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SYNTHESIS OF CRASH CUSHION GUIDANCE

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Crash cushions vary in shape, length, width, and cost. Each has unique properties and can be classified in one of three major categories: redirecting sacrificial, low maintenance, or nonredirecting sacrificial crash cushions. Redirecting sacrificial cushions require maintenance after they have been hit while low maintenance cushions typically do not. However, low maintenance systems generally have higher installation costs compared to redirecting sacrificial cushions. Nonredirecting sacrificial crash cushions, e.g. sand barrels, are generally less expensive; however these systems require total replacement after a crash has occurred which may be impractical at locations with high traffic volumes. Therefore, there is a need to identify the most cost-effective crash cushion category for highway scenarios with different road, traffic, and roadside characteristics. The purpose of this study was to determine benefit-cost ratios for each crash cushion category in a wide range of roadway and roadside characteristics. The probability-based encroachment tool Roadside Safety Analysis Program (RSAP) was used to model the scenarios and determine the benefit-cost ratios. It was found that redirecting sacrificial cushions are the most cost-effective cushions to be used on freeways and divided rural arterials, while each category competes with the unprotected condition on undivided rural arterials and local roads. In addition, by neglecting accident costs entirely, it was determined that low maintenance systems should be considered at accident frequencies greater than 1 accident every 1.2 years.

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TABLE OF CONTENTS

TECHNICAL REPORT DOCUMENTATION PAGE i

DISCLAIMER STATEMENT ii

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF FIGURES vi

LIST OF TABLES vii

1 INTRODUCTION 1
- 1.1 Background 1
- 1.2 Problem Statement 2
- 1.3 Objective 2
- 1.4 Scope 3

2 CRASH CUSHION SYSTEMS 4
- 2.1 Redirecting Sacrificial Crash Cushions 4
  - 2.1.1 QuadGuard 4
  - 2.1.2 Quest 5
  - 2.1.3 TRACC 5
  - 2.1.1 TAU II 6
- 2.2 Low Maintenance Crash Cushions 7
  - 2.2.1 QuadGuard Elite 7
  - 2.2.2 REACT 350 8
  - 2.2.3 SCI 9
- 2.3 Nonredirecting Sacrificial Crash Cushions 9

3 SURVEY OF CRASH CUSHION COSTS 13

4 HIGHWAY SCENARIO MODELING 16
- 4.1 Roadside Safety Analysis Program 16
  - 4.1.1 Encroachment Module 16
  - 4.1.2 Crash Prediction Module 18
  - 4.1.3 Crash Severity Module 18
  - 4.1.4 Benefit-Cost Analysis Module 21
- 4.2 Sensitivity Analysis 22
- 4.3 Parameter Values 28

5 SOCIETAL AND DIRECT COST ESTIMATION 30
- 5.1 Societal Costs 30
- 5.2 Direct Costs 30
  - 5.2.1 Installation Costs 30

5.2.2 Maintenance Costs 31
5.2.3 Repair and Traffic Control Costs 31

6 BENEFIT-COST ANALYSIS 35
6.1 BC Ratio 35
6.2 Baseline Condition and Alternative Designs 36

7 EXAMPLE APPLICATIONS 38
7.1 Developing the Design Charts 38
7.2 Understanding the Design Charts 40
7.3 Examples 41
7.3.1 Freeway Example 41
7.3.2 Divided Rural Arterial Example 41
7.3.3 Undivided Rural Arterial Example 42
7.3.4 Local Highway Example 42

8 PURELY MAINTENANCE COSTS 44
8.1 RSAP's Treatment of Crash Cushions 44
8.2 Impact Frequency 44

9 LIMITATIONS 46

10 CONCLUSIONS 48

11 REFERENCES 50

12 APPENDICES 52
Appendix A. State DOT Survey Questionnaire 53
Appendix B. Repair and Traffic Control Costs from Wisconsin DOT 55
Appendix C. Freeway Accident Costs 57
Appendix D. Divided Rural Arterial Accident Costs 63
Appendix E. Undivided Rural Arterial Accident Costs 69
Appendix F. Local Highway Accident Costs 75
Appendix G. Freeway Crash Cushion Synthesis 82
Appendix H. Divided Rural Arterial Crash Cushion Synthesis 83
Appendix I. Undivided Rural Arterial Crash Cushion Synthesis 84
Appendix J. Local Highway Crash Cushion Synthesis 85

LIST OF FIGURES

Figure 1. Typical Example of the QuadGuard 4
Figure 2. Typical Example of the Quest 5
Figure 3. Typical Example of the TRACC 6
Figure 4. Typical Example of the TAU II 7
Figure 5. Typical Example of the QuadGuard Elite 8
Figure 6. Typical Example of the REACT 350 8
Figure 7. Typical Example of the SCI 9
Figure 8. Typical Example of the Energite III 10
Figure 9. Inertial Sand Barrel Array used to Protect a Bridge Pier 11
Figure 10. RSAP Encroachment Rate Based on Cooper's Data 17
Figure 11. Encroachment Frequency Adjustment Factors 25
Figure 12. Probability of Impact on Tangent and Curved Roadways 26
Figure 13. Crash Cushion Recommendations for Undivided Rural Arterials, BC ≥ 4 26
Figure 14. Change in Accident Costs vs. Speed for QuadGuard Crash Cushions 28
Figure 15. Crash Cushion Placement on (a) Divided and (b) Undivided Highways 37
Figure 16. Example of Weighted Average System 38
Figure G-1. BC Ratios Greater than 4.0, Freeways. 82
Figure H-1. BC Ratios Greater than 4.0, Divided Rural Arterials 83
Figure I-1. BC Ratios Greater than 2.0, Undivided Rural Arterials 84
Figure I-2. BC Ratios Greater than 4.0, Undivided Rural Arterials 84
Figure J-1. BC Ratios Greater than 2.0, Local Highways 85
Figure J-2. BC Ratios Greater than 4.0, Local Highways 85

LIST OF TABLES

Table 1. Summary of Required Maintenance and Inventory for Selected Crash Cushions [3]. ... 12
Table 2. Summary of Costs and Dimensions of Each Crash Cushion from State DOT Surveys. 15
Table 3. Injury Level Percentages for Each Severity Index ... 20
Table 4. Societal Costs for Each Injury Level ... 20
Table 5. Societal Costs for Each Severity Index ... 20
Table 6. Sensitivity Analysis Results for Freeways ... 23
Table 7. Sensitivity Analysis Results for Local Road/Rural Arterials ... 25
Table 8. RSAP Modeling Parameter Values ... 29

1 INTRODUCTION

1.1 Background

Crash cushions are used to reduce the severity of an impact with a fixed, narrow object. This is usually accomplished using energy absorption to reduce the vehicle's kinetic energy and, ultimately, its speed at a safe deceleration rate. These features are ideal for fixed objects that cannot be removed, relocated, or shielded by longitudinal barriers [1]. The need for a crash cushion is partially dependent on the clear zone distance, which is the minimum distance at which a fixed object may be placed that still provides the driver with enough recovery room to avoid that fixed object. Further, the clear zone distance is dependent on the functional class of the highway. For example, a freeway would need a larger clear zone than a local highway because of increased exposure and speeds.

Crash cushions can be defined as either redirecting sacrificial, low maintenance, or nonredirecting sacrificial (inertial). Redirecting sacrificial crash cushions are typically constructed with energy absorbing cartridges. These cartridges are damaged while dissipating energy when the crash cushion is impacted. Maintenance crews are required to reset the crash cushion and replace the damaged cartridges. In contrast, low maintenance crash cushions often do not require immediate repair after an impact. They are designed to be restorable and reusable after most impacts. These crash cushions are often constructed with high-density polyethylene (HDPE) cylinders or similar materials that allow the crash cushion to regain up to 90 percent of its original shape after an impact.

Nonredirecting sacrificial crash cushions are primarily comprised of sand barrels that may be placed in different configurations depending on the size and shape of the fixed object. These crash cushions use the concept of kinetic energy dissipation (i.e., the kinetic energy of the vehicle is dissipated as the vehicle hits the barrels). The mass of each barrel varies. The lighter

barrels are hit first and the heavier barriers are struck as the vehicle continues through the crash cushion. The absorption of the vehicle's kinetic energy makes the vehicle slow down at a safe deceleration rate until it brings the vehicle's energy low enough that "bulldozing" through the sand will be enough to stop the vehicle (i.e., a velocity less than 10 mph or 16.1 km/h) [1]. Because any impacted barrel is typically destroyed, the repair costs for these systems can approach the initial installation costs since they may have to be completely replaced.

1.2 Problem Statement

Guidelines contained in the Roadside Design Guide (RDG) list crash cushions as acceptable alternatives for fixed objects that cannot be removed, relocated, or shielded by longitudinal barriers [1]. However, the use of a crash cushion may not be justified under certain traffic and roadside characteristics. For example, the installation of a high-cost crash cushion may not be economically justifiable on a road with low traffic volumes and large lateral offsets since the crash frequency will tend to be very low. As a result, the use of different crash cushions may depend on varying roadway, roadside, and traffic characteristics, making the selection of a specific crash cushion type challenging for highway engineers. Therefore, a need exists to develop crash cushion selection guidelines which can be used to assist engineers in selecting the crash cushion that results in the highest accident cost reduction per unit of direct cost (i.e., installation and repair cost) associated with the chosen crash cushion.

1.3 Objective

The objective of the research study was to develop crash cushion selection guidelines which would help highway engineers select the most cost-effective crash cushion to be used on various highway scenarios considering a wide range of roadway, roadside, and traffic characteristics.

1.4 Scope

The objective of this research study was achieved through various tasks. First, common crash cushion systems were examined to understand dimensions and associated costs for each system. Next, using the Roadside Safety Analysis Program (RSAP), several models were created to evaluate the effectiveness of each crash cushion for various roadway scenarios. Finally, a benefit-cost (BC) analysis was conducted to determine feasible placement for each type of crash cushion. Example situations were included to assist engineers in the future.

2 CRASH CUSHION SYSTEMS

Basic information associated with the crash cushions used in this study is presented in this chapter. All of these crash cushions were crash tested and certified under National Cooperative Highway Research Program (NCHRP) Report No. 350 test standards [2]. For more detailed information, refer to the manufacturer of each specific crash cushion.

2.1 Redirecting Sacrificial Crash Cushions

2.1.1 QuadGuard

The QuadGuard is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC. It is considered sacrificial because it utilizes crushable cartridges that need to be replaced after struck and damaged. These cartridges are placed within a structure of quad beams that are designed to "fish-scale" backward as a vehicle strikes the end. The dimensions for the QuadGuard are a function of the posted speed. For roadways posted at 45 mph (72.4 km/h) or less, the length is 9 ft (2.7 m) and the width is 2.5 ft (0.8 m). For roadways posted at 55 mph (88.5 km/h) and greater, the length is 15 ft (4.6 m), and the width is 2.5 ft (0.8 m). A typical QuadGuard system is shown in Figure 1.

Figure 1. Typical Example of the QuadGuard

2.1.2 Quest

The Quest crash cushion is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC. It telescopes backward while using square tube bending technology to dissipate kinetic energy. The dimensions for the Quest crash cushion are the same for any given speed. The length is 19 ft (5.8 m) and the width is 2.0 ft (0.6 m). A typical Quest crash cushion is shown in Figure 2.

Figure 2. Typical Example of the Quest

2.1.3 TRACC

The Trinity Attenuating Crash Cushion (TRACC) is a proprietary crash cushion manufactured by Trinity Highway Products, LLC. It telescopes backward while tearing through metal plates. The dimensions for the TRACC crash cushion are the same for any given speed.

The length is 21.25 ft (6.5 m) and the width is 2.0 ft (0.6 m). A typical TRACC is shown in Figure 3.

Figure 3. Typical Example of the TRACC

2.1.1 TAU II

The TAU II is a proprietary crash cushion manufactured by Barrier Systems, Inc. It is considered low maintenance because the system can be reset in less than 15 minutes. The dimensions for the TAU II crash cushion are the same for any given speed. The length is 23 ft (7.0 m) and the width is 4.0 ft (1.2 m). A typical TAU II system is shown in Figure 4.

Figure 4. Typical Example of the TAU II

2.2 Low Maintenance Crash Cushions

2.2.1 QuadGuard Elite

The QuadGuard Elite is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC. It is considered low maintenance because it utilizes self-restoring cylinders made from HDPE which usually requires little or no maintenance between impact events. The cylinders are placed within a structure of quad beams that are designed to fish-scale backward as a vehicle strikes the end. The dimensions for the QuadGuard Elite are a function of the posted speed. For roadways posted at 45 mph (72.4 km/h) or less, the length is 18 ft (5.5 m) and the width is 2.0 ft (0.6 m). For roadways posted at 55 mph (88.5 km/h) and greater, the length is 27 ft (8.2 m), and the width is 2.0 ft (0.6 m). A typical QuadGuard Elite system is shown in Figure 5.

Figure 5. Typical Example of the QuadGuard Elite

2.2.2 REACT 350

The Reusable Energy-Absorbing Crash Terminal (REACT 350) is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC. HDPE cylinders are placed in a single row and restrained by cables on either side. The dimensions for the REACT 350 are a function of the posted speed. The length is 28.75 ft (8.8 m) and the width is 3.0 ft (0.9 m). A typical REACT 350 system is shown in Figure 6.

Figure 6. Typical Example of the REACT 350

2.2.3 SCI

The Smart Cushion is a proprietary crash cushion manufactured by Smart Cushion Innovations (SCI) Products, Inc. It is considered low maintenance because the only repair required after most impact events is the replacement of two shear bolts. The dimensions for the SCI are a function of the posted speed. For roadways posted at 45 mph (72.4 km/h) or less, the length is 13.5 ft (4.1 m) and the width is 2.0 ft (0.6 m). For roadways posted at 55 mph (88.5 km/h) and greater, the length is 21.5 ft (6.6 m), and the width is 2.0 ft (0.6 m). A typical SCI system is shown in Figure 7.

Figure 7. Typical Example of the SCI

2.3 Nonredirecting Sacrificial Crash Cushions

Nonredirecting sacrificial crash cushions are typically represented by sand barrels which can be arrayed in numerous designs. These systems are manufactured by several companies. An example of a sand barrel system, the Energite III, is shown in Figure 8. Sand barrels can be arrayed to shield almost any fixed object. Further, sand barrels are inexpensive and easy to design and construct. However, repair costs can be high since the system usually requires total replacement of the impacted barrels. Sand barrels cannot redirect vehicles in the event of a side impact, do not guarantee that lighter barrels are struck first, and perform poorly in coffin corner

impacts. The number and weight of the barrels required is usually dependent on the posted speed of the highway. That is, higher speed highways generally require sand barrel configurations that contain more barrels. An actual configuration used to protect a pier is shown in Figure 9 and was developed using the procedure outlined in the RDG [1]. Note, the masses of the barrels increase as the system approaches the hazard. This provides a relatively safe deceleration rate for the vehicle until it slows to a safe velocity, which was specified in the RDG to be 10 mph (16.1 km/h) [1].

Figure 8. Typical Example of the Energite III

A summary of the required maintenance and possible inventory is included in Table 1 and was taken from the 2010 RDG [3]. The designation for sand filled barrels was altered to "Nonredirecting Sacrificial Crash Cushion" to more accurately reflect the maintenance requirements as they are listed in the table.

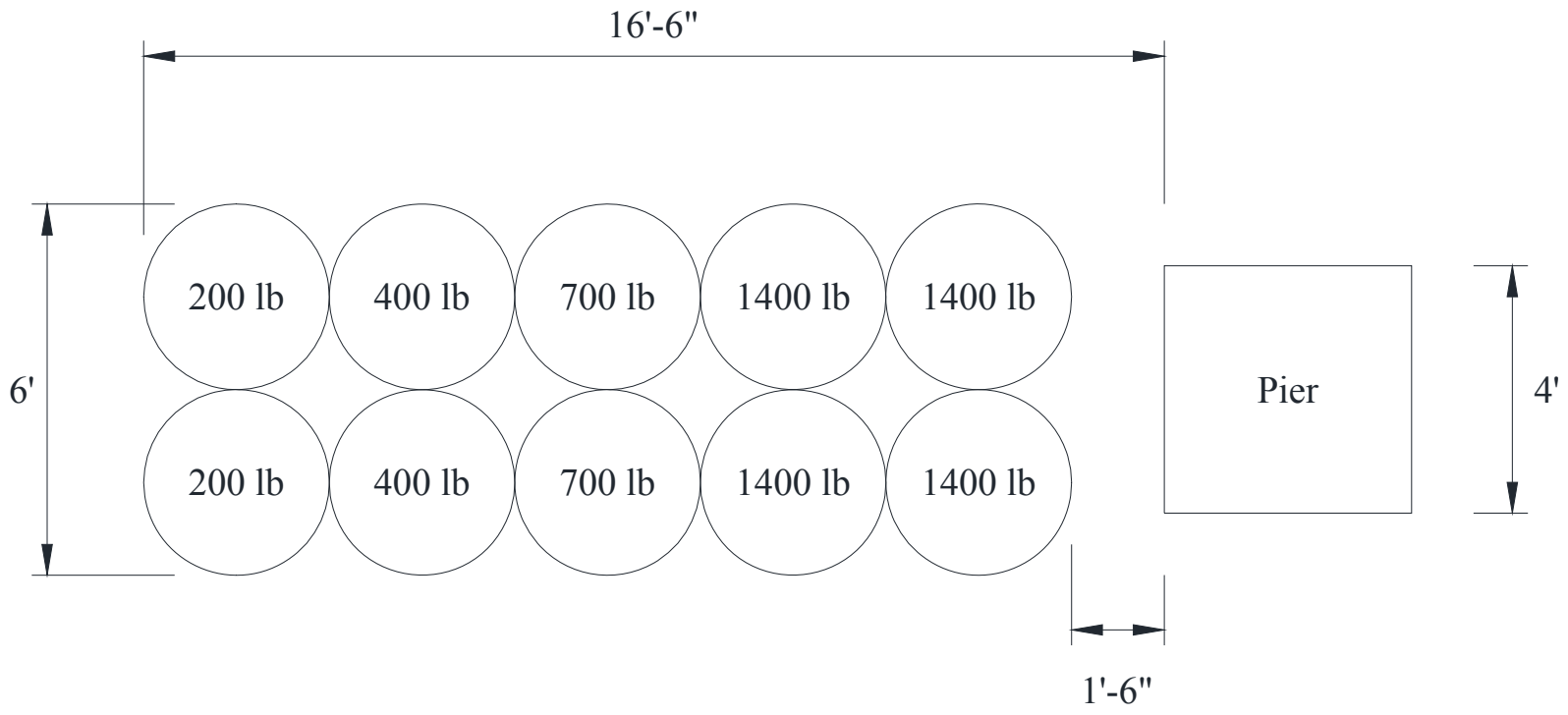

Figure 9. Inertial Sand Barrel Array used to Protect a Bridge Pier

Table 1. Summary of Required Maintenance and Inventory for Selected Crash Cushions [3].

Crash Cushion	Regular Maintenance	Crash Maintenance	Material Inventory
Redirecting Sacrificial Crash Cushions			
QuadGuard	Normally can be inspected on a drive-by; missing or displaced cartridges can be readily noted. Should be periodically inspected on-site to be certain that all parts are properly connected.	Nose, expended cartridges, and damaged fender panels should be replaced. Unit should be repositioned.	Spare cartridges, nose units, fender panels, and other parts per manufacturer's recommendation.
Universal TAU-II Family	Normally can be inspected on a drive-by. Periodic on-site inspections should be performed to be certain that all parts are properly connected.	After a frontal impact, the system can be pulled out to restore the proper length. Replace damaged cartridges. During some side impacts, the sliding panels may be damaged.	Cartridges, sliding panels, pipe panel mounts, and nose pieces per manufacturer's recommendations.
TRACC	Normally can be inspected on a drive-by. Periodic on-site inspections should be performed to be certain that all parts are properly connected.	The rip plates need replacement. Newer versions of the TRACC eliminate need for extensive disassembly. The nose and fender panels also may need replacement.	Replacement rip plates, nose sections, fender panels, and other replacement parts per manufacturer's recommendation.
QUEST	Normally can be drive-by inspected. Periodic on-site inspections should be performed to be certain that all parts are properly connnected.	The nose, fender panels, and energy-absorbing rails or tubes need replacement after impacts. Open design allows for easy repair.	The nose, fender panels, and energy-absorbing rails or tubes and other parts per manufacturer's recommendations.
Low Maintenance and/or Self-Restoring Crash Cushions			
QuadGuard LMC	Normally can be inspected on a drive-by. Periodic on-site inspections should be performed to be certain that all parts are properly connected.	Much of unit is reusable after a crash. Unit tends to self-restore to some extent but should be evaluated after each impact. Unit may need to be repositioned. When diameter of last cartridge becomes less than 660 mm [26 in.], all cartridges should be replaced.	Fender panels and other replacement parts per manufacturer's recommendation.
REACT 350	Can be inspected on a drive-by.	The system is considered fully reusable. Repositioning is normally all that is needed after an impact. After side impacts, inspect stabilizer rods. If the cylinders cannot be restored to 90 percent of the original diameter, they should be replaced.	Spare parts per manufacturer's recommendation.
SCI	Can be inspected on a drive-by for external damage. If the frontal collapse has been initiated, the unit should be inspected and reset.	The system will need two shear bolts and possibly a new delineator plate under design critieria impacts.	Shear bolts and delineator panel.
Nonredirecting Sacrificial Crash Cushion			
Sand Filled Barrels	Can be inspected on a drive-by for external damage. If lids are not riveted on, sand content should be checked periodically. See Section 8.4.3 for information on using sand-filled barrels in cold climates.	Individual sand barrels should be replaced after a crash; units damaged by nuisance hits also should be replaced. Debris should be removed from the site.	Spare barrels, sand support inserts, and lids; supply of sand.

3 SURVEY OF CRASH CUSHION COSTS

In order to estimate the cost of installation, maintenance, and repair of all crash cushions used in this study, a survey questionnaire was sent to the following Midwest States Pooled Fund States Departments of Transportation (DOTs): Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, Ohio, South Dakota, Wisconsin, and Wyoming. The survey questionnaire contained eight questions, as shown in Appendix A. The State DOTs were asked to provide information pertaining to each crash cushion that they currently implement. This information included the average installation cost, the average crash repair cost, and the average regular maintenance cost per year. Additional information included inventory need and costs for each crash cushion type, repair time needed once the cushion has been involved in a crash, and information on the test level and speed limit of each particular crash cushion used.

Only the States of Kansas, Minnesota, Nebraska, and Wisconsin replied to the survey. The remaining states did not answer the survey or they replied saying they did not have the information available. The States of Minnesota and Wisconsin submitted responses to this survey that adequately answered the questions being asked. Minnesota used estimates based on bid tabulations and engineering judgment. Wisconsin used bid tabulations and manufacturer data.

A third survey response was submitted by the State of Kansas, but data from this response was only partially used. Kansas provided cost information pertaining to three crash cushion types: Smart Cushion, sand barrels and QuadGuard. The cost information pertaining to the Smart Cushion seemed higher than expected, between two thousand and eight thousand dollars higher than the cost information submitted by the State of Wisconsin. This can potentially be attributed to the fact that the installation costs associated with the Smart Cushion were based on change orders after bid letting. Thus, the original bid submitted by the contractor was lower

than the cost submitted in the survey response. However, the changes which were added to the bid that increased the installation cost were unknown.

The cost information from Kansas DOT pertaining to sand barrels was not used either. The repair cost associated with this crash cushion was not indicative of an actual repair cost because the contractor was paid to replace all barrels regardless of whether the barrel was hit or not. This allowed the contractor to submit a bid that was significantly less per barrel than the actual cost. For example, if a 10 barrel array was hit and only 2 barrels were destroyed, the contractor may submit a bid for the cost of those 2 barrels. However, the average cost per barrel would actually be the contractor's bid divided by 10 barrels instead of 2 barrels. Because the cost information contained in the survey response was given in a cost-per-barrel format and the number of barrels to be replaced was unknown, the average repair cost per system could not be determined. Therefore, only Kansas' responses pertaining to the cost of the QuadGuard was used.

The State of Nebraska also submitted a response to the questionnaire. However, only the TRACC system was included in their response. They listed an average installation cost of $12,500, which was reasonable compared to other survey responses. However, the average annual repair cost was over $17,000. This large cost was likely the total cost of repairs across the state for that system and not the average cost per repair. As a result, the Nebraska survey response was not used in this research.

A summary of costs and dimensions of each crash cushion type evaluated in this study is shown in Table 2. Crash cushion size was directly associated with the safety performance of the crash cushion, which can have an impact on crash cushion costs. The length and width of some crash cushions varied with design speed. However, the costs were independent of the crash

cushion size since the States did not provide detailed cost information as a function of crash cushion size or safety performance level. In this table, the sixth column, "Maintenance Cost," was the sum of the repair and traffic control costs. This cost becomes useful when investigating high accident frequency or severity locations, at which point the cost savings of low maintenance systems begin to overwhelm the initial cost savings of the sacrificial crash cushions.

Table 2. Summary of Costs and Dimensions of Each Crash Cushion from State DOT Surveys

Crash Cushion Type	Crash Cusion	Installation Cost	Repair Cost	Traffic Control Costs	Maintenance Costs	Design Speed, mph (kmh)	Length, ft (m)	Width, ft (m)
Redirecting Sacrificial	QuadGuard	$17,769	$2,892	$3,475	$6,367	≤ 45 (72.4)	9 (2.74)	2.5 (0.76)
						≥ 55 (88.5)	15 (4.57)	2.5 (0.76)
	Quest	$11,510	$133	$1,675	$1,808	Any	19 (5.79)	2.0 (0.61)
	TRACC	$11,400	$3,246	$1,788	$5,034	Any	21.25 (6.48)	2.0 (0.61)
	TAU II	$15,433	$2,391	$1,225	$3,616	Any	23.0 (7.01)	4.0 (1.22)
Low Maintenance	QuadGuard Elite	$33,017	$2,285	$3,475	$5,760	≤ 45 (72.4)	18.0 (5.49)	2.0 (0.61)
						≥ 55 (88.5)	27.0 (8.23)	2.0 (0.61)
	REACT 350	$36,067	$1,727	$925	$2,652	Any	28.75 (8.76)	3.0 (0.91)
	SCI	$19,371	$48	$550	$598	≤ 45 (72.4)	13.5 (4.11)	2.0 (0.61)
						≥ 55 (88.5)	21.5 (6.55)	2.0 (0.61)
Nonredirecting Sacrificial	Sand Barrels	$2,540	$1,880	$1,225	$3,105	Any	16.5 (5.03)	6.0 (1.83)

4 HIGHWAY SCENARIO MODELING

The procedure used to model the highway scenarios is presented in the following sections. This chapter includes a description of the tool used to model the highway scenarios along with the roadway, roadside, and traffic parameters that were selected to characterize the wide range of scenarios.

4.1 Roadside Safety Analysis Program

RSAP is an encroachment probability based tool used to estimate the cost-effectiveness of roadside safety treatment alternatives [4]. RSAP uses four modules that are used to estimate the benefit-cost (BC) ratio: (i) encroachment, (ii) crash prediction, (iii) severity prediction, and (iv) BC analysis. First, vehicle encroachment probability was determined within the encroachment module. Then accident frequency was determined for each encroachment in the crash prediction module. Next, the average severity of the impact was calculated in the crash severity prediction module. Finally, the incremental BC ratios among the various alternatives were determined within the BC analysis module. These four modules are discussed in more detail in the sub-sections that follow.

4.1.1 Encroachment Module

The encroachment module uses two steps to determine encroachment frequency. First, an average encroachment rate is estimated and multiplied by the traffic volume to find the encroachment frequency. Second, the encroachment frequency is adjusted using factors corresponding to horizontal curvature and vertical grade. The encroachment module was strongly based on encroachment data developed by the Cooper study in the late 1970s [5]. However, Cooper's data has limitations. First, the encroachments of less than 13.1 ft (4 m) were undetectable due to paved shoulders. As such, the results were reanalyzed after excluding encroachments that extended less than 13.1 ft (4 m) laterally. Mak and Sicking estimated that

encroachments were underreported by a ratio of 2.466 and 1.878 on two-lane and multi-lane highways, respectively [4]. As a result, the encroachment frequencies were adjusted upward accordingly. Further, controlled and uncontrolled encroachments could not be distinguished. Examples of controlled encroachments include implements of husbandry driving off the pavement or a vehicle pulled over to the side of the road to switch drivers. However, it was believed that these controlled encroachments were less in number than the uncontrolled encroachments. In fact, a study was done that examined the number of impacts on longitudinal barriers and the number of actual reported accidents. From that study, as much as 60 percent of the accidents were reported to law enforcement officials [6]. Therefore, the encroachment frequencies were again modified by multiplying the frequency by 0.60. The results of the Cooper data and subsequent modifications are shown in Figure 10.

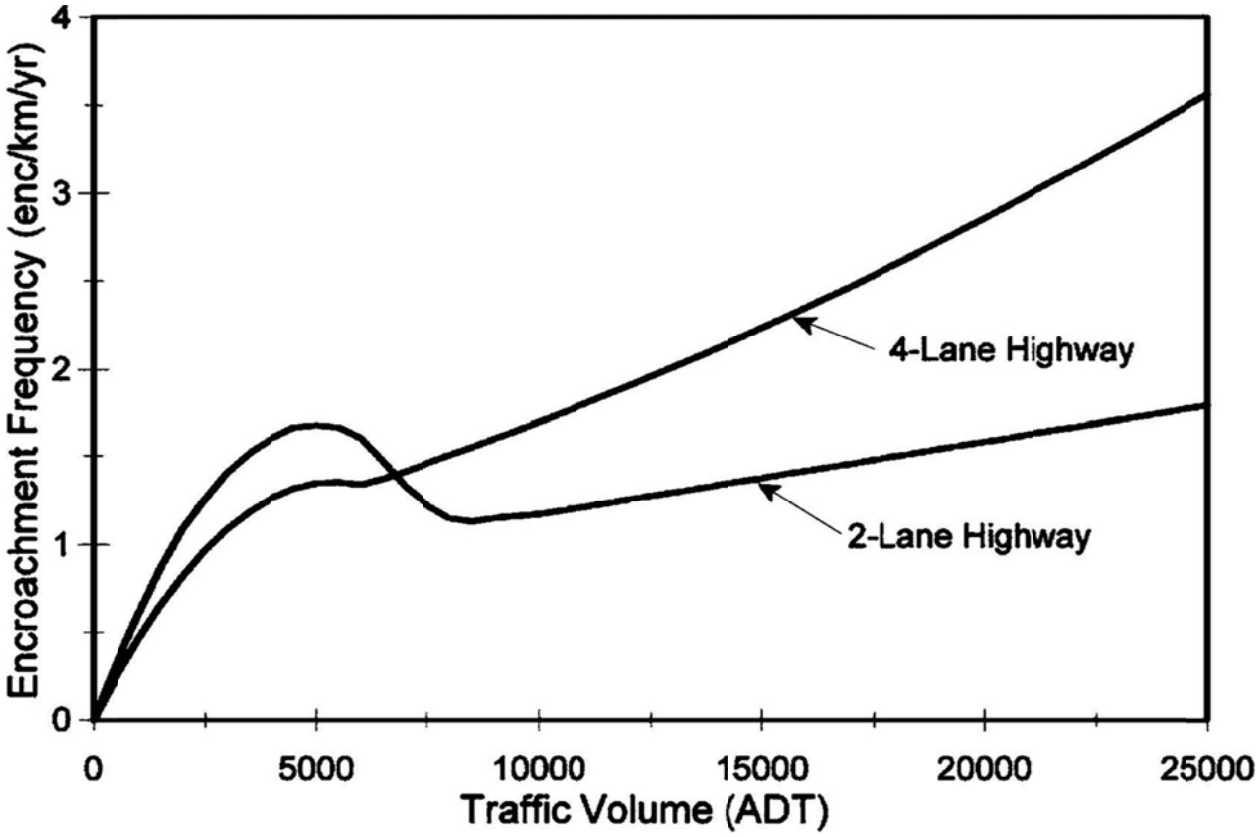

Figure 10. RSAP Encroachment Rate Based on Cooper's Data

4.1.2 Crash Prediction Module

After the encroachment module has predicted an encroachment, the crash prediction module predicts whether a crash will occur. First, RSAP sorts the roadside features by lateral and longitudinal placement. Second, RSAP determines the vehicle swath, or path, based on the impact speed, impact angle, and vehicle orientation distributions generated from reconstruction of real-world crashes [7]. The locations of the roadside features, as determined by user input, are compared with the vehicle swath and if the vehicle path encounters an obstacle, a crash occurs. If the vehicle has enough kinetic energy, it can penetrate through the object and continue on, possibly striking another object. However, this study focused on rigid fixed objects, such as bridge piers. Therefore, if the fixed object or the crash cushion were in the vehicle swath, a crash was predicted.

The crash prediction module assumes the vehicle maintains a constant angle relative to the center of the roadway throughout the event (i.e., a straight line) and a constant orientation. If the encroachment occurs on a curve, the encroachment angle remains constant relative to a tangent line attached to the center of the roadway at the point of the encroachment. It also assumes that the vehicle speed does not change as a result of braking. These three assumptions imply that driver behavior is ignored. Any attempts by the driver to maneuver away from the fixed object or to slow down before impact were not considered. Unfortunately, these assumptions do not truly represent real-world crashes. However, no better encroachment or crash data is available to overcome these limitations.

4.1.3 Crash Severity Module

Once a crash is predicted, the severity of that crash must be determined. The severity of the accident has the greatest effect on the overall accident cost. The severity indices used in RSAP were based on the ones published in the 1996 *Roadside Design Guide (RDG)* [8], but they

were adjusted. The values contained in the 1996 RDG had a linear relationship with design speed. However, impact speed is required. Therefore, RSAP uses severity indices based on impact speed instead of design speed. To adjust these values accordingly, the regression line of the impact speed versus severity index plot was set to pass through the origin. This regression line would give a severity index value of zero at an impact speed of 0 mph.

The next step in the crash severity module is to link the severity index value to an accident cost value. As such, accident cost values for each severity index need to be determined. The 1996 RDG presented suggested injury level distributions for each severity index, as shown in Table 3. Injury levels are coded in the KABCO scale, and the description of this scale is as follows:

- K – Fatal injury
- A – Severe or incapacitating injury
- B – Moderate or non-incapacitating injury
- C – Minor or possible injury, and
- O – Property Damage Only (PDO)

The severity indices range from 0 to 10 as shown in Table 3. The injury level distributions and the cost for each injury level, as shown in Tables 3 and 4, respectively, were used to estimate the costs associated with each severity index, as shown in Table 5. Current designations set PDO1 equal to PDO2 in societal costs, or $2,575. For example, the accident cost associated with a severity index equal to 1 may be calculated as:

$$(0.667\times2{,}575) + (0.237\times2{,}575) + (0.073\times23{,}960) + (0.023\times45{,}320) = \$5{,}100$$

Table 3. Injury Level Percentages for Each Severity Index

Severity Index (SI)	Injury Level (%)						
	None	PDO1	PDO2	Minor Injury - C	Moderate Injury - B	Severe Injury - A	Fatal - K
0	100.0	-	-	-	-	-	-
0.5	-	100.0	-	-	-	-	-
1	-	66.7	23.7	7.3	2.3	-	-
2	-	-	71.0	22.0	7.0	-	-
3	-	-	43.0	34.0	21.0	1.0	1.0
4	-	-	30.0	30.0	32.0	5.0	3.0
5	-	-	15.0	22.0	45.0	10.0	8.0
6	-	-	7.0	16.0	39.0	20.0	18.0
7	-	-	2.0	10.0	28.0	30.0	30.0
8	-	-	-	4.0	19.0	27.0	50.0
9	-	-	-	-	7.0	18.0	75.0
10	-	-	-	-	-	-	100.0

Table 4. Societal Costs for Each Injury Level

Injury Level	Cost (US$)
K	3,296,000
A	226,600
B	45,320
C	23,690
PDO	2,575

Table 5. Societal Costs for Each Severity Index

Severity Index	Cost (US$)
0	-
0.5	2,575
1	5,100
2	10,212
3	53,905
4	132,592
5	312,332
6	660,245
7	1,071,890
8	1,718,740
9	2,515,960
10	3,296,000

There are limitations regarding the validity of this process. In particular, the original SI scale was derived from survey responses submitted by highway safety officials such as engineers and law enforcement officials. Their responses were based on accidents that were more severe than average accidents, resulting in higher-speed collisions. As a result, the severity indices tend to be biased toward the higher speeds and not entirely representative of average impacts. Thus, the average accident costs will be over-estimated because the severity index used to estimate the cost was over-estimated. Additionally, the injury level percentages shown in Table 3 were based on engineering judgment. No evidence has been presented to support these values.

4.1.4 Benefit-Cost Analysis Module

The fourth and final module of RSAP conducts the BC analysis. BC ratios compare the economical feasibility of the safety treatment alternatives under investigation. Both benefits and direct costs need to be determined. Benefits are determined in terms of the accident cost reduction associated with the safety treatment alternative, while direct costs include crash cushion installation, repair, and/or maintenance costs.

Once the costs have been estimated, the benefit-cost ratios may be calculated using Equation 1.

$$BC_{2-1} = \frac{AC_1 - AC_2}{DC_2 - DC_1} \tag{1}$$

Where

BC_{2-1} = BC ratio of alternative 2 to alternative 1

AC_1, AC_2 = Annualized societal crash cost for alternatives 1 and 2, respectively

AC_1, AC_2 Annualized direct costs for alternatives 1 and 2, respectively

Note alternatives 1 and 2 refer to a scenario with no crash cushion and to a scenario with a crash cushion, respectively. This ratio is a measurement of the magnitude of the change in

safety performance over the change in up-front costs. This procedure was used to compare each crash cushion to a scenario with an unprotected bridge pier.

4.2 Sensitivity Analysis

Different highway scenarios were created by varying values of traffic, roadway, and roadside parameters used to characterize a specific scenario. A sensitivity analysis was conducted to determine highway and traffic characteristics that significantly affect accident costs. If a parameter had a significant influence on accident costs, then the parameter would be considered further in the study. On the other hand, if a parameter had limited or no influence on accident costs, than the parameter would be removed from the study.

Large fluctuations in baseline costs flagged potential parameters to examine in the detailed analysis. The parameters that were analyzed in the sensitivity analysis are shown in Tables 6 and 7. These parameters were then programmed into RSAP and their corresponding values were chosen based on typical ranges (i.e., low, medium, and high values) observed on freeways as well as on local roads and rural arterials. For example, average traffic volume values adopted for freeways were much higher than those adopted for local roads and rural arterials since freeways usually carry higher traffic volumes.

The parameters in Tables 6 and 7 were found to have a significant influence on accident costs. This significance was determined from engineering judgment and was primarily based on the assumption that fluctuations of less than ten percent were insignificant. The significant parameters included: (1) crash cushion offset; (2) crash cushion type; (3) average daily traffic; (4) horizontal curvature; and (5) speed limit. These five parameters were selected to characterize the highway scenarios evaluated in the study.

Table 6. Sensitivity Analysis Results for Freeways

Parameter	Range	Annual Accident Cost ($)	Percent Difference (%)
Crash Cushion Offset (ft)	10 (baseline)	1950.54	na
	12	1709.67	12.3%
	14	1509.47	22.6%
Crash Cushion Type	Redirecting (baseline)	1709.61	na
	Non-redirecting	2276.01	33.1%
Average Daily Traffic (veh./day)	5000 (baseline)	1709.67	na
	10000	2154.14	26.0%
	20000	3623.63	111.9%
Horizontal Curvature (degrees)	0 (baseline)	1709.67	na
	2	1871.31	9.5%
	4	3437.75	101.1%
Speed Limit (mph)	65 (baseline)	1709.67	na
	70	1875.62	9.7%
	75	2051.53	20.0%

Crash frequency on horizontal curves increases in comparison to straight segments, as shown in Tables 6 and 7. As a result, RSAP incorporates an adjustment factor for segments containing a horizontal curve. However, the probability of striking a fixed object decreases as the effective angle increases, which is the case for horizontal curves. Consequently, the accident costs generally decreased between 0 and 4 degrees of curvature, but increased on sharper curves. Therefore, each functional class was modeled with a tangent section and two curved sections. The traffic adjustment factor and the net effect from the decreased impact probability (i.e., dashed lines) are shown in Figure 11. In this figure, the average net factor shows that costs would be multiplied by a value less than one at curves less than four degrees, which follows the logic that the crash cushion is less likely to be hit by a straight-line encroachment. However, the increased severity of each impact on curves sharper than four degrees was enough to overcome the decreased probability of impact, and ultimately, the accident cost was increased.

Despite the increase in encroachment frequency, the accident costs in this study actually decreased as the curvature increased due to the geometry of the point hazard and the encroachment path. Although crash cushions are not points in space, they behave as such in encroachment models. Figure 11 shows a 1-ft (0.3-m), 25-ft (7.6-m), and 50-ft (15.2-m) length crash cushion. The first two behaved almost identically, while the third was not much different. At longer lengths, the object would behave less like a point hazard and more like a line hazard, however, crash cushions rarely approach even 50 ft (15.2 m). In general, as the encroachment angle increases, the risk of impacting a point hazard decreases. When that point hazard is on the outside of a left curve, the effective angle of encroachment is enlarged as the vehicle moves away from the roadway, as shown in Figure 12 [9]. The initial angle of encroachment and the offset to the center of the fixed object from the roadway were identical for both scenarios shown in Figure 12. However, the effective angles of encroachment were 21 and 24 degrees on the tangent and the curved sections, respectively, which resulted in projected areas with widths of 61 in. (1,549 mm) and 62 in. (1,575 mm), respectively. This increased width and steeper angle would ultimately increase the severity of that impact and the probability that the fixed object would be impacted.

Combining this increased effective encroachment angle with the fact that all crash cushions and unprotected piers were treated as point hazards caused the increased encroachment frequency on the curve to be offset by the reduced risk of impact for the point hazard. For cases involving the highest degree of curvature, the accident cost increased slightly. In other cases, especially for the intermediate degree of curvature, the accident cost decreased. The graphical results of an undivided rural arterial highway for BC ratios greater than 4.0 are shown in Figure 13 as an example of this trend.

Table 7. Sensitivity Analysis Results for Local Road/Rural Arterials

Parameter	Range	Annual Accident Cost ($)	Percent Difference (%)
Crash Cushion Offset (ft)	8 (baseline)	2593.90	na
	10	2132.84	17.8%
	12	1716.48	33.8%
Crash Cushion Type	Redirecting (baseline)	1353.00	na
	Non-redirecting	1716.48	26.9%
Average Daily Traffic (veh./day)	1000 (baseline)	497.56	na
	3000	1187.15	138.6%
	5000	1414.10	184.2%
Horizontal Curvature (degrees)	0 (baseline)	1353.00	na
	5	3230.22	138.7%
	10	2847.61	110.5%
Speed Limit (mph)	45 (baseline)	719.96	na
	55	1079.15	49.9%
	65	1414.10	96.4%

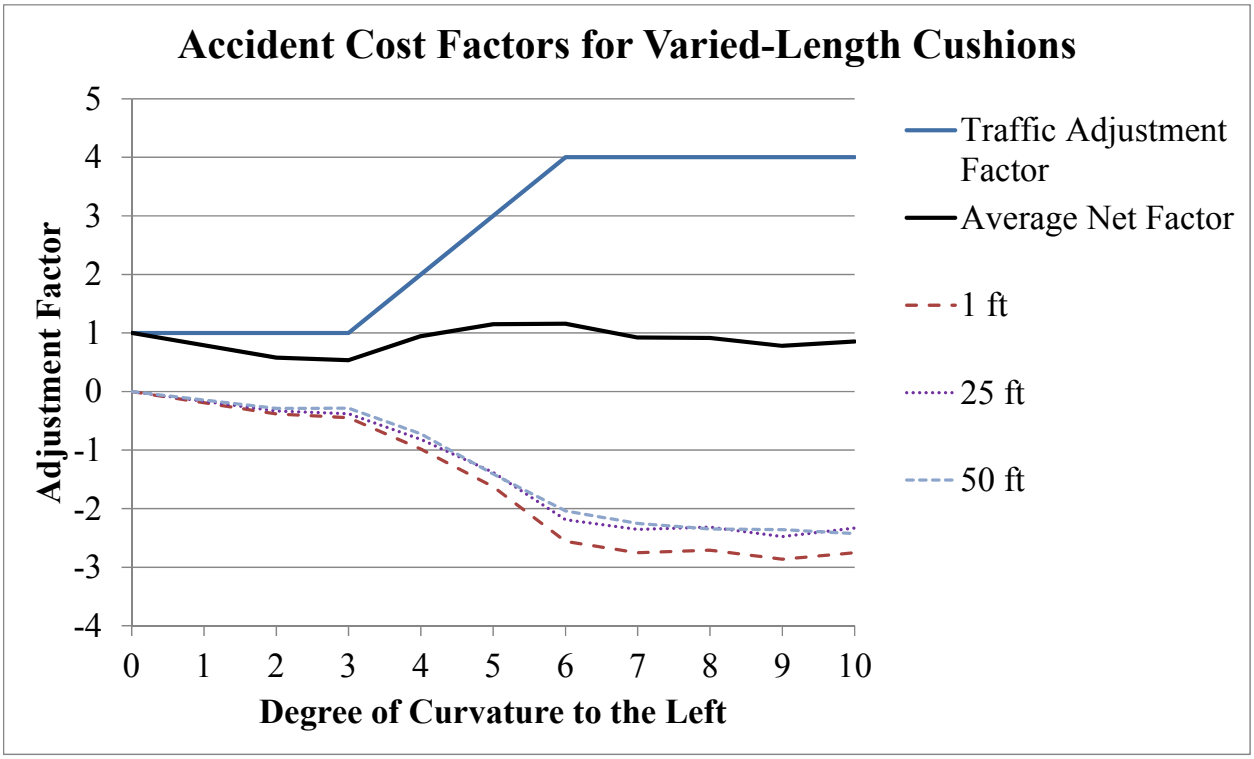

Figure 11. Encroachment Frequency Adjustment Factors

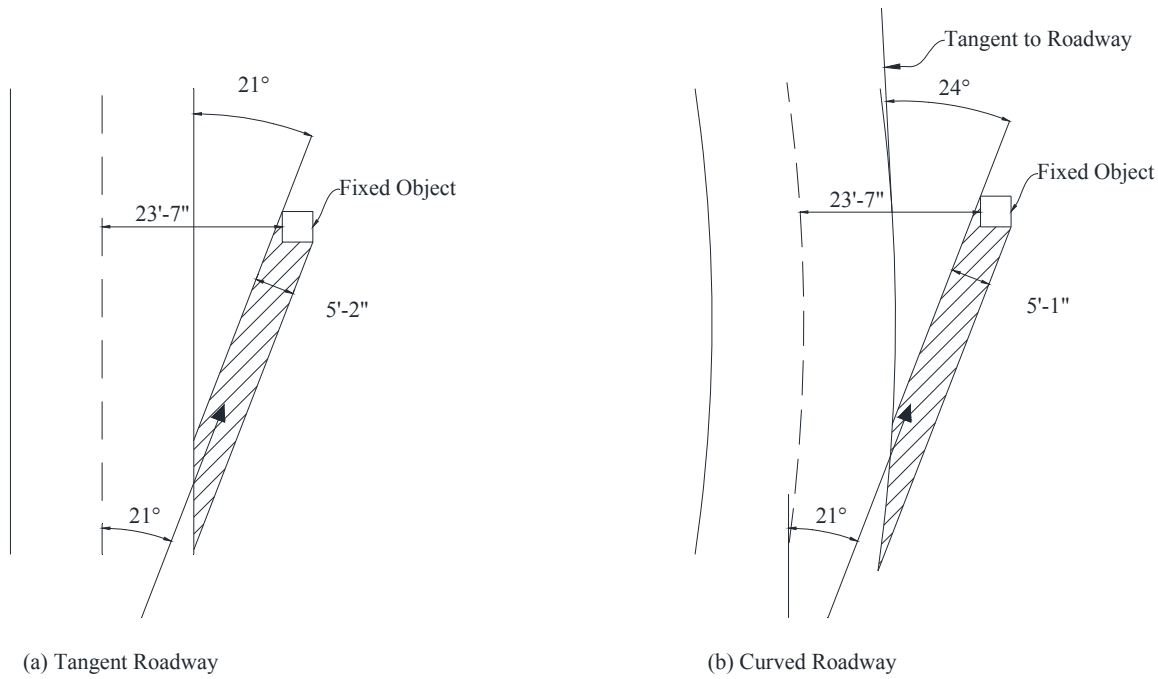

Figure 12. Probability of Impact on Tangent and Curved Roadways

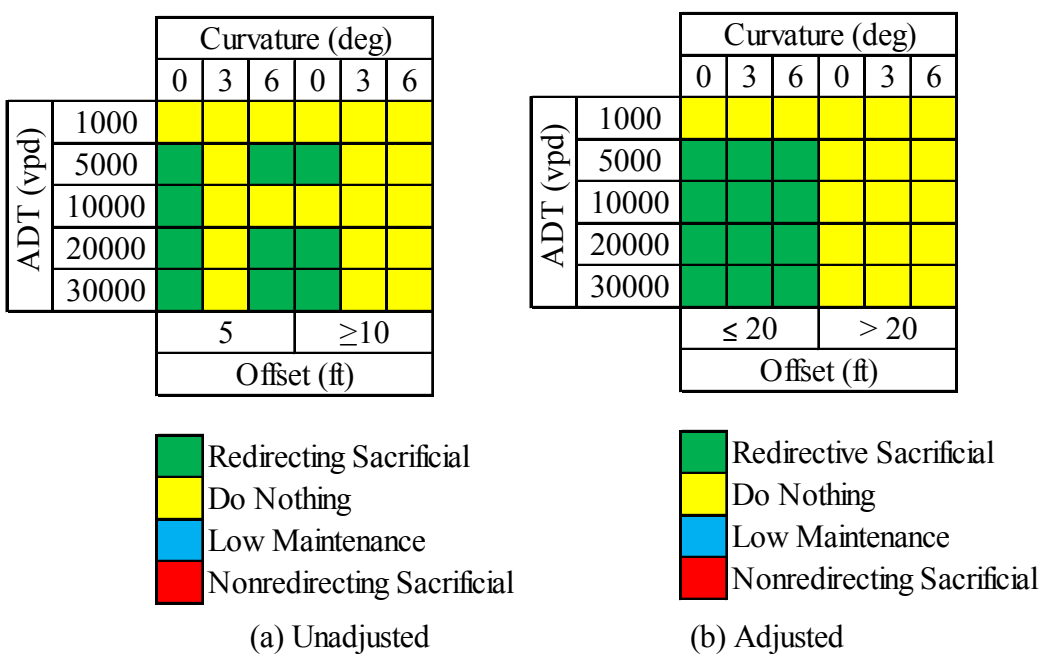

Figure 13. Crash Cushion Recommendations for Undivided Rural Arterials, BC ≥ 4

The unadjusted design chart illustrates the trend in which the accident cost decreased and then increased as the curvature increased, as shown in Figure 11. The adjusted design chart was created using engineering judgment based on conservative recommendations in favor of safer treatment options. Since it was assumed that any curve would introduce a greater probability of impact and a greater severity relative to a tangent roadway, when the redirecting sacrificial crash cushion was cost-effective on zero-degree curves, it was also considered cost-effective on all other curves at the same offset.

Further, increased impact speeds resulted in higher-than-average severities and, consequently, higher accident costs. However, the accident costs for both the unprotected and protected conditions rose at nearly the same rate. As a result, BC ratios tended to be consistent from one speed to another. Differences in BC ratios were more likely caused by the random number process used in Monte Carlo simulations or by the combined effect of the other three parameters (curvature, offset, and ADT). As a result, the design speed parameter was not included in the design charts. The relationship between the speed and the change in accident costs for each functional class, including rural arterial (RA), is shown in Figure 14.

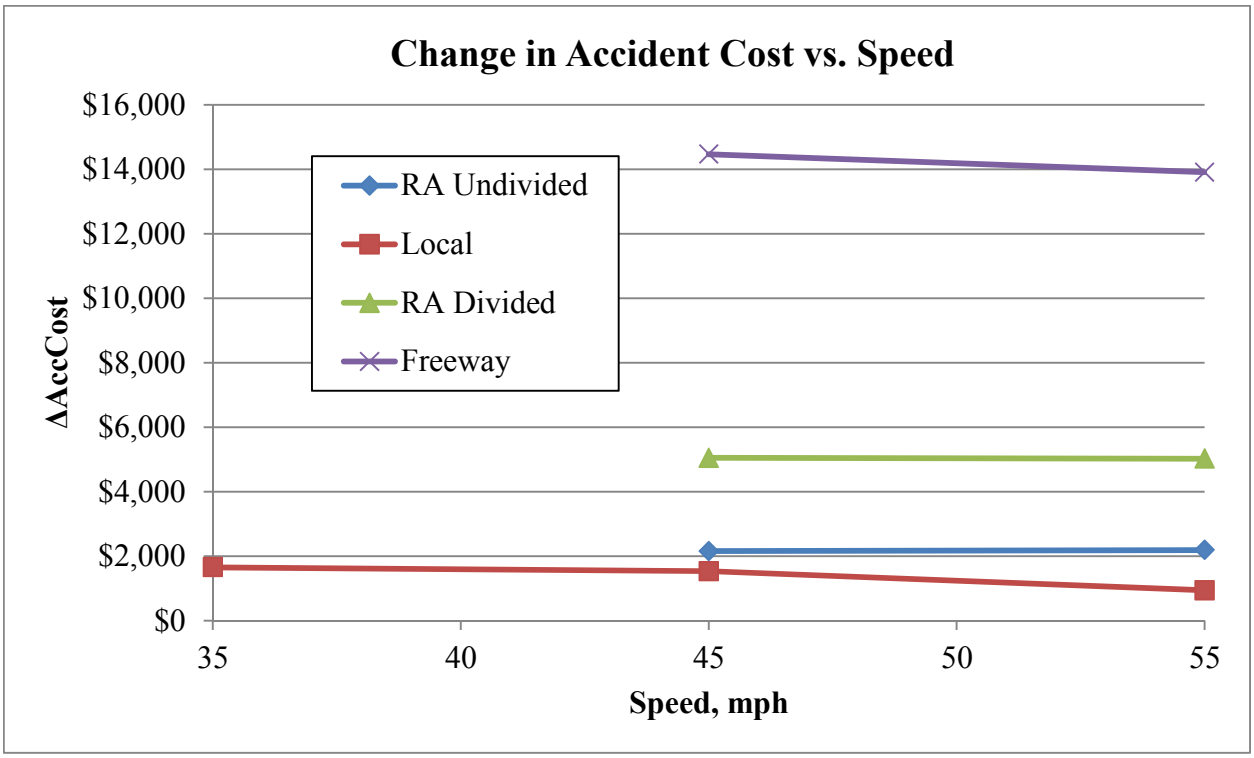

Figure 14. Change in Accident Costs vs. Speed for QuadGuard Crash Cushions

4.3 Parameter Values

The parameters used in RSAP include crash cushion offset, average daily traffic, horizontal curvature, and speed limit and are shown in Table 8. The values varied based on the functional roadway class. The traffic volume ranges were determined with assistance from the American Association of State Highway Transportation Officials (AASHTO) Green Book [10]. Curvature was chosen based on a summary of State standards given in NCHRP Report No. 638 [11]. Speeds and offsets were chosen to represent a range of possible values. Speeds greater than 55 mph (88.5 km/h) are not accurately modeled by RSAP [4]. Offsets were set out as far as 35 ft (10.7 m) to show that at large offsets, a crash cushion is no longer needed. According to the RDG, clear zones of 30 ft can allow as much as 80 percent of the vehicles enough room to recover [1]. By increasing this distance, even more errant vehicles would be able to safely

recover before impacting the fixed object. The exact critical offset was outside the scope of this research. Average daily traffic for freeways is higher than the average daily traffic for the other two functional classes since freeways usually carry higher traffic volumes. The same applies for horizontal curvature and offsets since different functional classes have different design values for these parameters.

Table 8. RSAP Modeling Parameter Values

Parameter	Freeways	Rural Arterials	Local Highways
ADT (1,000s)	5, 10, 25, 50, 75, 100	1, 5, 10, 20, 30	0.2, 0.5, 1, 3
Curvature, deg	0, 2, 4	0, 3, 6	0, 5, 10
Speed, mph (km/h)	45 (72.4), 55 (88.5)	45 (72.4), 55 (88.5)	35 (56.3), 45 (72.4), 55 (88.5)
Offset, ft (m)	5.0 (1.5), 15.0 (4.6) 25.0 (7.6), 35.0 (10.7)	5.0 (1.5), 10.0 (3.1), 15.0 (4.6), 20.0 (9.1), 35.0 (10.7)	5.0 (1.5), 10.0 (3.1), 15.0 (4.6), 20.0 (9.1), 35.0 (10.7)

5 SOCIETAL AND DIRECT COST ESTIMATION

5.1 Societal Costs

According to the Federal Highway Administration (FHWA), the average cost of a human life was $2.6 million dollars in 1994 [8]. This accounted for the loss of income over the remainder of the victim's life and the willingness of society to pay for the accident. That number has since increased through inflation. As recently as 2006, the cost of a fatality was estimated at $3.3 million [11]. Utilizing the latter value, the costs of each injury level on the KABCO scale (with K being a fatality and O being property damage only) are provided below.

K = $3,296,000

A = $226,600

B = $45, 320

C = $23,690

O = $2,575

Using this scale and the predicted accident frequency, RSAP was able to determine an accident cost for each crash cushion at each location. These accident costs were not influenced by the crash cushion's ability to reduce severity because RSAP is not capable of treating crash cushions differently. Instead, accident frequency, and subsequently accident cost, was determined by the location and the geometry of the crash cushion. These costs were in no way related to the installation, maintenance, and repair costs provided through a survey from State DOTs. The simulated accident costs are found in Appendices C through F.

5.2 Direct Costs

5.2.1 Installation Costs

Installation costs ascertained from the State of Wisconsin were used for redirecting sacrificial and low maintenance crash cushions. However, Wisconsin did not list inertial sand

barrels in their survey response. As a result, price estimates were taken from online transportation safety equipment dealers. Using a 1,400-lb (635-kg) barrel, the average cost from three dealers was $254 [9-13], which included discounts for order amounts greater than 10 barrels. Other installation costs were estimated through SCI Products, Inc. Both installation labor and material costs for a standard width unit were included in the estimate. Standard widths varied depending on the design speed, but in general, sand barrels were the least expensive crash cushion.

The standard widths of each crash cushion were adequate to shield a 4-ft (1.2-m) square fixed object. In addition, labor costs were assumed to be $50 per hour based on correspondence with the State of Wisconsin and SCI. Each crash cushion was assigned an estimated assembly and installation time. The Quest and REACT 350 required the least amount of assembly and installation time (6 hours), whereas the QuadGuard and QuadGuard Elite required the most amount of time (20 hours), as shown in Appendix B.

5.2.2 Maintenance Costs

Regular maintenance on crash cushions adds to the direct costs of the system and were important in determining BC ratios. Responses from other States indicated either a total maintenance cost for all crash cushions in the state or were a replication of the repair costs. Therefore, maintenance costs were set to zero for this analysis.

5.2.3 Repair and Traffic Control Costs

Repair costs were also ascertained from the State of Wisconsin when the data was available. State engineers provided researchers with cost data from SCI Products, Inc. Repair costs were estimated from the damage inflicted by standard head-on impact tests, which at the time, were NCHRP 350 test nos. 3-33 and 3-39 for frontal and side impacts, respectively. To estimate the actual repair cost, a weighted average of the two noted tests was used. The frontal

impact tests comprised 66 percent of the repair cost, while the side impact tests comprised 34 percent as shown in Appendix B.

The tests were conducted at 62.5 mph (100.6 km/h), which was intended to represent the 95th percentile of all impacts (i.e., 95 percent of all actual impacts occur at speeds lower than 62.5 mph or 100.6 km/h). However, to determine an actual average repair cost, the test data was reduced to match the average impact speed. A study was done to estimate vehicle impact conditions on various highway types [14]. The authors examined interstate accident data, among other types of highways, and determined that the average impact velocity was 45.3 mph (73.0 km/h). The ratio needed to determine the average repair cost was determined in Equation 2.

$$RepairCost = \left(\frac{x_{50}}{x_{95}}\right)(R) = \left(\frac{45.3}{62.5}\right)R = 0.725R \tag{2}$$

Where R was the weighted average repair cost required after an impact similar to the test conditions outlined in the survey response. For example, the Smart Cushion (SCI) had an average repair cost of $109, as shown in Appendix B. Using Equation 2, this was reduced to $79.07. These calculated average repair costs were programmed into RSAP, which then calculated an average annual repair cost based on the number of impacts per year and the average impact severity of the crash cushion.

A difference was observed when comparing each crash cushion type in the time required to make repairs (see Appendix B). When the crash cushion was located near the roadway (i.e., less than 10 feet or 3.0 m), maintenance crews were required to shut down a traffic lane for the duration of the repair. Costs included in lane closure repair were the use of a utility truck, labor for the truck driver, and labor for setup and take down of the traffic control systems. The costs associated with a lane closure repair may be large especially on two-lane highways with large

traffic volumes. Unfortunately, traffic delay costs could not be quantified and were not used for the analysis.

Traffic control cost estimates submitted by the Wisconsin DOT assumed a setup and take down time, including travel time, to be one hour each. Further, the use of the utility truck and truck driver labor hours for shipping the crash cushion or its replacement parts to the site required one hour each. This latter assumption did not allow for the truck driver to participate in the maintenance of the crash cushion. Therefore, it was assumed that the truck driver's labor was not included in the maintenance crew man-hours.

However, the traffic control cost of inertial crash cushions was not included in the survey response submitted by the Wisconsin DOT. Instead, the approximate time for repairs submitted by Minnesota DOT for the Energite III inertial crash cushion system was used in conjunction with the same assumptions made for the other crash cushions (i.e., setup and take down time, labor, and truck usage). As such, an average of four hours was required to repair inertial crash cushions.

Labor was assumed to be $50 per hour, and the utility truck cost $38 per hour for each crash cushion. A 2-man crew was used for set-up, take-down, and repair of the crash cushion. For each crash cushion, a fixed cost based on a set-up and take-down time of the work zone was assumed to be one hour for each phase. That is, set-up should take one hour and take-down one more hour, resulting in a total of 4 man-hours and a labor cost of $200. The truck was rented for one hour at $38, while the hourly wage for the truck driver was $87. Summing each fixed cost resulted in a total fixed traffic control cost of $325 for each crash cushion.

Since each crash cushion had a different repair time, each system also had a different variable repair cost. This variable cost was determined by the hourly truck rental rate (i.e., $38 per hour), the hourly wage rate of the truck driver (i.e., $87 per hour), and the labor of the 2-man

crew (i.e., $100 per crew per hour) resulting in a cost of $225 per hour. For example, the repair time for a sand barrel system was 4 hours based on the Minnesota DOT survey response, which resulted in a repair cost of $325 plus 4 times $225, or $1,225 per repair. Traffic control costs of the remaining crash cushions are summarized in Appendix B and were modified for use in this study using Equation 2.

Traffic control costs were only applicable if the roadway was shut down and was only required when the offset to the crash cushion was within 15 ft (4.6 m) of the pavement edge. Therefore, assuming the offset and traffic control cost were linearly related and the full cost was required at an offset of 5 ft (1.5 m), the traffic control cost was reduced by half at the 10-ft (3.0-m) offset distance. This was based on the assumption that less setup and takedown time were required when a shorter section of highway was closed.

6 BENEFIT-COST ANALYSIS

6.1 BC Ratio

The BC ratio is an indicator of an alternative's cost effectiveness, taking into account design life costs. The ratio calculated in Equation 1 from Chapter 4 pits accident costs against direct costs. It is reprinted here for clarification.

$$BC_{2-1} = \frac{(AC_1 - AC_2)}{(DC_2 - DC_1)} \tag{3}$$

Where

AC_1 = the accident cost of the baseline or "do-nothing" alternative design

AC_2 = the accident cost of the new alternative design.

DC_1 = the direct cost of the baseline design

DC_2 = the direct cost of the new design or safety treatment used

The accident costs used for each scenario and for each design alternative are found in Appendices C through F. The direct costs were described in Section 5.2. The costs were annualized using a design life of 25 years and an interest rate of 4 percent. This interest rate generally does not vary with time, so it is valid at any point in the design life. It is the difference between the nominal interest rate and the inflation rate. Using this design life and interest rate with the accident and direct costs of each crash cushion, the BC ratio was calculated using Equation 3. A ratio of 1.0 means that at the end of the 25-year design life, the accident costs and direct costs were offset. In general investment practices, this would not be worth the effort. Instead, a minimum ratio of 2.0 was suggested, with a ratio of 4.0 being preferred.

Often times, a matrix can be created to compare several alternatives at once and directly to one another. However, the ultimate comparison herein was with the baseline alternative only. Therefore, to eliminate the steps necessary to create a matrix, all BC ratios were constructed by

comparing each crash cushion to the baseline condition only because the objective of the research was to quantify the most beneficial crash cushion relative to the unprotected fixed object.

6.2 Baseline Condition and Alternative Designs

A fixed object was placed on each side of the road. For divided rural arterials and freeways, a fixed object was placed in the median as well. This fixed object was a 4-ft (1.22-m) square, similar to a bridge pier. When applicable, the median was 30 ft (9.14 m) wide. The lane width was 12 ft (3.66 m) and the shoulder width was 6 ft (1.83 m). Two lanes were used on local roads and undivided rural arterials. Four lanes (i.e., two in each direction) were used on freeways and divided arterials. A schematic of the baseline condition and the general protected condition is shown in Figure 15.

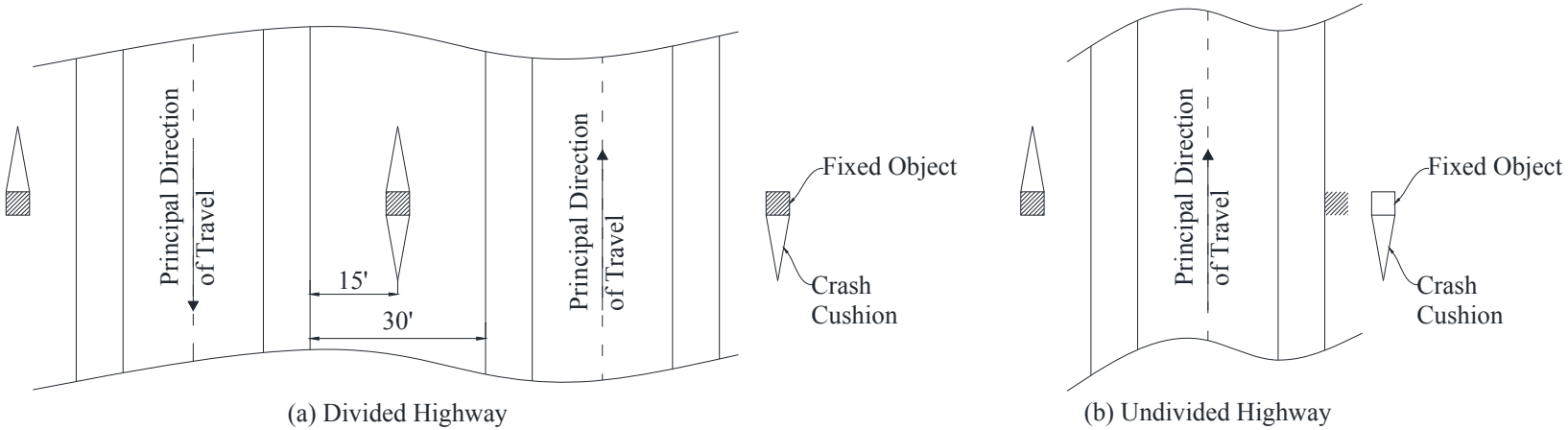

Figure 15. Crash Cushion Placement on (a) Divided and (b) Undivided Highways

7 EXAMPLE APPLICATIONS

7.1 Developing the Design Charts

A BC analysis was conducted using RSAP for each crash cushion. Two general BC ratio criteria were used, BC = 2 and BC = 4. The goal of this project was to recommend a redirecgting sacrificial, low-maintenance, or nonredirecting sacrificial crash cushion for each scenario and not a particular crash cushion. It may be possible to have a low maintenance crash cushion as the best option followed by three redirecting sacrificial crash cushions and then one low maintenance crash cushion. Although a low-maintenance crash cushion may have had the highest BC ratio, three out of the top five crash cushions in this hypothetical example were redirecting sacrificial. This would indicate that these crash cushions, as a group, were better suited for the application rather than the other crash cushion groups. Thus, a system of weighted averages was used to recommend a crash cushion type for each scenario. This system accounted for the number of crash cushion types above the BC threshold and the average BC ratios for each type. This system was best explained through the following example shown in Figure 16. The given BC ratios shown in Figure 16 were generated arbitrarily and do not reflect any of the tested scenarios.

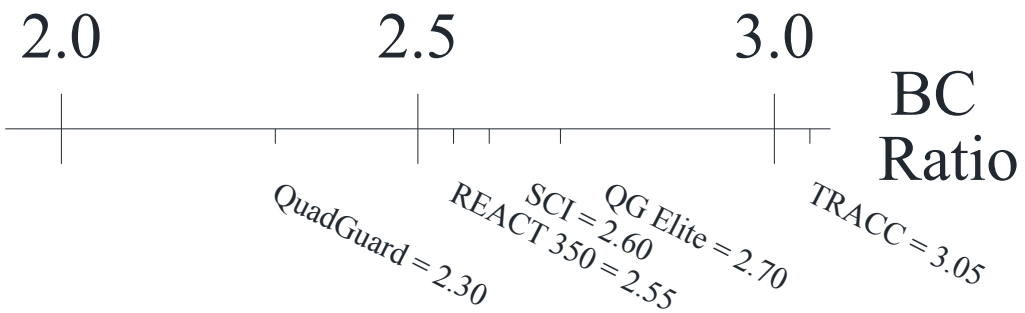

Figure 16. Example of Weighted Average System

Of the five crash cushions shown in Figure 16, the top and bottom are redirecting sacrificial (S) crash cushions and the middle three are low-maintenance (L) crash cushions. In this study, four redirecting sacrificial and three low-maintenance crash cushions were considered. A ratio of the number of beneficial crash cushions to the total number of crash cushions for each type was calculated (r_S and r_L). The average BC ratio of each type of crash cushion was determined (BC_S and BC_L), including the ones that did not exceed the BC threshold. By including any low BC ratios, a penalty was applied to the group as a whole. An index was used to rank the types of crash cushions (I_S and I_L). This index was the product of the ratio, r_i, and the average BC ratio, BC_i. These calculations are summarized below for the example shown in Figure 16.

$$r_S = \frac{2}{3} = 0.667 \tag{4}$$

$$r_L = \frac{3}{4} = 0.750 \tag{5}$$

$$BC_S = \frac{3.05+2.30}{2} = 2.675 \tag{6}$$

$$BC_L = \frac{2.70+2.60+2.55}{3} = 2.617 \tag{7}$$

$$I_S = r_S BC_S = 0.667 \times 2.675 = 1.783 \tag{8}$$

$$I_L = r_L BC_L = 0.750 \times 2.617 = 1.963 \tag{9}$$

Since I_L is greater than I_S, the best crash cushion type is the low-maintenance group, despite the fact that the highest BC ratio came from a sacrificial crash cushion (e.g., TRACC). As shown in the design charts in Appendices G through J, three colors were used to differentiate the most cost-effective crash cushion for each scenario (i.e., redirecting sacrificial, low maintenance, or "do nothing"). Nonredirecting sacrificial crash cushions were never more cost-beneficial than either of the remaining crash cushion types.

7.2 Understanding the Design Charts

Each chart employs a color-coded system to identify the best crash cushion type for each scenario. In order to use these charts, the engineer must know the traffic volume (ADT), the degree of curvature of the road (degrees), and the offset of the crash cushion from the roadway (ft). The engineer must also decide if a BC ratio of 2.0 is sufficient or if 4.0 is preferred. There are eight design charts, with each functional class having one chart for each BC ratio. The rural arterial highway was split into two categories, divided and undivided. This designation was important because divided rural arterials are treated like freeways; therefore, the speed and angle distribution of encroaching vehicles is different for the undivided and divided rural arterials.

In some scenarios, two crash cushion types appeared to be equal. When this occurred, the type that was chosen was based on the type used in similar scenarios. For example, if the only parameter that changed between scenarios was the degree of curvature, and all but one scenario used a redirecting sacrificial crash cushion, then the single outlier was changed to a redirecting sacrificial crash cushion. This is an acceptable practice because RSAP uses Monte Carlo simulation to create BC ratios; therefore, the results were not deterministic. It is possible that the difference between two types of crash cushions could switch if the analysis is rerun with a different random seed number in RSAP. As a result, engineering judgment was used to determine if the difference between two types was negligible.

In most cases, nonredirective sacrificial crash cushions (sand barrels) were not recommended, with the exception of small volumes on divided rural arterials with offsets greater than 20 ft (6.1 m). However, the engineer is encouraged to use judgment in deciding if sand barrels should be used on areas where no other crash cushion was cost-effective. Additionally, other forms of roadside safety protection should be investigated, such as a bullnose system or longitudinal barrier. Because nonredirective sacrificial crash cushions are exceptionally

undesirable in permanent settings, they should be limited to temporary usage, such as in a work zone.

7.3 Examples

Four example applications are described below, one for each highway type. These examples should help highway engineers to understand how the plots shown in Appendices G through J are used.

7.3.1 Freeway Example

Given the traffic and roadway characteristics described as follows, find the most cost-effective crash cushion type to be used.

- Freeway
- ADT = 75,000 vpd
- Offset = 15 ft (4.6 m)
- Degree of Curvature = 2 degrees
- Minimum BC ratio = 2.0

Solution:

- Appendix G, Figure G-1
- Select a Redirecting Sacrificial Crash Cushion

7.3.2 Divided Rural Arterial Example

Given the traffic and roadway characteristics described as follows, find the most cost-effective crash cushion type to be used.

- Divided Rural Arterial
- ADT = 10,000 vpd
- Offset = 10 ft (3.1 m)

- Degree of Curvature = 6 degrees
- Minimum BC ratio = 4.0

Solution:

- Appendix H, Figure H-1
- Select a Redirecting Sacrificial Crash Cushion

7.3.3 Undivided Rural Arterial Example

Given the traffic and roadway characteristics described as follows, find the most cost-effective crash cushion type to be used.

- Undivided Rural Arterial
- ADT = 5,000 vpd
- Offset = 5 ft (1.5 m)
- Degree of Curvature = 0 degrees
- Minimum BC ratio = 2.0

Solution:

- Appendix I, Figure I-1
- Select a Redirecting Sacrificial Crash Cushion

7.3.4 Local Highway Example

Given the traffic and roadway characteristics described as follows, find the most cost-effective crash cushion to be used.

- Local
- ADT = 200 vpd
- Offset = 5 ft (1.5 m)
- Degree of Curvature = 0 degrees

- Minimum BC ratio = 2.0

Problem:

- Appendix J, Figure J-1
- Select the “Do Nothing” alternative
- Alternatively, the least expensive inertial crash cushion could be used

8 PURELY MAINTENANCE COSTS

8.1 RSAP's Treatment of Crash Cushions

In RSAP version 2003.04.01, a crash cushion may be modeled as either redirecting or nonredirecting, and as a TL-2 or TL-3 system. For each of the four possible models, a SI scale is built into the program, meaning, each crash cushion in the industry is treated the same, assuming the geometries are identical. Without detailed test or accident data, this assumption must remain in force. However, by assuming accident costs associated with property damage, bodily injury, or fatality, are the same for each crash cushion, they can be analyzed based on maintenance costs alone. These costs may include the costs to repair the structure and to control traffic.

8.2 Impact Frequency

Assuming a linear relationship between life cycle costs and impact frequencies, a relationship can be established to estimate the life cycle cost, as a function of impact frequency, for each type of crash cushion using the slope-intercept equation. From simulations done by RSAP, it was determined that nonredirecting sacrificial crash cushions, such as sand barrels, should be not be considered in permanent locations. This conclusion would naturally extend to any high-frequency or high-severity location. Therefore, only redirecting sacrificial and low maintenance crash cushions were considered in this section.

The y-intercept of the equation was determined by the average annualized cost of each crash cushion type. The slope was the cost per impact, defined as the maintenance cost, which includes the cost to repair the system and to control traffic. The model for the life cycle cost of the crash cushion is given by Equation 10.

$$LC = (IC) + (MC) \times (IF) \tag{10}$$

Where LC = Life cycle costs

IC = Annualized installation cost

MC = Maintenance cost estimate for one impact

IF = Impact frequency (impacts per year)

An equation for a redirecting sacrificial family and a low maintenance family can be modeled after the manner of Equation 10. The two can be equated to determine the minimum impact frequency at which a low maintenance system becomes more cost-effective than a redirecting sacrificial system. The final expression for this minimum impact frequency is given in Equation 11.

$$IF_{min} = \frac{IC_{LM} - IC_{RS}}{MC_{RS} - MC_{LM}} \tag{11}$$

Where IF_{min} = Minimum impact frequency to consider low maintenance systems

IC_{LM} = Average annualized installation cost for low maintenance systems

IC_{RS} = Average annualized installation cost for redirecting sacrificial systems

MC_{LM} = Average maintenance cost of a low maintenance system

MC_{RS} = Average maintenance cost of a redirecting sacrificial system

For the cost information provided by State DOTs, the average installation costs, annualized over 25 years, for low maintenance and redirecting sacrificial crash cushions were $1,887 and $898, respectively. The average maintenance costs were $3,003 and $4,206, respectively. Using Equation 11, the minimum impact frequency at which to consider a low-maintenance system was 0.823 impacts per year or 1 impact every 1.2 years.

9 LIMITATIONS

The most important limitation associated with the benefit-cost analysis procedure corresponds to the accuracy of the installation, repair, and maintenance costs of the crash cushions used in the study. Installation, repair, and maintenance costs were based on limited data from the State DOTs. Therefore, the accuracy of the final results of this study was highly dependent on the cost values provided by the States. However, the accuracy of the information provided by the States was unknown. Since few States provided information (i.e., only Kansas, Minnesota, Nebraska, and Wisconsin), it was not possible to compare the cost values from different States for each crash cushion to evaluate the accuracy of the costs.

In addition, each crash cushion performs differently. In comparing similar lengths, some crash cushions will perform better than others by reducing impact severity. RSAP, however, does not adjust the impact severity of the crash cushion, so all crash cushions are treated equal on the basis of impact severity. The only differences were their impact frequency based on their dimensions and their direct costs. The effect of better-performing features was only partially represented by a given system's reduced repair costs.

Posted speed limits along many highways, especially freeways, are well above 55 mph (88.5 km/h). However, RSAP cannot accurately treat higher speeds because the speed distributions were based on a study that investigated impact conditions in accident reports in the 1970's [7], which was prior to the repeal of the national speed limit of 55 mph (88.5 km/h). This study indicated that the 50th percentile impact speed as determined by the cumulative distribution plot incorporated into RSAP was 27 mph (43.5 km/h). However, the current average impact speed on an interstate is about 45 mph (72.4 km/h) [14]. The latter study also indicated the 90th percentile impact speed was 66.0 mph (106.2 km/h) on interstates which is larger than the largest possible speed RSAP can use.

Engineering judgment was used to determine crash cushion types in scenarios where two types were possible. If the index, I_i, concluded that a redirecting sacrificial crash cushion was best, but all other similar scenarios required a low maintenance crash cushion, engineering judgment was used to overrule the index value. This exercise of engineering judgment was required when using RSAP due to the random number method used in Monte Carlo simulation. This was magnified in this study by not running all the crash cushions simultaneously and using the same seed number. However, the use of engineering judgment was limited and believed to be acceptable.

This study assumed only costs directly associated with the crash cushion (i.e., no grading or other similar costs were considered). As a result, this report is most applicable to new construction, where outside parameters, such as the grade, can be controlled. When examining a possible retrofit or a change in the type of crash cushion currently being used, there should not be any costs beyond those discussed herein. If there are, a more detailed benefit-cost analysis should be conducted by the engineer.

High frequency locations were not modeled. These locations represent a very small percentage of the total number of possible locations to install a crash cushion and warrant the use of a specific accident history to determine the type of protection needed at that location. The highest modeled impact frequency in this report was 0.11 impacts per year, and that was on a freeway with 100,000 vpd on a 4 degree curve with an offset of 5 ft (1.5 m). Most scenarios, especially low-volume scenarios, would experience impact frequencies far less than this. Therefore, if the accident frequency is known, this report should only be used at locations with fewer than 0.11 accidents per year (1 accident every 9 years). Otherwise, other systems may be considered as well, such as the bullose guardrail system or an energy absorbing terminal.

10 CONCLUSIONS

This report analyzed several crash cushions and categorized them as either redirecting sacrificial, low maintenance, or nonredirecting sacrificial. Nonredirecting sacrificial crash cushions were the least expensive up front, but had the highest ratio of repair costs to installation costs. Low-maintenance crash cushions tended to be the most expensive up front, but had the least expensive repair costs. Redirecting sacrificial crash cushions were in between for both installation costs and repair costs.

Traffic control costs added to the direct costs when the attenuator was near the side of the road. Low-maintenance crash cushions required very little time to repair and had the lowest traffic control costs. However, because installation costs made up a vast majority of the direct costs, the positive effect of the traffic control costs on the low-maintenance attenuators was almost negligible. As a result, the redirecting sacrificial crash cushion was recommended over the low-maintenance systems in nearly all scenarios where a redirecting crash cushion was cost-beneficial. In some cases, no crash cushion could be recommended based on minimum BC ratios of 2.0 and 4.0. In these cases, the engineer is encouraged to use judgment in determining what kind of, if any, crash cushion should be used.

Low-maintenance crash cushions were not recommended for any scenario due to high installation costs. By examining simulation results from this report, the highest expected frequency was 0.11 impacts per year or 1 impact every 9 years. By examining maintenance costs alone, it was shown that a minimum impact frequency at which to consider low-maintenance systems was 1 impact every 1.2 years, far more frequent than the scenarios considered herein.

Redirecting sacrificial crash cushions were found to be the most cost-effective class of crash cushion on freeways and divided rural arterials. Redirecting sacrificial crash cushions and the “do

nothing" alternative competed with each other on undivided rural arterials and local highways. For undivided rural arterials, redirecting sacrificial crash cushions were always the most cost-effective, except on highway scenarios with low traffic volumes and large offsets. This was attributed to the fact that scenarios with low traffic volumes and large crash cushion offsets tend to present low impact frequencies. Thus, the "do nothing" alternative was more attractive due to its zero-installation cost. For local highways, the "do nothing" alternative seemed to become even more attractive as these roads experienced the lowest traffic volumes.

11 REFERENCES

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12 APPENDICES

Appendix A. State DOT Survey Questionnaire

SURVEY QUESTIONNAIRE

Dear Pooled Fund State representative,

The Midwest Roadside Safety Facility (MwRSF) is conducting a study titled "Synthesis of Crash Cushion Guidance". The purpose of this study is to develop guidelines for determining where each class of crash cushion is most appropriate. For this study we have lumped crash cushions into three categories, sacrificial (such as sand tubs), repairable (such as quadguard with hex-foam cartridges), and restorable, (such as React). The first step in this study is to collect data on both current guidelines pertaining to crash cushion implementation and the costs associated with the use of each type of cushion. A short survey instrument has been developed for use in collecting this information. Please fill out a survey form for any crash cushion design that you can. **Please use one form for each crash cushion type you may want to mention.** We would also like a copy of any guidelines your State uses for determining where each class of crash cushion should be used. Please fill out this questionnaire with as accurate information as possible and return it to the address listed below. Also, if you have any questions, please do not hesitate in contacting the MwRSF through the contact information given below. Thank you for your time and cooperation.

Midwest Roadside Safety Facility
University of Nebraska-Lincoln 68588-0529
527 Nebraska Hall
Phone: (402) 472-9043
Fax: (402) 472-2022
Email: dbenicio@huskers.unl.edu or dsicking1@unl.edu

1. Crash Cushion device?

_____

2. What is the average installation (initial) cost of the crash cushion device cited above?
(US$)_____

3. What is the average crash repair cost of the crash cushion device cited in part 1?
(US$)_____

4. What is the average regular maintenance cost, per year, of the crash cushion device cited in part 1?
(US$)_____

5. Does this crash cushion device require your department to have replacement parts in your inventory?
( ) Yes ( ) No
If you marked yes, what is the average cost of your inventory for this crash cushion device?
(US$)_____

6. What is the average lane closure time required to repair the device described in part 1 after it has been involved in a crash? _____:_____ (hour : minutes)

7. What is the Test Level of the device cited in part 1? ( ). Test Level 1 ( ) Test Level 2 ( ) Test Level 3

8. What is the speed limit(s) under which the crash cushion device cited in part 1 is used?
_____(mph)

All these data will provide valuable information to future transportation needs. We thank you for your time and for sharing information with us.

_____
Dr. Dean Sicking, Director MwRSF

Appendix B. Repair and Traffic Control Costs from Wisconsin DOT

Initial Material Costs	**QuadGuard**	**QG Elite**	**Quest**	**React 350**	**SCI**	**Tau II**	**Tracc**
Standard Width Unit	$17,538	$32,017	$11,210	$35,767	$18,971	$14,883	$11,000
Installation Labor							
Labor Rate	$50	$50	$50	$50	$50	$50	$50
Assembly Manhours	8	8	0	0	0	6	0
Installation Manhours	12	12	6	6	8	5	8
Total Labor	$1,000	$1,000	$300	$300	$400	$550	$400
Total Installed Cost	**$18,538**	**$33,017**	**$11,510**	**$36,067**	**$19,371**	**$15,433**	**$11,400**
Repair Costs							
Frontal Impact - NCHRP350 Test #3-33							
Parts	$6,246	$5,219	$0	$3,781	$89	$5,595	$7,271
Manhours	13.0	13.0	6.0	2.0	1.5	3.0	17.0
Labor	$650	$650	$300	$100	$75	$150	$850
Total	$6,896	$5,869	$300	$3,881	$164	$5,745	$8,121
Side Impacts - NCHRP350 Test #3-39							
Parts	$4,962	$2,911	$0	$3,718	$0	$4,382	$5,162
Manhours	16.0	16.0	6.0	4.0	0.0	6.0	11.0
Labor	$800	$800	$300	$200	$0	$300	$550
Total	$5,762	$3,711	$300	$3,918	$0	$4,682	$5,712
Repair Cost Average 66% Frontal and 34% Side Impacts	**$6,518**	**$5,150**	**$300**	**$3,894**	**$109**	**$5,390**	**$7,318**
Traffic Control Costs	**$3,475**	**$3,475**	**$1,675**	**$925**	**$550**	**$1,225**	**$1,788**

Appendix C. Freeway Accident Costs

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
5000	0	45	5	46544.85	35069.22	38360.63	38390.67	38360.30	37667.73	38366.91	38460.77	55106.00
			15	37007.80	27910.94	27845.79	27855.92	27856.46	26899.22	27860.88	27971.77	42142.27
			25	30792.95	23334.76	23601.82	23669.56	23692.44	23081.11	23684.21	23821.96	36495.60
			35	26305.34	19617.18	19662.60	19709.30	19897.89	19372.75	19898.38	20148.92	31045.70
		55	5	57479.91	51249.90	53188.20	53361.08	53751.38	52784.34	53361.08	53041.87	67605.50
			15	46422.29	39256.01	38906.71	39047.21	40194.85	39376.07	39047.21	39506.46	53559.99
			25	38899.91	33939.74	33606.28	33751.37	34299.56	33489.01	33751.37	34145.19	46209.65
			35	33180.11	28221.15	28494.21	28593.65	28466.39	27761.80	28624.69	29058.34	39211.23
	2	45	5	28702.46	28105.13	28606.83	28653.29	28562.45	27724.67	28470.48	28068.86	36481.49
			15	23123.94	20792.31	21132.17	21230.59	21095.88	20298.98	20993.89	21272.61	29356.71
			25	20165.10	17599.45	17802.85	18053.45	17785.18	17072.83	17769.09	17844.60	24922.90
			35	26305.34	19617.18	19662.60	19709.30	19897.89	19372.75	19898.38	20148.92	31045.70
		55	5	34773.36	51249.90	53188.20	53361.08	53751.38	52784.34	53361.08	53041.87	67605.50
			15	28984.47	39256.01	38906.71	39047.21	40194.85	39376.07	39047.21	39506.46	53559.99
			25	25661.83	33939.74	33606.28	33751.37	34299.56	33489.01	33751.37	34145.19	46209.65
			35	33180.11	28221.15	28494.21	28593.65	28466.39	27761.80	28624.69	29058.34	39211.23
	4	45	5	32099.68	30946.40	32118.40	31261.56	32037.58	30936.35	32048.97	33147.27	43322.98
			15	26365.97	23160.94	23614.92	23815.29	23551.79	23292.58	23656.16	24513.40	33416.85
			25	22559.95	19666.98	19982.83	20014.42	19935.11	19853.18	20085.71	20685.86	29470.37
			35	26305.34	19617.18	19662.60	19709.30	19897.89	19372.75	19898.38	20148.92	31045.70
		55	5	40353.84	51249.90	53188.20	53361.08	53751.38	52784.34	53361.08	53041.87	67605.50
			15	33013.87	39256.01	38906.71	39047.21	40194.85	39376.07	39047.21	39506.46	53559.99
			25	28423.68	33939.74	33606.28	33751.37	34299.56	33489.01	33751.37	34145.19	46209.65
			35	33180.11	28221.15	28494.21	28593.65	28466.39	27761.80	28624.69	29058.34	39211.23
10000	0	45	5	58645.45	47921.48	48333.52	48371.37	48333.10	47460.48	48341.43	48459.69	69432.30
			15	46628.99	35167.15	35085.06	35097.83	35098.51	33892.40	35104.07	35243.79	53098.29
			25	38798.42	29401.26	29737.75	29823.10	29851.93	29081.67	29841.56	30015.12	45983.62
			35	33144.12	24717.20	24774.42	24833.26	25070.89	24409.22	25071.50	25387.18	39116.87
		55	5	72423.38	64573.70	67015.92	67233.73	67725.52	66507.06	67233.73	66831.54	85181.38
			15	58491.02	49461.67	49021.57	49198.60	50644.59	49612.94	49198.60	49777.24	67484.36
			25	49013.00	42763.30	42343.14	42525.95	43216.66	42195.39	42525.95	43022.16	58223.10
			35	41806.17	35558.00	35902.05	36027.34	35867.00	34979.23	36066.46	36612.84	49405.25

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
10000	2	45	5	36164.44	35411.83	36043.95	36102.49	35988.04	34932.45	35872.16	35366.12	45965.85
			15	29135.63	26197.84	26626.05	26750.05	26580.32	25576.25	26451.82	26803.00	36988.79
			25	25407.56	22174.91	22431.19	22746.94	22408.92	21511.38	22388.64	22483.78	31402.29
			35	33144.12	24717.20	24774.42	24833.26	25070.89	24409.22	25071.50	25387.18	39116.87
		55	5	43813.64	64573.70	67015.92	67233.73	67725.52	66507.06	67233.73	47022.46	85181.38
			15	36519.77	49461.67	49021.57	49198.60	50644.59	49612.94	49198.60	37051.12	67484.36
			25	32333.32	42763.30	42343.14	42525.95	43216.66	42195.39	42525.95	32432.16	58223.10
			35	41806.17	35558.00	35902.05	36027.34	35867.00	34979.23	36066.46	25387.18	49405.25
	4	45	5	40444.86	38991.77	40468.46	39388.85	40366.62	38979.10	40380.98	41764.80	54585.98
			15	33220.52	29182.26	29754.27	30006.72	29674.72	29348.12	29806.22	30886.33	42104.47
			25	28425.02	24779.95	25177.91	25217.71	25117.79	25014.55	25307.53	26063.72	37131.99
			35	33144.12	24717.20	24774.42	24833.26	25070.89	24409.22	25071.50	25387.18	39116.87
		55	5	50844.93	64573.70	67015.92	67233.73	67725.52	66507.06	67233.73	66831.54	85181.38
			15	41596.73	49461.67	49021.57	49198.60	50644.59	49612.94	49198.60	49777.24	67484.36
			25	35813.19	42763.30	42343.14	42525.95	43216.66	42195.39	42525.95	43022.16	58223.10
			35	41806.17	35558.00	35902.05	36027.34	35867.00	34979.23	36066.46	36612.84	49405.25
25000	0	45	5	123180.14	100655.29	101520.75	101600.27	101519.88	99687.01	101537.38	101785.76	145837.06
			15	97940.53	73865.83	73693.41	73720.23	73721.64	71188.32	73733.34	74026.80	111528.78
			25	81493.02	61755.03	62461.80	62641.08	62701.63	61083.75	62679.85	63044.40	96584.97
			35	69616.62	51916.53	52036.73	52160.32	52659.43	51269.65	52660.72	53323.77	82161.90
		55	5	152119.59	135631.97	140761.67	141219.19	142252.11	139692.84	141219.19	140374.39	178916.80
			15	122855.77	103890.35	102965.94	103337.78	106374.98	104208.09	103337.78	104553.17	141745.59
			25	102947.95	89820.95	88938.43	89322.41	90773.20	88628.09	89322.41	90364.66	122293.04
			35	87810.58	74686.77	75409.44	75672.60	75335.81	73471.12	75754.77	76902.40	103771.84
	2	45	5	75960.58	74379.76	75707.48	75830.44	75590.04	73372.86	75346.64	74283.75	96547.66
			15	61197.10	55026.50	55925.93	56186.39	55829.88	53720.91	55559.97	56297.59	77692.03
			25	53366.59	46576.65	47114.94	47778.14	47068.18	45182.96	47025.58	47225.42	65958.03
			35	69616.62	51916.53	52036.73	52160.32	52659.43	51269.65	52660.72	53323.77	82161.90
		55	5	92027.12	135631.97	140761.67	141219.19	142252.11	139692.84	141219.19	98766.98	178916.80
			15	76706.91	103890.35	102965.94	103337.78	106374.98	104208.09	103337.78	77822.98	141745.59
			25	67913.60	89820.95	88938.43	89322.41	90773.20	88628.09	89322.41	68121.20	122293.04
			35	87810.58	74686.77	75409.44	75672.60	75335.81	73471.12	75754.77	53323.77	103771.84

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
25000	4	45	5	84951.25	81899.13	85000.80	82733.17	84786.91	81872.52	84817.06	87723.69	114653.54
			15	69777.09	61295.03	62496.49	63026.75	62329.40	61643.41	62605.62	64874.30	88437.12
			25	59704.52	52048.32	52884.21	52967.81	52757.93	52541.09	53156.48	54744.79	77992.82
			35	69616.62	51916.53	52036.73	52160.32	52659.43	51269.65	52660.72	53323.77	82161.90
		55	5	106795.77	135631.97	140761.67	141219.19	142252.11	139692.84	141219.19	140374.39	178916.80
			15	87370.64	103890.35	102965.94	103337.78	106374.98	104208.09	103337.78	104553.17	141745.59
			25	75222.79	89820.95	88938.43	89322.41	90773.20	88628.09	89322.41	90364.66	122293.04
			35	87810.58	74686.77	75409.44	75672.60	75335.81	73471.12	75754.77	76902.40	103771.84
50000	0	45	5	291079.84	237852.67	239897.80	240085.67	239895.70	235564.58	239937.08	240524.02	344619.09
			15	231437.56	174548.05	174140.62	174203.98	174207.31	168220.98	174234.98	174928.44	263547.19
			25	192571.42	145929.72	147599.86	148023.50	148166.58	144343.45	148115.11	148976.56	228234.33
			35	164506.98	122680.94	122964.98	123257.01	124436.44	121152.33	124439.49	126006.31	194152.02
		55	5	359465.00	320504.03	332625.72	333706.88	336147.69	330100.06	333706.88	331710.56	422787.88
			15	290313.31	245497.25	243312.83	244191.50	251368.55	246248.06	244191.50	247063.52	334950.78
			25	243270.33	212250.66	210165.23	211072.61	214500.88	209431.89	211072.61	213535.48	288983.56
			35	207500.06	176487.97	178195.66	178817.53	178021.67	173615.34	179011.69	181723.59	245217.20
	2	45	5	179498.03	175762.48	178899.94	179190.50	178622.42	173383.14	178047.27	175535.62	228146.14
			15	144611.30	130029.92	132155.31	132770.78	131928.34	126944.75	131290.55	133033.56	183589.53
			25	126107.48	110062.57	111334.59	112901.76	111224.07	106769.23	111123.41	111595.64	155861.59
			35	164506.98	122680.94	122964.98	123257.01	124436.44	121152.33	124439.49	126006.31	194152.02
		55	5	217463.92	320504.03	332625.72	333706.88	336147.69	330100.06	333706.88	233390.50	422787.88
			15	181261.66	245497.25	243312.83	244191.50	251368.55	246248.06	244191.50	183898.95	334950.78
			25	160482.69	212250.66	210165.23	211072.61	214500.88	209431.89	211072.61	160973.27	288983.56
			35	207500.06	176487.97	178195.66	178817.53	178021.67	173615.34	179011.69	126006.31	245217.20
	4	45	5	200743.38	193531.09	200860.47	195501.97	200355.05	193468.22	200426.28	207294.77	270931.12
			15	164886.19	144842.73	147681.84	148934.88	147287.00	145665.97	147939.72	153300.70	208980.64
			25	141084.28	122992.38	124967.61	125165.16	124669.20	124156.80	125610.99	129364.23	184300.31
			35	164506.98	122680.94	122964.98	123257.01	124436.44	121152.33	124439.49	126006.31	194152.02
		55	5	252362.88	320504.03	332625.72	333706.88	336147.69	330100.06	333706.88	331710.56	422787.88
			15	206460.50	245497.25	243312.83	244191.50	251368.55	246248.06	244191.50	247063.52	334950.78
			25	177754.62	212250.66	210165.23	211072.61	214500.88	209431.89	211072.61	213535.48	288983.56
			35	207500.06	176487.97	178195.66	178817.53	178021.67	173615.34	179011.69	181723.59	245217.20

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
75000	0	45	5	535369.25	441956.47	439861.09	437209.00	445946.00	422238.38	445994.22	435932.97	625607.12
			15	424577.09	319800.62	320087.00	320181.75	320338.12	312183.62	323570.31	320674.94	484821.84
			25	356356.97	271793.06	274220.16	274140.28	274799.94	266969.22	274214.19	276229.62	418526.47
			35	309440.62	231617.09	230448.39	235091.06	230595.83	228383.36	234752.75	236889.62	363589.09
		55	5	660240.31	594770.75	615584.62	598677.69	604484.75	591778.56	598677.69	605620.12	773268.69
			15	531861.50	451972.00	461777.00	459652.38	467163.12	452357.62	459652.38	468479.66	614141.12
			25	449185.09	392263.97	393433.41	395050.59	394477.56	386937.16	395050.59	396022.12	531354.69
			35	390027.56	331828.81	333564.16	334856.12	333244.38	324587.69	336356.25	342795.59	460044.12
	2	45	5	325252.38	308332.88	309817.47	310656.78	309490.34	313328.75	321523.09	316805.38	414008.06
			15	263170.81	238922.42	244124.89	245196.25	243814.53	234347.14	242825.34	246297.44	331581.34
			25	232904.66	203063.31	207311.23	208078.62	207145.83	198893.61	206003.95	207991.16	288399.25
			35	309440.62	231617.09	230448.39	235091.06	230595.83	228383.36	234752.75	236889.62	363589.09
		55	5	397682.88	594770.75	615584.62	598677.69	604484.75	591778.56	598677.69	423872.16	773268.69
			15	330476.62	451972.00	461777.00	459652.38	467163.12	452357.62	459652.38	337470.78	614141.12
			25	296489.50	392263.97	393433.41	395050.59	394477.56	386937.16	395050.59	294135.97	531354.69
			35	390027.56	331828.81	333564.16	334856.12	333244.38	324587.69	336356.25	236889.62	460044.12
	4	45	5	367407.44	351680.72	354844.12	355849.47	354126.34	352522.84	353739.06	377381.16	496140.53
			15	295251.28	258584.81	264609.91	266789.25	263836.00	256819.16	259663.06	275269.34	378808.50
			25	258901.83	223671.50	227550.45	229662.52	226986.61	225141.11	225820.86	238073.06	337796.72
			35	309440.62	231617.09	230448.39	235091.06	230595.83	228383.36	234752.75	236889.62	363589.09
		55	5	463244.16	594770.75	615584.62	598677.69	604484.75	591778.56	598677.69	605620.12	773268.69
			15	371416.34	451972.00	461777.00	459652.38	467163.12	452357.62	459652.38	468479.66	614141.12
			25	327783.31	392263.97	393433.41	395050.59	394477.56	386937.16	395050.59	396022.12	531354.69
			35	390027.56	331828.81	333564.16	334856.12	333244.38	324587.69	336356.25	342795.59	460044.12
100000	0	45	5	855774.75	679423.56	677868.12	687261.31	678010.75	676222.69	710359.06	695435.25	994009.12
			15	677515.25	506192.66	511700.50	511487.03	511876.41	500010.97	512052.22	512731.69	774898.00
			25	571524.94	437502.62	438590.28	439765.78	441291.44	430200.34	445527.16	445670.84	673363.50
			35	500916.41	375711.16	372271.31	381155.47	372572.06	362212.84	380630.62	383709.38	588554.00
		55	5	1055576.38	950964.88	981916.88	957896.62	967297.50	946253.38	957896.62	968738.88	1237937.88
			15	848037.62	722138.88	736930.50	734788.62	745931.19	722459.38	734788.62	747683.75	979699.75
			25	719486.19	617334.75	625053.88	628527.00	645376.19	628012.56	628527.00	646068.38	850145.06
			35	631110.19	537022.88	538489.44	540691.81	537978.50	523630.50	544152.00	555556.50	743606.06

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
100000	2	45	5	513411.56	488370.03	511400.44	500708.12	510769.09	498829.03	508834.38	502039.00	656427.19
			15	417974.94	380869.97	389194.66	390755.50	388723.72	375263.12	387096.22	393065.28	528595.94
			25	373107.34	325109.31	331843.81	331074.75	331628.12	318605.91	332571.12	333469.59	466611.00
			35	500916.41	375711.16	372271.31	381155.47	372572.06	362212.84	380630.62	383709.38	588554.00
		55	5	636271.69	950964.88	981916.88	957896.62	967297.50	946253.38	957896.62	672394.19	1237937.88
			15	525442.88	722138.88	736930.50	734788.62	745931.19	722459.38	734788.62	537439.00	979699.75
			25	475059.62	617334.75	625053.88	628527.00	645376.19	628012.56	628527.00	470576.62	850145.06
			35	631110.19	537022.88	538489.44	540691.81	537978.50	523630.50	544152.00	383709.38	743606.06
	4	45	5	585485.19	557884.00	564633.44	565231.00	563487.25	559425.56	561346.38	598425.12	782622.12
			15	466709.72	412032.69	416362.81	419729.25	415081.62	404157.50	408645.53	433700.25	600220.69
			25	413214.66	357738.94	361522.50	364758.47	360607.38	357190.47	359150.72	379110.69	538750.81
			35	500916.41	375711.16	372271.31	381155.47	372572.06	362212.84	380630.62	383709.38	588554.00
		55	5	739477.88	950964.88	981916.88	957896.62	967297.50	946253.38	791791.69	968738.88	1237937.88
			15	588660.25	722138.88	736930.50	734788.62	745931.19	722459.38	590008.00	747683.75	979699.75
			25	524202.97	617334.75	625053.88	628527.00	645376.19	628012.56	517567.31	646068.38	850145.06
			35	631110.19	537022.88	538489.44	540691.81	537978.50	523630.50	544152.00	555556.50	743606.06

Appendix D. Divided Rural Arterial Accident Costs

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
1000	0	45	5	14362.02	9318.34	9479.32	9551.30	9345.82	9574.52	9365.70	10010.30	15464.35
			10	13762.63	8759.86	8220.41	8289.67	8237.30	7886.73	8648.01	8061.53	13261.88
			15	11624.19	7327.68	7247.29	7122.43	7579.31	6866.49	7398.46	7482.59	12052.29
			20	9823.21	6394.96	6705.25	6692.36	6554.82	5762.73	6048.27	6594.99	10980.59
			35	8436.00	5306.88	5358.65	5131.49	5511.24	5263.27	5416.13	5203.89	8571.74
		55	5	18599.76	13581.08	13903.55	13398.05	13068.42	12484.20	13147.54	14122.00	19442.86
			10	15675.98	10888.85	11491.52	11842.68	11775.92	12256.76	11601.70	11096.24	17095.56
			15	14766.88	10492.05	10049.39	10659.07	9760.35	9909.46	9858.34	10230.28	15611.73
			20	12133.29	8428.40	9303.11	9784.18	9266.43	9010.84	9053.02	9810.77	10980.59
			35	10412.58	7268.77	7252.20	7166.48	7917.66	7159.55	7385.96	7232.67	8571.74
	3	45	5	14429.45	9525.11	9918.24	9840.83	10080.90	8874.29	9767.51	9058.54	7772.11
			10	13699.96	8594.10	8739.64	8249.74	8376.72	8244.67	8092.27	8472.00	7006.63
			15	11378.06	6922.86	6967.61	7429.45	7632.72	6874.04	7372.38	7077.71	6010.86
			20	9831.64	6289.57	6764.60	6322.92	6653.04	6073.02	6876.05	6048.56	10980.59
			35	8046.20	5023.97	5197.13	5162.32	4853.22	5247.30	4941.37	4998.01	8571.74
		55	5	17820.44	12657.76	13665.91	12331.24	13312.87	12529.68	13598.28	13450.65	10184.28
			10	16253.34	11253.44	11560.59	11863.80	11524.49	10964.44	11534.19	11685.11	9057.68
			15	15418.79	10560.91	9984.18	9745.66	10340.27	10198.98	9911.77	10191.20	7826.28
			20	13251.41	9181.84	9426.83	8740.51	9512.35	8611.40	9404.62	9268.68	10980.59
			35	10645.18	7549.30	7444.43	7363.35	7122.40	7412.42	7418.12	7344.94	8571.74
	6	45	5	14989.72	9644.69	10259.42	9314.27	10096.27	9417.12	8871.09	9596.32	12264.57
			10	13193.79	8229.04	8089.78	8401.26	8304.68	8063.69	8004.17	8879.17	10855.74
			15	11149.88	7131.52	7477.49	7403.03	7041.20	6848.15	7159.73	7693.63	12052.29
			20	10069.22	6279.21	6836.67	6154.88	6714.71	6131.74	6723.04	6458.57	10980.59
			35	9069.06	5665.70	5350.78	5645.83	5261.87	5272.73	5248.43	5433.45	8571.74
		55	5	18045.60	12894.46	13754.58	13905.20	13784.39	13681.30	13065.84	13681.51	15891.32
			10	16991.11	11283.46	11118.51	11576.76	11214.99	10992.62	11622.16	10813.56	14388.78
			15	14643.25	10186.59	10338.70	10077.06	10134.06	8964.38	9765.04	10306.21	12714.20
			20	13123.71	9086.29	8555.00	8904.94	8924.53	9250.99	9596.16	8690.47	10980.59
			35	10550.74	7435.83	7557.20	7628.39	7472.08	7323.89	7470.34	7384.45	8571.74

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
5000	0	45	5	44655.02	28244.82	27608.97	28079.75	28358.54	28615.99	27194.73	28100.93	45822.24
			10	38640.70	24293.39	23973.76	25590.00	22886.09	24339.68	25184.82	23535.75	39296.13
			15	33348.48	20889.75	20484.79	22949.69	20776.78	21115.82	20941.52	22053.88	35712.02
			20	30221.47	18511.24	19247.41	19023.62	19951.13	18548.81	20243.62	18248.70	10980.59
			35	23785.10	15111.70	16127.74	15439.13	15168.38	15216.40	15466.12	15049.64	8571.74
		55	5	54746.79	38095.19	40224.25	39237.57	38273.67	36706.00	39297.39	37396.82	57610.92
			10	47692.28	32278.65	36002.48	33386.12	33872.32	34771.72	35198.70	35575.05	50655.68
			15	42194.10	29826.88	29812.41	29236.63	29668.07	29231.10	29570.35	30826.58	46258.94
			20	38263.64	25945.83	27299.96	27303.59	26919.78	25479.90	25308.96	27488.06	10980.59
			35	30559.74	21179.11	20269.32	21921.21	22039.45	21230.75	21690.47	22591.72	8571.74
	3	45	5	43705.96	28586.34	27682.63	26926.39	25540.76	27573.56	29087.02	29149.72	23029.47
			10	39361.77	24797.94	25042.76	24299.39	25973.97	24231.33	25707.84	24198.74	20761.27
			15	34625.40	22296.97	20352.04	21232.24	21536.20	19744.10	20789.25	21983.82	17810.72
			20	30228.31	18999.35	17958.19	18802.68	18524.62	19326.06	19122.36	18480.28	10980.59
			35	24628.36	16033.15	15999.31	15101.64	15241.42	15803.37	15919.27	16178.56	8571.74
		55	5	55159.50	38902.36	39859.71	40373.94	39176.78	39993.93	41129.07	40719.90	30176.92
			10	51011.00	36442.64	33917.09	35016.28	34254.76	34897.29	34264.28	35677.35	26838.72
			15	43229.17	29669.97	30287.67	30033.88	30784.07	29325.64	31869.22	30088.91	23189.96
			20	37643.16	26276.54	26511.10	26915.67	27750.52	25672.21	26179.45	27711.28	10980.59
			35	31897.18	22035.81	22024.04	22166.42	22134.89	20736.71	21314.89	21892.79	8571.74
	6	45	5	45113.53	28342.88	28154.14	28636.63	29880.47	28336.82	28569.17	28847.20	36341.02
			10	36593.35	23239.58	24829.72	22766.29	24660.01	25377.90	25352.01	25048.33	32166.53
			15	33952.04	20276.89	22097.61	21350.87	21393.34	21450.11	21957.40	21561.55	35712.02
			20	30597.44	18579.36	18927.02	19102.43	18763.58	18824.19	19589.36	19514.02	10980.59
			35	23817.97	14849.58	15012.88	15354.69	15069.44	15469.62	16201.03	14918.85	8571.74
		55	5	55374.84	39785.98	39052.60	39240.02	37517.92	37318.35	38076.93	39330.96	47087.41
			10	48092.40	35021.76	34932.27	34743.74	35314.14	32579.55	33777.00	35619.95	42635.24
			15	41929.12	29358.55	29388.90	29421.20	29914.23	29211.81	30344.66	29657.10	37673.32
			20	39889.67	27802.31	25628.75	27183.19	26731.10	26575.59	27496.72	28464.35	10980.59
			35	30026.96	20972.87	21535.82	22514.82	21065.50	20590.87	21150.95	20537.36	8571.74

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
10000	0	45	5	53997.93	33914.67	34799.43	37276.79	34953.88	36454.53	38847.84	37490.34	57734.98
			10	47930.86	30931.78	29474.21	29952.66	29945.21	29889.47	31841.00	32788.06	49512.23
			15	42680.65	27346.05	26264.06	25863.75	27211.71	26621.22	28253.17	26237.53	44996.33
			20	38094.45	23738.38	24832.27	25699.71	24107.46	23311.07	25010.86	25847.46	10980.59
			35	31411.02	19457.62	20075.90	19286.72	20065.77	19241.64	19084.25	20977.82	8571.74
		55	5	69295.27	49603.18	52696.68	51532.27	49912.17	48944.88	50907.17	50634.55	72588.45
			10	61952.98	42680.36	43873.64	41729.42	43878.96	42725.42	43744.27	44117.50	63825.00
			15	52688.39	37138.88	38662.30	39053.14	35321.91	37121.62	36584.30	37336.91	58285.21
			20	48693.75	33451.88	34044.90	36047.52	33403.78	33629.43	35070.11	33921.77	10980.59
			35	38676.77	27210.61	27531.88	26514.71	28002.60	26341.20	27601.25	29688.51	8571.74
	3	45	5	52774.93	33560.73	33780.39	39441.03	37189.14	33828.34	36189.43	36297.28	29016.61
			10	48697.93	31033.31	30908.30	31460.08	31266.99	28717.17	31884.62	30828.06	26158.73
			15	41650.48	26366.90	26220.92	28817.59	26784.85	25806.53	26928.60	26274.52	22441.10
			20	39697.87	25510.12	25403.30	24118.42	24024.82	24338.52	23314.54	23166.67	10980.59
			35	31354.73	19860.19	21085.04	19264.07	20181.23	18589.96	18871.45	19323.09	8571.74
		55	5	67959.10	50325.59	50709.80	48150.62	50030.32	47143.85	50208.66	49124.01	38022.23
			10	60101.46	42918.04	43572.84	43919.67	43346.58	43560.23	44932.43	46914.44	33816.18
			15	54152.42	36624.53	38299.56	37898.34	37100.20	36929.86	38122.42	38700.95	29218.82
			20	47833.07	32843.16	34635.65	33807.70	34011.67	33500.74	34263.17	34547.52	10980.59
			35	38018.74	26287.03	27427.17	27968.92	28793.78	27317.91	26167.27	27730.05	8571.74
	6	45	5	54478.62	32849.23	35965.20	34743.68	36486.37	34255.91	36299.65	34495.88	45788.84
			10	46805.21	29460.68	31287.83	28823.61	30634.28	30584.17	30055.06	30263.79	40529.09
			15	41952.76	26612.33	26241.63	28163.27	26445.45	25444.56	27588.39	26533.12	44996.33
			20	38660.00	24119.96	25196.42	24696.92	24659.21	22899.17	22986.43	23988.51	10980.59
			35	31760.28	20034.61	19448.14	19083.16	19964.39	18809.80	20554.88	20722.53	8571.74
		55	5	69619.70	49005.62	50280.55	50096.38	51355.92	48367.98	48673.60	49479.24	59329.06
			10	64051.39	44521.36	45794.25	43745.21	44527.35	42367.42	43981.03	42088.46	53719.43
			15	51188.38	35453.82	38535.11	39579.86	37192.30	37586.64	37746.54	35580.73	47467.52
			20	49857.70	34394.10	35494.63	34069.23	32565.20	32781.62	33019.05	36494.53	10980.59
			35	40481.38	27235.95	25183.69	27679.83	28315.78	25999.56	26160.46	29326.19	8571.74

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
20000	0	45	5	95888.45	59423.98	62516.62	59197.03	60711.61	62743.43	61090.53	59718.24	97119.92
			10	78051.69	50106.14	53056.22	51542.79	54315.36	46629.16	51002.88	50208.15	83287.88
			15	72668.47	46080.11	42985.13	44399.75	47221.35	41323.68	45700.89	44754.25	75691.38
			20	63617.46	41175.24	40402.44	40731.13	41683.36	41105.04	40350.40	41575.55	10980.59
			35	50874.84	31483.27	33246.65	33063.51	33200.89	31175.75	31976.59	32054.60	8571.74
		55	5	114356.68	81504.17	86630.16	86651.80	81830.81	81392.73	82181.94	78261.29	122105.95
			10	100566.57	70445.66	70182.21	71451.05	70858.30	66637.28	71263.25	72090.95	107364.36
			15	92176.98	65172.59	62376.51	62873.97	64293.16	61979.16	63521.20	63968.27	98045.50
			20	78310.45	54263.84	57700.14	59264.11	56254.53	54845.85	58603.28	58437.55	10980.59
			35	62393.09	44637.88	45795.51	49636.43	45809.50	44957.71	46610.38	49474.20	8571.74
	3	45	5	96397.43	60724.18	62765.21	59703.21	60392.42	61987.97	56482.95	61882.08	48810.80
			10	79294.59	50731.43	52007.03	48413.54	52211.62	52249.29	55098.11	53210.18	44003.37
			15	72081.70	44249.71	43619.86	44506.65	47566.38	45128.57	46740.75	41678.86	37749.69
			20	68485.53	42799.98	40960.75	41790.18	40364.61	39338.85	42156.04	41880.71	10980.59
			35	50434.05	31004.21	33257.02	32146.99	33207.60	30577.77	32090.16	33092.26	8571.74
		55	5	119432.37	84629.50	84333.18	84173.87	82283.42	80570.01	86529.04	89386.84	63959.77
			10	104186.86	71680.77	72189.98	70418.35	70198.61	73228.02	75252.02	75706.44	56884.49
			15	90357.99	62637.67	62649.15	65409.99	62811.44	62313.68	60138.63	64983.31	49150.96
			20	81314.59	55550.21	58076.13	59753.05	57207.56	57633.88	58934.18	58216.67	10980.59
			35	65703.66	44741.76	48030.53	46529.82	44925.89	46504.17	44294.39	47705.11	8571.74
	6	45	5	92994.58	60015.65	64306.33	58355.03	61523.72	53623.26	62336.37	59576.13	77024.52
			10	80614.95	51895.03	50815.03	51426.29	50758.00	52168.53	52022.23	51019.82	68176.73
			15	69654.49	43702.66	43494.41	46238.44	44789.91	40736.92	45754.30	45899.20	75691.38
			20	65666.70	39810.33	40739.68	44019.00	40290.88	39707.62	42360.94	43579.90	10980.59
			35	52697.22	32815.13	31744.75	35317.64	33431.79	31737.02	34483.16	34866.07	8571.74
		55	5	114754.47	78816.26	83381.17	79484.56	85685.02	83793.91	82087.12	81796.76	99801.44
			10	103869.69	72641.73	71998.54	68162.43	70620.68	72649.48	73439.54	76531.42	90365.09
			15	89767.76	64265.70	60753.80	65832.27	62752.60	64161.39	61728.79	67050.45	79848.34
			20	85742.83	59203.85	60367.11	57261.26	58299.37	56479.80	57850.44	60194.15	10980.59
			35	67673.95	45621.98	46208.16	46449.00	47924.71	44944.62	47417.18	47336.20	8571.74

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
30000	0	45	5	139573.98	89172.55	90341.71	88889.62	94079.30	88887.20	86422.06	92539.56	148385.84
			10	117653.92	74997.82	75429.45	83916.10	83521.67	75830.72	82071.33	81509.80	127252.36
			15	103993.51	67689.62	69660.88	72375.22	70032.06	70590.33	72033.25	66690.61	115645.97
			20	90409.38	56983.86	62106.55	63156.59	65208.38	61431.51	63587.70	62092.81	10980.59
			35	76964.35	48473.61	50540.97	49363.54	48548.34	48681.62	48052.34	52516.24	8571.74
		55	5	177610.45	126267.59	121977.78	122153.88	128396.23	127021.84	131715.88	135505.58	186561.05
			10	160160.69	110460.89	116078.30	106169.19	108142.13	103741.77	115362.39	111384.18	164037.92
			15	140180.42	95318.62	96356.39	101472.21	104051.72	94933.23	93843.96	100491.57	149800.02
			20	126670.94	86933.58	92479.93	86252.98	84821.51	87062.38	87449.42	88399.72	10980.59
			35	100612.69	69421.62	70255.76	70331.95	72995.99	63702.38	68728.38	69186.58	8571.74
	3	45	5	140332.45	90696.09	89202.10	92968.65	95956.57	92012.59	90139.04	87641.03	74576.16
			10	123097.67	79174.88	81399.80	78695.27	79990.93	75203.60	81338.64	74258.45	67231.08
			15	106887.94	65369.84	68094.38	66186.96	72916.73	62899.56	67238.44	66990.06	57676.32
			20	92656.97	60006.18	63697.82	66407.07	61519.34	62184.41	58726.79	62384.82	10980.59
			35	78794.67	49928.63	49626.14	49448.89	49264.52	47015.17	53408.66	50616.41	8571.74
		55	5	179266.59	122087.91	136102.45	125983.12	129887.93	121742.17	128606.71	133408.05	97721.70
			10	153307.91	106414.48	112402.00	110790.16	106847.24	103362.55	114192.68	120456.03	86911.65
			15	135063.94	94776.41	95426.77	93652.82	95917.57	95441.80	98908.77	101217.07	75095.88
			20	119348.17	81740.69	87331.99	85555.46	89852.44	83784.95	89689.88	86969.79	10980.59
			35	103172.62	71844.84	71049.04	69986.25	71119.71	68601.51	67921.62	74394.42	8571.74
	6	45	5	145218.45	92543.53	93619.50	95280.56	89333.60	90543.30	89450.70	91691.10	117682.83
			10	126709.22	80350.65	80517.23	82622.72	73230.30	77665.96	75356.26	79141.01	104164.62
			15	119829.98	74732.51	69938.98	69824.77	72166.46	67571.81	68525.13	69041.88	115645.97
			20	97154.88	60028.69	62253.09	61301.43	62013.45	62686.94	63152.96	63875.96	10980.59
			35	78952.00	49135.29	49339.14	50121.12	51241.81	47173.48	50266.59	48760.69	8571.74
		55	5	191273.27	133649.70	125819.45	126295.70	132988.83	129863.12	127783.34	130011.62	152482.80
			10	160627.50	111245.39	115347.86	111371.31	112108.66	109987.70	111576.50	111451.88	138065.38
			15	136950.67	97260.62	97604.40	94056.95	94552.88	91678.07	97543.34	96501.52	121997.21
			20	121899.55	85091.12	93086.02	88799.16	91390.96	87423.55	87896.65	92725.91	10980.59
			35	98759.72	68849.55	70978.07	65736.25	66701.55	68612.01	71866.95	71207.03	8571.74

Appendix E. Undivided Rural Arterial Accident Costs

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
1000	0	45	5	10092.72	7938.33	7786.42	7777.44	7793.66	7743.68	8759.99	7758.75	10016.54
			10	7185.65	5609.24	5424.83	5410.78	5434.93	5398.65	6169.37	5299.36	7116.85
			15	5075.51	3695.27	3621.01	3607.31	3620.97	3613.97	4240.81	3598.96	5051.13
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	12411.66	10225.09	10227.38	10217.66	9742.66	10151.87	10210.17	10234.25	12554.49
			10	8980.99	7256.11	7217.67	7202.48	6871.99	5398.65	7202.67	7131.12	9058.08
			15	6449.90	5024.07	5001.98	4996.49	4736.06	3613.97	4996.88	5007.31	6555.43
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	3	45	5	4739.85	3918.41	3897.73	3896.55	3895.79	3882.22	4304.36	3901.40	4845.10
			10	3662.26	3011.85	2982.96	2986.49	2982.71	2997.64	3333.84	3002.58	3689.33
			15	2566.35	2114.05	2094.32	2094.65	2094.68	2084.26	2303.22	2088.88	2577.90
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	5942.77	5134.47	5116.53	5116.96	4826.13	5147.60	5118.74	5210.46	6309.28
			10	4525.43	3900.64	3899.82	3908.10	3697.67	3908.87	3908.40	3936.54	4641.97
			15	3189.53	2723.96	2721.84	2726.30	2589.15	2718.59	2726.99	2739.49	3264.27
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	6	45	5	8058.81	6696.29	6573.41	6566.43	6576.85	6613.83	7199.36	6543.84	8412.67
			10	5647.32	4950.84	4865.59	4814.58	4867.36	4808.44	5390.53	4764.07	5995.12
			15	4126.84	3499.39	3414.95	3415.86	3414.44	3464.05	3805.55	3432.68	4206.73
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	9958.64	8445.22	8422.07	8419.29	8067.09	8427.77	8422.06	8604.41	10633.73
			10	7105.19	6195.91	6233.82	6282.32	6114.80	6395.33	6286.46	6390.36	7453.03
			15	5119.88	4568.59	4619.16	4622.05	4302.37	4578.57	4624.45	4653.27	5385.67
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
5000	0	45	5	28684.56	22561.56	22129.82	22104.29	22150.41	22008.35	24896.80	22051.17	28468.06
			10	20422.37	15942.06	15417.94	15377.99	15446.63	15343.54	17534.00	15061.35	20226.84
			15	14425.14	10502.34	10291.29	10252.34	10291.19	10271.27	12052.84	10228.63	14355.83
			20	3569.68	2517.17	2477.63	3422.03	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	879.61	646.33	641.78	744.28	649.69	878.06
		55	5	35275.23	29060.78	29067.27	2469.06	27689.65	28852.67	29018.38	29086.82	35681.17
			10	25524.92	20622.63	20513.39	645.66	19530.93	20356.98	20470.74	20267.39	25744.01
			15	18331.29	14278.95	14216.15	3422.03	13460.37	14224.80	14201.64	14231.31	18631.23
			20	3569.68	2517.17	2477.63	879.61	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	879.61	646.33	641.78	744.28	649.69	878.06
	3	45	5	13471.15	11136.53	11077.76	11074.42	11072.24	11033.67	12233.43	11088.18	13770.29
			10	10408.52	8560.00	8477.89	8487.91	8477.17	8519.60	9475.11	8533.64	10485.47
			15	7293.83	6008.35	5952.28	5953.21	5953.31	5923.69	6545.99	5936.82	7326.66
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	16889.99	14592.69	14541.72	14542.95	13716.37	14630.03	14548.01	14808.68	17931.62
			10	12861.75	11086.01	11083.71	11107.22	10509.17	11109.41	11108.07	11188.05	13192.96
			15	9064.99	7741.79	7735.77	7748.42	7358.62	7726.52	7750.38	7785.92	9277.40
			20	3569.68	2517.17	2477.63	3422.03	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	879.61	646.33	641.78	744.28	649.69	878.06
	6	45	5	22903.98	19031.56	18682.33	18662.49	18692.10	18797.21	20461.32	18598.27	23909.69
			10	16050.27	14070.80	13828.51	13683.54	13833.54	13666.09	15320.45	13540.00	17038.77
			15	11728.91	9945.64	9705.66	9708.24	9704.19	9845.19	10815.77	9756.03	11955.97
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	28303.51	24002.19	23936.39	23928.49	22927.53	23952.61	23936.38	24454.63	30222.17
			10	20193.69	17609.43	17717.18	17855.01	17378.89	18176.20	17866.79	18162.06	21182.29
			15	14551.24	12984.40	13128.14	13136.35	12227.80	13012.78	13143.18	13225.09	15306.63
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
10000	0	45	5	20008.37	15737.38	15436.23	15418.42	15450.59	15351.50	17366.28	15381.37	19857.34
			10	14245.23	11120.08	10754.49	10726.62	10774.50	10702.59	12230.50	10505.75	14108.84
			15	10061.98	7325.71	7178.49	7151.32	7178.42	7164.53	8407.22	7134.79	10013.63
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	24605.56	20270.79	20275.32	20256.06	19314.38	20125.63	20241.21	20288.95	24888.71
			10	17804.41	14384.92	14308.72	14278.59	13623.42	14199.62	14278.97	14137.12	17957.23
			15	12786.64	9960.00	9916.20	9905.31	9389.02	9922.23	9906.08	9926.77	12995.85
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	3	45	5	9396.54	7768.08	7727.08	7724.75	7723.23	7696.32	8533.20	7734.35	9605.20
			10	7260.26	5970.87	5913.59	5920.58	5913.08	5942.68	6609.18	5952.47	7313.94
			15	5087.67	4191.01	4151.90	4152.54	4152.62	4131.95	4566.03	4141.11	5110.57
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	11781.29	10178.85	10143.30	10144.15	9567.59	10204.90	10147.68	10329.51	12507.86
			10	8971.46	7732.84	7731.23	7747.63	7330.47	7749.15	7748.22	7804.01	9202.50
			15	6323.11	5400.14	5395.94	5404.76	5132.87	5389.48	5406.13	5430.92	6471.27
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	6	45	5	15976.23	13275.10	13031.50	13017.66	13038.32	13111.63	14272.40	12972.87	16677.74
			10	11195.55	9814.82	9645.81	9544.69	9649.32	9532.52	10686.48	9444.56	11885.07
			15	8181.27	6937.39	6769.99	6771.80	6768.97	6867.32	7544.33	6805.13	8339.66
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	19742.57	16742.27	16696.37	16690.86	15992.66	16707.68	16696.36	17057.86	21080.89
			10	14085.72	12283.12	12358.28	12454.42	12122.31	12678.46	12462.64	12668.60	14775.29
			15	10149.94	9057.02	9157.28	9163.01	8529.27	9076.82	9167.77	9224.91	10676.84
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
20000	0	45	5	27090.98	21308.15	20900.39	20876.28	20919.84	20785.67	23513.65	20826.11	26886.50
			10	19287.80	15056.39	14561.39	14523.66	14588.49	14491.12	16559.89	14224.61	19103.13
			15	13623.75	9918.88	9719.56	9682.77	9719.46	9700.65	11383.24	9660.38	13558.29
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	33315.51	27446.30	27452.43	27426.36	26151.34	27249.75	27406.25	27470.89	33698.89
			10	24106.87	19476.94	19373.76	19332.96	18445.88	19226.04	19333.48	19141.43	24313.79
			15	17312.89	13485.68	13426.37	13411.62	12712.58	13434.54	13412.67	13440.68	17596.17
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	3	45	5	12722.76	10517.84	10462.33	10459.17	10457.12	10420.69	11553.80	10472.17	13005.27
			10	9830.27	8084.45	8006.90	8016.36	8006.21	8046.29	8948.72	19141.43	9902.95
			15	6888.62	5674.55	5621.60	5622.47	5622.57	5594.59	6182.33	13440.68	6919.63
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	15951.66	13781.99	13733.85	13735.01	12954.35	13817.25	13739.79	13985.98	16935.43
			10	12147.21	10470.13	10467.95	10490.16	9925.32	10492.22	10490.96	10566.49	12460.02
			15	8561.38	7311.70	7306.01	7317.96	6949.81	7297.27	7319.80	7353.37	8761.99
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	6	45	5	21631.54	17974.26	17644.43	17625.69	17653.66	17752.93	19324.59	17565.04	22581.38
			10	15158.59	13289.10	13060.26	12923.35	13065.02	12906.87	14469.32	12787.78	16092.18
			15	11077.30	9393.11	9166.46	9168.90	9165.07	9298.24	10214.90	9214.03	11291.75
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	26731.10	22668.74	22606.60	22599.14	21653.79	22621.91	22606.59	23096.05	28543.17
			10	19071.82	16631.14	16732.90	16863.07	16413.40	17166.41	16874.20	17153.07	20005.50
			15	13742.84	12263.05	12398.80	12406.56	11548.48	12289.85	12413.01	12490.37	14456.26
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
30000	0	45	5	34173.60	26878.91	26364.55	26334.14	26389.08	26219.84	29661.01	26270.85	33915.66
			10	24330.36	18992.71	18368.29	18320.70	18402.48	18279.65	20889.28	17943.46	24097.42
			15	17185.52	12512.05	12260.62	12214.21	12260.50	12236.77	14359.25	12185.97	17102.94
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	42025.45	34621.81	34629.54	34596.65	32988.30	34373.88	34571.29	34652.82	42509.07
			10	30409.33	24568.95	24438.80	24387.34	23268.34	24252.46	24387.99	24145.72	30670.34
			15	21839.13	17011.35	16936.53	16917.93	16036.13	16946.84	16919.25	16954.59	22196.47
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	3	45	5	16048.97	13267.60	13197.58	13193.60	13191.01	13145.05	14574.40	13210.00	16405.35
			10	12400.28	10198.03	10100.21	10112.14	10099.34	10149.90	11288.25	10166.62	12491.96
			15	8689.57	7158.09	7091.30	7092.40	7092.53	7057.23	7798.62	7072.88	8728.68
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	20122.03	17385.12	17324.40	17325.86	16341.11	17429.61	17331.89	17642.45	21362.99
			10	15322.95	13207.42	13204.67	13232.68	12520.18	13235.28	13233.70	13328.98	15717.54
			15	10799.65	9223.25	9216.07	9231.15	8766.76	9205.05	9233.48	9275.82	11052.71
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
	6	45	5	27286.85	22673.42	22257.35	22233.72	22269.00	22394.22	24376.77	22157.21	28485.01
			10	19121.62	16763.37	16474.71	16302.01	16480.71	16281.21	18252.15	16130.99	20299.29
			15	13973.33	11848.83	11562.92	11566.00	11561.17	11729.15	12885.46	11622.93	14243.84
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06
		55	5	33719.63	28595.21	28516.83	28507.41	20092.26	28536.14	28516.82	29134.23	36005.44
			10	24057.92	20979.15	21107.51	21271.72	14831.72	21654.37	21285.76	21637.53	25235.70
			15	17335.75	15469.08	15640.32	15650.11	10538.91	15502.89	15658.24	15755.83	18235.68
			20	3569.68	2517.17	2477.63	2469.06	2477.45	2470.56	3004.19	2459.59	3554.15
			35	880.45	655.05	646.19	645.66	646.33	641.78	744.28	649.69	878.06

Appendix F. Local Highway Accident Costs

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
200	0	35	5	1135.68	703.73	700.97	701.23	700.92	683.76	707.35	693.35	1100.09
			10	832.87	504.68	502.24	497.81	501.95	483.19	502.16	479.78	801.12
			15	584.41	328.14	334.38	334.68	334.17	329.50	335.28	332.11	585.79
			20	425.53	227.11	228.13	228.18	228.15	224.30	228.79	344.31	399.50
			35	106.01	59.73	60.12	60.16	60.12	58.78	59.96	88.43	103.34
		45	5	1816.54	1266.19	1267.58	1268.38	1267.53	1244.84	1264.93	1258.10	1795.10
			10	1355.22	913.19	931.53	922.32	927.74	906.89	917.05	904.69	1331.61
			15	1007.13	648.29	652.73	653.66	652.21	645.68	653.02	650.35	993.96
			20	700.49	442.88	444.79	445.54	445.28	438.55	446.44	608.37	678.02
			35	179.57	115.46	114.66	114.92	114.66	112.57	114.19	159.85	175.80
		55	5	2390.29	1922.73	1802.46	1843.19	1805.46	1790.29	1843.38	1807.31	2412.02
			10	1781.7	1447.54	1347.57	1345.56	1350.50	1326.66	1345.73	1340.04	1788.41
			15	1335.96	1082.13	992.02	993.90	997.91	982.31	994.07	989.20	1349.07
			20	927.26	664.33	667.28	668.27	667.05	658.30	667.25	883.52	924.92
			35	244.2	172.21	173.37	174.01	173.37	171.10	172.53	220.77	241.62
	5	35	5	931.83	577.27	592.42	701.23	592.00	575.83	707.35	693.35	1100.09
			10	635.77	435.28	421.10	497.81	420.57	416.45	502.16	479.78	801.12
			15	454.46	295.08	308.22	334.68	307.83	293.76	335.28	332.11	585.79
			20	425.53	227.11	228.13	228.18	228.15	224.30	228.79	344.31	399.50
			35	106.01	59.73	60.12	60.16	60.12	58.78	59.96	88.43	103.34
		45	5	1485.22	1043.00	1267.58	1268.38	1056.68	1244.84	1264.93	1258.10	1795.10
			10	1014.76	785.37	931.53	922.32	802.15	906.89	917.05	904.69	1331.61
			15	778.18	583.38	652.73	653.66	567.14	645.68	653.02	650.35	993.96
			20	700.49	442.88	444.79	445.54	445.28	438.55	446.44	608.37	678.02
			35	179.57	115.46	114.66	114.92	114.66	112.57	114.19	159.85	175.80
		55	5	1963.39	1705.95	1802.46	1843.19	1614.97	1790.29	1843.38	1807.31	2412.02
			10	1333.27	1207.94	1347.57	1345.56	1350.50	1326.66	1345.73	1340.04	1788.41
			15	1040.88	858.73	992.02	993.90	866.82	982.31	994.07	989.20	1349.07
			20	927.26	664.33	667.28	668.27	667.05	658.30	667.25	883.52	924.92
			35	244.2	172.21	173.37	174.01	173.37	171.10	172.53	220.77	241.62

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
200	10	35	5	633.9	389.12	396.20	397.34	395.85	393.22	707.35	693.35	1100.09
			10	494.56	331.09	334.98	328.97	334.53	326.79	502.16	479.78	801.12
			15	318.78	204.77	222.51	224.72	222.33	220.04	335.28	332.11	585.79
			20	425.53	227.11	228.13	228.18	228.15	224.30	228.79	344.31	399.50
			35	106.01	59.73	60.12	60.16	60.12	58.78	59.96	88.43	103.34
		45	5	1005.12	688.56	1267.58	1268.38	696.36	1244.84	1264.93	1258.10	1795.10
			10	784.76	588.89	931.53	922.32	584.07	906.89	917.05	904.69	1331.61
			15	524.7	393.39	652.73	653.66	403.54	645.68	653.02	650.35	993.96
			20	700.49	442.88	444.79	445.54	445.28	438.55	446.44	608.37	678.02
			35	179.57	115.46	114.66	114.92	114.66	112.57	114.19	159.85	175.80
		55	5	1357.34	1167.23	1802.46	1843.19	1068.55	1790.29	1843.38	1807.31	2412.02
			10	1020.09	923.87	1347.57	1345.56	867.30	1326.66	1345.73	1340.04	1788.41
			15	674.75	626.16	992.02	993.90	602.30	982.31	994.07	989.20	1349.07
			20	927.26	664.33	667.28	668.27	667.05	658.30	667.25	883.52	924.92
			35	244.2	172.21	173.37	174.01	173.37	171.10	172.53	220.77	241.62
500	0	35	5	2839.19	1759.33	1752.43	1753.08	1752.30	1709.41	1768.39	1733.36	2750.23
			10	2082.18	1261.70	1255.61	1244.53	1254.86	1207.98	1255.41	1199.45	2002.80
			15	1461.02	820.36	835.96	836.71	835.44	823.74	838.20	830.27	1464.48
			20	425.53	227.11	570.33	570.45	570.38	560.75	571.96	860.77	998.74
			35	106.01	59.73	150.29	150.39	150.29	146.96	149.91	221.08	258.35
		45	5	4541.36	3165.48	3168.95	3170.94	3168.83	3112.10	3162.33	3145.26	4487.75
			10	3388.04	2282.97	2328.82	2305.79	2319.34	2267.22	2292.64	2261.71	3329.02
			15	2517.82	1620.72	1631.82	1634.15	1630.53	1614.20	1632.54	1625.88	2484.90
			20	700.49	442.88	1111.97	1113.84	1113.19	1096.38	1116.10	1520.92	1695.04
			35	179.57	115.46	286.64	287.29	286.64	281.42	285.47	399.62	439.50
		55	5	5975.73	4806.81	4506.15	4607.96	4513.65	4475.72	4608.46	4518.27	6030.05
			10	4454.25	3618.84	3368.94	3363.89	3376.24	3316.65	3364.33	3350.11	4471.02
			15	3339.89	2705.32	2480.04	2484.76	2494.78	2455.78	2485.16	2473.00	3372.67
			20	927.26	664.33	1668.20	1670.67	1667.61	1645.75	1668.13	2208.79	2312.30
			35	244.2	172.21	433.43	435.03	433.43	427.74	431.33	551.92	604.04

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
500	5	35	5	2329.58	1443.18	1481.05	1753.08	1479.99	1439.57	1768.39	1733.36	2750.23
			10	1589.43	1088.21	1052.74	1244.53	1051.42	1041.14	1255.41	1199.45	2002.80
			15	1136.15	737.70	770.55	836.71	769.57	734.39	838.20	830.27	1464.48
			20	425.53	227.11	570.33	570.45	570.38	560.75	571.96	860.77	998.74
			35	106.01	59.73	150.29	150.39	150.29	146.96	149.91	221.08	258.35
		45	5	3713.05	2607.50	3168.95	3170.94	2641.71	3112.10	3162.33	3145.26	4487.75
			10	2536.91	1963.42	2328.82	2305.79	2005.37	2267.22	2292.64	2261.71	3329.02
			15	1945.44	1458.44	1631.82	1634.15	1417.84	1614.20	1632.54	1625.88	2484.90
			20	700.49	442.88	1111.97	1113.84	1113.19	1096.38	1116.10	1520.92	1695.04
			35	179.57	115.46	286.64	287.29	286.64	281.42	285.47	399.62	439.50
		55	5	4908.47	4264.87	4506.15	4607.96	4037.44	4475.72	4608.46	4518.27	6030.05
			10	3333.18	3019.84	3368.94	3363.89	3376.24	3316.65	3364.33	3350.11	4471.02
			15	2602.21	2146.82	2480.04	2484.76	2167.06	2455.78	2485.16	2473.00	3372.67
			20	927.26	664.33	1668.20	1670.67	1667.61	1645.75	1668.13	2208.79	2312.30
			35	244.2	172.21	433.43	435.03	433.43	427.74	431.33	551.92	604.04
	10	35	5	1584.76	972.79	990.50	993.35	989.64	983.06	1768.39	1733.36	2750.23
			10	1236.4	827.72	837.44	822.41	836.32	816.97	1255.41	1199.45	2002.80
			15	796.95	511.93	556.26	561.79	555.82	550.10	838.20	830.27	1464.48
			20	425.53	227.11	570.33	570.45	570.38	560.75	571.96	860.77	998.74
			35	106.01	59.73	150.29	150.39	150.29	146.96	149.91	221.08	258.35
		45	5	2512.79	1721.39	3168.95	3170.94	1740.91	3112.10	3162.33	3145.26	4487.75
			10	1961.9	1472.22	2328.82	2305.79	1460.17	2267.22	2292.64	2261.71	3329.02
			15	1311.75	983.47	1631.82	1634.15	1008.86	1614.20	1632.54	1625.88	2484.90
			20	700.49	442.88	1111.97	1113.84	1113.19	1096.38	1504.24	1520.92	1695.04
			35	179.57	115.46	286.64	287.29	286.64	281.42	392.74	399.62	439.50
		55	5	3393.35	2918.08	4506.15	4607.96	2671.38	4475.72	4608.46	4518.27	6030.05
			10	2550.22	2309.67	3368.94	3363.89	2168.24	3316.65	3364.33	3350.11	4471.02
			15	1686.87	1565.41	2480.04	2484.76	1505.74	2455.78	2485.16	2473.00	3372.67
			20	927.26	664.33	1668.20	1670.67	1667.61	1645.75	2103.22	2208.79	2312.30
			35	244.2	172.21	433.43	435.03	433.43	427.74	538.82	551.92	604.04

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
1000	0	35	5	5394.46	3342.73	3329.62	3330.85	3329.37	3247.88	3359.93	3293.39	5225.44
			10	3956.14	2397.23	2385.66	2364.61	2384.24	2295.17	2385.27	2278.95	3805.33
			15	2775.94	1558.69	1588.32	1589.75	1587.33	1565.11	1592.58	1577.52	2782.52
			20	425.53	227.11	1083.62	1083.85	1083.73	1065.43	1634.40	1635.47	1897.61
			35	106.01	59.73	285.55	285.74	285.55	279.22	418.91	420.06	490.86
		45	5	8628.59	6014.41	6021.01	6024.78	6020.78	5912.99	6008.43	5975.99	8526.72
			10	6437.27	4337.64	4424.76	4381.01	4406.75	4307.73	4356.01	4297.26	6325.13
			15	4783.87	3079.36	3100.46	3104.89	3098.01	3066.97	3101.83	3089.17	4721.30
			20	700.49	442.88	2112.73	2116.30	2115.06	2083.13	2858.05	2889.74	3220.58
			35	179.57	115.46	544.62	545.86	544.62	534.70	746.20	759.28	835.04
		55	5	11353.88	9132.95	8561.68	8755.13	8575.94	8503.86	8756.08	8584.71	11457.10
			10	8463.07	6875.80	6400.98	6391.39	6414.87	6301.63	6392.23	6365.21	8494.93
			15	6345.79	5140.11	4712.08	4721.04	4740.08	4665.98	4721.81	4698.71	6408.08
			20	700.49	442.88	3169.58	3174.27	2115.06	3126.92	3996.11	4196.71	4393.38
			35	244.2	172.21	823.52	826.55	544.62	812.70	1023.76	1048.65	1147.67
	5	35	5	4426.2	2742.05	2814.00	3330.85	2811.99	2735.18	3359.93	3293.39	5225.44
			10	3019.91	2067.60	2000.21	2364.61	1997.70	1978.16	2385.27	2278.95	3805.33
			15	2158.69	1401.64	1464.04	1589.75	1462.19	1395.34	1592.58	512.51	2782.52
			20	425.53	227.11	1083.62	1083.85	1083.73	1065.43	1634.40	1635.47	1897.61
			35	106.01	59.73	285.55	285.74	285.55	279.22	418.91	420.06	490.86
		45	5	7054.8	4954.24	6021.01	6024.78	5019.25	5912.99	6008.43	1966.47	8526.72
			10	4820.13	3730.49	4424.76	4381.01	3810.20	4307.73	4356.01	1342.33	6325.13
			15	3696.33	2771.03	3100.46	3104.89	2693.90	3066.97	3101.83	894.87	4721.30
			20	700.49	442.88	2112.73	2116.30	2115.06	2083.13	2858.05	2889.74	3220.58
			35	179.57	115.46	544.62	545.86	544.62	534.70	746.20	759.28	835.04
		55	5	9326.09	8103.25	8561.68	8755.13	7671.13	8503.86	8756.08	2609.27	11457.10
			10	6333.05	5737.69	6400.98	6391.39	6414.87	6301.63	6392.23	1818.16	8494.93
			15	4944.2	4078.95	4712.08	4721.04	4117.41	4665.98	4721.81	1255.05	6408.08
			20	927.26	664.33	3169.58	3174.27	3168.46	3126.92	3996.11	4196.71	4393.38
			35	244.2	172.21	823.52	826.55	823.52	1021.31	1023.76	1048.65	1147.67

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
1000	10	35	5	3011.04	1848.31	1881.96	1887.37	1880.31	3457.68	3359.93	1123.71	5225.44
			10	2349.15	1572.67	1591.14	1562.59	1589.00	2638.68	2385.27	789.64	3805.33
			15	1514.21	972.66	1056.90	1067.41	1056.06	1875.25	1592.58	512.51	2782.52
			20	425.53	227.11	1083.62	1083.85	1083.73	1609.53	1634.40	1635.47	1897.61
			35	106.01	59.73	285.55	285.74	285.55	412.74	418.91	420.06	490.86
		45	5	4774.3	3270.65	6021.01	6024.78	3307.73	5908.88	6008.43	1966.47	8526.72
			10	3727.62	2797.22	4424.76	4381.01	2774.31	4506.19	4356.01	1342.33	6325.13
			15	2492.32	1868.58	3100.46	3104.89	1916.83	3136.37	3101.83	894.87	4721.30
			20	700.49	442.88	2112.73	2116.30	2115.06	2842.46	2858.05	2889.74	3220.58
			35	179.57	115.46	544.62	545.86	544.62	741.94	746.20	759.28	835.04
		55	5	6447.37	5544.35	8561.68	8755.13	5075.63	7623.20	8756.08	2609.27	11457.10
			10	4845.42	4388.36	6400.98	6391.39	4119.66	6115.90	6392.23	1818.16	8494.93
			15	3205.05	2974.27	4712.08	4721.04	2860.91	4302.28	4721.81	1255.05	6408.08
			20	927.26	664.33	3169.58	3174.27	3168.46	4147.57	3996.11	4196.71	4393.38
			35	244.2	172.21	823.52	826.55	823.52	1021.31	1023.76	1048.65	1147.67
3000	0	35	5	12870.99	7975.64	7944.36	7947.29	7943.76	12582.50	8016.68	1123.71	12467.72
			10	9439.21	5719.71	5692.10	5641.88	5688.72	8930.92	5691.18	789.64	9079.38
			15	6623.29	3718.97	3789.68	3793.08	3787.31	5772.31	3799.85	512.51	6638.98
			20	425.53	227.11	2585.49	2586.03	2585.73	3840.29	3899.62	3902.17	4527.62
			35	106.01	59.73	681.30	681.76	681.30	984.78	999.51	1002.24	1171.17
		45	5	20587.5	14350.17	14365.93	14374.92	14365.37	21983.69	14335.90	1966.47	20344.45
			10	15359.11	10349.46	10557.33	10452.92	10514.34	15159.84	10393.28	1342.33	15091.54
			15	11414.14	7347.25	7397.60	7408.17	7391.75	10020.46	7400.87	894.87	11264.87
			20	700.49	442.88	5040.91	5049.41	5046.47	6782.02	6819.21	6894.82	7684.20
			35	179.57	115.46	1299.45	1302.40	1299.45	1770.25	1780.41	1811.62	1992.38
		55	5	27089.96	21790.89	20427.87	20889.44	20461.89	29297.78	20891.69	2609.27	27336.24
			10	20192.58	16405.41	15272.51	15249.64	15305.64	20419.38	15251.62	1818.16	20268.61
			15	15140.82	12264.13	11242.85	11264.24	11309.66	14088.76	11266.08	1255.05	15289.44
			20	927.26	664.33	7562.52	7573.71	5046.47	9895.96	9534.58	10013.20	10482.44
			35	244.2	172.21	1964.88	1972.13	1299.45	2436.80	2442.65	2502.04	2738.31

ADT	Curvature (deg)	Speed (mph)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
3000	5	35	5	10560.76	6542.43	6714.11	7947.29	6709.31	11497.90	8016.68	1123.71	12467.72
			10	7205.4	4933.22	4772.42	5641.88	4766.44	7880.81	5691.18	789.64	9079.38
			15	5150.55	3344.26	3493.14	3793.08	3488.73	5369.26	3799.85	512.51	6638.98
			20	425.53	227.11	2585.49	2586.03	2585.73	3840.29	3899.62	3902.17	4527.62
			35	106.01	59.73	681.30	681.76	681.30	984.78	999.51	1002.24	1171.17
		45	5	16832.51	11820.64	14365.93	14374.92	11975.74	19442.66	14335.90	1966.47	20344.45
			10	11500.66	8900.83	10557.33	10452.92	9091.01	13665.57	10393.28	1342.33	15091.54
			15	8819.32	6611.58	7397.60	7408.17	6427.54	9166.44	7400.87	894.87	11264.87
			20	700.49	442.88	5040.91	5049.41	5046.47	6782.02	6819.21	6894.82	7684.20
			35	179.57	115.46	1299.45	1302.40	1299.45	1770.25	1780.41	1811.62	1992.38
		55	5	22251.72	19334.06	20427.87	20889.44	18303.04	25484.14	20891.69	2609.27	27336.24
			10	15110.42	13689.93	15272.51	15249.64	15305.64	18169.33	15251.62	1818.16	20268.61
			15	11796.67	9732.24	11242.85	11264.24	9824.00	12645.64	11266.08	1255.05	15289.44
			20	927.26	664.33	7562.52	7573.71	7559.84	9895.96	9534.58	10013.20	10482.44
			35	244.2	172.21	1964.88	1972.13	1964.88	2436.80	2442.65	2502.04	2738.31
	10	35	5	7184.23	4409.99	4490.29	4503.19	4486.35	8249.91	8016.68	1123.71	12467.72
			10	5605	3752.33	3796.40	3728.28	3791.30	6295.79	5691.18	789.64	9079.38
			15	3612.84	2320.74	2521.73	2546.79	2519.71	4474.28	3799.85	512.51	6638.98
			20	425.53	227.11	2585.49	2586.03	2585.73	3840.29	3899.62	3902.17	4527.62
			35	106.01	59.73	681.30	681.76	681.30	984.78	999.51	1002.24	1171.17
		45	5	11391.31	7803.65	14365.93	14374.92	7892.12	14098.39	14335.90	1966.47	20344.45
			10	8893.96	6674.06	10557.33	10452.92	6619.42	10751.62	10393.28	1342.33	15091.54
			15	5946.58	4458.38	7397.60	7408.17	4573.50	7483.27	7400.87	894.87	11264.87
			20	700.49	442.88	5040.91	5049.41	5046.47	6782.02	6819.21	6894.82	7684.20
			35	179.57	115.46	1299.45	1302.40	1299.45	1770.25	1780.41	1811.62	1992.38
		55	5	15383.19	13228.63	20427.87	20889.44	12110.27	18188.68	20891.69	2609.27	27336.24
			10	11561	10470.48	15272.51	15249.64	9829.36	14592.33	15251.62	1818.16	20268.61
			15	7647.12	7096.51	11242.85	11264.24	6826.03	10265.08	11266.08	1255.05	15289.44
			20	927.26	664.33	7562.52	7573.71	7559.84	9895.96	9534.58	10013.20	10482.44
			35	244.2	172.21	1964.88	1972.13	1964.88	2436.80	2442.65	2502.04	2738.31

Appendix G. Freeway Crash Cushion Synthesis

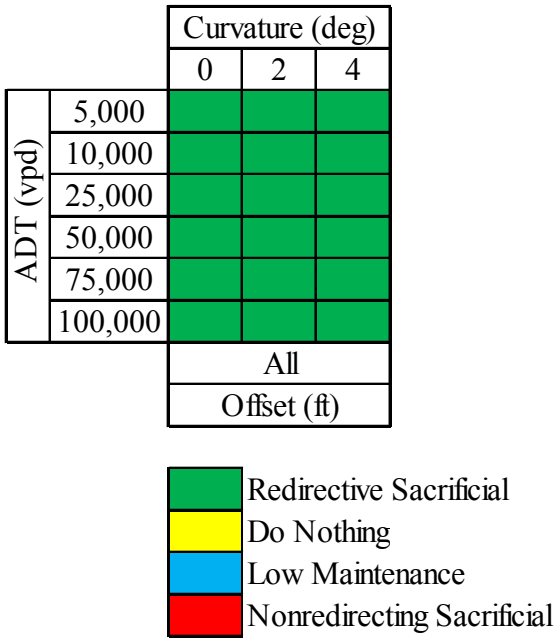

Figure G-1. BC Ratios Greater than 4.0, Freeways.

Appendix H. Divided Rural Arterial Crash Cushion Synthesis

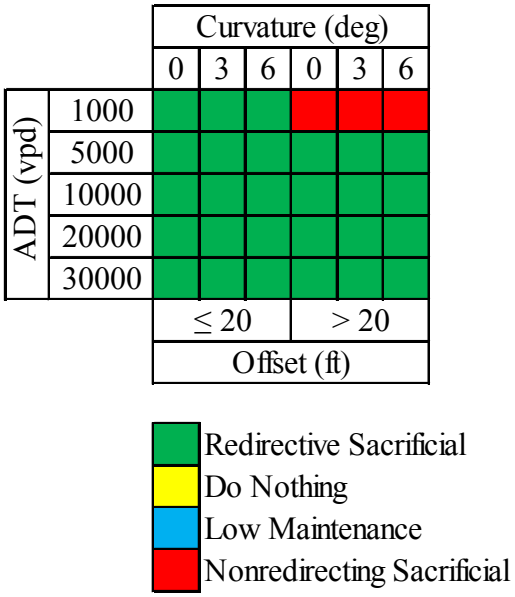

Figure H-1. BC Ratios Greater than 4.0, Divided Rural Arterials

Appendix I. Undivided Rural Arterial Crash Cushion Synthesis

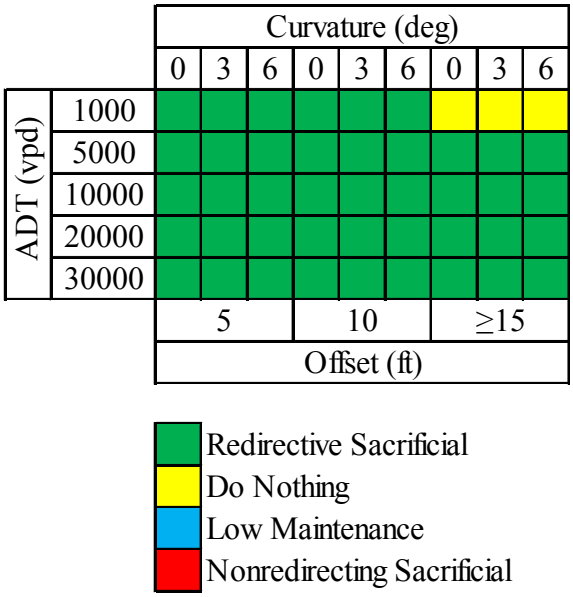

Figure I-1. BC Ratios Greater than 2.0, Undivided Rural Arterials

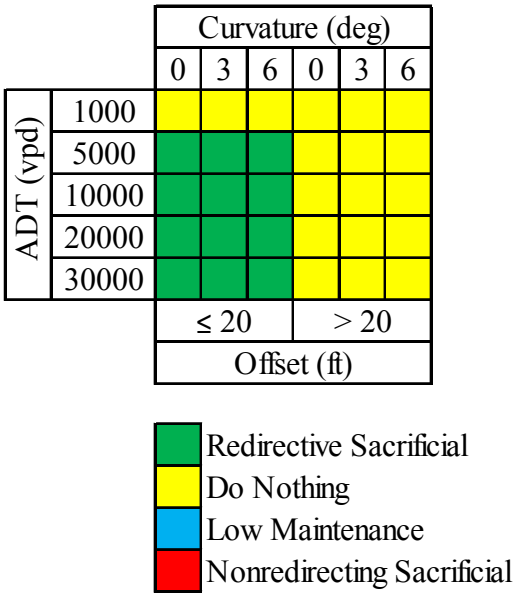

Figure I-2. BC Ratios Greater than 4.0, Undivided Rural Arterials

Appendix J. Local Highway Crash Cushion Synthesis

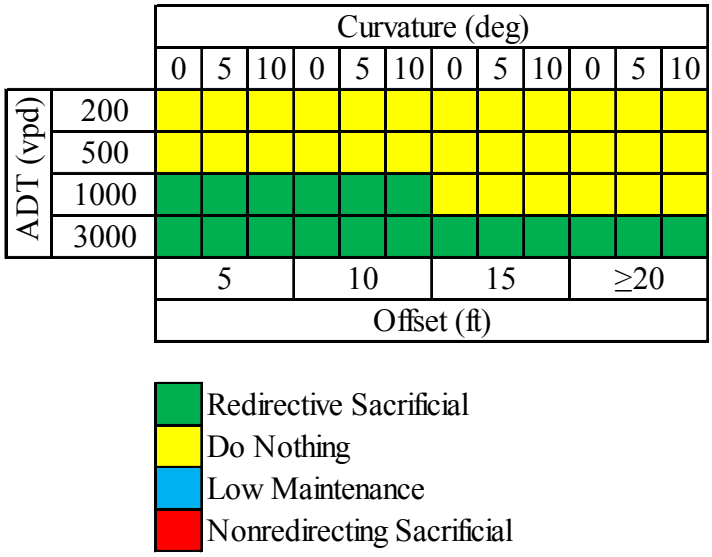

Figure J-1. BC Ratios Greater than 2.0, Local Highways

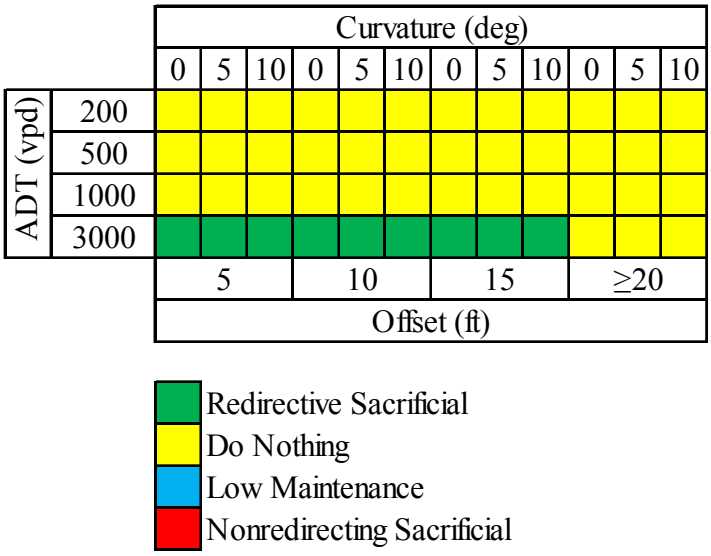

Figure J-2. BC Ratios Greater than 4.0, Local Highways

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