	1169	$39,005.94
13	2	26	50	612	628	197	825	229	$11,492.43
13	2	26	100	587	603	247	850	279	$13,010.21
13	2	26	250	512	528	397	925	429	$17,563.58
13	2	26	500	387	403	647	1050	679	$25,152.51
13	2	26	1000	137	153	1147	1300	1179	$39,286.59
13	3	39	50	592	608	217	825	249	$12,099.54
13	3	39	100	567	583	267	850	299	$13,617.33
13	3	39	250	492	508	417	925	449	$18,170.69
13	3	39	500	367	383	667	1050	699	$25,759.63
13	3	39	1000	117	133	1167	1300	1199	$39,847.88
20	1.5	30	50	606	622	203	825	235	$11,674.56
20	1.5	30	100	581	597	253	850	285	$13,192.35
20	1.5	30	250	506	522	403	925	435	$17,745.71
20	1.5	30	500	381	397	653	1050	685	$25,334.65
20	1.5	30	1000	131	147	1153	1300	1185	$39,454.98
20	2	40	50	590	606	219	825	251	$12,160.25
20	2	40	100	565	581	269	850	301	$13,678.04
20	2	40	250	490	506	419	925	451	$18,231.40
20	2	40	500	365	381	669	1050	701	$25,820.34
20	2	40	1000	115	131	1169	1300	1201	$39,904.01
20	3	60	50	559	575	250	825	282	$13,101.28
20	3	60	100	534	550	300	850	332	$14,619.07
20	3	60	250	459	475	450	925	482	$19,172.43
20	3	60	500	334	350	700	1050	732	$26,741.64
20	3	60	1000	84	100	1200	1300	1232	$40,774.02
26	1.5	39	50	592	608	217	825	249	$12,099.54
26	1.5	39	100	567	583	267	850	299	$13,617.33
26	1.5	39	250	492	508	417	925	449	$18,170.69
26	1.5	39	500	367	383	667	1050	699	$25,759.63
26	1.5	39	1000	117	133	1167	1300	1199	$39,847.88
26	2	52	50	572	588	237	825	269	$12,706.66
26	2	52	100	547	563	287	850	319	$14,224.44
26	2	52	250	472	488	437	925	469	$18,777.81
26	2	52	500	347	363	687	1050	719	$26,366.74
26	2	52	1000	97	113	1187	1300	1219	$40,409.18
26	3	78	50	531	547	278	825	310	$13,951.24
26	3	78	100	506	522	328	850	360	$15,469.03
26	3	78	250	431	447	478	925	510	$20,022.39
26	3	78	500	306	322	728	1050	760	$27,527.46
26	3	78	1000	56	72	1228	1300	1260	$41,559.83

7.3.4 Slope Flattening

One other possible alternative was slope flattening. As the slope becomes flatter, the vehicle's propensity for instability decreases, and with it, the severity index decreases. However, the cost of slope flattening can make this alternative infeasible. Costs would be comprised of fill material, transportation of that material, labor costs, and right-of-way purchases. Each one of these components can range from almost nothing to exuberant amounts. As a result, it was difficult to conduct an explicit benefit-to-cost analysis without increasing the RSAP simulation matrix beyond a reasonable size. Instead, the engineer is referred to *Roadside Grading Guidance – Phase 1* [17].

In that report, a baseline slope can be prescribed. The steepest slope available is 2H:1V. From that baseline, alternative slopes of 3H:1V, 4H:1V, and 6H:1V can be specified. Additionally, the engineer is given the freedom to determine the costs for each alternative. For the purpose of low-volume roads, a rural local highway can be selected, and a traffic volume of interest may be entered. A generic guardrail option was also used to demonstrate the functionality of slope flattening. That report showed that on low-volume (less than 500 vpd) roads, guardrail had higher accident costs than even the steepest slope, thus resulting in a negative B/C ratio.

From this report, it was recommended that the engineer not use the results as a means of justifying the use of a longitudinal barrier. Instead, the results of the slope modification could be used in lieu of the guardrail recommendations presented in this report.

7.4 Simulation Results

The results of the slope analysis are shown in Tables 40 through 49. The results of the slope analyses are shown in an extended graphical form in Appendix C. For benefit-to-cost ratios of 2 and 4, the analyses indicated that there was no need to install a barrier along a 3H:1V slope. For the 1.5H:1V and 2H:1V slopes, there was no need to install a barrier for roads with less than 150 ADT. There were also many cases where installing a barrier on a 2H:1V slope was unnecessary. In general, the results indicated that smaller lateral offsets and longer slopes would most likely create a scenario where a barrier was recommended for slopes of 1.5H:1V and 2H:1V.

When the W-beam cost was analyzed as $18.16 per lf ($59.58 per linear meter), it was recommended to install W-beam guardrail instead of cable guardrail in all situations. However, when the cost of W-beam guardrail installation was analyzed as $45 per lf ($147.64 per linear meter), W-beam guardrail was only recommended for a 0-ft lateral offset, where it was the only alternative. At 3-ft (0.9-m) lateral offsets and greater, cable guardrail was also analyzed and provided lower costs. Therefore, cable guardrail was recommended over W-beam guardrail for those analysis scenarios.

7.5 Discussion

Steep slopes can pose a severe risk to motorists if they are close to the roadway and long. It is necessary and cost-effective to shield 1.5H:1V and 2H:1V slopes on roads with an ADT greater than 150 vpd. Benefit-to-cost ratios increased linearly with ADT for steep slopes, typically beginning around 0.25 and increasing to 4 or 5 in some cases. For a 3H:1V slope, benefit-to-cost ratios were typically less than 1, and negative in many cases.

A couple of assumptions were made in this analysis, including: (1) slopes steeper than 1.5H:1V would not be present on low-volume roadways and (2) the slope extended to a width calculated by the drop height and slope rate. Because it was assumed that the slope continued out to its greatest width based on height and rate, the length of the barrier was determined using the greatest width of the slope. This decision subsequently affects implementation costs that were given per linear ft (lf). The costs ranged from approximately $8,200 for the shortest W-beam guardrail installation at $18.16 per lf ($59.58 per linear meter) to almost $72,000 for the longest W-beam guardrail installation at $45 per lf ($147.64 per linear meter). The cable guardrail costs also ranged between those two numbers. The highest costs were for 3H:1V slopes, as the geometric roadside feature stretched the farthest from the roadway, thus increasing its potential to be struck by an errant vehicle. The 3H:1V slope, which extended far beyond the clear zone, had the smallest severity but had the highest cost. Therefore, it yielded significantly smaller benefit-to-cost ratios.

7.6 Conclusions and Recommendations

The slope analysis evaluated the cost-effectiveness of shielding slopes adjacent to the roadway. The study was based on field data taken on actual roadways in Kansas and Nebraska. Two treatment methods were considered during the analysis. The baseline option considered was to do nothing to the current situation. This decision involved modeling the site with different slopes, lengths, lateral offsets, and drop heights. The first treatment alternative was to install W-beam guardrail to shield the slope. In this case, two different costs of guardrail were evaluated: $18.16 per ft ($59.58 per meter), an average of several states; and $45 per ft ($147.64 per meter), a cost from KDOT. The second treatment alternative was to install cable guardrail. This option was only considered for lateral offsets greater than 3 ft (0.9 m), because it had been shown that there must be at least 4 ft (1.2 m) behind cable guardrail before the break point of a slope [25]. A third alternative that was not considered in this analysis involved slope flattening, which would effectively reduce the severity index [17].

Recommendations were categorized by drop height. For a benefit-to-cost ratio of 2.0 and for a W-beam guardrail installation cost of $18.16 per foot ($59.58 per meter), W-beam guardrail was recommended at many lateral offsets with slopes of 2H:1V or steeper on roadways with greater than 300 vpd and drop heights of 7 ft (2.1 m). As the drop height increased, this range increased as well. Slope rate influenced the results as well. For all 3H:1V slopes, doing nothing was the only recommended alternative.

Using a W-beam guardrail installation cost of $45 per ft ($147.64 per meter), it is recommended that W-beam guardrail be installed at a 0-ft lateral offset and slopes of 1.5H:1V or steeper on roadways with an ADT greater than 300 vpd and drop heights greater than 26 ft (7.9 m). For a 3-ft (0.9-m) lateral offset or greater, it is recommended that cable guardrail be installed on roadways with an ADT greater than 250 vpd and drop heights greater than 26 ft (7.9 m).

For a benefit-to-cost ratio of 4.0 and for W-beam guardrail installation costs of $45 per ft ($147.64 per meter), neither W-beam guardrail nor cable barrier were recommended. It should be noted that these recommendations are general and encompass a wide range of scenarios. The data presented in this chapter and also in Appendix C should be studied for specific scenario recommendations.

Table 40. Slope Results, Drop Height < 10 ft (3.05 m), B/C = 2, W-beam = $18.16/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	< 75	0 - 324	325 - 500	
		75 - 175	0 - 299	300 - 500	
		> 175	0 - 224	225 - 500	
	1.5 - 5.0	< 75	0 - 349	350 - 500	
		75 - 175	0 - 299	300 - 500	
		> 175	0 - 274	275 - 500	
	5.1 - 8.5	< 75	0 - 374	375 - 500	
		75 - 374	0 - 349	350 - 500	
		375 - 750	0 - 324	325 - 500	
		> 750	0 - 299	300 - 500	
	> 8.5	< 175	0 - 399	400 - 500	
		≥ 175	0 - 349	350 - 500	
1.76H:1V - 2.5H:1V	< 1.5	< 75	0 - 374	375 - 500	
		75 - 174	0 - 349	350 - 500	
		175 - 750	0 - 324	325 - 500	
		> 750	0 - 299	300 - 500	
	1.5 - 5.0	< 175	0 - 374	375 - 500	
		≥ 175	0 - 349	350 - 500	
	5.1 - 8.5	< 75	0 - 424	425 - 500	
		75 - 175	0 - 399	400 - 500	
		> 175	0 - 374	375 - 500	
	> 8.5	< 75	0 - 449	450 - 500	
		75 - 175	0 - 424	425 - 500	
		> 175	0 - 399	400 - 500	
> 2.5H:1V	All	All	0 - 500		

Table 41. Slope Results, 10 ft (3.05 m) ≤ Drop Height < 16.5 ft (5.03 m), B/C = 2, W-beam = $18.16/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	< 75	0 - 149	150 - 500	
		75 - 175	0 - 124	125 - 500	
		> 175	0 - 99	100 - 500	
	1.5 - 5.0	< 75	0 - 174	175 - 500	
		75 - 175	0 - 149	150 - 500	
		> 175	0 - 124	125 - 500	
	5.1 - 8.5	< 75	0 - 224	225 - 500	
		75 - 174	0 - 199	200 - 500	
		175 - 750	0 - 174	175 - 500	
		> 750	0 - 149	150 - 500	
	> 8.5	< 75	0 - 274	275 - 500	
		75 - 17			
		> 175	0 - 199	200 - 500	
1.76H:1V - 2.5H:1V	< 1.5	< 75	0 - 199	200 - 500	
		75 - 175	0 - 174	174 - 500	
		> 175	0 - 149	150 - 500	
	1.5 - 5.0	< 75	0 - 224	225 - 500	
		75 - 175			
		> 175	0 - 174	175 - 500	
	5.1 - 8.5	< 75	0 - 299	300 - 500	
		75 - 175	0 - 274	275 - 500	
		> 175	0 - 224	225 - 500	
	> 8.5	< 75	0 - 349	350 - 500	
		75 - 175	0 - 324	325 - 500	
		> 175	0 - 274	275 - 500	
> 2.5H:1V	All	All	0 - 500		

Table 42. Slope Results, Drop Height ≥ 16.5 ft (5.03 m), B/C = 2, W-beam = $18.16/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	< 75	0 - 124	125 - 500	
		> 75	0 - 99	99 - 500	
	1.5 - 5.0	All	0 - 99	125 - 500	
	5.1 - 8.5	< 175	0 - 174	175 - 500	
		≥ 175	0 - 149	150 - 500	
	> 8.5	< 175	0 - 224	225 - 500	
		≥ 175	0 - 174	175 - 500	
1.76H:1V - 2.5H:1V	< 1.5	All	0 - 149	150 - 500	
	1.5 - 5.0	< 175	0 - 174	175 - 500	
		≥ 175	0 - 149	150 - 500	
	5.1 - 8.5	< 175	0 - 224	225 - 500	
		≥ 175	0 - 199	200 - 500	
	> 8.5	< 175	0 - 274	275 - 500	
		≥ 175	0 - 249	250 - 500	
> 2.5H:1V	All	All	0 - 500		

Table 43. Slope Results, Drop Height < 10 ft (3.05 m), B/C = 4, W-beam = $18.16/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	≤ 1.5	< 175	0 - 500		
		≥ 175	0 - 474	475 - 500	
	> 1.5	All	0 - 500		
≥ 1.75H:1V	All	All	0 - 500		

Table 44. Slope Results, 10 ft (3.05 m) ≤ Drop Height < 16.5 ft (5.03 m), B/C = 4, W-beam = $18.16/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	< 75	0 - 500		
		75 - 175	0 - 474	475 - 500	
		> 175	0 - 424	425 - 500	
	1.5 - 5.0	< 175	0 - 500		
		≥ 175	0 - 474	475 - 500	
	> 5.0	All	0 - 500		
≥ 1.75H:1V	All	50	0 - 500		

Table 45. Slope Results, Drop Height ≥ 16.5 ft (5.03 m), B/C = 4, W-beam = $18.16/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	< 75	0 - 449	450 - 500	
		75 - 175	0 - 399	400 - 500	
		> 175	0 - 374	375 - 500	
	1.5 - 5.0	< 175	0 - 474	475 - 500	
		≥ 175	0 - 424	425 - 500	
	> 5.0	All	0 - 500		
≥ 1.75H:1V	All	All	0 - 500		

Table 46. Slope Results, Drop Height < 10 ft (3.05 m), B/C = 2, W-beam = $45/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	All	0 - 474	475 - 500	
	1.5 - 5.0	< 75	0 - 500		
		75 - 175	0 - 474		475 - 500
		> 175	0 - 399		400 - 500
	5.1 - 8.5	< 175	0 - 500		
		≥ 175	0 - 474		475 - 500
	> 8.5	All	0 - 500		
≥ 1.75H:1V	All	All	0 - 500		

Table 47. Slope Results, 10 ft (3.05 m) ≤ Drop Height < 16.5 ft (5.03 m), B/C = 2, W-beam = $45/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	All	0 - 424	425 - 500	
	1.5 - 5.0	< 75	0 - 449		450 - 500
		75 - 175	0 - 399		400 - 500
		> 175	0 - 299		300 - 500
	5.1 - 8.5	< 175	0 - 500		
		≥ 175	0 - 424		425 - 500
	> 8.5	All	0 - 500		
1.76H:1V - 2.5H:1V	< 1.5	All	0 - 500		
	1.5 - 5.0	< 175	0 - 500		
		≥ 175	0 - 449		450 - 500
	5.1 - 8.5	All	0 - 500		
	> 8.5	All	0 - 500		
> 2.5H:1V	All	All	0 - 500		

Table 48. Slope Results, Drop Height ≥ 16.5 ft (5.03 m), B/C = 2, W-beam = $45/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
< 1.75H:1V	< 1.5	< 375	0 - 349	350 - 500	
		≥ 375	0 - 374	375 - 500	
	1.5 - 5.0	< 75	0 - 474		475 - 500
		75 - 175	0 - 374		375 - 500
		> 175	0 - 274		275 - 500
	5.1 - 8.5	< 75	0 - 474		475 - 500
		75 - 175	0 - 449		450 - 500
		> 175	0 - 374		375 - 500
	> 8.5	< 175	0 - 500		
		≥ 175	0 - 449		450 - 500
1.76H:1V - 2.5H:1V	< 1.5	All	0 - 500		
	1.5 - 5.0	< 175	0 - 500		
		≥ 175	0 - 399		400 - 500
	< 5.0	All	0 - 500		
> 2.5H:1V	All	All	0 - 500		

Table 49. Slope Results, All Drop Heights, B/C = 4, W-beam = $45/lf

Slope Rate	Offset [ft]	Length [ft]	Do Nothing	Install W-Beam	Install Cable
All	All	All	0 - 500		

8 ANALYSIS OF DITCHES

8.1 Introduction

In some areas, a foreslope may invert to a backslope within the clear zone. The combination of foreslopes and backslopes create a ditch, which must be evaluated as well. Generally, roadside ditches do not have very steep slopes, although they sometimes rise into walls or steeper backslopes.

8.2 Modeling Procedure

8.2.1 Ditch Details

The best representation for ditches was to use a 4H:1V foreslope, a 4H:1V backslope, and a second backslope at 1H:1V or 2H:1V. Parallel ditches may be selected in RSAP. However, drop heights cannot be configured to model specific ditches. By using foreslopes and backslopes, the slope rate and the drop height of each component could be controlled. A 4H:1V slope was chosen due to the fact that it is a fairly common for ditches on low-volume roads. This second backslope rate was varied in the study. Four widths, which included the foreslope and backslope, were determined for the ditch setup. These widths were 5, 9, 14, and 18 ft (1.5, 2.7, 4.3 and 5.5 m). The widths were based on the maximum clear zone of 18 ft for a 4H:1V slope at 55 mph [1]. A graphical representation of this setup is shown in Figure 20.

For a ditch width of 5 ft (1.5 m), the first backslope of 4H:1V was not used. With the given slope, the width was filled by the foreslope. For the 9- and 14-ft (2.7- and 4.3-m) widths, the first backslope was 5 ft (1.5 m) wide. This backslope width determined the foreslope width and the foreslope height. For the final width of 18 ft (5.5 m), the first backslope was evaluated at widths of 5 ft (1.5 m) and 10 ft (3.0 m). The height of the second backslope was set at a constant 15 ft (4.6 m) for all configurations. A summary of the RSAP parameters is shown in Table 50.

The heights and widths of the foreslopes and backslopes at the four overall widths are shown in a schematic in Figure 21 and are quantified in Table 51. The same lateral offsets and lengths as the foreslopes were used for the ditches as well.

8.2.2 Road Modeling

The ditch analysis was conducted on a straight section of road with no vertical grade. The road segment was 1,500 ft (457.2 m) long in order to accommodate the longest ditch of 1,000 ft (304.8 m). The ditches were centered in the road geometry, and starting distances varied depending on length of the ditch. The roadway was modeled as a rural local road with two lanes of travel and an undivided median. A lane width of 12 ft (3.7 m) and a shoulder width of 2 ft (0.6 m) were used. The nominal percent of trucks was set to 2 percent, and the speed limit was 55 mph (88.5 km/h). The traffic growth factor was zero, and the encroachment rate adjustment factor was left unchanged at the default value of 1.

The width of the slope was held constant at 18 ft (5.5 m) for barrier calculations. For a 4H:1V slope with a 55 mph (88.5 km/h) speed limit and an ADT of less than 750, the 2006 RDG specifies 18 ft (5.5 m) as the maximum clear zone. Even in the case of a 5-ft (1.5-m) ditch width, the backslope will be at least 15 ft (4.6 m) wide for the 1H:1V case and 30 ft (9.1 m) wide for the 2H:1V case. The total width of the ditch will always exceed 18 ft (5.5 m). The Roadside Design Guide concludes that when the feature extends past the clear zone, the designer can choose to shield only the portion of the clear zone. In that case, L_H would equal L_C, as shown in Figure 18 [1].

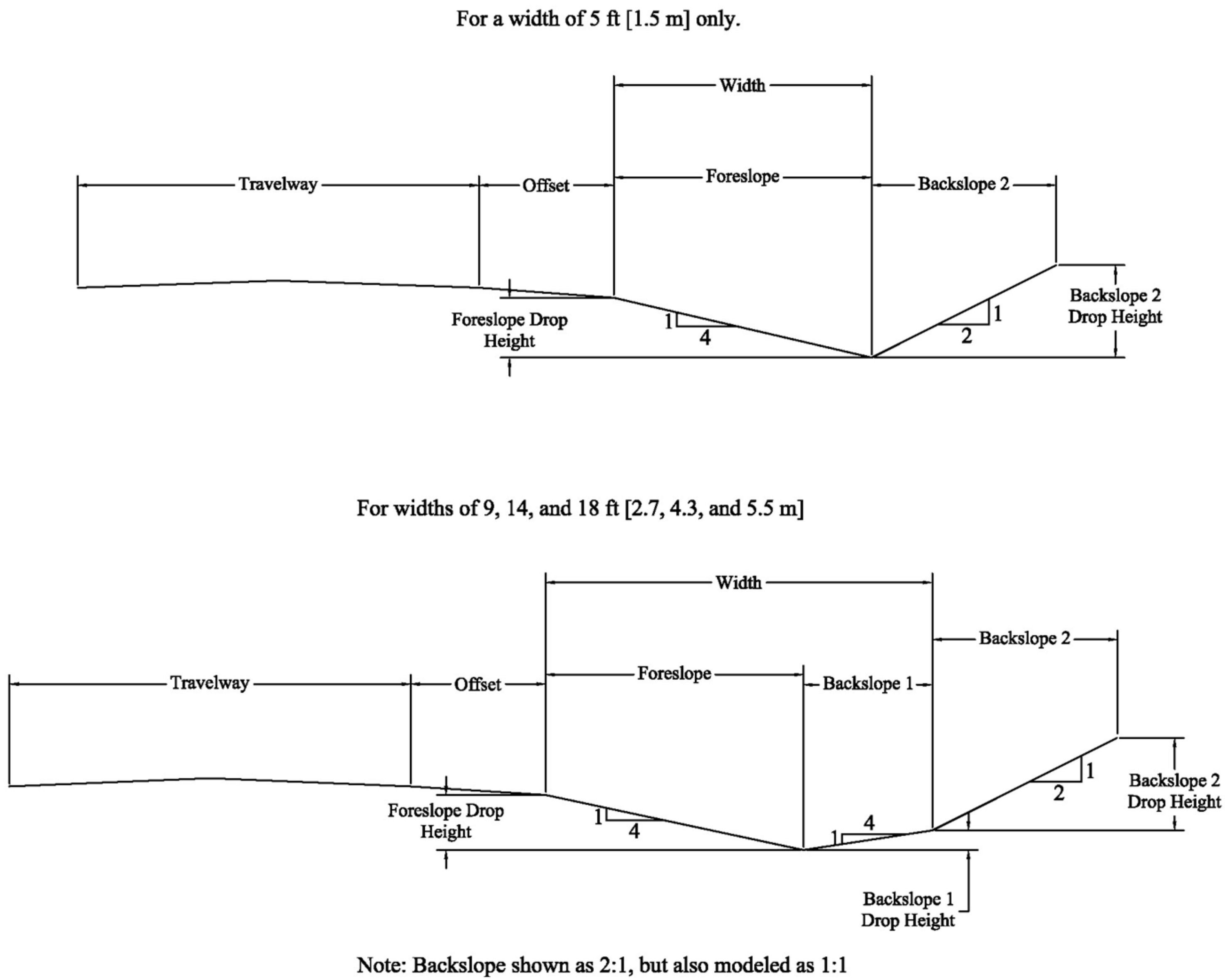


Figure 20. Schematic of Ditches in RSAP

Table 50. Summary of RSAP Parameters for Ditches

Ditch Profile		Foreslope - 4H:1V, Backslope 2 - 1H:1V or 2H:1V
Backslope 1 Width	ft (m)	5 ft and 10 ft (1.5 m and 3 m)
Fill Height		Dependent on Backslope 1
Length	ft (m)	50, 100, 250, 500, 1000 (15, 30.5, 76, 152, 305)
Lateral Offset	ft (m)	0, 3, 7, 10 (0, 0.9, 2.1, 3)
ADT	vpd	50, 100, 150, 200, 250, 300, 350, 400, 450, 500

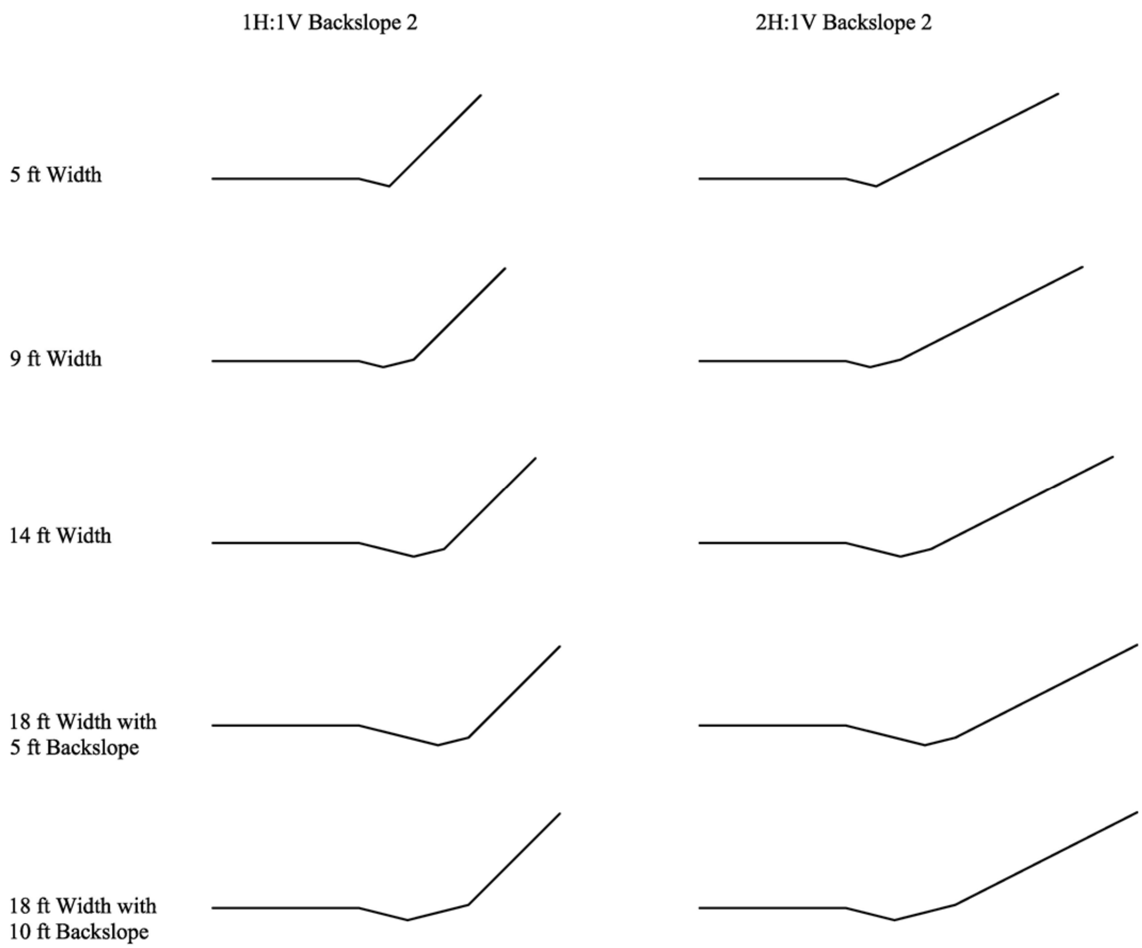


Figure 21. Schematic of Ditches Modeled in RSAP

Table 51. Slope Dimensions for Ditch Cross-section

Ditch Width ft (m)	Backslope1		Foreslope	
	Height ft (m)	Width ft (m)	Height ft (m)	Width ft (m)
5 (1.5)	0.00 (0.00)	0 (0)	1.25 (0.38)	5 (1.5)
9 (2.7)	1.25 (0.38)	5 (1.5)	1.00 (0.30)	4 (1.2)
14 (4.3)	1.25 (0.38)	5 (1.5)	2.25 (0.69)	9 (2.7)
18 (5.5)	1.25 (0.38)	5 (1.5)	3.25 (0.99)	13 (4.0)
18 (5.5)	2.50 (0.76)	10 (3.0)	2.00 (0.61)	8 (2.4)

8.3 Treatment Options

Several different treatment options were evaluated during the simulation. These included doing nothing, installing W-beam guardrail, and installing cable guardrail. These treatment options are discussed in greater detail in the following section.

8.3.1 "Do Nothing"

Many ditches along roadsides are not currently shielded with a barrier. Therefore, the first alternative involved a ditch analysis without the use of a barrier. The ditches were modeled in the same manner as the slopes (i.e., using intersecting slopes in increments to reach the overall drop height). This alternative had no cost associated with it.

8.3.2 Install W-Beam Guardrail

The second alternative was to install W-beam guardrail. Guardrail lengths and costs were determined in the same manner as that used for slope shielding. The slope and ditch width in this case were different, so the guardrail lengths and costs were slightly different. Two costs were again considered for the W-beam guardrail installation and are shown in Tables 52 and 53. The

W-beam guardrail option was considered for lateral offsets of 0, 3, 7, and 10 ft (0, 1, 2.1, and 3 m).

Table 52. W-Beam Guardrail Location and Costs for Ditches, $18.16 per lf

Width of Ditch (ft)	Length of Ditch (ft)	Upstream Terminal Start (ft)	Upstream Guardrail Start (ft)	Guardrail Length (ft)	Downstream Terminal Start (ft)	Total Length (ft)	Cost
18	50	637.5	650	175	825	200	$8,572.75
18	100	612.5	625	225	850	250	$9,775.85
18	250	537.5	550	375	925	400	$13,385.15
18	500	412.5	425	625	1050	650	$19,400.65
18	1000	162.5	175	1125	1300	1150	$31,059.45

Table 53. W-Beam Guardrail Location and Costs for Ditches, $45 per lf

Width of Ditch (ft)	Length of Ditch (ft)	Upstream Terminal Start (ft)	Upstream Guardrail Start (ft)	Guardrail Length (ft)	Downstream Terminal Start (ft)	Total Length (ft)	Cost
18	50	637.5	650	175	825	200	$13,018.13
18	100	612.5	625	225	850	250	$15,999.38
18	250	537.5	550	375	925	400	$24,943.13
18	500	412.5	425	625	1050	650	$38,841.88
18	1000	162.5	175	1125	1300	1150	$66,404.38

8.3.3 Install Cable Guardrail

The third alternative was to install a cable guardrail system. The method used for determining the cable lengths and costs was the same as used for cable guardrail on slopes. Again, the costs and barrier lengths were slightly different due to the varying widths of the ditches. The cable guardrail option was only considered for lateral offsets of 3, 7, and 10 ft (0.9, 2.1, and 3 m). The guardrail costs and locations are shown in Table 54.

Table 54. Cable Guardrail Location and Costs for Ditches

Width of Ditch (ft)	Length of Ditch (ft)	Upstream Terminal Start (ft)	Upstream Guardrail Start (ft)	Guardrail Length (ft)	Downstream Terminal Start (ft)	Total Length (ft)	Cost
18	50	624	640	185	825	217	$11,128.16
18	100	599	615	235	850	267	$12,645.95
18	250	524	540	385	925	417	$17,199.31
18	500	399	415	635	1050	667	$24,788.25
18	1000	149	165	1135	1300	1167	$38,949.81

8.4 Simulation Results

The results of the ditch analysis are shown in Table 55. For benefit-to-cost ratios of 2 and 4, the "do nothing" option was recommended. This finding was for all foreslope widths, lengths, lateral offsets, and backslopes. Benefit-to-cost ratios were always negative, indicating that both the accident cost and the installation cost of each barrier were greater than the corresponding costs for doing nothing. Because the RSAP results did not indicate any possible cost-beneficial solution other than doing nothing, the graphical results were not included in an Appendix.

Table 55. Ditch Results

B/C Ratio	Width	Backslope Rate	Offset	Length	Do Nothing (ADT)	Install W-Beam (ADT)	Install Cable (ADT)
2, 4	all	all	all	all	0-500		

8.5 Discussion

The main assumption in this analysis was that the ditch would be formed by 4H:1V foreslopes and backslopes, and then the backslope would continue with a steeper slope (i.e., second backslope). The 1H:1V and 2H:1V slopes that were modeled for the second backslopes had high severities, but they were offset far enough from the roadway that their severities did not significantly affect the analysis. As discussed previously, the accident and installation costs of both the W-beam and cable guardrail alternatives were too high to be cost-effective in this analysis.

RSAP does not adjust the path of the errant vehicle in any simulation. In reality, the direction of the vehicle will be angled down the foreslope upon encroachment into the roadside. This result would effectively increase the lateral extent of encroachment and the angle of impact beyond the toe of the foreslope. As a result, the impact frequency for the backslopes was underestimated due to the straight-line encroachment module. Additionally, the angle of impact may have also been less than expected. Both of these limitations, when fixed, may increase accident costs for an unprotected ditch. However, the increased accident costs for an unprotected ditch would need to be an order of magnitude larger in order for W-beam or cable guardrail to be cost-effective. For example, the accident cost of the unprotected slope was $22.03 for a second backslope of 1H:1V, a lateral offset of 0 ft (0 m), a ditch length of 50 ft (15.2 m), a traffic volume of 50 vpd, a drop height of 1 ft (0.3 m), and a 5-ft (1.5-m) width. The accident cost of a W-beam guardrail was $78.70. In order for the B/C ratio to exceed 2.0, the accident cost of the unprotected slope would have to increase to approximately $1,200 to compensate for the installation cost of the W-beam guardrail system, which is over 5,000 percent larger.

8.6 Conclusions and Recommendations

For this analysis, there were no field measurements for which to base the modeling. Instead, a model was created to generalize possible ditch configurations. Three alternatives were analyzed - the baseline option “do nothing” and install a cable or W-beam guardrail. As with the slopes, two W-beam installation costs were analyzed. However, even at the lower cost, none of the scenarios met minimum benefit-to-cost ratios for installing a cable or W-beam guardrail system. The particular scenarios that were modeled were not severe enough to recommend the use of a barrier. A more severe ditch configuration might result in a higher benefit-to-cost ratio for installing a barrier, but that situation was not studied. Therefore, it is recommended to “do nothing” for ditches specifically at a 4H:1V foreslope, with a “Backslope 2” of 1H:1V or 2H:1V.

9 ANALYSIS OF BRIDGES

9.1 Introduction

Bridges are common fixed objects located on low-volume roadways. Treatments for bridges on low-volume roadways have traditionally consisted of field-constructed barriers or hazard indicators, including delineators or object markers. Barriers that are constructed on bridges have different configurations, varying from wood post-and-beam designs to angle iron and concrete post-and-beam configurations. However, many barrier designs are not crashworthy and could actually increase occupant risk when an errant vehicle strikes a barrier.

Three bridge railing configurations were observed in the field. One bridge rail consisted of an angle iron railing system bolted to the side of the bridge deck. Another consisted of concrete posts attached to the bridge deck with W-beam guardrail mounted across the face of the posts. The third system included a steel, through-truss configuration upon which a steel angle iron rail was mounted. For modeling purposes, the truss configuration was treated like the first angle iron bridge. A benefit-to-cost analysis was undertaken to determine what safety treatment, if any, would provide significant safety improvement over these designs.

9.2 Modeling Procedure

Bridge shapes and sizes were determined based on results from the field investigation. Bridge models were developed to represent the bridges observed. To accurately model the bridges, the sizes and shapes of the bridges were matched to features available in the RSAP analysis module. Following the development of the bridge geometry, hazardous features on the bridge were identified and matched to the corresponding features available in RSAP.

9.2.1 Bridge Details

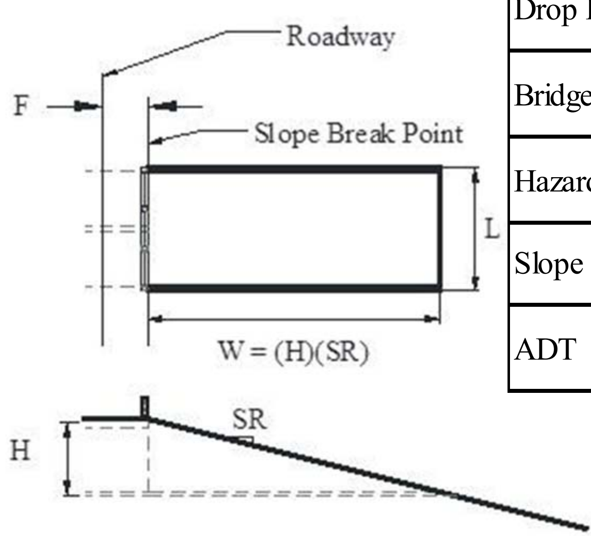
Two types of bridge railings were modeled in RSAP. Bridge type 1 consisted of an angle iron railing with a height of 31 ½ in. (0.8 m) above the bridge deck. It was decided to model this railing system as a Test Level 1 (TL-1) bridge rail in RSAP. The ends of the guardrail were modeled as blunt ends. Basic dimensions measured from one of the bridges with an angle iron railing included a length of 69.75 ft (21.26 m) and a depth of 15.17 ft (4.62 m), as measured from the top of the bridge deck to the water in the creek.

The second bridge rail type consisted of concrete posts attached to the bridge deck with W-beam guardrail mounted on the face of the concrete posts. The top of the rail was typically 22 in. (0.56 m) above the road, which was less than the minimum required W-beam guardrail height [1]. Therefore, this system was also modeled as a TL-1 bridge rail with blunt ends in RSAP. The posts were 8 to 10 in. (0.20 to 0.25 m) wide and spaced on 6.25 ft (1.9 m) centers.

Both bridges were modeled in RSAP using pre-existing features. Bridges observed in the field were modeled most representatively by RSAP's predefined vertical foreslopes. The bridge depth was specified as a drop height. Therefore, the fixed object was representative of the actual bridge conditions.

Bridge drop-offs were treated as very steep foreslopes. Foreslope depths were incrementally stepped down to match the approximate depth from the sloped ground to the bottom of the bridge at a lateral location from the roadway. Three steps were believed to accurately capture the behavior of the sloped terrain without compromising the accuracy of the analysis. However, the only predefined drop heights in RSAP less than 7 ft (2.1 m) were 0 ft (0 m) and 1 ft (0.3 m), and neither of these had any severity associated with them. Therefore, the 7-ft (2.1-m) drop height was only modeled using one foreslope. The 13-ft (4-m) drop height was modeled using two foreslopes and the 20-ft (6-m) drop height was modeled using three foreslopes.

The culvert study used intersecting slopes to model the drop from the top of the culvert into the drainage canal below. At the time, this selection was believed to be the most appropriate method of modeling the culvert. It was later determined that using foreslopes provides a more accurate approximation for modeling drops-off of culverts and bridges. However, using intersecting slopes overestimates accident costs and produces a more conservative evaluation model because the intersecting slopes have higher severities than corresponding foreslopes. Therefore, the culvert analysis procedure was still valid. Bridges were modeled using the dimensions observed in the field investigation. Due to the uncertainty regarding RSAP's sensitivity to small alterations, four bridge lengths and three bridge heights (drop-offs) were chosen for the analysis. A representative bridge with primary dimensions as used in the analysis is shown in Figure 22.



Drop Height	ft (m)	H	7, 13, 20 (2, 4, 6)
Bridge Length	ft (m)	L	25, 50, 100, 150 (7.6, 15.2, 30.5, 45.7)
Hazard Offset	ft (m)	F	0, 3, 5 (0, 0.9, 1.5)
Slope		SR	1.5H:1V for all
ADT	vpd		50, 100, 150, 200, 250, 300, 350, 400, 450, 500

Figure 22. Representative Bridge and Primary Dimensions

9.2.2 Side Slope Details

An important consideration with modeling bridges was the definition of side slopes. Since, side slopes were not the objective of this bridge analysis, it was conservatively decided to model all slopes as 1.5H:1V.

In order to be consistent through all of the runs, it was decided to use a typical slope width based on the deepest bridge height. Based on the maximum bridge depth of 20 ft (6 m), the slope width was chosen to be 30 ft (9.1 m). It should be noted that the slope extends beyond the clear zone of the roadway, which is 18 ft (5.5 m), and the effective range of encroachment probability used in RSAP. Because each slope extended past the 18-ft (5.5-m) limit in RSAP, the probability of lateral extent approached zero for each model, thus providing consistency for the scenario. A schematic of the slope details is shown in Figure 23.

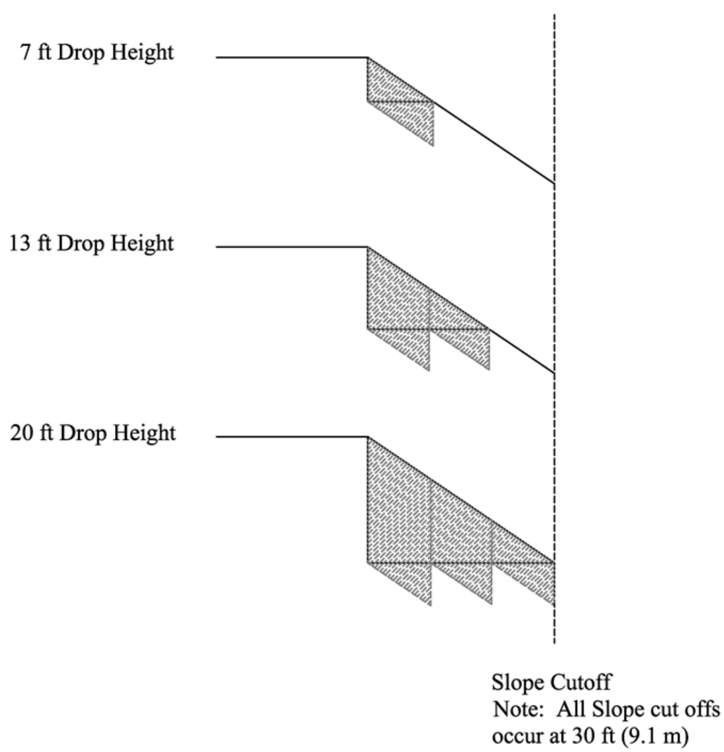


Figure 23. Slope Modeling Dimensions and Simulated Drop-Off Heights

9.2.3 Road Modeling

The bridge analysis was conducted on a straight section of road with no vertical grade. The road was 1,000 ft (304.8 m) long. The bridges were centered in the road geometry, and starting distances varied depending on the length of the bridge. The roadway was modeled as a rural local road with two lanes of travel and an undivided median. A lane width of 12 ft (3.7 m) and a shoulder width of 2 ft (0.6 m) were used. The nominal percent of trucks was set to two percent, and the speed limit was 55 mph (88.5 km/h). The traffic growth factor was zero, and the encroachment rate adjustment factor was left unchanged at the default value of 1.

9.3 Treatment Options

Several different treatment options were evaluated during the simulation. These options included doing nothing, removing existing railing, and installing a W-beam bridge rail. These treatment options are discussed in greater detail in the following sections.

9.3.1 Do Nothing

The “do nothing” option or baseline option was to model the bridges as they were documented in the field. This selection was configured using the parameters discussed previously. The slope and bridge drops were configured using foreslope sections. There was no initial or direct cost for this alternative.

9.3.2 Remove Existing Rail

The second treatment option was to remove the current railing. The removal option was necessary if any other treatment option was considered. Therefore, the removal option was treated as the new baseline when analyzing the remaining treatment options.

Cost estimates for this alternative were provided by KDOT. Costs were broken into two areas: (1) removal of the existing bridge rail and (2) traffic control, mobilization, and contingency. Removal of the existing bridge rail was determined to be $20 per linear foot ($65.62 per linear meter) for steel angle iron rail. To remove the W-beam guardrail with concrete posts, the cost along the bridge length was $20 per linear foot ($65.62 per linear meter) and $5 per linear foot ($16.40 per linear meter) for the approach and terminal section. Traffic control and mobilization were estimated to be 10 percent and 7.5 percent of the total cost, respectively. The traffic control cost was not to exceed $2,000. Contingency was included as 15 percent of the total cost, which covers anything that might not be covered in the other costs. These costs are shown in Table 56.

9.3.3 Install TL-3 Bridge Rail

The third treatment option involved shielding the drop-off with a W-beam bridge rail in front of the bridge deck edge. The bridge rail lengths and costs were determined in a similar manner to that used for shielding slopes in Chapter 7.

Cost estimates for this alternative were also provided by KDOT. There are three components of an adequate bridge rail system: (1) a bridge rail; (2) an approach transition section; and (3) end terminals. In order to consider this alternative, the existing bridge rail must also be removed. Therefore, the costs included the removal of the existing bridge rail, traffic control and mobilization, contingency, and the installation of a bridge rail, approach transition section, and end terminals. The costs for removal, traffic control, mobilization, and contingency were stated in the previous section. The cost for installing an adequate retrofit bridge rail was $100 per linear foot ($328.08 per linear meter). The approach transition section cost was $50 per linear foot ($164.04 per linear meter). The terminal cost was taken from the cost of a FLEAT terminal, which was $2,100 per 37.5 ft (11.4 m) terminal. The terminals were modeled as 12.5 ft

(3.8 m); and the cost of the extra 25 ft (7.6 m) on each end was subtracted from the cost of the approach transition section. The costs for this alternative are also shown in Table 56.

9.3.4 Delineation

Delineation will reduce accident frequency, but it will not reduce the severity of the accident. As a result, the benefit of delineation was not quantifiable in this report. For a more detailed discussion on the use of delineation, see Section 5.5.

9.4 RSAP Results

The results from the bridge analysis are shown in Tables 57 and 58. The results of the bridge analyses are shown in an extended graphical form in Appendix D. For a benefit-to-cost ratio of 4.0, the analyses indicated that the "do nothing" option was preferred. The alternative to remove the existing rail always had a negative benefit-to-cost ratio, thus indicating that the accident cost without the rail was higher. Note that this finding is strongly correlated to the fact that neither the steel nor concrete system alternatives incorporated exceptionally strong posts. As a result, the existing barrier systems that were evaluated proved to have some beneficial effect. The findings may have been different if more rigid posts or end sections had been incorporated.

For a benefit-to-cost ratio of 2.0, it became more beneficial to install an approved bridge rail as the drop height increased. At 7 ft (2.1 m), the recommendation was made to install an approved bridge rail for ADT's above 450 vpd. At a 13 ft (4.0 m) drop height, the minimum ADT was 400 vpd for installing an approved bridge rail. Finally, at a drop height of 20 ft (6.1 m), the minimum ADT was 350 vpd for installing an approved bridge rail. These minimum ADT's were the same for either an existing angle iron rail or an existing W-beam rail. However, the results indicated a wider range of bridge lengths and lateral offsets over which it was economical to replace the angle iron with an approved bridge rail.

Table 56. TL-3 Bridge Rail Alternative - Guardrail Locations and Costs for Bridges

Drop Height (ft)	Slope (XH:1V)	Width of Slope (ft)	Length of Bridge (ft)	Upstream Terminal Start (ft)	Upstream Guardrail Start (ft)	Guardrail Length (ft)	Downstream Terminal Start (ft)	Total Length (ft)	Cost for Removal (Angle Iron)	Cost for Removal (W-Beam)	Cost for Bridge Rail Installation (Remove Ang. Iron)	Cost for Bridge Rail Installation (Remove W-Beam)
7	1.5	10.5	25	412.5	425	137.5	562.5	162.5	$662.50	$1,040.13	$13,680.63	$14,058.25
7	1.5	10.5	50	400	412.5	162.5	575	237.5	$1,325.00	$1,702.63	$17,655.63	$18,033.25
7	1.5	10.5	100	375	387.5	212.5	600	287.5	$2,650.00	$3,027.63	$25,673.13	$26,022.25
7	1.5	10.5	150	350	362.5	262.5	625	337.5	$3,975.00	$4,352.63	$33,023.13	$33,372.25
13	1.5	19.5	25	400	412.5	150	562.5	225	$662.50	$1,040.13	$14,508.75	$14,886.38
13	1.5	19.5	50	387.5	400	175	575	250	$1,325.00	$1,702.63	$18,483.75	$18,861.38
13	1.5	19.5	100	362.5	375	225	600	300	$2,650.00	$3,027.63	$26,438.75	$26,787.88
13	1.5	19.5	150	337.5	350	275	625	350	$3,975.00	$4,352.63	$33,788.75	$34,137.88
20	1.5	30	25	375	387.5	175	562.5	250	$662.50	$1,040.13	$16,165.00	$16,542.63
20	1.5	30	50	362.5	375	200	575	275	$1,325.00	$1,702.63	$20,620.00	$20,969.13
20	1.5	30	100	337.5	350	250	600	325	$2,650.00	$3,027.63	$27,970.00	$28,319.13
20	1.5	30	150	312.5	325	300	625	375	$3,975.00	$4,352.63	$35,320.00	$35,669.13

9.5 Discussion

Bridges can be a severe fixed object when an existing rail is inadequate. However, as indicated by the RSAP analysis, the benefits of installing even low-cost bridge rails did not exceed the direct costs associated with very low traffic volumes. It was assumed that the slope leading up to the bridge was a 1.5H:1V slope. Based on the field data, this was the most appropriate slope rate to apply. The longer bridge lengths had a higher installation cost for the approved bridge rail. Although it would seem that a long bridge with an inadequate barrier would pose a high risk to errant motorists, the benefits of installing an approved bridge rail did not increase sufficiently enough to overcome the high cost of installation.

It should be noted that RSAP does not account for the potential for occupant compartment penetration by one of the existing rails. In such an unfortunate event, the severity could be extreme. Therefore, further study could be given to this harmful event by examining accident data for reports of occupant compartment penetration on low-volume roads. When this data is available, a user-defined model could be created to match the severity determined by those accident reports.

9.6 Conclusions and Recommendations

The bridge analysis was based on field data taken from two different bridges. Three alternatives were considered: do nothing; remove the existing rail; and install an approved bridge rail. The baseline option was to "do nothing," and all other alternatives were compared to this alternative. The second alternative to remove the existing rail leaves the bridge unshielded, thus giving it a very high accident cost. The third alternative to install an approved bridge rail decreased accident costs but increased installation costs. Therefore, installing an approved bridge rail was only beneficial in certain scenarios.

For a benefit-to-cost ratio of 2.0, installing an approved bridge rail was recommended for roadways with an ADT greater than 350 vpd and only for shorter bridges, such as 25 and 50 ft (7.6 and 15.2 m). This volume occurred on drop heights greater than 20 ft (6.1 m). As the drop height decreased, the "do nothing" option became more cost-effective. Additionally, the 350 vpd recommendation was for a 25-ft (7.6-m) long bridge. As length increased, the cost to shield the bridge outgrew the benefit, and the "do nothing" alternative became more cost effective. Finally, lateral offsets also influenced the recommendation of installing an approved bridge rail. For lateral offsets of 0 ft (0 m), it was always recommended to install a bridge rail, but those recommendations were made only for volumes greater than 350 vpd. When lateral offsets greater than 3 ft (0.9 m) were available, the "do nothing" option was the only recommended alternative.

When a benefit-to-cost ratio of 4.0 was required, the RSAP analyses indicated that doing nothing to the existing bridge was the only cost-effective alternative amongst those considered.

Table 57. Bridge Results, B/C = 2

Existing Rail Type	Drop Height (ft)	Length (ft)	Offset (ft)	Do Nothing (ADT)	Install Approved Bridge Rail (ADT)
Angle Iron	0 - 10	0 - 37.5	0 - 1.5	0-449	450-500
			> 1.5	0-500	
		> 37.5	all	0-500	
	10.1 - 16.5	0 - 37.5	0 - 1.5	0-399	400-500
			> 1.5	0-500	
		37.6 - 75	0 - 1.5	0-449	450-500
			> 1.5	0-500	
		> 75	all	0-500	
	> 16.5	0 - 37.5	0 - 1.5	0-349	350-500
			1.6 - 4	0-399	400-500
			> 4	0-449	450-500
		37.6 - 75	0 - 1.5	0-399	400-500
			> 1.5	0-500	
		75.1 - 125	0 - 1.5	0-449	450-500
			> 1.5	0-500	
		> 125	all	0-500	
W-Beam	0 - 10	0 - 37.5	0 - 1.5	0-449	450-500
			> 1.5	0-500	
		> 37.5	all	0-500	
	10.1 - 16.5	0 - 37.5	0 - 1.5	0-399	400-500
			> 1.5	0-500	
		37.6 - 75	0 - 1.5	0-449	450-500
			> 1.5	0-500	
		> 75	all	0-500	
	> 16.5	0 - 37.5	0 - 1.5	0-349	350-500
			1.6 - 4	0-449	450-500
			> 4	0-500	
		37.6 - 75	0 - 1.5	0-399	400-500
			> 1.5	0-500	
		75.1 - 125	0 - 1.5	0-449	450-500
			> 1.5	0-500	
		> 125	all	0-500	

Table 58. Bridge Results, B/C = 4

Existing Rail Type	Drop Height (ft)	Length (ft)	Offset (ft)	Do Nothing (ADT)	Install Approved Bridge Rail (ADT)
Angle Iron	all	all	all	0-500	
W-Beam	all	all	all	0-500	

10 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

10.1 Summary

The safety treatment of fixed objects and geometric features found along low-volume roads has become an important consideration for state and local government agencies because these roads make up a large portion of a state's transportation network. Many fixed objects and geometric features exist along these roads, such as culverts, trees, slopes, ditches, and bridges. However, the low traffic volumes found on these roads often lead engineers to believe that treating these deadly obstacles is not cost-effective because the probability of an accident may be low. In an effort to eliminate inconsistent designs through engineering judgment, benefit-to-cost analyses were conducted for the most commonly found obstacles on low-volume roads. These analyses were completed using RSAP, which estimated the impact frequency for each obstacle over varying traffic volumes on a rural local road. Additionally, RSAP predicted the severity of the accident as well as the associated annual accident cost. Various treatment options were investigated after determining the corresponding annual accident costs. Using installation cost data, a benefit-to-cost ratio was calculated for each design alternative. These benefit-to-cost ratios were used to determine the minimum traffic volumes at which those design alternatives became cost-effective. Because these guidelines were based solely on benefit-to-cost analyses, the engineer is encouraged to use these guidelines as a foundation. Some locations may require more robust treatment options.

Additionally, in order to model rural local highways, the RSAP data files had to be adjusted. As referenced in Chapter 4, the user interface incorrectly codes most roadway functional classes. As a result, the "road.dat" file was modified so that the numerical code for a rural local road functional class was set to 25. It should be noted that the user interface would have programmed a code of 21, which represents a freeway functional class.

10.2 Recommendations

10.2.1 Future RSAP Analyses

Because the user interface incorrectly codes most roadway functional classes, it is recommended that the analyst examine the "road.dat" file, which is generated by the user interface before conducting an RSAP analysis. If the modeled functional class is anything other than a rural arterial highway, the numerical code in this data file should be modified according to the values presented in this report. Those values are reprinted in Table 59 to stress the importance of this step in all future uses of RSAP version 2003.04.01.

Table 59. Functional Class Codes for "road.dat"

Functional Class	Old Code	New Code
Freeway	22	21
Urban Arterial	25	12
Urban Local	24	15
Rural Arterial	22	22
Rural Local	21	25

10.2.2 Culverts

From the field investigation, culverts were the most commonly-observed obstacle found along low-volume roads in the State of Kansas. Some of the culverts contained unapproved rails attached to their headwalls which included concrete post-and-beam systems. These systems were utilized to formulate the baseline model. Treatment options for the culverts included the removal of the existing railing system, installation of a long-span W-beam guardrail system, and installation of a culvert grate. In general, non-crashworthy fixed objects and geometric features should be removed for benefit-to-cost ratios of 2.0. In addition to this removal, it was often recommended to install a long-span W-beam guardrail. However, the need for guardrail decreased as the road width increased. Thus, it was often sufficient to remove the existing system. The option to install a grate was only economical on shorter culverts, typically less than 4 ft (1.2 m) long, as measured parallel to the roadway. However, the length of the culvert along the road could increase as the drop height increased. For heights greater than 8 ft (2.4 m), grates could be installed for lengths between 8 and 10 ft (2.4 and 3.0 m) if there was an existing wingwall. The installation of wingwalls and grates on 30-ft (9.1-m) wide roads was only recommended for culverts measuring less than 6 ft (1.8 m) long and on slopes greater than 3H:1V with traffic volumes above 300 vpd. This option displayed a dependence on road width. Therefore, recommendations for 36-ft (11.0-m) wide roads were limited to 3H:1V slopes with drop heights greater than 8 ft (2.4 m) and culvert lengths less than 4 ft (1.2 m).

As the benefit-to-cost ratio increased to 4.0, each of the aforementioned trends existed, but their amplitudes increased. In other words, “doing nothing” was a viable option in some cases where traffic volumes reached up to 150 vpd. Concrete post removal demonstrated a range of effectiveness for every scenario. Installing guardrail was still recommended but not as frequently. Finally, the culvert grate option, both on existing wingwalls and when wingwalls would need to be constructed, was only recommended for drop heights greater than 8 ft (2.4 m). Even then, the recommendation was limited to short-length culverts with ADT’s greater than 350 vpd. Additional details on the specific modeled scenarios are provided in Chapter 5 and Appendix A.

10.2.3 Trees

Roadside trees are also very common along rural, low-volume roads. They are often intentionally placed to provide aesthetics, block wind, or provide shade. However, trees greatly increase safety risks to errant motorists which strike them. Without the assistance of a site-specific benefit-to-cost analysis, it is recommended that all trees within the clear zone along low-volume roads should be removed if adequate funds are available. In recognition of the fact that safety improvement funds are not always available, benefit-to-cost analyses were conducted to investigate the efficacy of tree removal using costs gathered from tree removal experts, county forestry commissioners, and county engineers. Benefit-to-cost ratios were determined by RSAP and were used to make recommendations based on the number of trees present and the size of those trees.

For benefit-to-cost ratios of 2.0, recommendations were made in four installments based on the number of trees present. For one tree, removal was recommended for all diameters and lateral offsets, regardless of traffic volume. As the number of trees increased and tree spacing became a factor, the option to allow trees to remain in place became viable. When 2 to 10 trees were present in the clear zone and for volumes over 300 vpd, tree removal was recommended for all tree spacings. For all traffic volumes, trees spacings of 4 ft (1.2 m) away from each other and lateral offsets less than 10 ft (3.0 m), it was recommended to remove the trees. As tree spacing increased, the minimum lateral offset decreased. When 11 to 25 trees were present in the clear zone, the “doing nothing” option became even more viable as the cost to remove trees began to exceed the benefit. Traffic volume ranges increased as tree spacing increased. As spacing exceeded 15 ft (4.6 m), tree removal was recommended for all volumes with lateral offsets less than 3 ft (0.9 m) and for many other scenarios with larger offsets. For more than 25 trees in the clear zone, RSAP results were similar to those observed for the 11 to 25 trees category with one exception. The upper range of traffic volumes associated with the "do nothing" option increased from 100-200 vpd to 200-300 vpd.

For benefit-to-cost ratios of 4.0, it was still recommended to remove the single tree for all diameters, lateral offsets, and traffic volumes. Again, the viability of the "do nothing" option increased as the number of trees increased. As a result of the stricter requirement of a B/C ratio equal to 4.0, the cost of tree removal made it less attractive. Even though the same trends were observed, the range of traffic volumes over which the "do nothing" option was viable increased relative to a B/C ratio equal to 2.0. Additional details on the specific modeled scenarios are provided in Chapter 6 and Appendix B.

10.2.4 Slopes

Roadside slopes are commonly used to control the movement of water and prevent roads from flooding. This fact is especially important on low-volume roads, which are often constructed using crushed limestone or gravel. As a result, foreslopes are commonly found along low-volume roads. The side slopes vary but typically range from 1.5H:1V to 6H:1V. Most roadside slopes were found to be steeper than 2H:1V, as observed in the field investigation. By rotating the errant vehicle about its longitudinal axis, slopes introduce instability and ultimately increase rollover propensity. As a result, several options were investigated to determine cost-effective ways of treating these geometric roadside features on low-volume roads. These treatment options included the installation of either W-beam or cable guardrail. Additionally, the engineer may consider slope flattening, which was the focus of another report funded by the Wisconsin Department of Transportation [17]. For purposes of the benefit-to-cost analyses contained herein, two different costs were utilized for W-beam guardrail based on correspondence with several State DOT's. Also, recommendations were categorized according to drop height, starting at 7 ft (2.1 m) and increasing to 26 ft (7.9 m).

For benefit-to-cost ratios of 2.0 and a W-beam guardrail cost of $18.16 per linear foot ($59.58 per linear meter), cable guardrail installation was never recommended. The most common recommended treatment was the "do nothing" option, effectively leaving the existing slope unprotected. However, the option to install W-beam guardrail became cost-effective as slope length increased, especially on 1.5H:1V slopes. For the longest considered slopes (about 1000 ft or 305 m) and lateral offsets of 0 ft, the maximum traffic volume at which the slope could remain unprotected was 300 vpd for drop heights of 7 ft (2.1 m) and decreased to 200 vpd for drop heights of 26 ft (7.9 m). As lateral offset increased and slopes became flatter, these maximum traffic volumes increased.

For a W-beam guardrail cost of $45 per linear ft ($147.64 per linear meter), cable guardrail became a viable option but only for lateral offsets of 3 ft (0.9 m) or greater. This result occurred due to the design recommendation that prohibits cable guardrail placement immediately adjacent to the road. Naturally, W-beam guardrail became less viable as installation costs increased. For lateral offsets of 0 ft (0 m), the "do nothing" option was recommended for all scenarios with drop heights of 7 ft (2.1 m) or less. As the drop height increased, the recommended traffic range for the "do nothing" option decreased. At a drop height of 26 ft (7.9 m), the maximum allowable traffic volume for the "do nothing" option was 300 vpd on slopes of 1.5H:1V or steeper. Cable guardrail was primarily recommended for treating 1.5H:1V slopes. However, these cable guardrail recommendations were extended to 2H:1V slopes as the drop height increased. The minimum traffic volume for which cable guardrail was recommended was

250 vpd when associated with 26-ft (7.9-m) drop heights, 1.5H:1V slopes, a 3-ft (0.9-m) lateral offset, and a slope length greater than 250 ft (76.2 m).

For benefit-to-cost ratios of 4.0 and a W-beam guardrail cost of $18.16 per linear ft ($59.58 per linear meter), the “do nothing” option was recommended for all scenarios at a 7-ft (2.1-m) drop height. As the drop height increased, W-beam guardrail installation became a viable option but only for 1.5H:1V slopes. Even then, W-beam guardrail installation recommendations were made more frequently for small lateral offsets and long slope lengths. In fact, lateral offsets of 7 ft (2.1 m) or greater required no treatment for all drop heights. However, neither cable nor W-beam guardrail installation were viable guardrail options as the cost of the W-beam guardrail was increased to $45 per linear ft ($147.64 per linear meter). In addition, the “do nothing” option was the most cost-effective treatment analyzed herein. Additional details on the specific modeled scenarios are provided in Chapter 7 and Appendix C.

10.2.5 Ditches

V-ditches are often constructed alongside low-volume roads for purposes of controlling the flow of runoff water. However, no ditches were documented in the field investigation for use in this study. Instead, representative ditch cross-sections were assumed based on recommendations in the AASHTO RDG. A foreslope of 4H:1V was used in all cases. However, three different backslopes were utilized and consisted of 4H:1V, 2H:1V, and 1H:1V. Each backslope configuration was configured with a constant height of 15 ft (4.6 m). As with roadside slopes, W-beam and cable guardrail treatment options were investigated. The cost variations for guardrail installation were similar to those used for roadside foreslopes.

In contrast to the recommendations for the other obstacles presented previously, the recommendations for the ditches were very straight forward as the “do nothing” option was preferred. For all guardrail installation options, which also have an associated severity, the accident costs relative to the baseline "do nothing" option increased for every scenario. Further, all ditch cross-sections that vary significantly from those described herein should be evaluated with a specific benefit-to-cost analysis.

10.2.6 Bridges

Although less common than culverts, bridges are often used to span large creeks or streams which traverse under low-volume roads. Bridges differ from culverts in that bridge spans are longer than culverts. From the Kansas field investigation, bridges were often configured with angle-iron railing systems or concrete posts which supported W-beam rails. For these low-volume bridges, treatment options included doing nothing, removing the existing railing, and/or the installin an approved bridge railing. Safety treatment recommendations provided for two different existing railing structures – angle-iron and W-beam.

From the analysis, removal of the existing railing configurations was never recommended, regardless of its type or of the scenario. This result occurred due to the fact that RSAP predicted higher accident costs when the guardrail was removed. However, RSAP did not account for the possibility of occupant compartment penetration by the railing components, which could increase the accident costs when the railing system was left in place and potentially increase the benefit to removing the existing railing configuration.

For a benefit-to-cost ratio of 2.0, it was recommended to install an approved bridge railing for traffic volumes above 350 vpd and for a drop height of 20 ft (6.1 m). As the drop height decreased, the minimum traffic volume at which the installation of an approved bridge railing became viable increased to 450 vpd at a drop height of 7 ft (2.1 m). These minimum traffic volumes corresponded to bridge lengths of 25 ft (7.6 m) or less. However, the installation of an approved bridge railing became either less viable or not viable at all as the length of the bridge increased. Finally, lateral offsets of 0 ft (0 m) required safety treatment beyond the "do nothing" option for all bridge lengths and vertical heights. However, recommendations for using approved bridge railing for lateral offsets greater than 0 ft (0 m) were reserved for drop heights of 20 ft (6.1 m) or greater.

For existing W-beam railing systems, it was often recommended to implement the "do nothing" option. This result occurred because the direct costs to remove the existing structure and retrofit the bridge with an approved system exceeded the accident cost reductions associated with the upgrade to the safer design. Lateral offsets of 0 ft (0 m) required the installation of an approved bridge railing, regardless of the length or height of the bridge. Recommendations for the two railing systems were similar except on the 20-ft (6.1-m) drop heights. At this height, the recommendation to remove the existing rail and install an approved system was given for lateral offsets of 3 ft (0.9 m) or less if the bridge was less than or equal to 25 ft (7.6 m) long. For lengths greater than 25 ft (7.6 m), this option was recommended on lateral offsets of 0 ft (0 m) only.

For a benefit-to-cost ratio of 4.0, the costs associated with removing and replacing the existing rails exceeded the required benefit. As a result, it was recommended to allow the existing railings to remain in place for all scenarios, regardless of the type of bridge railing. Additional details on the specific modeled scenarios are provided in Chapter 9 and Appendix D.

It should be noted that only two bridges were observed in the field investigation and used to create the representative model in this report. As a result, if the bridge under consideration is significantly different than the model described herein, a site-specific benefit-to-cost analysis may be needed.

10.3 Conclusions

The roadside obstacles analyzed in this report can pose significant risk to motorists. As a result, the safest option, regardless of cost, should always be considered before making a final recommendation regarding obstacle treatment. Roadside safety engineers should strive to create the safest roadside environment as possible with available funding. The obstacle should be removed from the clear zone, such as for trees. When this option is not possible, such as for culverts and bridges, the motorist should be shielded from the obstacle. If all prior options are unavailable for implementation, delineation should be used as a last resort with the hope that accident frequency will be reduced.

When implementation costs are significant, the recommendations contained herein can be used to configure consistent designs that provide cost-effective safety treatments for common obstacles found along low-volume roads.

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12 APPENDICES

Appendix A. Culvert Treatment Recommendations and Analysis Results

Table A-1. Key for Constant Slope Culvert Recommendations

	Do Nothing
	Remove Deficient System
	Install Guardrail
	Install Culvert Grate
*	Install culvert grate if wingwalls are previously constructed; else, remove deficient system
**	Install culvert grate if wingwalls are previously constructed; else, install guardrail

Table A-2. Foreslope, Culvert Drop < 2 ft (0.6 m), Road Width < 30 ft (9.1 m)

Road < 30 ft Wide

B/C Cutoff Ratio 2.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-3. Foreslope, Culvert Drop < 2 ft (0.6 m), Road Width 30-31.9 ft (9.1-9.7 m)

Road 30-32 ft Wide															
B/C Cutoff Ratio	**Culvert Length: ≤ 4 ft**							B/C Cutoff Ratio	**Culvert Length: ≤ 4 ft**						
2.00	**Side Slope Rate**							4.00	**Side Slope Rate**						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: 6 ft**							**Traffic Volume**	**Culvert Length: 6 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: 8 ft**							**Traffic Volume**	**Culvert Length: 8 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: 10 ft**							**Traffic Volume**	**Culvert Length: 10 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: ≥ 12 ft**							**Traffic Volume**	**Culvert Length: ≥ 12 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-4. Foreslope, Culvert Drop < 2 ft (0.6 m), Road Width 32-33.9 ft (9.8-10.3 m)

							Road 32-34 ft Wide								
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: 6 ft**							**Traffic Volume**	**Culvert Length: 6 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: 8 ft**							**Traffic Volume**	**Culvert Length: 8 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: 10 ft**							**Traffic Volume**	**Culvert Length: 10 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: ≥ 12 ft**							**Traffic Volume**	**Culvert Length: ≥ 12 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-5. Foreslope, Culvert Drop < 2 ft (0.6 m), Road Width 34-35.9 ft (10.4-10.9 m)

									Road 34-36 ft Wide						
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 6 ft							Traffic Volume	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 8 ft							Traffic Volume	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 10 ft							Traffic Volume	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							Traffic Volume	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-6. Foreslope, Culvert Drop < 2 ft (0.6 m), Road Width ≥ 36 ft (11.0 m)

													Road > 36 ft Wide		
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 6 ft							Traffic Volume	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 8 ft							Traffic Volume	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 10 ft							Traffic Volume	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							Traffic Volume	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-7. Foreslope, Culvert Drop 2-3.9 ft (0.6-1.2 m), Road Width < 30 ft (9.1 m)

Road < 30 ft Wide															
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350				*				350							
400				*				400							
450				*				450							
500				4				500							
Traffic Volume	**Culvert Length: 6 ft**							**Traffic Volume**	**Culvert Length: 6 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400				*				400							
450				*				450							
500				*				500							
Traffic Volume	**Culvert Length: 8 ft**							**Traffic Volume**	**Culvert Length: 8 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450				*				450							
500				*				500							
Traffic Volume	**Culvert Length: 10 ft**							**Traffic Volume**	**Culvert Length: 10 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: ≥ 12 ft**							**Traffic Volume**	**Culvert Length: ≥ 12 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-8. Foreslope, Culvert Drop 2-3.9 ft (0.6-1.2 m), Road Width 30-31.9 ft (9.1-9.7 m)

			Road 30-32 ft Wide												
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400				*				400							
450				*				450							
500				*				500							
Traffic Volume	Culvert Length: 6 ft							Traffic Volume	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450				*				450							
500				*				500							
Traffic Volume	Culvert Length: 8 ft							Traffic Volume	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500				*				500							
Traffic Volume	Culvert Length: 10 ft							Traffic Volume	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							Traffic Volume	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-9. Foreslope, Culvert Drop 2-3.9 ft (0.6-1.2 m), Road Width 32-33.9 ft (9.8-10.3 m)

							Road 32-34 ft Wide								
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400				*				400							
450				*				450							
500				*				500							
Traffic Volume	Culvert Length: 6 ft							Traffic Volume	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450				*				450							
500				*				500							
Traffic Volume	Culvert Length: 8 ft							Traffic Volume	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 10 ft							Traffic Volume	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							Traffic Volume	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-10. Foreslope, Culvert Drop 2-3.9 ft (0.6-1.2 m), Road Width 34-35.9 ft (10.4-10.9 m)

Road 34-36 ft Wide

B/C Cutoff Ratio 2.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450				*			
500				*			
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500				*			
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-11. Foreslope, Culvert Drop 2-3.9 ft (0.6-1.2 m), Road Width ≥ 36 ft (11.0 m)

Road > 36 ft Wide

B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500				*			
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-12. Foreslope, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width < 30 ft (9.1 m)

Road < 30 ft Wide

B/C Cutoff Ratio 2.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300				*			
350				*			
400				**			
450				**	**		
500				4	**		
Traffic Volume	**Culvert Length: 6 ft**						
50							
100							
150							
200							
250							
300							
350							
400				**			
450				**			
500				**			
Traffic Volume	**Culvert Length: 8 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 10 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: ≥ 12 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 6 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 8 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 10 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: ≥ 12 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-13. Foreslope, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width 30-31.9 ft (9.1-9.7 m)

Road 30-32 ft Wide															
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300				*				300							
350				*				350							
400				**				400							
450				**	*			450							
500				4	**			500							
Traffic Volume	Culvert Length: 6 ft							**Traffic Volume**	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400				**				400							
450				**				450							
500				**				500							
Traffic Volume	Culvert Length: 8 ft							**Traffic Volume**	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 10 ft							**Traffic Volume**	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							**Traffic Volume**	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-14. Foreslope, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width 32-33.9 ft (9.8-10.3 m)

								Road 32-34 ft Wide							
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300				*				300							
350				*				350							
400				*				400							
450				**				450							
500				**				500							
Traffic Volume	Culvert Length: 6 ft							**Traffic Volume**	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450				**				450							
500				**				500							
Traffic Volume	Culvert Length: 8 ft							**Traffic Volume**	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 10 ft							**Traffic Volume**	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							**Traffic Volume**	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-15. Foreslope, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width 34-35.9 ft (10.4-10.9 m)

Road 34-36 ft Wide

B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350				*			
400				*			
450				*			
500				**	**		
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-16. Foreslope, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width ≥ 36 ft (11.0 m)

													Road > 36 ft Wide		
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350				*				350							
400				*				400							
450				*				450							
500				**				500							
Traffic Volume	Culvert Length: 6 ft							**Traffic Volume**	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500				**				500							
Traffic Volume	Culvert Length: 8 ft							**Traffic Volume**	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200		#VALUE!						200		#VALUE!					
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: 10 ft							**Traffic Volume**	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							**Traffic Volume**	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-17. Foreslope, Culvert Drop ≥ 8 ft (2.4 m), Road Width < 30 ft (9.1 m)

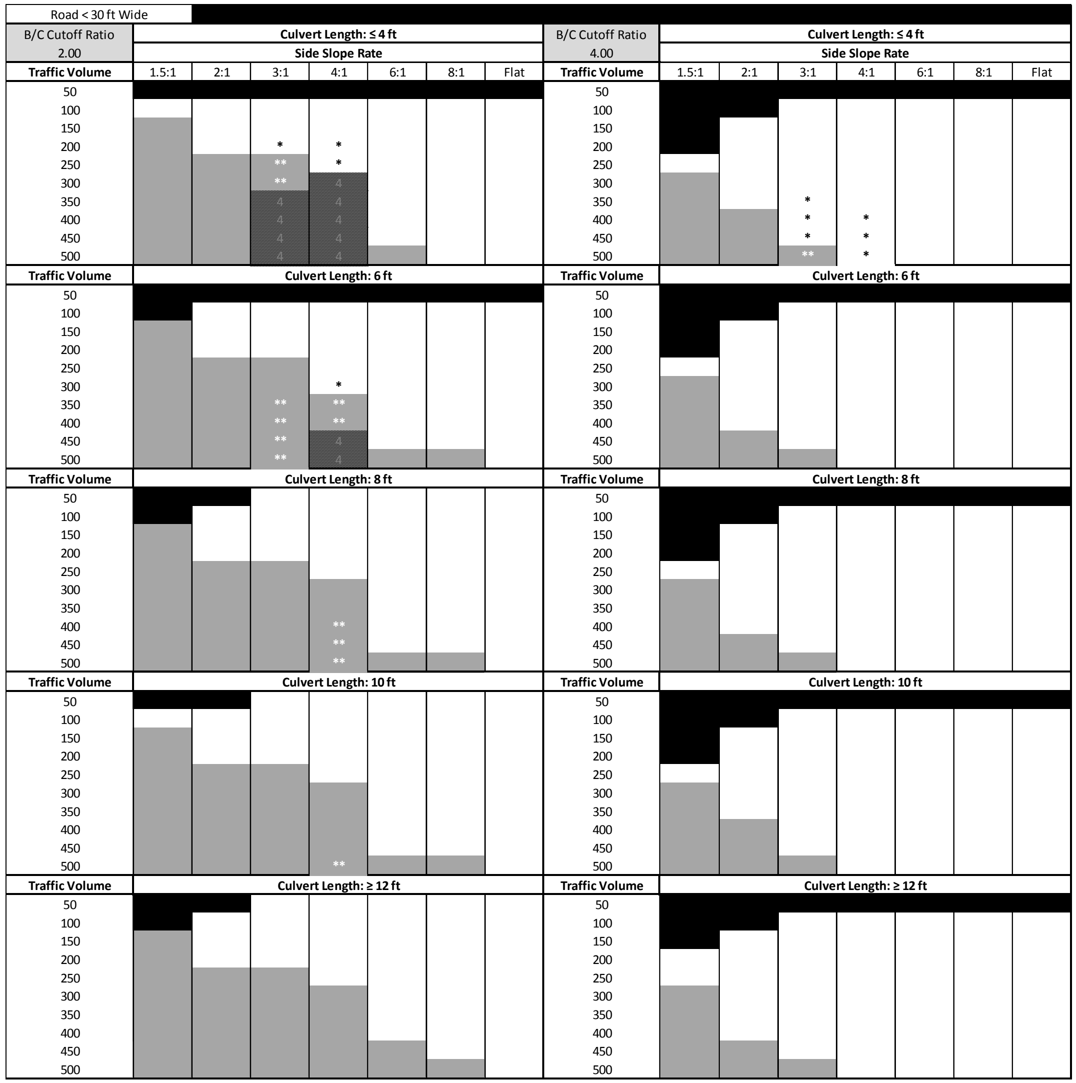

Table A-18. Foreslope, Culvert Drop ≥ 8 ft (2.4 m), Road Width 30-31.9 ft (9.1-9.7 m)

Road 30-32 ft Wide

B/C Cutoff Ratio 2.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200			*				
250			*	*			
300			**	*			
350			**	4			
400			4	4			
450			4	4			
500			4	4			
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300				*			
350				**			
400			**	**			
450				**			
500			**	4			
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450				**			
500				**			
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft						
	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400			*				
450			*	*			
500			4	*			
Traffic Volume	Culvert Length: 6 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 8 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: 10 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	Culvert Length: ≥ 12 ft						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-19. Foreslope, Culvert Drop ≥ 8 ft (2.4 m), Road Width 32-33.9 ft (9.8-10.3 m)

							Road 32-34 ft Wide								
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	**Traffic Volume**	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200			*					200							
250			*	*				250							
300			**	*				300							
350			**	4				350							
400			**	4				400							
450			4	4				450			*				
500			4	4				500			*	*			
Traffic Volume	**Culvert Length: 6 ft**							**Traffic Volume**	**Culvert Length: 6 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350				**				350							
400				**				400							
450			**	**				450							
500			**	**				500							
Traffic Volume	**Culvert Length: 8 ft**							**Traffic Volume**	**Culvert Length: 8 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450				**				450							
500				**				500							
Traffic Volume	**Culvert Length: 10 ft**							**Traffic Volume**	**Culvert Length: 10 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	**Culvert Length: ≥ 12 ft**							**Traffic Volume**	**Culvert Length: ≥ 12 ft**						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-20. Foreslope, Culvert Drop ≥ 8 ft (2.4 m), Road Width 34-35.9 ft (10.4-10.9 m)

										Road 34-36 ft Wide					
B/C Cutoff Ratio	Culvert Length: ≤ 4 ft							B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate							4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat	Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50								50							
100								100							
150								150							
200								200							
250			*	*				250							
300			**	*				300							
350			**	4				350							
400			**	4				400							
450			**	4				450			*				
500			4	4				500			*	*			
Traffic Volume	Culvert Length: 6 ft							Traffic Volume	Culvert Length: 6 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350				*				350							
400				**				400							
450				**				450							
500			**	**				500							
Traffic Volume	Culvert Length: 8 ft							Traffic Volume	Culvert Length: 8 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500				**				500							
Traffic Volume	Culvert Length: 10 ft							Traffic Volume	Culvert Length: 10 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							
Traffic Volume	Culvert Length: ≥ 12 ft							Traffic Volume	Culvert Length: ≥ 12 ft						
50								50							
100								100							
150								150							
200								200							
250								250							
300								300							
350								350							
400								400							
450								450							
500								500							

Table A-21. Foreslope, Culvert Drop ≥ 8 ft (2.4 m), Road Width ≥ 36 ft (11.0 m)

Road > 36 ft Wide

B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
2.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250			*				
300			*				
350			**	*			
400			**	*			
450			**	**			
500			4	**			
Traffic Volume	**Culvert Length: 6 ft**						
50							
100							
150							
200							
250							
300							
350							
400				**			
450				**			
500				**			
Traffic Volume	**Culvert Length: 8 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 10 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: ≥ 12 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

B/C Cutoff Ratio	Culvert Length: ≤ 4 ft						
4.00	Side Slope Rate						
Traffic Volume	1.5:1	2:1	3:1	4:1	6:1	8:1	Flat
50							
100							
150							
200							
250							
300							
350							
400							
450			*				
500			*				
Traffic Volume	**Culvert Length: 6 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 8 ft**						
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: 10 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							
Traffic Volume	**Culvert Length: ≥ 12 ft**						
50							
100							
150							
200							
250							
300							
350							
400							
450							
500							

Table A-22. Key for Ditch Culvert Recommendations

	Do Nothing
	Remove Deficient System
	Install Guardrail

Table A-23. Ditch, Culvert Drop < 4 ft (1.2 m), Road Width < 30 ft (9.1 m)

	Road <30 ft Wide									
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-24. Ditch, Culvert Drop < 4 ft (1.2 m), Road Width 30-31.9 ft (9.1-9.7 m)

			Road 30-32 ft Wide							
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-25. Ditch, Culvert Drop < 4 ft (1.2 m), Road Width 32-33.9 ft (9.8-10.3 m)

					Road 32-34 ft Wide					
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-26. Ditch, Culvert Drop < 4 ft (1.2 m), Road Width 34-35.9 ft (10.4-10.9 m)

							Road 34-36 ft Wide			
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-27. Ditch, Culvert Drop < 4 ft (1.2 m), Road Width ≥ 36 ft (11.0 m)

										Road ≥ 36 ft Wide
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-28. Ditch, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width < 30 ft (9.1 m)

	Road <30 ft Wide									
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-29. Ditch, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width 30-31.9 ft (9.1-9.7 m)

			Road 30-32 ft Wide							
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-30. Ditch, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width 32-33.9 ft (9.8-10.3 m)

					Road 32-34 ft Wide					
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-31. Ditch, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width 34-35.9 ft (10.4-11.0 m)

							Road 34-36 ft Wide			
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-32. Ditch, Culvert Drop 4-7.9 ft (1.2-2.4 m), Road Width ≥ 36 ft (11.0 m)

									Road ≥ 36 ft Wide	
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-33. Ditch, Culvert Drop ≥ 8 ft (2.4 m), Road Width < 30 ft (9.1 m)

	Road <30 ft Wide									
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-34. Ditch, Culvert Drop ≥ 8 ft (2.4 m), Road Width 30-31.9 ft (9.1-9.7 m)

			Road 30-32 ft Wide							
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-35. Ditch, Culvert Drop ≥ 8 ft (2.4 m), Road Width 32-33.9 ft (9.8-10.3 m)

					Road 32-34 ft Wide					
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-36. Ditch, Culvert Drop ≥ 8 ft (2.4 m), Road Width 34-35.9 ft (10.4-10.9 m)

							Road 34-36 ft Wide			
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	Culvert Length: ≤ 4 ft		Culvert Length: 4-6 ft		Culvert Length: 6-8 ft		Culvert Length: 8-10 ft		Culvert Length: ≥ 10 ft	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Table A-37. Ditch, Culvert Drop ≥ 8 ft (2.4 m), Road Width ≥ 36 ft (11.0 m)

									Road ≥ 36 ft Wide	
	Side Slope Rate									
B/C Cutoff Ratio 2.00	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1	1.5:1	2:1
Traffic Volume	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										
B/C Cutoff Ratio 4.00	**Culvert Length: ≤ 4 ft**		**Culvert Length: 4-6 ft**		**Culvert Length: 6-8 ft**		**Culvert Length: 8-10 ft**		**Culvert Length: ≥ 10 ft**	
50										
100										
150										
200										
250										
300										
350										
400										
450										
500										

Appendix B. Tree Treatment Recommendations and Analysis Results

Table B-1. Single Tree, B/C Ratio = 2

1 Tree	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

Cost to Remove One 6-in. (152-mm) Diameter Tree: **$160**
Cost to Remove One 10-in. (254-mm) Diameter Tree: **$190**
Cost to Remove One 15-in. (305-mm) Diameter Tree: **$220**

Key:
Do Nothing
Remove Tree

Table B-2. 2-10 Trees, B/C Ratio = 2

2-10 Trees at 4 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

2-10 Trees at 15 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

2-10 Trees at 30 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

Cost to Remove Four 6-in. Diameter Trees:	**$640**	Key:	Do Nothing
Cost to Remove Four 10-in. Diameter Trees:	**$760**		Remove Tree
Cost to Remove Four 15-in. Diameter Trees:	**$880**		

Table B-3. 11-25 Trees, B/C Ratio = 2

11-25 Trees at 4 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50									■	■		
100					■	■	■		■	■		
150	■	■			■	■	■	■	■	■	■	■
200	■	■	■		■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

11-25 Trees at 15 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■	■			■	■		
100	■	■	■		■	■	■	■	■	■	■	■
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

11-25 Trees at 30 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50	■	■			■	■	■	■	■	■	■	
100	■	■	■	■	■	■	■	■	■	■	■	
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

Cost to Remove Ten 6-in. Diameter Trees:	**$1,600**	Key:		Do Nothing
Cost to Remove Ten 10-in. Diameter Trees:	**$1,900**		■	Remove Tree
Cost to Remove Ten 15-in. Diameter Trees:	**$2,200**			

Table B-4. More than 25 Trees, B/C Ratio = 2

> 25 Trees at 4 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100					■							
150					■	■	■		■			
200	■				■	■	■	■	■	■	■	■
250	■	■			■	■	■	■	■	■	■	■
300	■	■	■		■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

> 25 Trees at 15 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■	■			■			
100	■	■			■	■	■		■	■		
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

> 25 Trees at 30 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50	■	■			■	■			■	■		
100	■	■	■	■	■	■	■	■	■	■	■	■
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

Cost to Remove Twenty-Five 6-in. Diameter Trees:	**$4,000**	Key:	Do Nothing
Cost to Remove Twenty-Five 10-in. Diameter Trees:	**$4,750**	■	Remove Tree
Cost to Remove Twenty-Five 15-in. Diameter Trees:	**$5,500**		

Table B-5. Single Tree, B/C Ratio = 4

1 Tree	**0 - 5.9 in. Diameter Tree**				**6 - 11.9 in. Diameter Tree**				**12+ in. Diameter Tree**			
	Offset from Edge of Road				**Offset from Edge of Road**				**Offset from Edge of Road**			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

Cost to Remove One 6-in. (152-mm) Diameter Tree: **$160**
Cost to Remove One 10-in. (254-mm) Diameter Tree: **$190**
Cost to Remove One 15-in. (305-mm) Diameter Tree: **$220**

Key:
Do Nothing
Remove Tree

Table B-6. 2-10 Trees, B/C Ratio = 4

2-10 Trees at 4 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50									■	■		
100	■				■	■	■		■	■	■	
150	■	■			■	■	■	■	■	■	■	■
200	■	■	■		■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

2-10 Trees at 15 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■				■			
100	■	■			■	■	■	■	■	■		
150	■	■	■		■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

2-10 Trees at 30 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■	■			■	■		
100	■	■	■		■	■	■	■	■	■	■	■
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

Cost to Remove Four 6-in. Diameter Trees:	**$640**	Key:	Do Nothing
Cost to Remove Four 10-in. Diameter Trees:	**$760**	■	Remove Tree
Cost to Remove Four 15-in. Diameter Trees:	**$880**		

Table B-7. 11-25 Trees, B/C Ratio = 4

11-25 Trees at 4 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100					■	■			■			
150					■	■			■			
200	■				■	■			■	■		
250	■	■			■	■	■	■	■	■	■	
300	■	■	■		■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

11-25 Trees at 15 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■	■			■	■		
100					■	■			■	■		
150	■	■			■	■	■	■	■	■	■	
200	■	■	■		■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

11-25 Trees at 30 ft Spacing	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■	■	■	■	■			
100	■	■			■	■	■	■	■	■		
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

Cost to Remove Ten 6-in. Diameter Trees:	**$1,600**	Key:	(blank) Do Nothing
Cost to Remove Ten 10-in. Diameter Trees:	**$1,900**		■ Remove Tree
Cost to Remove Ten 15-in. Diameter Trees:	**$2,200**		

Table B-8. More than 25 Trees, B/C Ratio = 4

> 25 Trees at 4 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50												
100												
150												
200					■							
250	■	■			■	■			■			
300	■	■			■	■	■		■	■		
350	■	■	■		■	■	■		■	■	■	
400	■	■	■	■	■	■	■	■	■	■	■	
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

> 25 Trees at 15 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■	■			■			
100					■	■			■			
150	■				■	■	■	■	■	■	■	
200	■	■			■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

> 25 Trees at 30 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft	0-2.9 ft	3-6.9 ft	7-9.9 ft	10+ ft
50					■							
100	■	■			■	■	■	■	■	■	■	
150	■	■	■	■	■	■	■	■	■	■	■	■
200	■	■	■	■	■	■	■	■	■	■	■	■
250	■	■	■	■	■	■	■	■	■	■	■	■
300	■	■	■	■	■	■	■	■	■	■	■	■
350	■	■	■	■	■	■	■	■	■	■	■	■
400	■	■	■	■	■	■	■	■	■	■	■	■
450	■	■	■	■	■	■	■	■	■	■	■	■
500	■	■	■	■	■	■	■	■	■	■	■	■

Cost to Remove Twenty-Five 6-in. Diameter Trees:	**$4,000**	Key:	Do Nothing
Cost to Remove Twenty-Five 10-in. Diameter Trees:	**$4,750**	■	Remove Tree
Cost to Remove Twenty-Five 15-in. Diameter Trees:	**$5,500**		

Table B-9. Maximum Cost for Tree Removal at B/C Ratio = 2, Single Tree

1 Tree	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$840	$630	$460	$400	$1,840	$1,430	$1,110	$880	$1,830	$1,670	$1,210	$980
100	$1,680	$1,260	$920	$800	$3,670	$2,850	$2,220	$1,750	$3,650	$3,340	$2,420	$1,960
150	$2,510	$1,880	$1,390	$1,210	$5,510	$4,280	$3,330	$2,630	$5,480	$5,010	$3,630	$2,930
200	$3,350	$2,510	$1,850	$1,610	$7,340	$5,700	$4,430	$3,500	$7,300	$6,680	$4,840	$3,910
250	$4,190	$3,140	$2,310	$2,010	$9,180	$7,130	$5,540	$4,380	$9,130	$8,350	$6,050	$4,890
300	$5,030	$3,770	$2,770	$2,410	$11,010	$8,550	$6,650	$5,250	$10,950	$10,020	$7,260	$5,870
350	$5,860	$4,400	$3,240	$2,810	$12,850	$9,980	$7,760	$6,130	$12,780	$11,690	$8,470	$6,840
400	$6,700	$5,030	$3,700	$3,220	$14,680	$11,400	$8,870	$7,000	$14,600	$13,360	$9,680	$7,820
450	$7,540	$5,650	$4,160	$3,620	$16,520	$12,830	$9,980	$7,880	$16,430	$15,030	$10,890	$8,800
500	$8,380	$6,280	$4,620	$4,020	$18,350	$14,260	$11,090	$8,750	$18,250	$16,700	$12,090	$9,780

Table B-10. Maximum Cost for Tree Removal at B/C Ratio = 2, 2-10 Trees

2-10 Trees at	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
< 10 ft Spacing	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$870	$720	$570	$460	$2,040	$1,740	$1,330	$1,030	$2,280	$1,910	$1,390	$1,180
100	$1,740	$1,450	$1,130	$910	$4,080	$3,490	$2,660	$2,060	$4,550	$3,830	$2,780	$2,350
150	$2,610	$2,170	$1,700	$1,370	$6,110	$5,230	$3,990	$3,090	$6,830	$5,740	$4,170	$3,530
200	$3,480	$2,900	$2,270	$1,830	$8,150	$6,970	$5,320	$4,130	$9,110	$7,660	$5,550	$4,700
250	$4,350	$3,620	$2,840	$2,290	$10,190	$8,720	$6,640	$5,160	$11,380	$9,570	$6,940	$5,880
300	$5,220	$4,350	$3,400	$2,740	$12,230	$10,460	$7,970	$6,190	$13,660	$11,490	$8,330	$7,050
350	$6,090	$5,070	$3,970	$3,200	$14,260	$12,200	$9,300	$7,220	$15,940	$13,400	$9,720	$8,230
400	$6,970	$5,800	$4,540	$3,660	$16,300	$13,950	$10,630	$8,250	$18,210	$15,320	$11,110	$9,400
450	$7,840	$6,520	$5,100	$4,120	$18,340	$15,690	$11,960	$9,280	$20,490	$17,230	$12,500	$10,580
500	$8,710	$7,250	$5,670	$4,570	$20,380	$17,430	$13,290	$10,320	$22,770	$19,150	$13,880	$11,750

2-10 Trees at	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
10-25 ft Spacing	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$1,400	$1,100	$870	$700	$3,050	$2,550	$1,940	$1,580	$3,290	$2,610	$1,990	$1,680
100	$2,790	$2,200	$1,730	$1,390	$6,100	$5,100	$3,880	$3,160	$6,580	$5,210	$3,990	$3,370
150	$4,190	$3,300	$2,600	$2,090	$9,150	$7,650	$5,820	$4,740	$9,870	$7,820	$5,980	$5,050
200	$5,590	$4,410	$3,470	$2,780	$12,200	$10,200	$7,760	$6,320	$13,160	$10,420	$7,970	$6,740
250	$6,980	$5,510	$4,340	$3,480	$15,250	$12,760	$9,690	$7,900	$16,450	$13,030	$9,970	$8,420
300	$8,380	$6,610	$5,200	$4,180	$18,290	$15,310	$11,630	$9,480	$19,740	$15,630	$11,960	$10,100
350	$9,770	$7,710	$6,070	$4,870	$21,340	$17,860	$13,570	$11,060	$23,020	$18,240	$13,950	$11,790
400	$11,170	$8,810	$6,940	$5,570	$24,390	$20,410	$15,510	$12,640	$26,310	$20,840	$15,950	$13,470
450	$12,570	$9,910	$7,800	$6,260	$27,440	$22,960	$17,450	$14,220	$29,600	$23,450	$17,940	$15,160
500	$13,960	$11,010	$8,670	$6,960	$30,490	$25,510	$19,390	$15,800	$32,890	$26,060	$19,930	$16,840

2-10 Trees at	0 - 5.9 in. Diameter Tree				6 - 11.9 in. Diameter Tree				12+ in. Diameter Tree			
> 25 ft Spacing	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$1,690	$1,460	$1,050	$960	$4,050	$3,360	$2,610	$2,070	$4,410	$3,650	$2,730	$1,670
100	$3,390	$2,920	$2,100	$1,920	$8,100	$6,710	$5,220	$4,140	$8,820	$7,310	$5,470	$3,330
150	$5,080	$4,380	$3,150	$2,880	$12,150	$10,070	$7,820	$6,200	$13,230	$10,960	$8,200	$5,000
200	$6,780	$5,840	$4,210	$3,840	$16,210	$13,420	$10,430	$8,270	$17,640	$14,620	$10,930	$6,670
250	$8,470	$7,300	$5,260	$4,800	$20,260	$16,780	$13,040	$10,340	$22,050	$18,270	$13,670	$8,330
300	$10,170	$8,760	$6,310	$5,760	$24,310	$20,130	$15,650	$12,410	$26,460	$21,930	$16,400	$10,000
350	$11,860	$10,220	$7,360	$6,720	$28,360	$23,490	$18,260	$14,480	$30,860	$25,580	$19,130	$11,670
400	$13,550	$11,680	$8,410	$7,680	$32,410	$26,850	$20,860	$16,540	$35,270	$29,240	$21,870	$13,330
450	$15,250	$13,140	$9,460	$8,640	$36,460	$30,200	$23,470	$18,610	$39,680	$32,890	$24,600	$15,000
500	$16,940	$14,600	$10,520	$9,600	$40,510	$33,560	$26,080	$20,680	$44,090	$36,550	$27,340	$16,670

Table B-11. Maximum Cost for Tree Removal at B/C Ratio = 2, 11-25 Trees

11-25 Trees at < 10 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$1,210	$1,030	$760	$620	$2,690	$2,320	$1,450	$1,470	$3,030	$2,470	$1,950	$1,530
100	$2,430	$2,060	$1,530	$1,250	$5,380	$4,650	$2,890	$2,950	$6,060	$4,940	$3,900	$3,050
150	$3,640	$3,090	$2,290	$1,870	$8,070	$6,970	$4,340	$4,420	$9,090	$7,400	$5,850	$4,580
200	$4,850	$4,120	$3,060	$2,500	$10,770	$9,300	$5,780	$5,890	$12,120	$9,870	$7,810	$6,110
250	$6,070	$5,150	$3,820	$3,120	$13,460	$11,620	$7,230	$7,370	$15,150	$12,340	$9,760	$7,630
300	$7,280	$6,180	$4,580	$3,750	$16,150	$13,940	$8,670	$8,840	$18,180	$14,810	$11,710	$9,160
350	$8,490	$7,200	$5,350	$4,370	$18,840	$16,270	$10,120	$10,310	$21,210	$17,280	$13,660	$10,690
400	$9,710	$8,230	$6,110	$4,990	$21,530	$18,590	$11,570	$11,790	$24,240	$19,740	$15,610	$12,210
450	$10,920	$9,260	$6,880	$5,620	$24,220	$20,910	$13,010	$13,260	$27,270	$22,210	$17,560	$13,740
500	$12,130	$10,290	$7,640	$6,240	$26,910	$23,240	$14,460	$14,730	$30,300	$24,680	$19,520	$15,270

11-25 Trees at 10-25 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$2,390	$1,980	$1,510	$1,280	$830	$4,550	$2,870	$490	$5,580	$4,760	$3,660	$3,020
100	$4,770	$3,950	$3,020	$2,560	$1,670	$9,090	$5,740	$990	$11,150	$9,530	$7,330	$6,040
150	$7,160	$5,930	$4,530	$3,840	$2,500	$13,640	$8,610	$1,480	$16,730	$14,290	$10,990	$9,050
200	$9,550	$7,900	$6,040	$5,120	$3,340	$18,180	$11,470	$1,980	$22,300	$19,060	$14,650	$12,070
250	$11,930	$9,880	$7,550	$6,400	$4,170	$22,730	$14,340	$2,470	$27,880	$23,820	$18,320	$15,090
300	$14,320	$11,850	$9,050	$7,680	$5,010	$27,270	$17,210	$2,970	$33,460	$28,590	$21,980	$18,110
350	$16,700	$13,830	$10,560	$8,960	$5,840	$31,820	$20,080	$3,460	$39,030	$33,350	$25,640	$21,130
400	$19,090	$15,810	$12,070	$10,240	$6,680	$36,360	$22,950	$3,950	$44,610	$38,120	$29,310	$24,150
450	$21,480	$17,780	$13,580	$11,520	$7,510	$40,910	$25,820	$4,450	$50,180	$42,880	$32,970	$27,160
500	$23,860	$19,760	$15,090	$12,800	$8,350	$45,450	$28,690	$4,940	$55,760	$47,640	$36,640	$30,180

11-25 Trees at > 25 Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$3,650	$3,130	$2,350	$1,880	$8,510	$7,120	$4,430	$4,440	$8,990	$7,380	$5,690	$4,690
100	$7,300	$6,260	$4,710	$3,770	$17,020	$14,240	$8,860	$8,870	$17,980	$14,750	$11,390	$9,370
150	$10,940	$9,400	$7,060	$5,650	$25,530	$21,350	$13,290	$13,310	$26,970	$22,130	$17,080	$14,060
200	$14,590	$12,530	$9,410	$7,530	$34,040	$28,470	$17,730	$17,750	$35,960	$29,510	$22,780	$18,750
250	$18,240	$15,660	$11,770	$9,420	$42,550	$35,590	$22,160	$22,190	$44,950	$36,880	$28,470	$23,440
300	$21,890	$18,790	$14,120	$11,300	$51,060	$42,710	$26,590	$26,620	$53,940	$44,260	$34,160	$28,120
350	$25,540	$21,930	$16,470	$13,180	$59,560	$49,820	$31,020	$31,060	$62,930	$51,640	$39,860	$32,810
400	$29,190	$25,060	$18,830	$15,060	$68,070	$56,940	$35,450	$35,500	$71,920	$59,010	$45,550	$37,500
450	$32,830	$28,190	$21,180	$16,950	$76,580	$64,060	$39,880	$39,930	$80,910	$66,390	$51,240	$42,190
500	$36,480	$31,320	$23,530	$18,830	$85,090	$71,180	$44,310	$44,370	$89,900	$73,770	$56,940	$46,870

Table B-12. Maximum Cost for Tree Removal at B/C Ratio = 2, More than 25 Trees

> 25 Trees at < 10 ft Spacing	0-6 in. Diameter Tree				6-11 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft
50	$1,910	$1,640	$1,240	$1,020	$4,370	$3,680	$2,820	$2,340	$4,650	$3,950	$3,000	$2,460
100	$3,830	$3,290	$2,480	$2,040	$8,750	$7,360	$5,650	$4,670	$9,310	$7,900	$6,010	$4,920
150	$5,740	$4,930	$3,720	$3,060	$13,120	$11,050	$8,470	$7,010	$13,960	$11,840	$9,010	$7,370
200	$7,660	$6,580	$4,960	$4,080	$17,500	$14,730	$11,290	$9,340	$18,610	$15,790	$12,010	$9,830
250	$9,570	$8,220	$6,200	$5,100	$21,870	$18,410	$14,120	$11,680	$23,260	$19,740	$15,010	$12,290
300	$11,490	$9,870	$7,440	$6,120	$26,250	$22,090	$16,940	$14,020	$27,920	$23,690	$18,020	$14,750
350	$13,400	$11,510	$8,680	$7,150	$30,620	$25,770	$19,770	$16,350	$32,570	$27,630	$21,020	$17,210
400	$15,320	$13,150	$9,920	$8,170	$34,990	$29,460	$22,590	$18,690	$37,220	$31,580	$24,020	$19,660
450	$17,230	$14,800	$11,160	$9,190	$39,370	$33,140	$25,410	$21,020	$41,870	$35,530	$27,020	$22,120
500	$19,150	$16,440	$12,400	$10,210	$43,740	$36,820	$28,240	$23,360	$46,530	$39,480	$30,030	$24,580

> 25 Trees at 10-25 ft Spacing	0-6 in. Diameter Tree				6-11 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft
50	$5,120	$4,380	$3,340	$2,740	$11,530	$9,810	$7,530	$6,040	$12,140	$10,030	$7,800	$6,490
100	$10,240	$8,770	$6,680	$5,480	$23,060	$19,620	$15,050	$12,080	$24,290	$20,060	$15,590	$12,980
150	$15,360	$13,150	$10,020	$8,230	$34,580	$29,440	$22,580	$18,120	$36,430	$30,090	$23,390	$19,470
200	$20,470	$17,540	$13,350	$10,970	$46,110	$39,250	$30,100	$24,160	$48,570	$40,120	$31,190	$25,960
250	$25,590	$21,920	$16,690	$13,710	$57,640	$49,060	$37,630	$30,200	$60,720	$50,150	$38,980	$32,450
300	$30,710	$26,300	$20,030	$16,450	$69,170	$58,870	$45,160	$36,240	$72,860	$60,180	$46,780	$38,940
350	$35,830	$30,690	$23,370	$19,200	$80,690	$68,690	$52,680	$42,270	$85,000	$70,200	$54,570	$45,430
400	$40,950	$35,070	$26,710	$21,940	$92,220	$78,500	$60,210	$48,310	$97,150	$80,230	$62,370	$51,920
450	$46,070	$39,450	$30,050	$24,680	$103,750	$88,310	$67,730	$54,350	$109,290	$90,260	$70,170	$58,410
500	$51,180	$43,840	$33,390	$27,420	$115,280	$98,120	$75,260	$60,390	$121,440	$100,290	$77,960	$64,900

> 25 Trees at > 25 ft Spacing	0-6 in. Diameter Tree				6-11 in. Diameter Tree				12+ in. Diameter Tree			
	Offset from Edge of Road				Offset from Edge of Road				Offset from Edge of Road			
Traffic Volume	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft
50	$8,500	$7,050	$5,600	$4,620	$18,740	$15,790	$12,020	$9,930	$19,640	$16,660	$12,690	$10,480
100	$17,000	$14,100	$11,190	$9,240	$37,470	$31,570	$24,030	$19,870	$39,280	$33,330	$25,380	$20,950
150	$25,510	$21,150	$16,790	$13,850	$56,210	$47,360	$36,050	$29,800	$58,920	$49,990	$38,070	$31,430
200	$34,010	$28,200	$22,390	$18,470	$74,950	$63,140	$48,070	$39,740	$78,560	$66,660	$50,760	$41,900
250	$42,510	$35,250	$27,980	$23,090	$93,690	$78,930	$60,080	$49,670	$98,200	$83,320	$63,450	$52,380
300	$51,010	$42,300	$33,580	$27,710	$112,420	$94,710	$72,100	$59,610	$117,840	$99,990	$76,140	$62,850
350	$59,510	$49,350	$39,170	$32,330	$131,160	$110,500	$84,120	$69,540	$137,480	$116,650	$88,830	$73,330
400	$68,020	$56,400	$44,770	$36,940	$149,900	$126,280	$96,140	$79,480	$157,120	$133,320	$101,530	$83,800
450	$76,520	$63,440	$50,370	$41,560	$168,630	$142,070	$108,150	$89,410	$176,760	$149,980	$114,220	$94,280
500	$85,020	$70,490	$55,960	$46,180	$187,370	$157,850	$120,170	$99,350	$196,400	$166,650	$126,910	$104,750

Table B-13. Maximum Cost for Tree Removal at B/C Ratio = 4, Single Tree

1 Tree	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$420	$310	$230	$200	$920	$710	$550	$440	$910	$840	$600	$490
100	$840	$630	$460	$400	$1,840	$1,430	$1,110	$880	$1,830	$1,670	$1,210	$980
150	$1,260	$940	$690	$600	$2,750	$2,140	$1,660	$1,310	$2,740	$2,510	$1,810	$1,470
200	$1,680	$1,260	$920	$800	$3,670	$2,850	$2,220	$1,750	$3,650	$3,340	$2,420	$1,960
250	$2,090	$1,570	$1,160	$1,000	$4,590	$3,560	$2,770	$2,190	$4,560	$4,180	$3,020	$2,440
300	$2,510	$1,880	$1,390	$1,210	$5,510	$4,280	$3,330	$2,630	$5,480	$5,010	$3,630	$2,930
350	$2,930	$2,200	$1,620	$1,410	$6,420	$4,990	$3,880	$3,060	$6,390	$5,850	$4,230	$3,420
400	$3,350	$2,510	$1,850	$1,610	$7,340	$5,700	$4,430	$3,500	$7,300	$6,680	$4,840	$3,910
450	$3,770	$2,830	$2,080	$1,810	$8,260	$6,420	$4,990	$3,940	$8,210	$7,520	$5,440	$4,400
500	$4,190	$3,140	$2,310	$2,010	$9,180	$7,130	$5,540	$4,380	$9,130	$8,350	$6,050	$4,890

Table B-14. Maximum Cost for Tree Removal at B/C Ratio = 4, 2-10 Trees

2-10 Trees at < 10 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$440	$360	$280	$230	$1,020	$870	$660	$520	$1,140	$960	$690	$590
100	$870	$720	$570	$460	$2,040	$1,740	$1,330	$1,030	$2,280	$1,910	$1,390	$1,180
150	$1,310	$1,090	$850	$690	$3,060	$2,610	$1,990	$1,550	$3,420	$2,870	$2,080	$1,760
200	$1,740	$1,450	$1,130	$910	$4,080	$3,490	$2,660	$2,060	$4,550	$3,830	$2,780	$2,350
250	$2,180	$1,810	$1,420	$1,140	$5,090	$4,360	$3,320	$2,580	$5,690	$4,790	$3,470	$2,940
300	$2,610	$2,170	$1,700	$1,370	$6,110	$5,230	$3,990	$3,090	$6,830	$5,740	$4,170	$3,530
350	$3,050	$2,540	$1,980	$1,600	$7,130	$6,100	$4,650	$3,610	$7,970	$6,700	$4,860	$4,110
400	$3,480	$2,900	$2,270	$1,830	$8,150	$6,970	$5,320	$4,130	$9,110	$7,660	$5,550	$4,700
450	$3,920	$3,260	$2,550	$2,060	$9,170	$7,840	$5,980	$4,640	$10,250	$8,620	$6,250	$5,290
500	$4,350	$3,620	$2,840	$2,290	$10,190	$8,720	$6,640	$5,160	$11,380	$9,570	$6,940	$5,880

2-10 Trees at 10-25 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$700	$550	$430	$350	$1,520	$1,280	$970	$790	$1,640	$1,300	$1,000	$840
100	$1,400	$1,100	$870	$700	$3,050	$2,550	$1,940	$1,580	$3,290	$2,610	$1,990	$1,680
150	$2,090	$1,650	$1,300	$1,040	$4,570	$3,830	$2,910	$2,370	$4,930	$3,910	$2,990	$2,530
200	$2,790	$2,200	$1,730	$1,390	$6,100	$5,100	$3,880	$3,160	$6,580	$5,210	$3,990	$3,370
250	$3,490	$2,750	$2,170	$1,740	$7,620	$6,380	$4,850	$3,950	$8,220	$6,510	$4,980	$4,210
300	$4,190	$3,300	$2,600	$2,090	$9,150	$7,650	$5,820	$4,740	$9,870	$7,820	$5,980	$5,050
350	$4,890	$3,850	$3,030	$2,440	$10,670	$8,930	$6,790	$5,530	$11,510	$9,120	$6,980	$5,890
400	$5,590	$4,410	$3,470	$2,780	$12,200	$10,200	$7,760	$6,320	$13,160	$10,420	$7,970	$6,740
450	$6,280	$4,960	$3,900	$3,130	$13,720	$11,480	$8,720	$7,110	$14,800	$11,720	$8,970	$7,580
500	$6,980	$5,510	$4,340	$3,480	$15,250	$12,760	$9,690	$7,900	$16,450	$13,030	$9,970	$8,420

2-10 Trees at > 25 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$850	$730	$530	$480	$2,030	$1,680	$1,300	$1,030	$2,200	$1,830	$1,370	$830
100	$1,690	$1,460	$1,050	$960	$4,050	$3,360	$2,610	$2,070	$4,410	$3,650	$2,730	$1,670
150	$2,540	$2,190	$1,580	$1,440	$6,080	$5,030	$3,910	$3,100	$6,610	$5,480	$4,100	$2,500
200	$3,390	$2,920	$2,100	$1,920	$8,100	$6,710	$5,220	$4,140	$8,820	$7,310	$5,470	$3,330
250	$4,240	$3,650	$2,630	$2,400	$10,130	$8,390	$6,520	$5,170	$11,020	$9,140	$6,830	$4,170
300	$5,080	$4,380	$3,150	$2,880	$12,150	$10,070	$7,820	$6,200	$13,230	$10,960	$8,200	$5,000
350	$5,930	$5,110	$3,680	$3,360	$14,180	$11,750	$9,130	$7,240	$15,430	$12,790	$9,570	$5,830
400	$6,780	$5,840	$4,210	$3,840	$16,210	$13,420	$10,430	$8,270	$17,640	$14,620	$10,930	$6,670
450	$7,620	$6,570	$4,730	$4,320	$18,230	$15,100	$11,740	$9,310	$19,840	$16,450	$12,300	$7,500
500	$8,470	$7,300	$5,260	$4,800	$20,260	$16,780	$13,040	$10,340	$22,050	$18,270	$13,670	$8,330

Table B-15. Maximum Cost for Tree Removal at B/C Ratio = 4, 11-25 Trees

11-25 Trees at < 10 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$610	$510	$380	$310	$1,350	$1,160	$720	$740	$1,520	$1,230	$980	$760
100	$1,210	$1,030	$760	$620	$2,690	$2,320	$1,450	$1,470	$3,030	$2,470	$1,950	$1,530
150	$1,820	$1,540	$1,150	$940	$4,040	$3,490	$2,170	$2,210	$4,550	$3,700	$2,930	$2,290
200	$2,430	$2,060	$1,530	$1,250	$5,380	$4,650	$2,890	$2,950	$6,060	$4,940	$3,900	$3,050
250	$3,030	$2,570	$1,910	$1,560	$6,730	$5,810	$3,610	$3,680	$7,580	$6,170	$4,880	$3,820
300	$3,640	$3,090	$2,290	$1,870	$8,070	$6,970	$4,340	$4,420	$9,090	$7,400	$5,850	$4,580
350	$4,250	$3,600	$2,670	$2,180	$9,420	$8,130	$5,060	$5,160	$10,610	$8,640	$6,830	$5,340
400	$4,850	$4,120	$3,060	$2,500	$10,770	$9,300	$5,780	$5,890	$12,120	$9,870	$7,810	$6,110
450	$5,460	$4,630	$3,440	$2,810	$12,110	$10,460	$6,510	$6,630	$13,640	$11,110	$8,780	$6,870
500	$6,070	$5,150	$3,820	$3,120	$13,460	$11,620	$7,230	$7,370	$15,150	$12,340	$9,760	$7,630

11-25 Trees at 10-25 ft Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$1,190	$990	$750	$640	$420	$2,270	$1,430	$250	$2,790	$2,380	$1,830	$1,510
100	$2,390	$1,980	$1,510	$1,280	$830	$4,550	$2,870	$490	$5,580	$4,760	$3,660	$3,020
150	$3,580	$2,960	$2,260	$1,920	$1,250	$6,820	$4,300	$740	$8,360	$7,150	$5,500	$4,530
200	$4,770	$3,950	$3,020	$2,560	$1,670	$9,090	$5,740	$990	$11,150	$9,530	$7,330	$6,040
250	$5,970	$4,940	$3,770	$3,200	$2,090	$11,360	$7,170	$1,240	$13,940	$11,910	$9,160	$7,550
300	$7,160	$5,930	$4,530	$3,840	$2,500	$13,640	$8,610	$1,480	$16,730	$14,290	$10,990	$9,050
350	$8,350	$6,910	$5,280	$4,480	$2,920	$15,910	$10,040	$1,730	$19,520	$16,680	$12,820	$10,560
400	$9,550	$7,900	$6,040	$5,120	$3,340	$18,180	$11,470	$1,980	$22,300	$19,060	$14,650	$12,070
450	$10,740	$8,890	$6,790	$5,760	$3,760	$20,450	$12,910	$2,220	$25,090	$21,440	$16,490	$13,580
500	$11,930	$9,880	$7,550	$6,400	$4,170	$22,730	$14,340	$2,470	$27,880	$23,820	$18,320	$15,090

11-25 Trees at > 25 Spacing	0 - 5.9 in. Diameter Tree Offset from Edge of Road				6 - 11.9 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft	0 - 2.9 ft	3 - 6.9 ft	7 - 9.9 ft	10+ ft
50	$1,820	$1,570	$1,180	$940	$4,250	$3,560	$2,220	$2,220	$4,490	$3,690	$2,850	$2,340
100	$3,650	$3,130	$2,350	$1,880	$8,510	$7,120	$4,430	$4,440	$8,990	$7,380	$5,690	$4,690
150	$5,470	$4,700	$3,530	$2,820	$12,760	$10,680	$6,650	$6,660	$13,480	$11,070	$8,540	$7,030
200	$7,300	$6,260	$4,710	$3,770	$17,020	$14,240	$8,860	$8,870	$17,980	$14,750	$11,390	$9,370
250	$9,120	$7,830	$5,880	$4,710	$21,270	$17,790	$11,080	$11,090	$22,470	$18,440	$14,230	$11,720
300	$10,940	$9,400	$7,060	$5,650	$25,530	$21,350	$13,290	$13,310	$26,970	$22,130	$17,080	$14,060
350	$12,770	$10,960	$8,240	$6,590	$29,780	$24,910	$15,510	$15,530	$31,460	$25,820	$19,930	$16,410
400	$14,590	$12,530	$9,410	$7,530	$34,040	$28,470	$17,730	$17,750	$35,960	$29,510	$22,780	$18,750
450	$16,420	$14,100	$10,590	$8,470	$38,290	$32,030	$19,940	$19,970	$40,450	$33,200	$25,620	$21,090
500	$18,240	$15,660	$11,770	$9,420	$42,550	$35,590	$22,160	$22,190	$44,950	$36,880	$28,470	$23,440

Table B-16. Maximum Cost for Tree Removal at B/C Ratio = 4, More than 25 Trees

> 25 Trees at < 10 ft Spacing	0-6 in. Diameter Tree Offset from Edge of Road				6-11 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft
50	$960	$820	$620	$510	$2,190	$1,840	$1,410	$1,170	$2,330	$1,970	$1,500	$1,230
100	$1,910	$1,640	$1,240	$1,020	$4,370	$3,680	$2,820	$2,340	$4,650	$3,950	$3,000	$2,460
150	$2,870	$2,470	$1,860	$1,530	$6,560	$5,520	$4,240	$3,500	$6,980	$5,920	$4,500	$3,690
200	$3,830	$3,290	$2,480	$2,040	$8,750	$7,360	$5,650	$4,670	$9,310	$7,900	$6,010	$4,920
250	$4,790	$4,110	$3,100	$2,550	$10,940	$9,210	$7,060	$5,840	$11,630	$9,870	$7,510	$6,150
300	$5,740	$4,930	$3,720	$3,060	$13,120	$11,050	$8,470	$7,010	$13,960	$11,840	$9,010	$7,370
350	$6,700	$5,760	$4,340	$3,570	$15,310	$12,890	$9,880	$8,180	$16,280	$13,820	$10,510	$8,600
400	$7,660	$6,580	$4,960	$4,080	$17,500	$14,730	$11,290	$9,340	$18,610	$15,790	$12,010	$9,830
450	$8,620	$7,400	$5,580	$4,590	$19,680	$16,570	$12,710	$10,510	$20,940	$17,760	$13,510	$11,060
500	$9,570	$8,220	$6,200	$5,100	$21,870	$18,410	$14,120	$11,680	$23,260	$19,740	$15,010	$12,290

> 25 Trees at 10-25 ft Spacing	0-6 in. Diameter Tree Offset from Edge of Road				6-11 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft
50	$2,560	$2,190	$1,670	$1,370	$5,760	$4,910	$3,760	$3,020	$6,070	$5,010	$3,900	$3,250
100	$5,120	$4,380	$3,340	$2,740	$11,530	$9,810	$7,530	$6,040	$12,140	$10,030	$7,800	$6,490
150	$7,680	$6,580	$5,010	$4,110	$17,290	$14,720	$11,290	$9,060	$18,220	$15,040	$11,690	$9,740
200	$10,240	$8,770	$6,680	$5,480	$23,060	$19,620	$15,050	$12,080	$24,290	$20,060	$15,590	$12,980
250	$12,800	$10,960	$8,350	$6,860	$28,820	$24,530	$18,810	$15,100	$30,360	$25,070	$19,490	$16,230
300	$15,360	$13,150	$10,020	$8,230	$34,580	$29,440	$22,580	$18,120	$36,430	$30,090	$23,390	$19,470
350	$17,910	$15,340	$11,690	$9,600	$40,350	$34,340	$26,340	$21,140	$42,500	$35,100	$27,290	$22,720
400	$20,470	$17,540	$13,350	$10,970	$46,110	$39,250	$30,100	$24,160	$48,570	$40,120	$31,190	$25,960
450	$23,030	$19,730	$15,020	$12,340	$51,870	$44,160	$33,870	$27,180	$54,650	$45,130	$35,080	$29,210
500	$25,590	$21,920	$16,690	$13,710	$57,640	$49,060	$37,630	$30,200	$60,720	$50,150	$38,980	$32,450

> 25 Trees at > 25 ft Spacing	0-6 in. Diameter Tree Offset from Edge of Road				6-11 in. Diameter Tree Offset from Edge of Road				12+ in. Diameter Tree Offset from Edge of Road			
Traffic Volume	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft	0-3 ft	3-7 ft	7-10 ft	10+ ft
50	$4,250	$3,520	$2,800	$2,310	$9,370	$7,890	$6,010	$4,970	$9,820	$8,330	$6,350	$5,240
100	$8,500	$7,050	$5,600	$4,620	$18,740	$15,790	$12,020	$9,930	$19,640	$16,660	$12,690	$10,480
150	$12,750	$10,570	$8,390	$6,930	$28,110	$23,680	$18,030	$14,900	$29,460	$25,000	$19,040	$15,710
200	$17,000	$14,100	$11,190	$9,240	$37,470	$31,570	$24,030	$19,870	$39,280	$33,330	$25,380	$20,950
250	$21,250	$17,620	$13,990	$11,540	$46,840	$39,460	$30,040	$24,840	$49,100	$41,660	$31,730	$26,190
300	$25,510	$21,150	$16,790	$13,850	$56,210	$47,360	$36,050	$29,800	$58,920	$49,990	$38,070	$31,430
350	$29,760	$24,670	$19,590	$16,160	$65,580	$55,250	$42,060	$34,770	$68,740	$58,330	$44,420	$36,660
400	$34,010	$28,200	$22,390	$18,470	$74,950	$63,140	$48,070	$39,740	$78,560	$66,660	$50,760	$41,900
450	$38,260	$31,720	$25,180	$20,780	$84,320	$71,030	$54,080	$44,710	$88,380	$74,990	$57,110	$47,140
500	$42,510	$35,250	$27,980	$23,090	$93,690	$78,930	$60,080	$49,670	$98,200	$83,320	$63,450	$52,380

Appendix C. Slope Treatment Recommendations and Analysis Results

Table C-1. 7 ft (2.1 m) Drop Height, B/C Ratio = 2, W-beam = $18.16/lf

7 ft [2.1 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-2. 13 ft (4 m) Drop Height, B/C Ratio = 2, W-beam = $18.16/lf

13 ft [4 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-3. 20 ft (6.1 m) Drop Height, B/C Ratio = 2, W-beam = $18.16/lf

20 ft [6.1 m] Drop	0 ft [0 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250				W-Beam			W-Beam			W-Beam			W-Beam		
300	W-Beam			W-Beam			W-Beam	W-Beam		W-Beam	W-Beam		W-Beam		
350	W-Beam			W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
400	W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
450	W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
500	W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	

20 ft [6.1 m] Drop	3 ft [0.9 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250							W-Beam			W-Beam			W-Beam		
300	W-Beam			W-Beam			W-Beam			W-Beam			W-Beam		
350	W-Beam			W-Beam			W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
400	W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
450	W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
500	W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	

20 ft [6.1 m] Drop	7 ft [2.1 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300							W-Beam			W-Beam			W-Beam		
350				W-Beam			W-Beam			W-Beam			W-Beam		
400	W-Beam			W-Beam			W-Beam			W-Beam			W-Beam		
450	W-Beam			W-Beam			W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	
500	W-Beam			W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam		W-Beam	W-Beam	

20 ft [6.1 m] Drop	10 ft [3 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400							W-Beam			W-Beam			W-Beam		
450				W-Beam			W-Beam			W-Beam			W-Beam		
500	W-Beam			W-Beam			W-Beam			W-Beam			W-Beam		

(white)	Do Nothing
(grey)	Install W-Beam
(black)	Install Cable

Table C-4. 26 ft (8 m) Drop Height, B/C Ratio = 2, W-beam = $18.16/lf

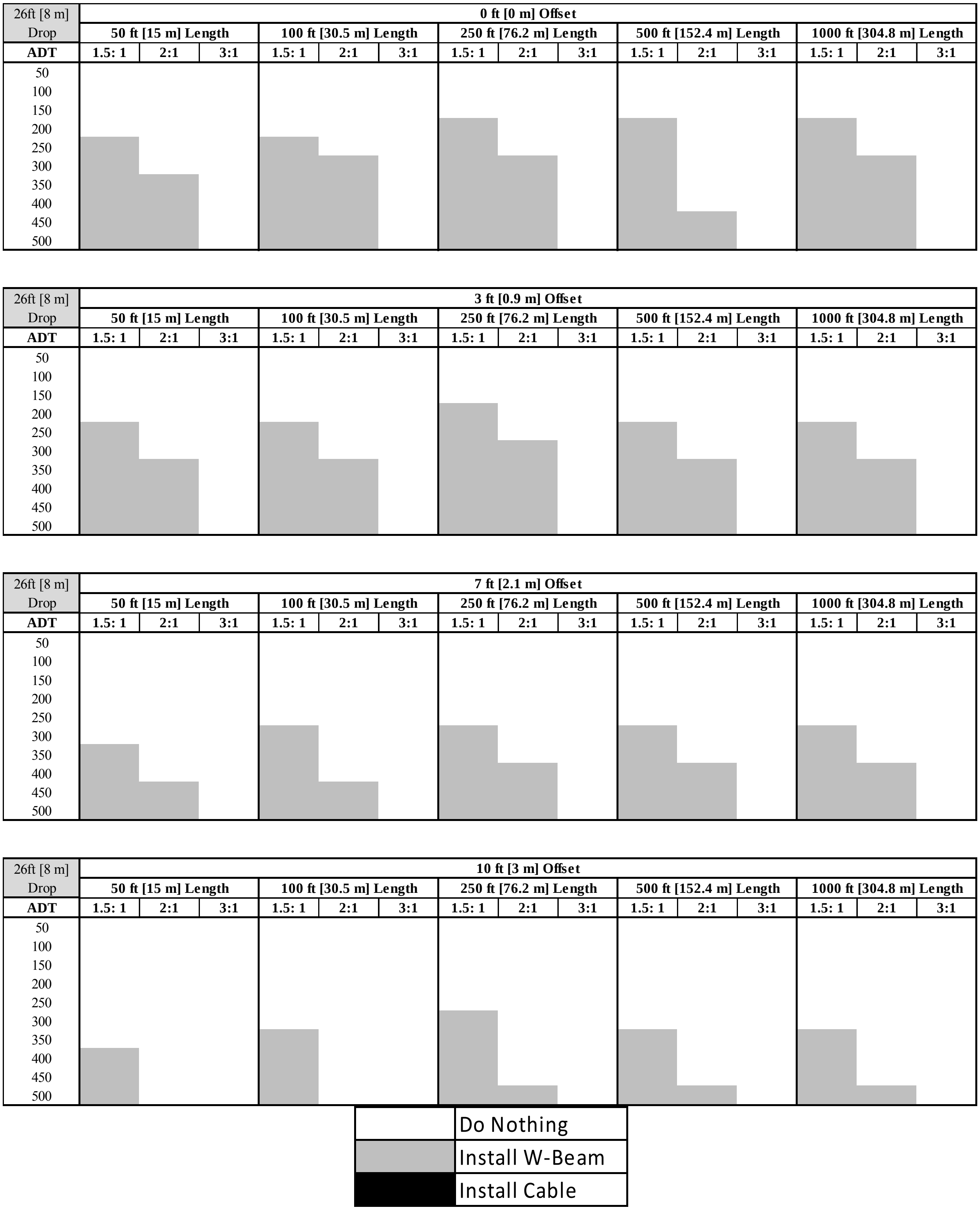

Table C-5. 7 ft (2.1 m) Drop Height, B/C Ratio = 4, W-beam = $18.16/lf

7 ft [2.1 m] Drop	0 ft [0 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m] Drop	3 ft [0.9 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m] Drop	7 ft [2.1 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m] Drop	10 ft [3 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

(white)	Do Nothing
(gray)	Install W-Beam
(black)	Install Cable

Table C-6. 13 ft (4 m) Drop Height, B/C Ratio = 4, W-beam = $18.16/lf

13 ft [4 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-7. 20 ft (6.1 m) Drop Height, B/C Ratio = 4, W-beam = $18.16/lf

20 ft [6.1 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-8. 26 ft (8 m) Drop Height, B/C Ratio = 4, W-beam = $18.16/lf

26ft [8 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

26ft [8 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

26ft [8 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

26ft [8 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-9. 7 ft (2.1 m) Drop Height, B/C Ratio = 2, W-beam = $45/lf

7 ft [2.1 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

(white)	Do Nothing
(gray)	Install W-Beam
(black)	Install Cable

Table C-10. 13 ft (4 m) Drop Height, B/C Ratio = 2, W-beam = $45/lf

13 ft [4 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-11. 20 ft (6.1 m) Drop Height, B/C Ratio = 2, W-beam = $45/lf

20 ft [6.1 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-12. 26 ft (8 m) Drop Height, B/C Ratio = 2, W-beam = $45/lf

26ft [8 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350	W-Beam			W-Beam			W-Beam								
400	W-Beam			W-Beam			W-Beam			W-Beam			W-Beam		
450	W-Beam			W-Beam			W-Beam			W-Beam			W-Beam		
500	W-Beam			W-Beam			W-Beam	W-Beam		W-Beam			W-Beam		

26ft [8 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300							Cable			Cable			Cable		
350				Cable			Cable			Cable			Cable		
400	Cable			Cable			Cable	Cable		Cable			Cable		
450	Cable			Cable	Cable		Cable	Cable		Cable	Cable		Cable	Cable	
500	Cable	Cable		Cable	Cable		Cable	Cable		Cable	Cable		Cable	Cable	

26ft [8 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400							Cable			Cable			Cable		
450				Cable			Cable			Cable			Cable		
500	Cable			Cable			Cable	Cable		Cable			Cable		

26ft [8 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450							Cable			Cable			Cable		
500							Cable			Cable			Cable		

(white)	Do Nothing
(grey)	Install W-Beam
(black)	Install Cable

Table C-13. 7 ft (2.1 m) Drop Height, B/C Ratio = 4, W-beam = $45/lf

7 ft [2.1 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

7 ft [2.1 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

(white)	Do Nothing
(gray)	Install W-Beam
(black)	Install Cable

Table C-14. 13 ft (4 m) Drop Height, B/C Ratio = 4, W-beam = $45/lf

13 ft [4 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

13 ft [4 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

	Do Nothing
	Install W-Beam
	Install Cable

Table C-15. 20 ft (6.1 m) Drop Height, B/C Ratio = 4, W-beam = $45/lf

20 ft [6.1 m]	0 ft [0 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	3 ft [0.9 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	7 ft [2.1 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

20 ft [6.1 m]	10 ft [3 m] Offset														
Drop	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

(white)	Do Nothing
(gray)	Install W-Beam
(black)	Install Cable

Table C-16. 26 ft (8 m) Drop Height, B/C Ratio = 4, W-beam = $45/lf

26ft [8 m] Drop	0 ft [0 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

26ft [8 m] Drop	3 ft [0.9 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

26ft [8 m] Drop	7 ft [2.1 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

26ft [8 m] Drop	10 ft [3 m] Offset														
	50 ft [15 m] Length			100 ft [30.5 m] Length			250 ft [76.2 m] Length			500 ft [152.4 m] Length			1000 ft [304.8 m] Length		
ADT	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1	1.5: 1	2:1	3:1
50															
100															
150															
200															
250															
300															
350															
400															
450															
500															

(white)	Do Nothing
(gray)	Install W-Beam
(black)	Install Cable

Appendix D. Bridge Treatment Recommendations and Analysis Results

Table D-1. Existing Angle-Iron Rail, B/C Ratio = 2

7 ft [2.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500	■											

13 ft [4 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450	■											
500	■			■								

20 ft [6.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400	■											
450	■			■								
500	■	■		■			■					

□	Do Nothing
■	Remove Existing and Install Approved Bridge Rail

Table D-2. Existing W-beam Rail, B/C Ratio = 2

7 ft [2.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500	■											

13 ft [4 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450	■											
500	■			■								

20 ft [6.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400	■											
450	■			■								
500	■			■			■					

	Do Nothing
■	Remove Existing and Install Approved Bridge Rail

Table D-3. Existing Angle-Iron Rail, B/C Ratio = 4

7 ft [2.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

13 ft [4 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

20 ft [6.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

(white)	Do Nothing
(black)	Remove Existing and Install Approved Bridge Rail

Table D-4. Existing W-beam Rail, B/C Ratio = 4

7 ft [2.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

13 ft [4 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

20 ft [6.1 m] Drop	25 ft [7.6 m] Length			50 ft [15 m] Length			100 ft [30.5 m] Length			150 ft [45.7 m] Length		
	Offset											
ADT	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]	0 ft [0 m]	3 ft [0.9 m]	5 ft [1.5 m]
50												
100												
150												
200												
250												
300												
350												
400												
450												
500												

	Do Nothing
	Remove Existing and Install Approved Bridge Rail

END OF DOCUMENT