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GUIDELINES FOR CRASH CUSHION SELECTION

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16. Abstract (Limit: 200 words)
Crash cushions have unique properties and vary in shape, length, width, and cost. For this study, crash cushions were grouped together according to their repair costs, and each group was compared to each other in a benefit-cost analysis. Installation costs were obtained from State DOTs, but repair costs were obtained from crash test results provided by each system's manufacturer. Based on the average repair costs, each system considered in this study was sorted into one of three major categories in order to analyze and evaluate the cost-effectiveness of the grouped crash cushions. The categories were: (1) redirecting with repair costs greater than $1,000 (RGM); (2) redirecting with repair costs less than $1,000 (RLM); and (3) non-redirecting sacrificial (NRS). RGM systems often require higher repair costs than RLM systems after being hit, but RLM systems generally have higher installation costs. NRS systems (e.g., sand barrels) are generally less expensive, often require total replacement after a crash has occurred, and may be impractical at locations with high traffic volumes. This research study was performed to identify the optimal cost-effective crash cushion category and all other cost-effective categories for highway scenarios with different roadway, traffic, and roadside characteristics using the Roadside Safety Analysis Program (RSAP). RGM and RLM systems were the most cost-effective systems for freeways and divided rural arterials, while all three categories competed with the unprotected condition on undivided rural arterials and local roads. When only life cycle costs were considered, the minimum impact frequency to recommend RLM systems was determined. For the costs supplied by States and manufacturers, this minimum impact frequency ranged from 0.41 to 0.66 impacts per year (or 1 accident for every 2.45 to 1.52 years), depending on the applicable functional class.

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1 INTRODUCTION

1.1 Problem Statement

Guidelines contained in the Roadside Design Guide (RDG) list crash cushions as acceptable devices for shielding 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, roadway, 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 tends to be very low. As a result, the use of different crash cushions may depend on various roadway, roadside, and traffic characteristics. Thus, the selection of a specific crash cushion type is often a challenge for highway engineers. Therefore, a need exists to develop procedures/tools for guiding the selection of a crash cushion that results in the highest reduction in accident cost per unit of direct cost (i.e., installation and repair cost).

1.2 Objective

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

1.3 Scope

The objective of this research study was achieved through various tasks. First, common crash cushion systems were examined in order to understand dimensions and associated costs for each system via manufacturer product sheets as well as surveys sent out to State Departments of Transportation (DOTs) and manufacturers. Crash cushion categories were generated to assist in the investigation and development of selection guidelines in terms of broad categories rather than specific systems. Next, using the Roadside Safety Analysis Program (RSAP), roadway parameters were chosen for the study based on their influence in determining accident cost. Then, by modifying these parameters, several models were created to evaluate the effectiveness of each crash cushion for various roadway scenarios. Next, mobilization, installation, maintenance, and repair costs were estimated. Costs associated with the severity of an accident were determined based on the 2010 Federal Highway Administration (FHWA) comprehensive costs. Finally, a benefit-cost (BC) analysis was conducted to determine feasible placement for each type of crash cushion. Example applications of the results were included to assist engineers in the selection process.

2 CRASH CUSHION SYSTEMS

Redirecting and non-redirecting crash cushions were chosen for comparison based on their common usage throughout the Midwest. A range of impact performance and maintenance was desired to study the contrasting approaches of life cycle costs. Some systems were designed to cost less initially but cost more per impact, while others cost more initially but cost less per impact. Overall, seven proprietary redirecting systems were studied and compared to one another as well as to a generic non-redirecting system, represented by inertial sand barrels.

2.1 QuadGuard

The QuadGuard is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC [2]. It utilizes crushable cartridges that need to be replaced after head-on impact events. These cartridges are placed within a structure of quad beams that are designed to “fish-scale” backward as a vehicle strikes the end. The length of a typical QuadGuard system is 21 ft (6.4 m), and a common width is 2.0 ft (0.6 m). A typical QuadGuard system is shown in Figure 1.

Figure 1. Typical QuadGuard System

2.2 QUEST

The QUEST crash cushion is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC [3]. It telescopes backward to dissipate kinetic energy. The length of a typical QUEST system is 19 ft (5.8 m) and a common width is 2.0 ft (0.6 m). A typical QUEST crash cushion is shown in Figure 2.

Figure 2. Typical QUEST System

2.3 TRACC

The Trinity Attenuating Crash Cushion (TRACC) is a proprietary crash cushion manufactured by Trinity Highway Products, LLC [4]. It telescopes backward while tearing through metal plates. The length of a typical TRACC system is 21.25 ft (6.5 m) and a common width is 2.0 ft (0.6 m). A typical TRACC is shown in Figure 3.

Figure 3. Typical TRACC System

2.4 TAU II

The TAU II is a proprietary crash cushion manufactured by Barrier Systems, Inc. [5]. It absorbs the kinetic energy of the vehicle using disposable energy absorbing cartridges. The length of a typical TAU II is 23 ft (7.0 m) and a common width is 4.0 ft (1.2 m). A typical TAU II system is shown in Figure 4.

Figure 4. Typical TAU II System

2.5 QuadGuard Elite

The QuadGuard Elite is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC [6]. It utilizes self-restoring cylinders made from HDPE and usually requires minimal 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 length of a typical QuadGuard Elite system is 27 ft (8.2 m), and a common width is 2.0 ft (0.6 m). A typical QuadGuard Elite system is shown in Figure 5.

Figure 5. Typical QuadGuard Elite System

2.6 REACT 350

The Reusable Energy-Absorbing Crash Terminal (REACT 350) is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc. [7], a subsidiary of Trinity Highway Products, LLC. HDPE cylinders are placed in a single row and restrained by cables on either side. The length of a typical REACT 350 system is 28.75 ft (8.8 m) and a common width is 3.0 ft (0.9 m). A typical REACT 350 system is shown in Figure 6.

Figure 6. Typical REACT 350 System

2.7 SCI

The Smart Cushion is a proprietary crash cushion manufactured by Smart Cushion Innovations (SCI) Products, Inc. [8]. The only repair required pertains to head-on impact events where only the replacement of two shear bolts is needed. The length of a typical SCI system is 21.5 ft (6.6 m), and a common width is 2.0 ft (0.6 m). A typical SCI system is shown in Figure 7.

Figure 7. Typical SCI System

2.8 Non-Redirecting Systems (NRS)

Non-redirecting systems (NRS) 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 any fixed object. Further, sand barrels may initially be inexpensive to install. However, repair costs can be high; since, the system usually requires a 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 may perform poorly in coffin-corner impact events. The number and weight of the barrels is usually dependent on the posted speed of the highway. That is, high-speed highways generally require sand barrel configurations that contain more barrels. A sand barrel array that was used to protect a pier is shown in Figure 9 and was developed using the procedure outlined in the RDG. Note, the mass of the barrels increases within rows as the system approaches the hazard. This configuration 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 Energite III System

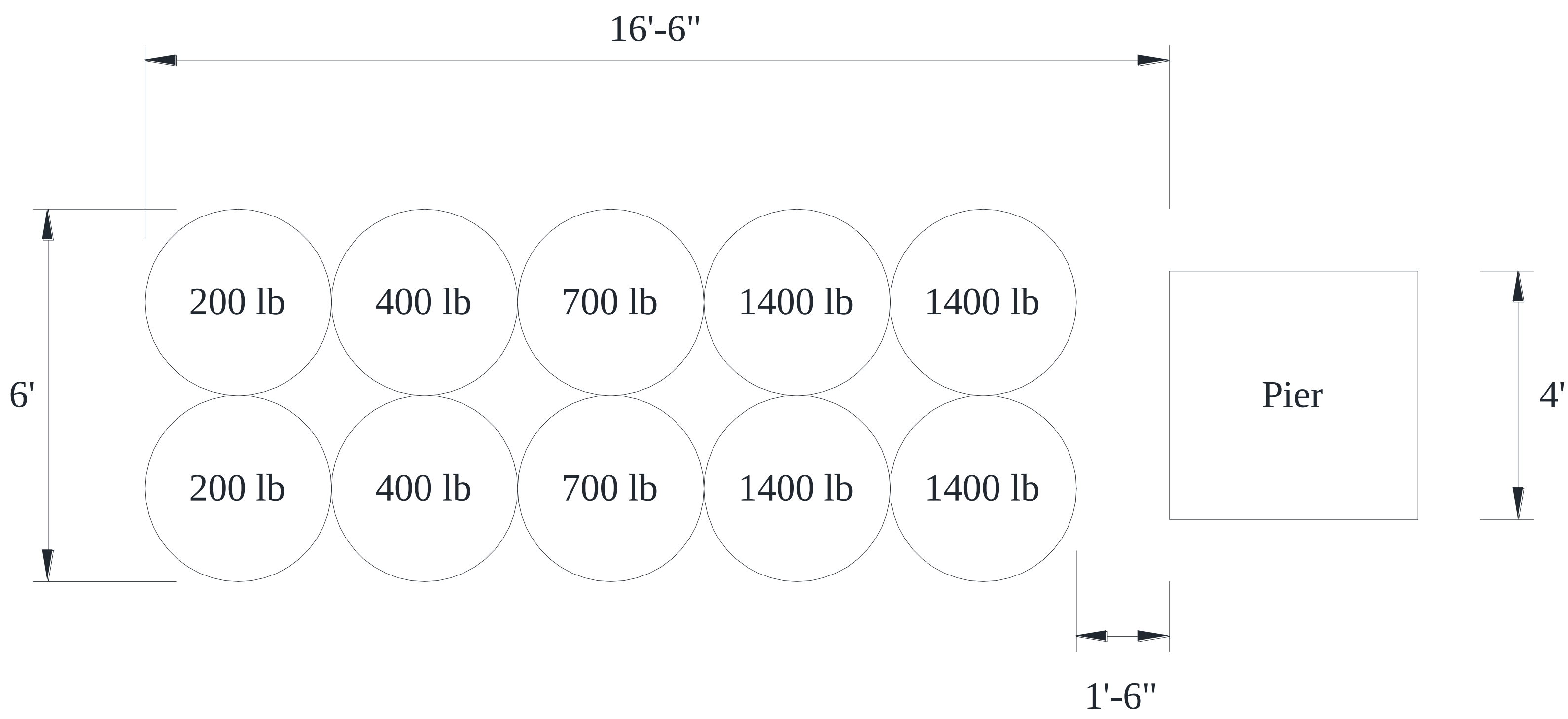


Figure 9. Inertial Sand Barrel Array used to Protect a Bridge Pier

3 SURVEY OF CRASH CUSHION COSTS

In order to estimate the installation cost of the crash cushions used in this study, a survey questionnaire was sent to the members states of the Midwest States Pooled Fund Program, including: 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 needs and additional maintenance costs for each crash cushion type, repair time needed once the cushion has been involved in a crash, and information corresponding to a particular crash cushion, such as the test level and speed limit of the road.

Only the States of Kansas, Minnesota, Nebraska, and Wisconsin replied to the survey, while the remaining states did not respond or noted that the information was unavailable. The States of Minnesota and Wisconsin submitted responses to this survey that adequately answered the questions. Minnesota used estimates based on bid tabulations and prior experience in repairing crash cushions. 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 finding 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 to the bid that increased the installation cost could not be known for all occurrences.

The sand barrel cost information obtained from the Kansas DOT was not used as the repair cost was not indicative of an actual repair cost. Contractors were paid to replace all barrels regardless of whether fewer barrels were impacted. This practice would allow a contractor to submit a bid for system repair that was significantly less per barrel than the actual repair cost. For example, if a 10 barrel array was hit and only 2 barrels were destroyed, the contractor might submit a bid for the cost of all 10 barrels but replace only the two damaged barrels. Then, the repair cost per barrel paid by the State 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 the Kansas DOT’s response pertaining to the cost of the QuadGuard was used.

The State of Nebraska also responded to the questionnaire. However, only the TRACC system was reported and with 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 may likely have corresponded to the total cost of repairs across the state and not the average cost per repair. However, it is possible that each crash repair required significant removal effort and replacement parts, thus corresponding to the higher costs. At any rate, the Nebraska survey data was not used in this research study.

Installation costs ascertained from the State DOTs were used in this study and are shown in Appendix C. However, Wisconsin did not list non-redirecting systems 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 [9-11], which included discounts for order amounts greater than 10 barrels. 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) by 2-ft (0.6-m) fixed object. A summary of installation costs and dimensions [2-8] for each crash cushion evaluated in this study is shown in Table 1. Dimensions were taken from manufacturer product sheets for typical Test Level 3 (TL-3) crash cushion designs [2-8]. Crash cushion size was directly associated with the safety performance of the crash cushion, which can also 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.

Table 1. Installation Costs and Dimensions [2-8] Used in the Benefit-Cost Analysis

Crash Cushion	Installation Cost	Length, ft (m)	Width, ft (m)
QuadGuard	$17,769	21 (6.40)	2.0 (0.61)
QUEST	$11,510	19 (5.79)	2.0 (0.61)
TRACC	$11,400	21.25 (6.48)	2.0 (0.61)
TAU II	$15,433	23.0 (7.01)	4.0 (1.22)
QuadGuard Elite	$33,017	27.0 (8.23)	2.0 (0.61)
REACT 350	$36,067	28.75 (8.76)	3.0 (0.91)
SCI	$19,371	21.5 (6.55)	2.0 (0.61)
Sand Barrels	$2,540	16.5 (5.03)	6.0 (1.83)

4 REPAIR COST ESTIMATION

4.1 Mobilization Costs

Whether installing a new system or repairing a damaged one, a crew must be mobilized to the location. As a result, a cost will be incurred that includes transportation. However, these costs were not included in the present study because mobilization is highly variable and dependent on the site location. For example, costs could be high if the travel distance to the site is long or costs could be low if the travel distance is short. Despite the exclusion of these costs, the BC analysis conducted herein was valid. The cost to mobilize, a direct cost, was equal for all systems compared in the analysis. Therefore, when the direct costs of two systems were subtracted, the mobilization costs canceled out of the analysis.

4.2 Regular Maintenance Costs

Regular maintenance on crash cushions is typically included in the direct costs of the system and, if it existed, it was important in determining BC ratios. Responses from State DOTs indicated either a total maintenance cost for all crash cushions (as opposed to average maintenance costs per system) in the state or were a replication of the repair costs. Therefore, maintenance costs were set to zero for this analysis, and this practice was confirmed in correspondence with DOT officials who noted that these systems do not typically receive maintenance unless they are struck, at which point the maintenance cost becomes a repair cost.

4.3 Repair Costs

Repair costs were ascertained from crash test approximations. Manufacturers were asked to supply the estimated cost for repair parts following a standard NCHRP Report No. 350 crash test [12], as well as the estimated time in man-hours to make the repair. An example of the survey sent out to manufacturers is given in Appendix B. A summary of the test designations conducted for each system is given in Table 2, where the shaded tests were mutual among each system.

Table 2. NCHRP Report No. 350 Crash Tests Conducted for Each System

Test Designation No.						
SCI	TRACC	TAU II	QuadGuard	QG Elite	REACT 350	QUEST
		3-30	3-30	3-30	3-30	3-30
3-31	3-31	3-31	3-31	3-31	3-31	3-31
3-32		3-32	3-32	3-32	3-32	3-32
3-33	3-33	3-33	3-33	3-33	3-33	3-33
		3-36	3-36	3-36		3-36
3-37	3-37	3-37	3-37	3-37	3-37	3-37
	3-38	3-38	3-38	3-38	3-38	3-38
3-39	3-39	3-39	3-39	3-39		3-39

Each mutual test was conducted at NCHRP Report No. 350 TL-3, which uses a 2000P vehicle and an impact velocity of 62.1 mph (100 km/h). Test no. 3-31 was head-on, test no. 3-33 was on the nose at 15 degrees, and test no. 3-37 was along the side at 20 degrees. The nominal impact severities were 569 kip-ft (772 kJ), 531 kip-ft (720 kJ), and 66.4 kip-ft (90 kJ), respectively. The average costs reported by manufacturers for all tests and for mutual tests are shown in Table 3. Reported repair cost data is presented in Appendix D and E.

Table 3. Summary of Reported Repair Costs

System	Average Repair Cost For All Tests	Avg Repair Cost For Mutual Tests
SCI	$60.60	$67.33
REACT 350	$58.33	$66.67
QuadGuard Elite	$519.38	$638.33
TRACC	$1,434.00	$1,933.33
TAU II	$2,059.31	$2,518.83
QuadGuard	$2,932.38	$3,909.67
QUEST	$8,406.25	$9,683.33

Only mutual tests were used to compare each system so that the nonlinearity inherent in the energy of the tests had no influence on the results. Some systems did not conduct low-energy tests, like test no. 3-36, which may have significantly skewed average repair costs. However, the test velocity was higher than what would be observed in real-world run-off-road accidents [13]. Therefore, the average repair costs ascertained from standardized testing were reduced according to reductions in velocity. It was assumed that the repair cost was directly related to the impact severity (IS) or incoming energy. The IS can be determined using Equation 1 [12].

$$IS = \frac{1}{2} m (v \cdot \sin\theta)^2 \cdot \frac{1}{1000} \quad (1)$$

Where IS = impact severity in kJ,
m = mass in kg,
v = velocity in m/s, and
θ = impact angle in radians.

As indicated, test velocities exceeded real-world average velocities. Therefore, the test data was reduced to match the average impact speed. A study was performed to estimate vehicle impact conditions on various highway types [13]. The authors of that study determined average impact velocities for various functional classes. Freeways were 45.3 mph (73.0 km/h), arterials for US and State routes were 39.3 mph (63.2 km/h), and local highways were 34.9 mph (56.2 km/h). By substituting the ratio of the average impact speed to the test impact speed into the velocity term in Equation 1, the reduced impact severity, $\overline{IS}$, became a function of IS according to Equation 2.

$$\overline{IS} = \left(\frac{v_{50}}{v_{85}}\right)^2 (IS) \quad (2)$$

Where $\overline{IS}$ = reduced impact severity
IS = impact severity of the test conditions,
v_{50} = velocity of an average impact, and
v_{85} = target velocity of the crash test.

Applying the average impact velocities to Equation 2, the IS was reduced for Freeways, Arterials, and Local Highways using ratios of 0.5253, 0.3954, and 0.3118, respectively. Since it was assumed that repair cost was directly related to IS, the average repair costs for mutual tests were multiplied by these same ratios. Therefore, the costs associated with the reduced velocity approach are shown in Table 4.

Table 4. Repair Costs for Test Designation Nos. 3-31, 3-33, and 3-37 with Reduced IS

System	Freeway Avg Repair Cost*	Arterial Avg Repair Cost*	Local Avg Repair Cost*
SCI	$35.83	$26.97	$21.27
REACT 350	$35.47	$26.70	$21.06
QG Elite	$339.67	$255.65	$201.61
TRACC	$1,028.77	$774.30	$610.62
TAU II	$1,340.33	$1,008.79	$795.55
QG	$2,080.43	$1,565.82	$1,234.83
QUEST	$5,152.74	$3,878.17	$3,058.39

*Not including mobilization costs

4.4 Labor Costs

A difference was observed in repair time when comparing each crash cushion type. Crash cushion repair costs included the use of a utility truck and labor for a 2-man crew to make repairs. Labor costs were assumed to be $50 per hour based on correspondence with the State of Wisconsin.

Labor cost estimates obtained by the Wisconsin DOT assumed a setup and takedown time, including travel time, to be one hour each. However, it should be noted that travel time to the location dropped out of the BC analysis, as stated in section 4.1. 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 but was included in the cost of the truck useage.

The labor 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 takedown 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 cost of a utility truck was assumed to be $125 per hour for each crash cushion. A 2-man crew was used for setup, takedown, and repair of the crash cushion. For each crash cushion, a fixed cost based on a setup and takedown time of the work zone was assumed to be one hour for each phase. That is, setup should take one hour and takedown 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 $125. A summation of each fixed cost resulted in a total fixed labor 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. The variable cost of labor was determined by the hourly truck rental rate 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 labor cost of 4 times $225, or $900 per repair. Labor costs of the remaining crash cushions are summarized in Table 5 and were determined using Equation 3.

$$L_{cost} = Hourly_{cost}(RepairTime_{avg}) \tag{3}$$

Where L_{cost} = total labor cost
$Hourly_{cost}$ = hourly rate to repair the system ($225)
$RepairTime_{avg}$ = average time required to repair the system

Table 5. Summary of Labor Costs

System	Man hours for Repairs	Labor Cost*
SCI	1.33	$300.00
REACT 350	1.00	$225.00
QG Elite	1.00	$225.00
TRACC	2.33	$525.00
TAU II	0.78	$174.75
QG	1.17	$262.50
QUEST	3.00	$675.00

*Not including mobilization costs

5 NEW CATEGORIES BASED ON REPAIR COSTS

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 the safety performance standards of the National Cooperative Highway Research Program (NCHRP) Report No. 350 [12]. For more detailed information, the reader should contact the specific crash cushion manufacturer.

For this study, crash cushion categories were established to represent the cost performances of each system for use in benefit-cost analyses. A threshold for average repair costs was selected to place systems in groups congruent with other commonly-used crash cushion categories, such as those depicted in the RDG [1]. A distinction was made between redirecting systems in terms of average repair costs either below or above $1,000. This threshold was chosen because it separated the systems into groups congruent with the RDG. For simplicity, the Roman numeral for 1,000 (M) was used in the designations. The resulting categories were: (1) Redirecting with repair costs Less than or equal to $1,000 (RLM); (2) Redirecting with repair costs Greater than $1,000 (RGM); and (3) Non-Redirecting Sacrificial (NRS).

These categories were chosen in lieu of the commonly used categories to emphasize the importance of the cost performance for this study, primarily because the safety performances of the individual systems could not be compared using RSAP. The distinction between RLM and RGM categories was chosen based on the average repair cost per unit of impact severity, as shown in Figure 10, which was discussed in more detail in Section 4.3.

The repair costs of the RLM category were low for the systems used in this study because they either used the concept of restorability or ensured that the cost of the repair parts was inexpensive. However, installation costs were high for these systems.

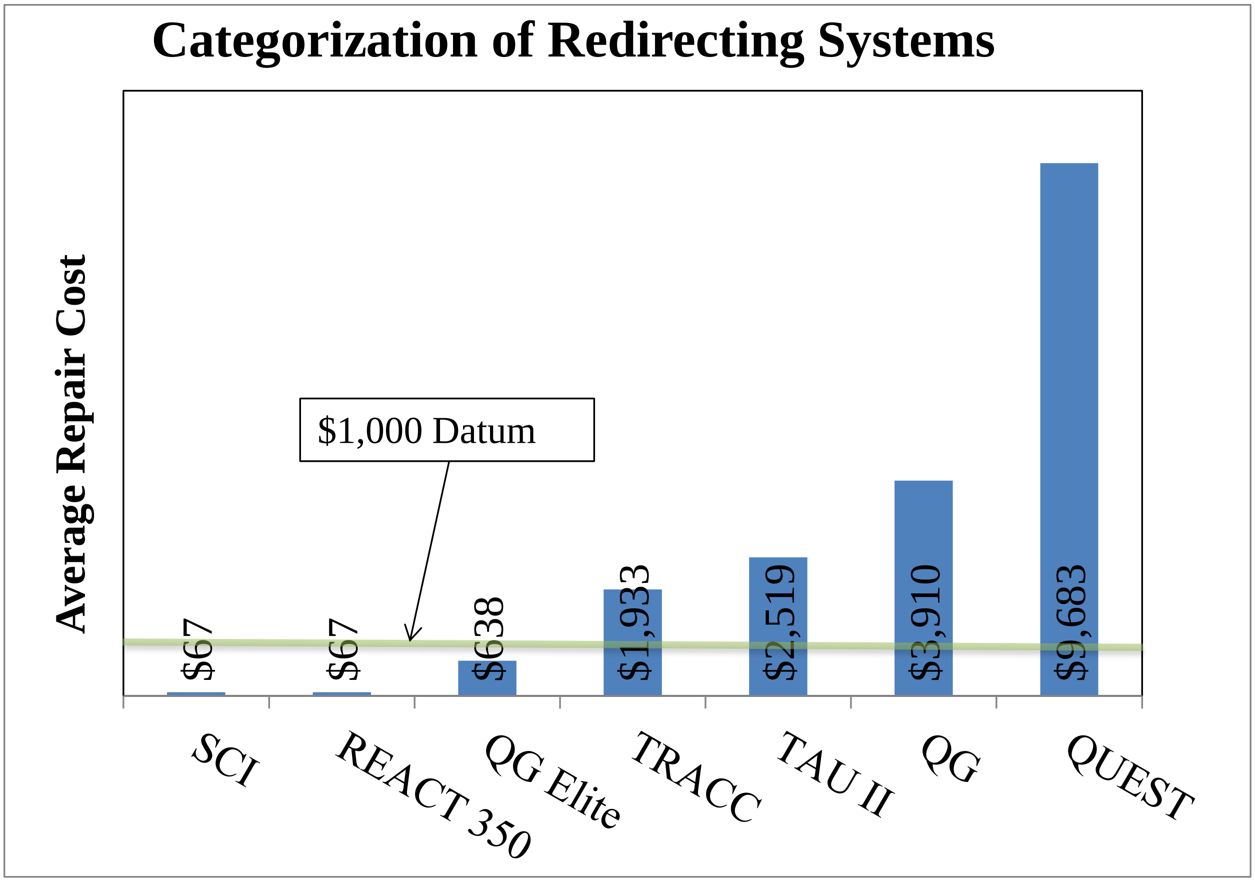


Figure 10. Categorization of Redirecting Crash Cushions

In contrast, the repair costs for the RGM category were higher per impact. RGM systems generally make use of permanent deformation or damage to dissipate energy. As a result, the cost of repair parts can be expensive. However, installation costs were low for these systems.

NRS 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 incremental momentum transfer to sand particles (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 barrels 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 typically suffers significant permanent deformation, and may have to be replaced, the repair costs for these systems can approach the initial installation costs, especially for high-energy head-on impacts. On the other hand, these systems typically had the lowest installation costs.

A summary of the three new categories is given in Table 6, along with similar designations proposed in the roadside safety community. Additionally, each system used in this analysis is categorized accordingly.

Table 6. Crash Cushion Categories and Alternative Designations

Category	RDG Designation	Study Definition	System
RLM	Low Maintenance	Repair Cost (RC) ≤ $1,000	SCI
			REACT 350
			QuadGuard Elite
RGM	Reusable	Repair Cost (RC) > $1,000	TAU II
			QUEST
			TRACC
			QuadGuard
NRS	Sacrificial	NA	Sand Barrels

The systems shown in Table 6 are described in more detail in the following sections. The dimensions given for each system were used for this research project, but many of the systems have a wide range of possible lengths and widths. Additionally, in order to compare systems under similar design considerations, the typical TL-3 design for each system was considered for this analysis.

A summary of the required maintenance and possible inventory is included in Table 7 and was taken from the 2011 RDG [1]. The designation for sand-filled barrels was altered to "Non-redirecting Sacrificial Systems" to more accurately reflect the maintenance requirements as they are listed in the table.

Table 7. Summary of Required Maintenance and Inventory for Selected Crash Cushions [1]

Crash Cushion	Regular Maintenance	Crash Maintenance	Material Inventory
Redirecting Systems with Repair Costs Greater than or Equal to $1,000 (RGM)			
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.
Redirecting Systems with Repair Costs Less than $1,000 (RLM)			
QuadGuard Elite	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 criteria impacts.	Shear bolts and delineator panel.
Non-redirecting Sacrificial System (NRS)			
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.

6 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 selected to characterize the wide range of scenarios.

6.1 Societal Costs

According to the Federal Highway Administration (FHWA), the average cost of a human life was $2.6 million dollars in 1994 [14]. 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. In 2010, the gross domestic product implicit price deflator was 111.141 [15]. Utilizing this value, the costs of each injury level on the KABCO scale (with K being a fatality and O being property damage only) scaled up for inflation according to the following equation:

$$AccCost = P\left[\frac{GDP_{2010}}{GDP_{1994}}\right] \tag{4}$$

Where, GDP_{2010} = 111.141 [15]
GDP_{1994} = 80.507 [15]
P = the principal in 1994 dollars.

Using this approach, the cost of a fatality in 2010 was $3.59 million dollars. The KABCO scale of describing the level of severity of an accident in terms of injury was adopted for use in many benefit-cost analysis programs. That scale is described in detail below.

- 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)

By scaling the remaining levels of severity, the costs of each level of the KABCO scale were determined and are shown in Table 8.

Table 8. Societal Costs for Each Injury Level in 2010

Injury Level	Cost (US$)
K	3,589,335
A	248,492
B	49,698
C	26,230
PDO	2,761

Using this scale and the predicted accident frequency, the Roadside Safety Analysis Program (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.

6.2 Roadside Safety Analysis Program (RSAP v. 2003.04.25)

RSAP is an encroachment probability based tool used to estimate the cost-effectiveness of roadside safety treatment alternatives [16]. 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 sections that follow.

6.2.1 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 [17]. 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, Cooper's results were reanalyzed after excluding encroachments that extended less than 13.1 ft (4 m) laterally. From the encroachments that exceeded 13.1 ft (4 m), a regression model was developed and was used to extrapolate back to the 0 to 13.1 ft (0 to 4 m) region [16]. Regression coefficients were fit to observed data, and at a lateral offset of 0 ft (0 m), the encroachment rate was underreported by 319.9 and 204.4 percent for two-lane undivided highways and multi-lane highways, respectively. However, the percent of encroachment beyond 13.1 ft (4 m) was 77.1 and 91.9 percent, respectively. Applying these percentages, the y-intercepts of the regression model were 246.6 (319.9*0.771) and 187.8 (204.4*0.919), respectively. Physically speaking, the percent exceeding a lateral encroachment of 0 ft (0 m) should be 100 percent; so, the regression model was normalized by dividing by 100. Therefore, 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 [16]. 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 conducted 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 [18]. 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 11.

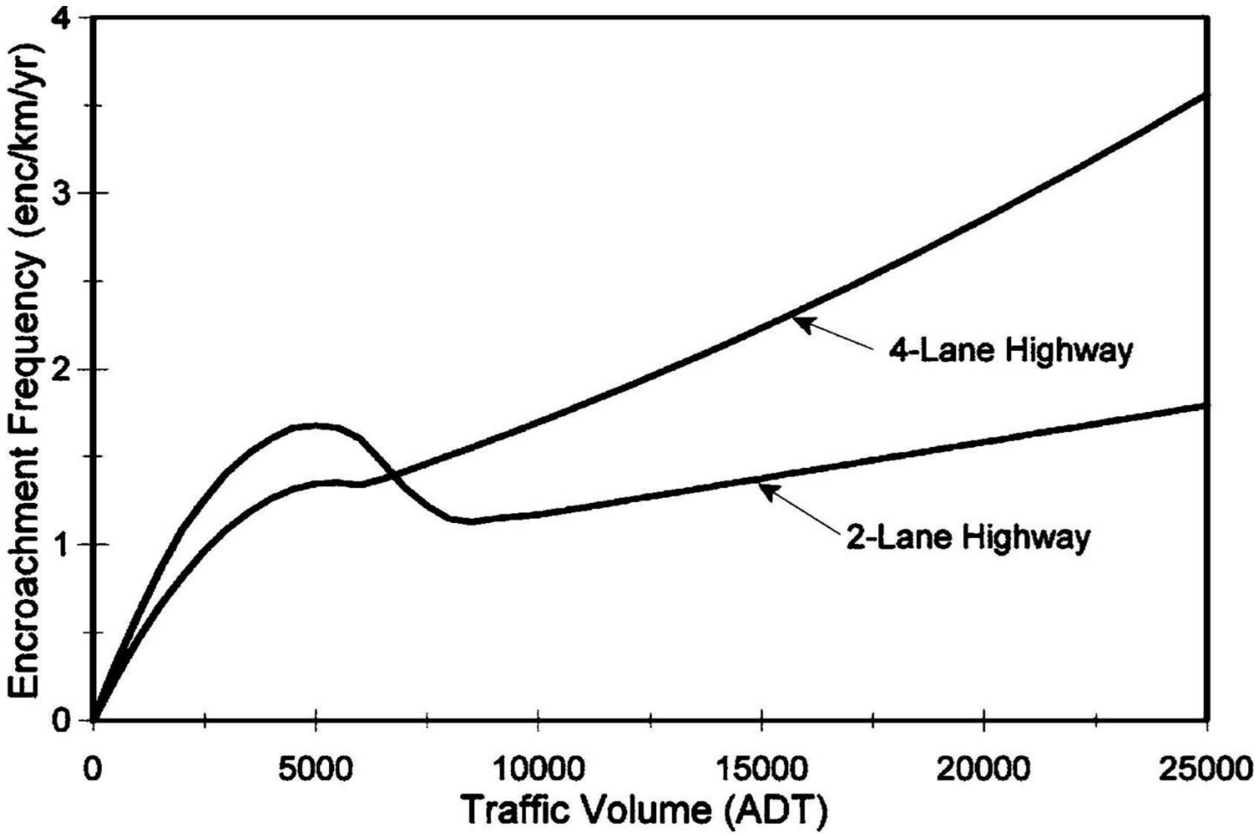


Figure 11. RSAP Encroachment Rate Based on Cooper's Data [17]

6.2.2 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 [19]. The locations of the roadside features, as determined by user input, are compared to the vehicle swath. 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. This study focused on rigid fixed objects shielded by crash cushions. Therefore, if the kinetic energy was high enough prior to an impact event with the crash cushion, penetration through that system was predicted. If the fixed object was in the vehicle swath, a secondary impact with that object was also predicted. In this scenario, the impact with the highest severity index was used to determine the overall severity of the crash.

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.

6.2.3 Crash Severity Module

Once a crash is predicted, the severity of that crash must be determined. The severity of the accident has a significant effect on the overall accident cost. The severity indices used in RSAP were based on the ones published in the 1996 RDG [14], 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 9. The simulated accident costs are found in Appendices F through I.

The severity indices range from 0 to 10 as shown in Table 9. The injury level distributions and the cost for each injury level, as shown in Tables 9 and 8, respectively, were used to estimate the costs associated with each severity index, as shown in Table 10. Current designations set PDO1 equal to PDO2 in societal costs, or $2,761. For example, the accident cost associated with a severity index equal to 1 may be calculated as:

$$(0.667\times 2{,}761) + (0.237\times 2{,}761) + (0.073\times 26{,}230) + (0.023\times 49{,}698) = \$5{,}554$$

Table 9. Injury Level Percentages for Each Severity Index [14]

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 10. Societal Costs for Each Severity Index

Severity Index	Accident Cost
0	$ -
0.5	$ 2,761
1	$ 5,554
2	$ 11,210
3	$ 58,920
4	$ 144,705
5	$ 340,545
6	$ 719,551
7	$ 1,167,942
8	$ 1,872,252
9	$ 2,740,209
10	$ 3,589,335

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 9 were based on engineering judgment. No evidence has been presented to support these values.

6.2.4 Benefit-Cost Analysis Module

The fourth and final module of RSAP calculates the BC ratios to be used in the incremental BC analysis. BC ratios compare the economic 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 5.

$$BC_{2-1} = \frac{AC_1 - AC_2}{DC_2 - DC_1} \quad (5)$$

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
DC_1, DC_2 = Annualized direct costs for alternatives 1 and 2, respectively

Alternative 2 refers to the proposed safety improvement with respect to alternative 1, which, for example, could be the baseline condition. This ratio is a measurement of the magnitude of the change in safety performance over the change in up-front costs, including installation, maintenance, and repair costs. This procedure was used to compare each crash cushion category to a scenario with an unprotected bridge pier and also to compare each category directly to one another for a variety of roadway, roadside, and traffic characteristics.

6.3 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 in RSAP. If a parameter had a significant influence on accident cost change, then the parameter would be considered further in the study. On the other hand, if a parameter had limited or no influence on accident cost change, the parameter would be removed from the study.

Parameters for analysis were chosen according to the likelihood that they could vary from one installation site to another. If a parameter was intended to remain stoic for all installations, then it was not considered in the sensitivity analysis. For example, crash cushions are generally installed on flat conditions, so the percent grade feature in RSAP was not adjusted.

Large fluctuations in baseline costs identified potential parameters to examine in the detailed analysis. The parameters analyzed in the sensitivity analysis are shown in Table 11. These parameter values programmed into RSAP 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 evaluated for freeways were much higher than those evaluated for local roads and rural arterials; since, freeways usually carry higher traffic volumes.

A parameter was defined as significant if the results fluctuated by more than twenty percent. As a result, the significant parameters included: (1) crash cushion offset; (2) average daily traffic; and (3) horizontal curvature. These three parameters were selected to characterize the highway scenarios evaluated in the study. It should be noted that the number of lanes on a local highway was above the twenty-percent threshold, but this parameter was not considered in the detailed analysis since local roads do not tend to have more than two lanes.

Table 11. Sensitivity Analysis Results for (a) Freeways and (b) Local Road

Parameter	Range	Annual Accident Cost ($)	Percent Difference (%)
Crash Cushion Offset (ft)	6	2,840.88	27.5%
	12 (baseline)	2,227.42	na
	18	1,729.37	22.4%
Average Daily Traffic (veh/day)	5,000	2,453.54	20.6%
	10,000 (baseline)	3,091.41	na
	20,000	5,200.27	68.2%
Horizontal Curvature (degrees)	0	2,453.54	26.7%
	2 (baseline)	1,937.24	na
	4	3,534.91	82.5%
No. of Lanes	4	2,453.54	12.3%
	6 (baseline)	2,798.80	na
	8	3,309.96	18.3%
Lane Width (ft)	10	2,453.54	6.7%
	12 (baseline)	2,299.99	na
	14	2,114.62	8.1%
Shoulder Width (ft)	8	2,453.54	0.0%
	10 (baseline)	2,453.54	na
	12	2,453.54	0.0%

(a)

Parameter	Range	Annual Accident Cost ($)	Percent Difference (%)
Crash Cushion Offset (ft)	3	566.98	37.7%
	8 (baseline)	411.81	na
	13	276.02	33.0%
Average Daily Traffic (veh/day)	1,000	411.81	58.1%
	3,000 (baseline)	982.57	na
	5,000	1,170.41	19.1%
Horizontal Curvature (degrees)	0	411.81	38.9%
	5 (baseline)	673.73	na
	10	638.37	5.2%
No. of Lanes	2	411.81	25.3%
	4 (baseline)	551.41	na
	6	626.56	13.6%
Lane Width (ft)	8	411.81	6.8%
	10 (baseline)	385.59	na
	12	373.34	3.2%
Shoulder Width (ft)	4	411.81	0.0%
	6 (baseline)	411.81	na
	8	411.81	0.0%

(b)

A further analysis of curved segments was necessary because of the nonlinear relationship between curvature and accident costs. The sensitivity analysis indicated that the accident cost was reduced on 2-degree curves but increased on 4-degree curves relative to tangent segments on freeways. In RSAP, curvature is treated by increasing encroachment probability by a factor between 1 and 4 [16], as shown in Figure 12 as the "Traffic Adjustment Factor." The effect of this adjustment was studied for three crash cushions with varying lengths.

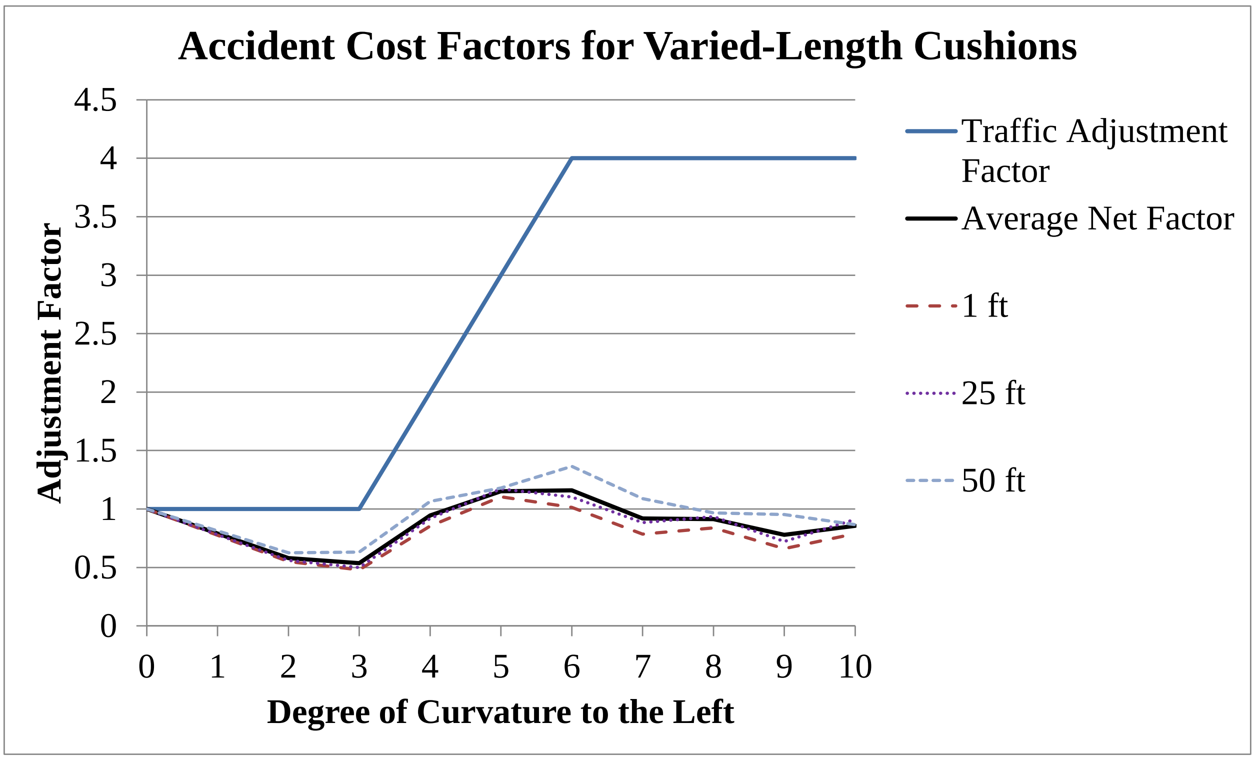


Figure 12. Encroachment Frequency Adjustment Factors

The accident costs of the three systems were simulated for horizontal curvatures ranging from straight to 10 degrees for a left-hand curve. A curvature adjustment factor was determined by dividing those curvature accident costs by the accident cost of a straight segment for a given crash cushion length (i.e., the adjustment factor for a given system on a tangent segment was 1.0). The average adjustment factor for the three system lengths was plotted to compare the effect of curvature at various degrees. For curvatures between 0 and 4 degrees, the simulated accident cost is typically reduced, as shown in Figure 12. However, this does not reflect research on curved highways. For example, consider the effective encroachment angle used in an assumed straight-line encroachment analysis, as described by Figure 13. On a tangent segment, in this example, the roadway departure angle was 20 degrees, and due to the assumption of straight-line encroachments in RSAP, the impact angle was also 20 degrees. For a 4-ft by 2-ft (1.2-m by 0.6-m) fixed object, the projected width at that angle was 3 ft – 5 in. (0.99 m). When the highway curved to the left and the vehicle departed the roadway at the same location (see the horizontal dashed line), the effective angle of encroachment increased to 23 degrees, which in turn increased the projected width to 3 ft – 5 in. (1.04 m). Therefore, as the curvature increases, the probability of being struck increases, and the impact severity increases because the effective angle of impact increases. Additionally, according to the NCHRP Report No. 500, accident rates on curved highway segments are about three times more likely than on tangent segments [20].

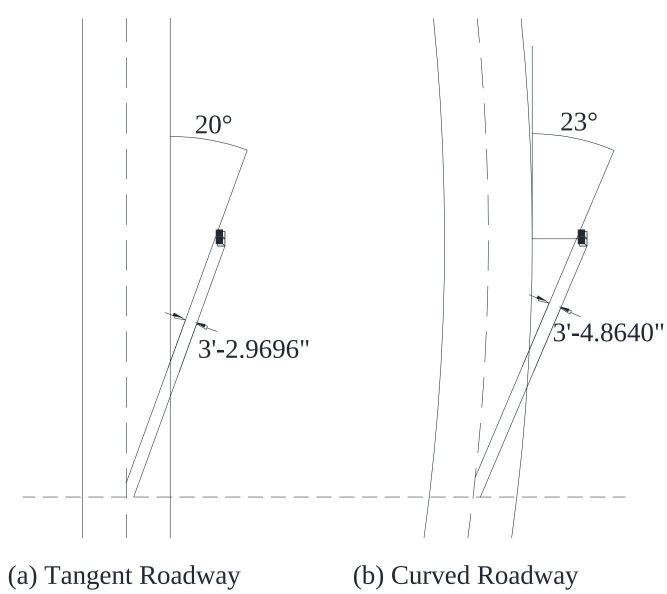


Figure 13. Probability of Impact on Tangent and Curved Roadways

6.4 Parameter Values

The parameters used in RSAP included crash cushion offset, average daily traffic, and horizontal curvature, as shown in Table 12. 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) Geometric Design of Highways and Streets [21]. Curvature was chosen based on a summary of State standards given in NCHRP Report No. 638 [22]. Offsets were set out as far as 35 ft (10.7 m) to determine if at large lateral offsets, a crash cushion would be cost-effective. 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. However, identifying the exact critical offset was outside the scope of this research. Average daily traffic for freeways was 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 common design values for these parameters.

Table 12. 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
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)

6.5 Speed Limit in RSAP

The user interface of RSAP version 2003.04.01 includes a speed limit input. The impact speeds were, in part, determined from the speed and angle distributions for the functional class [16]. For posted speed limits above 55 mph (88.5 km/h), the impact speed is extrapolated from real-world data, which was collected when the national speed limit was 55 mph (88.5 km/h). According to the RSAP Engineer's Manual, this extrapolation was not considered reliable [16]. As a result, only a speed limit of 55 mph (88.5 km/h) was used in the current study to correspond with the TL-3 condition.

7 BENEFIT-COST ANALYSIS

7.1 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 5 from Chapter 6 pits accident costs against direct costs. It is reprinted here for clarification.

$$BC_{2-1} = \frac{(AC_1 - AC_2)}{(DC_2 - DC_1)} \tag{6}$$

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

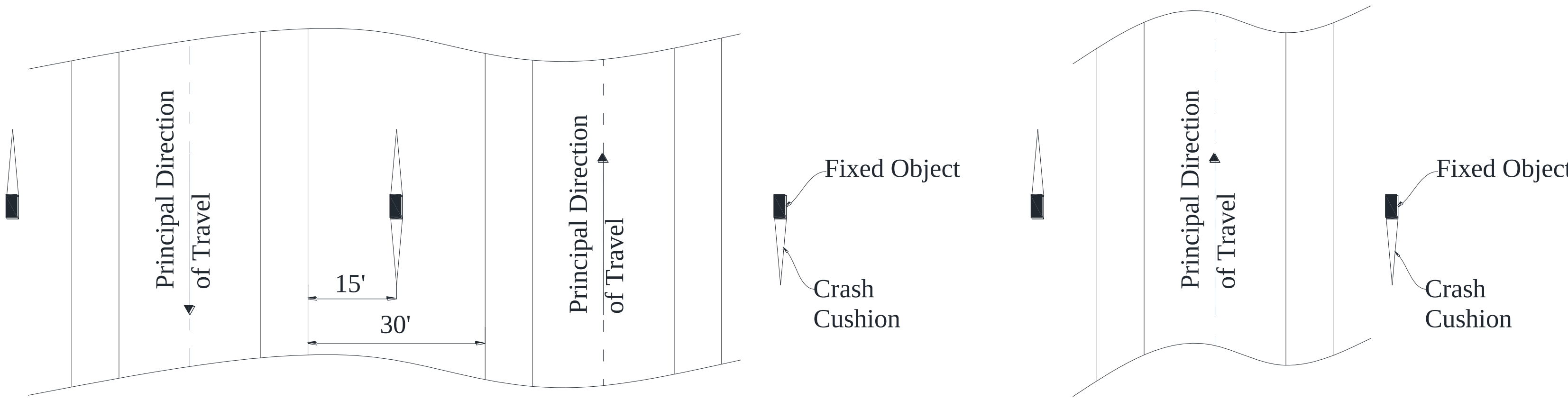
The accident costs used for each scenario and for each design alternative are found in Appendices F through I. The direct costs were described in Chapter 4. The costs were annualized using a design life of 25 years and an interest rate of 4 percent. This interest rate generally does not vary with time, 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 6. A ratio of 1.0 meant 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.

A matrix can be created to compare several alternatives at once and directly to one another, providing the optimal cost-effective option. Results of this analysis indicate a single category for each highway scenario. Additionally, the protected condition can be directly compared to only the unprotected condition for each highway scenario. This will inform engineers of cost-effective options other than the one recommended using the incremental procedure.

7.2 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 4 ft (1.2 m) long by 2 ft (0.6 m) wide, similar to a bridge pier. Considering the limitation of only linear encroachments in RSAP, this bridge pier was effectively equal to a 4-ft (1.2-m) square bridge pier. Default options in RSAP allow for 1.5-ft (0.5-m), 4-ft (1.2-m), and 7-ft (2.1-m) wide rectangular fixed objects. Since the desired width was 2 ft (0.6 ft), a 4-ft (1.2-m) wide object was chosen over a 1.5-ft (0.5-m) wide object because a larger pier (wider equates to higher impact frequency for the unprotected condition) would promote the use of a crash cushion, rather than the “do nothing” alternative.

The smaller pier, 4 ft by 2 ft (1.2 m by 0.6 m), was used to select the crash cushion designs such that the smallest footprint of each system could be compared with one another. When applicable, the median was 30 ft (9.1 m) wide. The lane width was 12 ft (3.7 m) and the shoulder width was 8 ft (2.4 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 14.



(a) Divided Highway (b) Undivided Highway

Figure 14. Crash Cushion Placement on (a) Divided and (b) Undivided Highways

8 METHODS OF BENEFIT-COST ANALYSES

A benefit-cost analysis was conducted in two ways: (1) an index method was developed to compare categories of crash cushions to only the baseline option and (2) an incremental method was incorporated to ascertain the optimal cost-effective option for each highway scenario.

8.1 Index Method

A BC analysis was conducted using RSAP for each highway scenario. Two general BC ratio criteria were used, BC = 2 and BC = 4. One goal of this project was to determine cost-effective options for a given highway scenario rather than a particular crash cushion. It may be possible to have a RLM crash cushion as the best option, but there may be four RGM crash cushions and then one RLM crash cushion that are also cost-effective. In this case, both the RLM and the RGM would be cost-effective.

A system of weighted averages was used to determine if a category was cost-effective for each highway scenario. This system accounted for the number of crash cushion types above the BC threshold and the average BC ratios for each type. Effectively, if one system within the category exceeded the BC threshold, the category as a whole was deemed cost-effective, thus tending towards implementing a crash cushion. This system was best explained through the following example shown in Figure 15. The given BC ratios shown in Figure 15 were generated arbitrarily and do not reflect any of the tested scenarios.

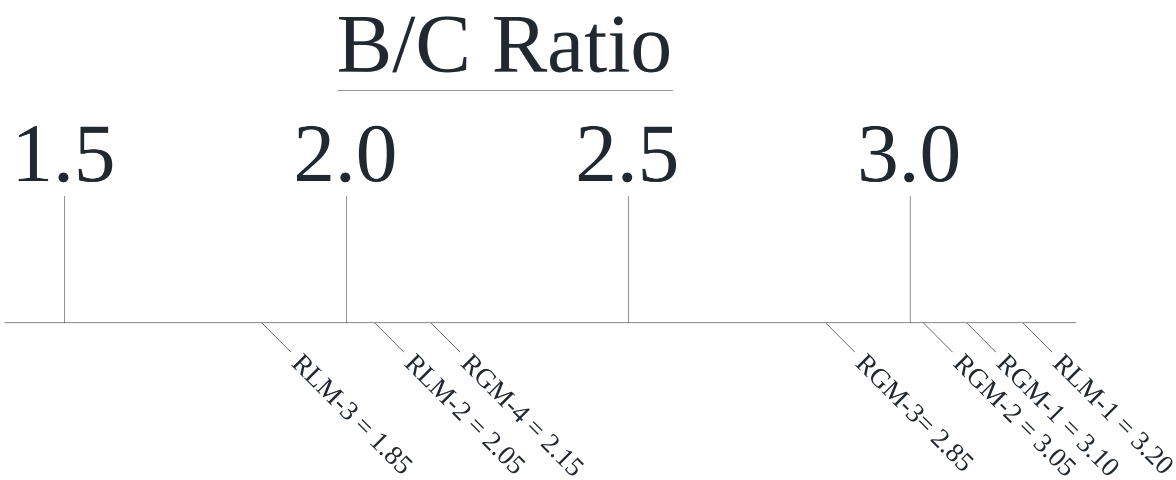


Figure 15. Example of Weighted Average System

In the hypothetical example illustrated by Figure 15, four RGM and three RLM crash cushions were considered. A ratio of the number of beneficial crash cushions to the total number of crash cushions for each category was calculated (r_{RGM} and r_{RLM}). The average BC ratio of each type of crash cushion was determined (BC_{RGM} and BC_{RLM}), 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_{RGM} and I_{RLM}). 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 15 and Equations 7 through 12.

$$r_{RGM} = \frac{4}{4} = 1.000 \tag{7}$$

$$r_{RLM} = \frac{2}{3} = 0.667 \tag{8}$$

$$BC_{RGM} = \frac{3.100+3.050+2.850+2.150}{4} = 2.788 \tag{9}$$

$$BC_{RLM} = \frac{3.200+2.050+1.850}{3} = 2.367 \tag{10}$$

$$I_{RGM} = r_{RGM}BC_{RGM} = 1.000 \times 2.788 = 2.788 \tag{11}$$

$$I_{RLM} = r_{RLM}BC_{RLM} = 0.667 \times 2.367 = 1.579 \tag{12}$$

Where r_{RGM}, r_{RLM} = ratio of cost-effective systems to the total number of systems in the category
BC_{RGM}, BC_{RLM} = average BC ratio of each category using all systems in that category
I_{RGM}, I_{RLM} = cost-effective index for each category, where $I > 0$ is cost-effective

Since I_{RGM} and I_{RLM} were non-zero, both categories in this arbitrary example were cost-effective. Occasionally, the results of the BC analysis indicated counter-intuitive recommendations. For example, the recommendation might be to do nothing for ADTs of 10,000 vpd, but the recommendation might be to install a crash cushion for ADTs of 5,000 vpd. This particular phenomena was the result of the Cooper encroachment data used in RSAP. Therefore, the following rules were adopted in order to provide consistent and conservative recommendations:

1. If there was a cost-effective option on tangent segments, then that option was the minimum recommendation on curved segments, as per results of prior research [20].
2. If there was a cost-effective option at a lower ADT, then that option was the minimum recommendation for higher ADTs.
3. If there was a cost-effective option at larger lateral offsets, then that option was the minimum recommendation for smaller lateral offsets.

8.2 Incremental Method

It is possible that the option with the highest BC ratio (say option “A”) with respect to the unprotected condition may not be the optimal option. Consider another option (say option “B”) whose BC ratio is smaller with respect to the unprotected condition compare with option “A.” The additional cost of option “A” may not be offset by its increased benefit when compared to “B.” Therefore, even though the BC ratio of “A” with respect to the unprotected condition is greater than “B,” the BC ratio of “B” with respect to “A” may be larger than the threshold (e.g., BC = 2).

Because of this possibility, an incremental BC analysis was conducted by categorizing each system after individual simulations were carried out. This categorization was conducted by averaging the simulated accident costs for each highway scenario within each category. Similarly, the direct costs (i.e., annualized installation, repair, labor) were averaged for each highway scenario. Then, Equation 6 could be applied to determine all possible BC ratios. Finally, the resulting matrix of BC ratios was interpreted according to the method outlined in the RSAP Engineer's Manual [16]. The results of this analysis were adjusted according to the three rules described in Section 8.1. An example BC matrix is shown in Figure 16, along with one method of reading the matrix. In this example, the first comparison is between RLM and RGM. Since the BC ratio (-0.70) was less than 2.0, the RLM was not more cost-effective than the RGM. Next, the RGM was compared to the NRS. Since the BC ratio (26.99) was more than 2.0, the RGM option was more cost-effective than the NRS option. Finally, the RGM was compared to the baseline condition ("do nothing" option). Since the BC ratio (21.04) was more than 2.0, the RGM option was recommended as the optimal cost-effective option.

	Baseline	NRS	RGM	RLM
Baseline		0.11	21.04	10.75
NRS			26.99	12.16
RGM				-0.70
RLM				

Figure 16. Example BC Matrix for Incremental Method

9 SIMULATION RESULTS

9.1 Understanding the Design Charts

Each chart employs a color-coded system to identify the best crash cushion category for each scenario. In order to use these charts, the roadway designer or engineer must know the traffic volume (ADT), the degree of curvature of the road (degrees), and the lateral offset of the crash cushion away 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 to assist engineers in selecting the optimal cost-effective option and eight design charts that list all cost-effective options, with each functional class having one chart for each BC ratio. The rural arterial highway was split into two categories, divided and undivided. This distinction was important because divided rural arterials are treated more like freeways in RSAP. Therefore, the speed and angle distribution of encroaching vehicles is different for the undivided and divided rural arterials.

In most cases, NRS crash cushions were not recommended, with the exception of divided rural arterials with offsets of 20 ft (6.1 m). For the later situation, NRS crash cushions were acceptable, although they were not the optimal cost-effective option. However, the engineer is encouraged to use judgment in deciding if NRS systems 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 system. Because NRS crash cushions were not found to be the desired alternative for most cases in permanent settings, they should be limited to temporary usage, such as in construction or work zones.

One important observation for the benefit-cost analysis was that regardless of the repair costs, the recommendations were the same, thus indicating that the installation cost in the simulated scenarios played a far more prominent role in the BC analysis than the maintenance costs.

9.2 Optimal Cost-Effective Recommendations

Based on the incremental BC analysis results, the optimal cost-effective designs subject to the three rules of adjustment are presented in this section. Recall, mobilization costs were not included in the BC analysis; however, because the mobilization costs would be approximately equal for the two systems, the effect of omitting these costs was negligible. Mobilization costs were not included in the BC analysis.

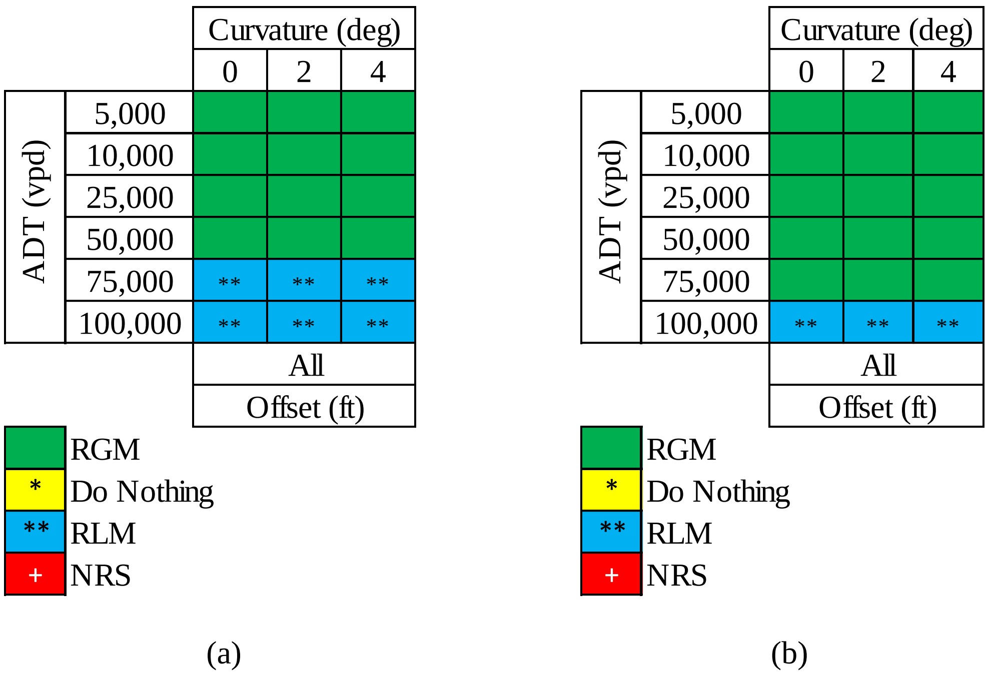


Figure 17. Freeway Guidance for BC Ratios ≥ (a) 2.0 and (b) 4.0

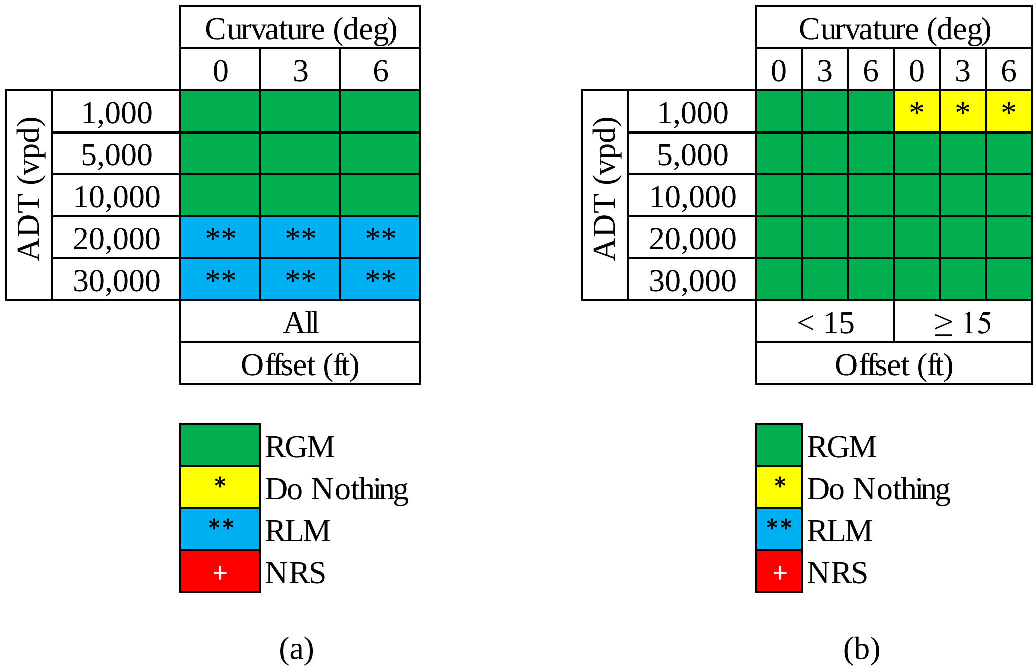


Figure 18. Divided Rural Arterial Guidance for BC Ratios ≥ (a) 2.0 and (b) 4.0

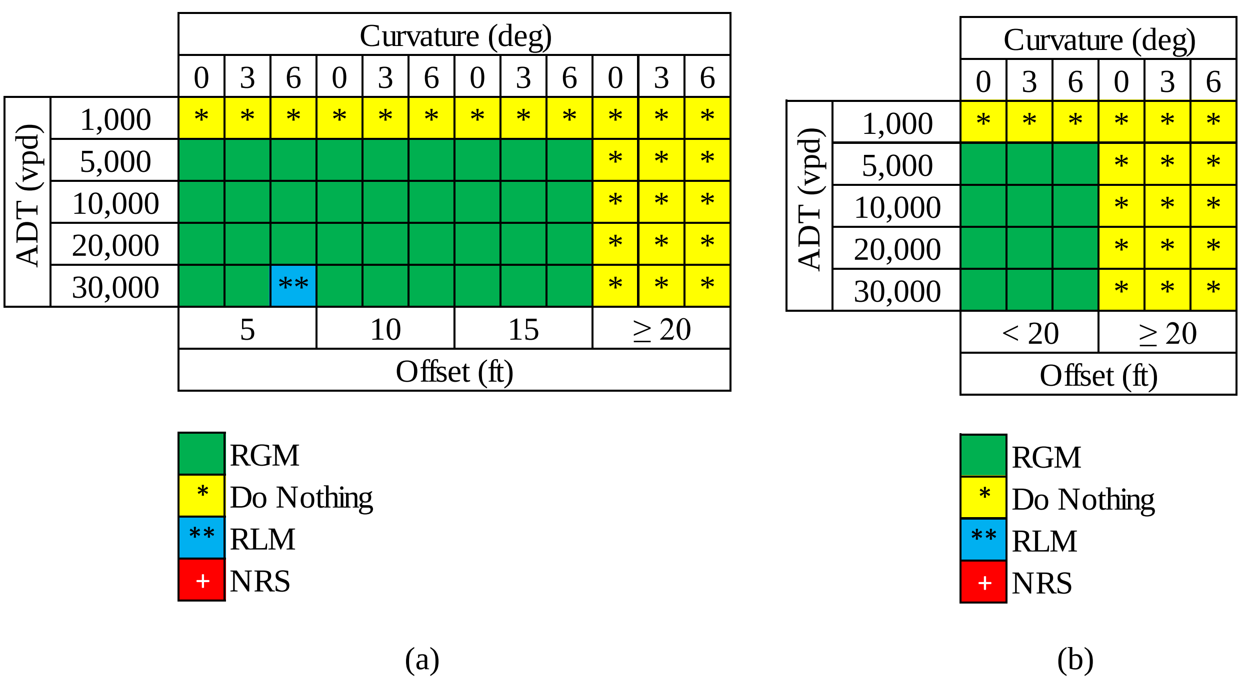
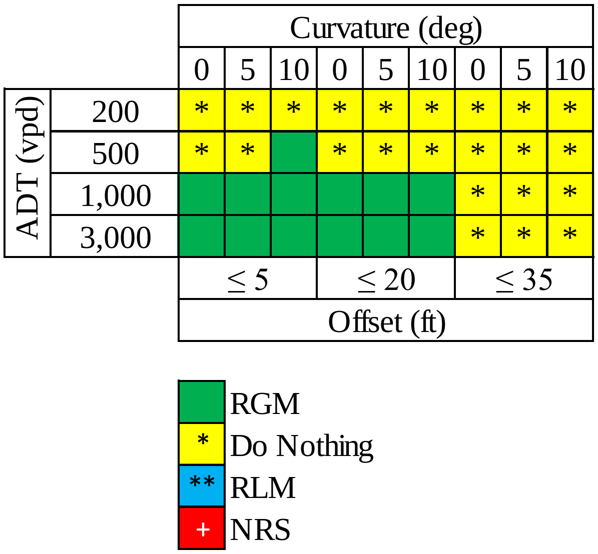
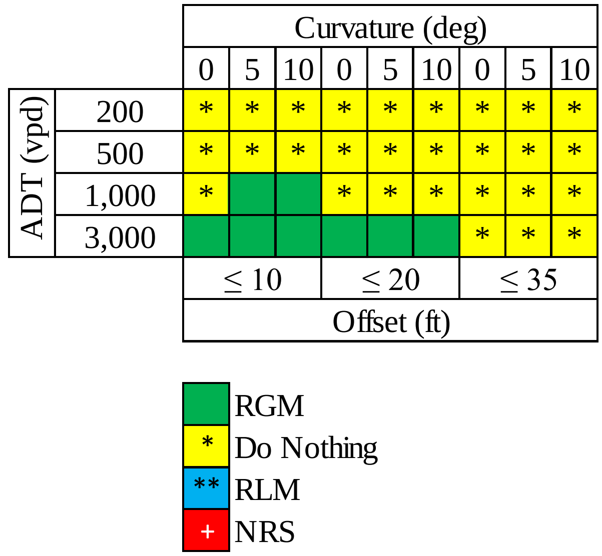


Figure 19. Undivided Rural Arterial Guidance for BC Ratios ≥ (a) 2.0 and (b) 4.0





(a) (b)

Figure 20. Local Highway Guidance for BC Ratios ≥ (a) 2.0 and (b) 4.0

9.3 All Cost-Effective Options

Using the index method, all cost-effective options for each highway scenario are presented in this section. As before, mobilization costs were not included in the BC analysis. Since the mobilization costs would be approximately equal for the two systems, the effect of omitting these costs was negligible.

For freeways, all of the simulated scenarios indicated that both RGM and RLM systems were cost-effective for both BC ratio thresholds of 2.0 and 4.0, as shown in Figure 21. Redirecting (RLM and RGM) and Non-redirecting (NRS) systems had to be considered separately. Therefore, the rules designated for adjusting the design charts in the previous section were applied to RLM and RGM systems in the following charts. However, those rules were slightly adjusted for NRS systems. Notably, the aforementioned rule for offsets stated that if a category was cost-effective at a larger offset, it would also be cost effective at a smaller offset. However, NRS systems did not abide by this rule. By nature, they can allow an errant vehicle to pass through them and strike a fixed object. This can be especially severe as the fixed object and crash cushion is close to the road, for which case the accident cost reduction may be small, or even negative. As the lateral offset increases, this severity naturally decreases to a point where the NRS system may be cost-effective, but then as the lateral offset continues to increase, the accident frequency may become too small for the NRS to be cost-effective. This was apparent on divided rural arterials, as shown in Figure 22. For this functional class, only RGM systems were cost-effective at the lowest simulated ADT, but elsewhere, the recommendations were the same for BC thresholds of 2.0 and 4.0.

For undivided rural arterials, NRS systems were not cost-effective for any simulated scenario, and on lateral offsets greater than or equal to 20 ft (6.1 m), none of the three categories were cost-effective at either BC threshold, as shown in Figure 23. However, at smaller lateral offsets, RGM were commonly cost-effective and RLM systems became cost-effective as the traffic volume increased or the lateral offset approach the minimum simulated value.

Finally, RLM systems were cost-effective on local highways only at the larger simulated ADTs, but RGM systems were cost effective for as little as 500 vpd, when the BC threshold was 2.0, as shown in Figure 24. Further, as lateral offset increased to large enough values, none of the three categories were cost effective, despite an increase in traffic volume and horizontal curvature.

		Curvature (deg)		
		0	2	4
ADT (vpd)	5,000	B	B	B
	10,000	B	B	B
	25,000	B	B	B
	50,000	B	B	B
	75,000	B	B	B
	100,000	B	B	B
		All		
		Offset (ft)		

Key:

A	All Systems		E	RGM only
B	RGM and RLM		F	RLM only
C	RLM and NRS		G	NRS only
D	RGM and NRS		N	None

(a) BC Ratio = 2.0

		Curvature (deg)		
		0	2	4
ADT (vpd)	5,000	B	B	B
	10,000	B	B	B
	25,000	B	B	B
	50,000	B	B	B
	75,000	B	B	B
	100,000	B	B	B
		All		
		Offset (ft)		

Key:

A	All Systems		E	RGM only
B	RGM and RLM		F	RLM only
C	RLM and NRS		G	NRS only
D	RGM and NRS		N	None

(b) BC Ratio = 4.0

Figure 21. All Cost-Effective Options for Freeways

ADT (vpd)	Curvature (deg)														
	0	3	6	0	3	6	0	3	6	0	3	6	0	3	6
1,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
5,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
10,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
20,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
30,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
	5			10			15			20			35		
	Offset (ft)														

Key:

A	All Systems
B	RGM and RLM
C	RLM and NRS
D	RGM and NRS

E	RGM only
F	RLM only
G	NRS only
N	None

(a) BC Ratio = 2.0

ADT (vpd)	Curvature (deg)														
	0	3	6	0	3	6	0	3	6	0	3	6	0	3	6
1,000	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
5,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
10,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
20,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
30,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B
	5			10			15			20			35		
	Offset (ft)														

Key:

A	All Systems
B	RGM and RLM
C	RLM and NRS
D	RGM and NRS

E	RGM only
F	RLM only
G	NRS only
N	None

(b) BC Ratio = 4.0

Figure 22. All Cost-Effective Options for Divided Rural Arterials

		Curvature (deg)											
		0	3	6	0	3	6	0	3	6	0	3	6
ADT (vpd)	1,000	E	E	E	E	E	E	E	E	E	N	N	N
	5,000	B	B	B	B	B	B	B	B	B	N	N	N
	10,000	B	B	B	B	B	B	B	B	B	N	N	N
	20,000	B	B	B	B	B	B	B	B	B	N	N	N
	30,000	B	B	B	B	B	B	B	B	B	N	N	N
		5			10			15			≥ 20		
		Offset (ft)											

Key:

A	All Systems	E	RGM only
B	RGM and RLM	F	RLM only
C	RLM and NRS	G	NRS only
D	RGM and NRS	N	None

(a) BC Ratio = 2.0

		Curvature (deg)											
		0	3	6	0	3	6	0	3	6	0	3	6
ADT (vpd)	1,000	N	N	N	N	N	N	N	N	N	N	N	N
	5,000	B	B	B	B	B	B	E	E	E	N	N	N
	10,000	B	B	B	B	B	B	E	E	E	N	N	N
	20,000	B	B	B	B	B	B	E	E	E	N	N	N
	30,000	B	B	B	B	B	B	E	E	E	N	N	N
		5			10			15			≥ 20		
		Offset (ft)											

Key:

A	All Systems	E	RGM only
B	RGM and RLM	F	RLM only
C	RLM and NRS	G	NRS only
D	RGM and NRS	N	None

(b) BC Ratio = 4.0

Figure 23. All Cost-Effective Options for Undivided Rural Arterials

ADT (vpd)	Offset (ft)	5			10			15			20			35		
	Curvature (deg)	0	5	10	0	5	10	0	5	10	0	5	10	0	5	10
ADT (vpd)	200	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	500	E	E	E	N	N	E	N	N	N	N	N	N	N	N	N
	1,000	B	B	B	E	E	B	E	E	E	E	E	E	N	N	N
	3,000	B	B	B	B	B	B	B	B	B	B	B	B	E	E	E

Key:

A	All Systems
B	RGM and RLM
C	RLM and NRS
D	RGM and NRS
E	RGM only
F	RLM only
G	NRS only
N	None

(a) BC Ratio = 2.0

ADT (vpd)	Offset (ft)	5			10			15			20			35		
	Curvature (deg)	0	5	10	0	5	10	0	5	10	0	5	10	0	5	10
ADT (vpd)	200	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	500	E	E	E	N	N	E	N	N	N	N	N	N	N	N	N
	1,000	B	B	B	E	E	B	E	E	E	E	E	E	N	N	N
	3,000	B	B	B	B	B	B	B	B	B	B	B	B	E	E	E

Key:

A	All Systems
B	RGM and RLM
C	RLM and NRS
D	RGM and NRS
E	RGM only
F	RLM only
G	NRS only
N	None

(b) BC Ratio = 4.0

Figure 24. All Cost-Effective Options for Local Highways

10 EXAMPLES

Four example applications are described below, one for each highway type. These examples should help highway engineers to understand how the design charts shown in Chapter 9 are used.

10.1 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:

- Figure 17a
- Select a RLM Crash Cushion

Other Cost-Effective Solutions:

- Figure 21a
- RGM is also cost-effective

10.2 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:

- Figure 18b
- Select a RGM Crash Cushion

Other Cost-Effective Solutions:

- Figure 22b
- RLM is also cost-effective

10.3 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 = 1,000 vpd
- Offset = 5 ft (1.5 m)
- Degree of Curvature = 0 degrees
- Minimum BC ratio = 2.0

Solution:

- Figure 19a
- Select "Do Nothing"

Other Cost-Effective Solutions:

- Figure 23a

- RGM is also cost-effective (note: the “Do Nothing” is the optimal option, not the only option)

10.4 Local Highway Example

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

- Local
- ADT = 3,000 vpd
- Offset = 5 ft (1.5 m)
- Degree of Curvature = 0 degrees
- Minimum BC ratio = 2.0

Solution:

- Figure 20a
- Select a RGM Crash Cushion

Other Cost-Effective Solutions:

- Figure 24a
- RLM is also cost-effective

11 PURELY MAINTENANCE COSTS

11.1 RSAP's Treatment of Crash Cushions

In RSAP version 2003.04.01, a crash cushion may be modeled as either redirecting or non-redirecting and as a Test Level 2 (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 within the same category 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 category, they can be analyzed based on maintenance costs alone. These costs may include the costs to repair the structure. This approach should only be used when the impact frequency is known at the location *a priori*, and may be especially relevant in "black spots," gore areas, exit ramps, and any other abnormal location that may violate driver expectation. Impact frequency is typically defined as the number of impacts per year resulting in required maintenance, where the impact event specifically involves the crash cushion or the fixed object the crash cushion would be called upon to shield.

11.2 Impact Frequency

Assuming a linear relationship between life cycle costs and impact frequencies, a mathematical 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 the incremental BC analysis, it was determined that NRS 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 locations. Therefore, only RGM and RLM 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 13.

$$LC = (IC) + (MC) \times (IF) \tag{13}$$

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 RGM family and a RLM family can be modeled after the manner of Equation 13. The two can be equated to determine the minimum impact frequency at which a redirecting RLM system becomes more cost-effective than a redirecting RGM system. The final expression for this minimum impact frequency is given in Equation 14.

$$IF_{min} = \frac{IC_{RLM} - IC_{RGM}}{MC_{RGM} - MC_{RLM}} \tag{14}$$

Where IF_{min} = Minimum impact frequency to consider RLM systems
IC_{RLM} = Average annualized installation cost for RLM systems
IC_{RGM} = Average annualized installation cost for RGM systems
MC_{RLM} = Average maintenance cost of a RLM system
MC_{RGM} = Average maintenance cost of a RGM system

For the cost information provided by State DOTs, the average installation costs, annualized over 25 years, for RLM and RGM crash cushions were \$1,887 and \$910, respectively. Using these values as constants and varying the maintenance costs according to which FHWA crash tests were used and whether or not labor costs were included, Table 13 was developed for reference. When considering only the three mutual FHWA crash tests and the full velocity of the crash test and when including labor costs, the average maintenance costs were \$507 and \$4,921, respectively. Using Equation 14, the minimum impact frequency at which to consider a redirecting RLM system was 0.22 impacts per year or 1 impact every 4.52 years. This condition represented the lowest impact frequency. The highest recommended impact frequency was for the condition of using the three mutual tests and the reduced IS for a Local highway and when labor costs were neglected, resulting in a frequency of 0.74 impacts per year or 1 impact every 1.36 years.

Table 13. Minimum Impact Frequency for Using RLM Systems.

	Conditions		Freeway	Arterials	Local Highways
Impacts Per Year	Using full labor costs	Using all FHWA crash test results	0.27		
		Using only 3 mutual FHWA results	0.22		
		Using reduced Velocity for 3 mutual results	0.41	0.53	0.66
	Using zero labor costs	Using all FHWA crash test results	0.25		
		Using only 3 mutual FHWA results	0.23		
		Using reduced Velocity for 3 mutual results	0.44	0.58	0.74
	Conditions		**Freeway**	**Arterials**	**Local Highways**
Years Between Impacts	Using full labor costs	Using all FHWA crash test results	3.69		
		Using only 3 mutual FHWA results	4.52		
		Using reduced Velocity for 3 mutual results	2.45	1.88	1.52
	Using zero labor costs	Using all FHWA crash test results	3.99		
		Using only 3 mutual FHWA results	4.33		
		Using reduced Velocity for 3 mutual results	2.29	1.72	1.36

11.3 High Impact-Frequency Location Example

A particular location is struck 1 time every 2 years. All other traffic and roadway characteristics were the same as the Freeway example (Section 10.1). Find the most cost-effective crash cushion type to be used. Use an average impact velocity (reduced impact severity) and only mutual FHWA crash test results.

$$Impact\ Frequency = \frac{1\ impact}{2\ years} = 0.5\ impacts/year$$

The minimum impact frequency for recommending RLM systems on a freeway (impact severity was reduced using a speed of 45.3 mph or 73.0 km/h) based on only mutual FHWA crash tests is 0.41 impacts per year (see Table 13). Therefore, a RLM system would be recommended for the case of 0.5 impacts per year or more. Alternatively, the maximum number of times between impacts to recommend a RLM system for this example is 2.45 years. Because an impact occurs every 2 years, a RLM system would be recommended.

12 CONCLUSIONS AND RECOMMENDATIONS

This report analyzed several crash cushions and categorized them as redirecting with repair costs greater than $1,000 (RGM), redirecting with repair costs less than $1,000 (RLM), or non-redirecting sacrificial (NRS). NRS crash cushions were the least expensive up front, although they had the highest ratio of repair costs to installation costs. RLM crash cushions tended to be the most expensive up front, but they had the lowest ratio of repair costs to installation costs. The installation costs for RGM systems were more than for the NRS but less than RLM systems. Similarly, the ratio of the repair costs to the installation costs for RGM systems was more than for RLM systems but less than the NRS.

RLM crash cushions required very little repair time and as such, had the lowest labor costs. However, because installation costs made up a vast majority of the direct costs, the positive effect of the labor costs on these systems was small in the BC analyses. As a result, the RGM crash cushion was recommended over the RLM for more scenarios where a redirecting crash cushion was deemed to be cost-effective. In some locations, a crash cushion is typically not used, based on minimum BC ratios of 2.0 and 4.0. In these cases, the engineer is encouraged to use field experience and site-specific engineering analyses to determine which crash cushion should be used, if any at all.

RLM systems are cost-effective at locations that experience high crash rates. The purpose in utilizing RSAP was to generate impact frequencies at locations where such a parameter would be unknown, and the maximum simulated impact frequency was 0.13 impacts per year or 1 impact every 7.7 years, as observed on freeways with traffic volumes of 100,000 vpd. Therefore, the BC analytical results apply to general roadside conditions, rather than to specific, high-frequency locations, such as “black spots,” gore areas, exit ramps, or any other location that may violate driver expectation.

When only the impact frequency was studied, a RSAP analysis was not needed. By plotting the impact frequency against the life cycle costs (installation plus the cost per impact), it was shown that a minimum impact frequency at which to consider RLM systems over RGM systems was between 0.22 and 0.74 impacts per year. This observation depended on: (1) whether labor costs were included; (2) if all the FHWA crash data were used (versus only the mutual tests); (3) if the IS from the crash tests were reduced to represent an average impact event; and (4) which functional class was used to reduce the IS.

For the simulated scenarios, RGM crash cushions were the optimal cost-effective category of crash cushions on freeways and divided rural arterials for a minimum BC ratio of 2.0 and for traffic volumes up to 75,000 and 20,000 vpd, respectively, as shown in Figures 17 and 18. RGM crash cushions and the “do nothing” alternative competed with each other on undivided rural arterials and local highways. For undivided rural arterials, RGM crash cushions were always the optimal cost-effective option, except on highway scenarios with low traffic volumes and large lateral offsets, as shown in Figure 19. This finding 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, as shown in Figure 20.

A summary of the recommendations for selecting various categories of crash cushions is given in Table 14. These design guidelines are segregated by functional class, and recommendations are made for various ranges of impact frequencies. For example, if the impact frequency is less than

0.13 impacts per year (or 1 impact every 7.7 years) on a freeway, then the engineer is encouraged to use Figure 17 for guidance. For this design guideline, it was assumed that labor costs were included in the analysis, that only the mutual crash test data was used, and that the impact severity was reduced to represent an average impact (see Table 13). For impact frequencies between the lower and upper bounds (e.g., "0.13 – 0.41" for freeways), field experience and site-specific engineering analyses are recommended because the RSAP scenarios could not reasonably reproduce those frequencies unless traffic volumes were increased to over 800,000 vpd for some highway types. Therefore, it was uncertain if the RGM, RLM, NRS, or "do nothing" option was most viable.

For locations where impact frequency is unknown (e.g., new construction locations), a low impact frequency should be assumed such that the results of the BC analysis are applicable. In general, this may result in the lowest up-front installation costs for a crash cushion. Then, after the system has been in place for a substantial period, one should conduct a site-specific analysis to ascertain actual impact frequencies. If there were no incidents, then the process should be repeated periodically until the engineer is certain that a RLM system is not needed. However, if the impact frequency is high enough, as indicated by Table 13, then the use of a RLM system should be considered.

Table 14. Design Guidelines for Crash Cushion Selection

Functional Class	Impacts per Year	Optimal Recommendation	For Additional Cost-Effective Options
Freeway	< 0.13 or unknown	Figure 17	Figure 21
	0.13 – 0.41	Site-Specific Engineering Analysis	na
	> 0.41	RLM	na
Divided Rural Arterial	< 0.05 or unknown	Figure 18	Figure 22
	0.05 – 0.53	Site-Specific Engineering Analysis	na
	> 0.53	RLM	na
Undivided Rural Arterial	< 0.02 or unknown	Figure 19	Figure 23
	0.02 – 0.53	Site-Specific Engineering Analysis	na
	> 0.53	RLM	na
Local	< 0.01 or unknown	Figure 20	Figure 24
	0.01 – 0.66	Site-Specific Engineering Analysis	na
	> 0.66	RLM	na

13 LIMITATIONS AND FUTURE WORK

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. These costs were based on limited data from the State DOTs and manufacturers. Therefore, the accuracy of the final results of this study was highly dependent on the provided cost value, and the sample size of survey results was small. Only a few States provided information (i.e., only Kansas, Minnesota, Nebraska, and Wisconsin). Also, some of the data supplied by the States was not realistic and was discarded assuming that the questions in the survey were misinterpreted or could not be answered to the level of precision needed. Thus, the sample size of the data was further reduced.

In addition, each crash cushion performs differently. In comparing similar lengths, some crash cushions will perform better than others by reducing occupant risk. RSAP, however, does not adjust the severity index of the crash cushion. Thus, all crash cushions are treated equal on the basis of impact conditions. The only differences were their direct costs and their impact frequencies based on their dimensions. 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 the 1970's [19], which was prior to the repeal of the national speed limit of 55 mph (88.5 km/h). Therefore, modern-day traffic behavior may differ from that of the 1970's in a way that may alter the speed and angle distributions used by RSAP to simulate impact conditions.

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 locations that closely match those simulated. Otherwise, for a possible retrofit or a change in the type of crash cushion currently being used, the associated costs may be significantly different than those used in this report, and a case-specific benefit-cost analysis should be conducted by the engineer.

High frequency locations were not modeled; including “black spots,” gore areas, exit ramps, or any other location that may violate driver expectation. 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 0.13 impacts per year, and that was on a freeway with 100,000 vpd on a 4 degree curve and a lateral offset of 5 ft (1.5 m). Most scenarios, especially low-volume roadway scenarios, would experience impact frequencies far less than 0.13 impacts per year. Therefore, if the accident frequency is known, the BC analysis results contained herein should only be used at locations with fewer than the maximum accident frequency recommended in Chapter 12. Otherwise, other systems may be considered as well, such as the bullnose guardrail system or a longitudinal barrier with an energy-absorbing terminal.

For future studies, States should consider recording repair times for each system as well as the level of damage to the system. This data should be correlated with accident data collected by police or medical personnel such that accident severity may be studied for each system. With this data, the severity indexes used by RSAP could be altered to reflect the performance of each system, whereas at the moment, they are all treated equally. In addition to the time required to repair the system, the time between the impact event and the repair should be noted for each incident. This information could be used to demonstrate the necessity for repairing damaged crash cushions as quickly as possible.

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15 APPENDICES

Appendix A. State DOT Survey Questionnaire

Questionnaire on Current Guidelines for Crash Cushion Use
August 12, 2009

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. Example Survey of Repair Costs and Repair Time

Questionnaire on Repair Costs for Crash Cushions
July 18, 2012

Dear Company X 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, non-redirecting sacrificial (such as sand barrels), redirecting sacrificial, and redirecting low-maintenance. To complete this study, MwRSF requires repair cost information for each of the systems considered in this study and commonly used by many State Departments of Transportation (DOTs). A short survey has been developed for use in collecting this information. In-service performance evaluation data is preferable, but if crash testing data is all that is available, that will suffice as well. Please give an estimated cost for materials and an estimated time to repair the attenuator in total man hours. If you could fill out this survey and return it to the address below or email it to one of the listed contacts, your participation will be greatly appreciated. Thank you for your time.

Midwest Roadside Safety Facility
Nebraska Transportation Center
University of Nebraska-Lincoln
2200 Vine Street
130 Whittier Building
Lincoln, Nebraska 68583-0853
(402) 472-0970
kevin.schrum@huskers.unl.edu or kpolivka2@unl.edu

System*	Performance Evaluation (PE) or FHWA testing (FT)**	Average Cost of Repair Parts ($)	Average Repair Time (total man hours)***
System Y			

* Provide information that most closely matches the system description.

** Indicate if the estimated costs and time of repair were from in-service performance evaluations (PE) or from Federal Highway Administration (FHWA) crash testing (FT).

*** Does not include the time required to mobilize maintenance crews.

Appendix C. Summary of State DOT Survey Responses

Table C-1. Summary of Responses to State DOT Surveys*

State	System	Average Installation Cost ($)	Average Repair Cost	Average Regular Maintenance Cost per Year	Replacement Parts Required in Inventory	Average Cost of Inventory	Average Lane Closure Time (hrs)	Test Level	Speed Limit (mph)	Length (ft)	Width (ft)
Kansas	SCI	21,000 - 28,600	1,153	Unknown	No	NA	0.33	2 and 3	40 - 70		
	QuadGuard	17,000	6,300	500	Yes			2 and 3	40 - 70		
	Sand Barrels	3,400	60 - 80 per barrel		No	NA		2 and 3	35 - 70		
Minnesota	Great System	3,000	4,025.03	20,125.16	Yes	5,000	4	3	60		
	REACT 350	30,000 - 45,000	27,788.83	27,788.83	Yes	432	5	3	70		
	Energite Barrels	5,000	3,700.14	14,800.56	Yes	226.8	4	3	60		
	QuadGuard	40,000	4,271.31	98,240.09	Yes	150,785.35	6	3	65 - 70		
	QuadGuard Elite	40,000	4,271.31	98,240.09	Yes	150,785.35	6	3	65 - 70		
	TAU II	18,500	3,924.62	47,095.42	Yes	55,127.00	4	3	65		
Nebraska	TRACC	12,500	17,260		Yes	NA	3	3	65		
New York Upstate	TAU II	18,000	low		Yes	18138.50		3		27	2
	QuadGuard	18,000			Yes			3		36	2
	REACT 350	18,000	low	low	No	NA		3		30	2
	TRACC	18,000			Yes		low	3		21	2
	SCI	18,000	81		Yes	1.00	2	3		22	2
New York Downstate	TAU II	30,000	low		Yes	18138.50		3		27	2
	QuadGuard	30,000			Yes			3		36	2
	REACT 350	30,000	low	low	No	NA		3		30	2
	TRACC	30,000			Yes		low	3		21	2
	SCI	30,000	81		Yes	1.00	2	3		22	2

*Responses shown here are unaltered from how they were received from the State DOTs

Appendix D. All FHWA Repair Cost Data from Manufacturers

System	NCHRP 350 TL-3 Test	Parts Cost	Man Hours (hr)	Total Repair Cost*	Average Repair Cost
SCI	31	$1	2	$101	$61
	32	$1	2	$101	
	33	$1	2	$101	
	37	$0	0	$0	
	39	$0	0	$0	
TRACC, TL-3	31	$1,320	2.5	$1,445	$1,434
	33	$2,420	2.5	$2,545	
	37	$1,710	2	$1,810	
	38	$610	1.5	$685	
	39	$610	1.5	$685	
TAU II	30	$2,985	3	$3,135	$2,148
	31	$3,480	3	$3,630	
	32	$3,960	3	$4,110	
	33	$3,960	3	$4,110	
	36	$0	3	$150	
	37	$0	3	$150	
	38	$1,118	3	$1,268	
	39	$480	3	$630	
QG TL-3	30	$4,475	1	$4,525	$2,932
	31	$4,475	1	$4,525	
	32	$4,475	1	$4,525	
	33	$5,519	1.5	$5,594	
	36	$0	0	$0	
	37	$1,560	1	$1,610	
	38	$1,530	1	$1,580	
	39	$1,050	1	$1,100	
QG Elite TL-3	30	$0	1	$50	$519
	31	$0	1	$50	
	32	$0	1	$50	
	33	$745	1	$795	
	36	$0	0	$0	
	37	$1,020	1	$1,070	
	38	$1,530	1	$1,580	
	39	$510	1	$560	
REACT 350	30	$0	1	$50	$58
	31	$0	1	$50	
	32	$0	1	$50	
	33	$50	1	$100	
	37	$0	1	$50	
	38	$0	1	$50	
QUEST TL-3	30	$9,000	3	$9,150	8406.25
	31	$9,000	3	$9,150	
	32	$9,000	3	$9,150	
	33	$9,800	3	$9,950	
	36	$0	0	$0	
	37	$9,800	3	$9,950	
	38	$9,800	3	$9,950	
	39	$9,800	3	$9,950	

*Assuming a labor cost of $50 per hour

Appendix E. FHWA Repair Cost Data for Shared Tests

System	NCHRP 350 TL-3 Test	Parts Cost	Man Hours (hr)	Total Repair Cost*	Average Repair Cost
SCI	31	$1	2	$101	$67.33
	33	$1	2	$101	
	37	$0	0	$0	
REACT 350	31	$0	1	$50	$66.67
	33	$50	1	$100	
	37	$0	1	$50	
QG Elite	31	$0	1	$50	$638.33
	33	$745	1	$795	
	37	$1,020	1	$1,070	
TRACC	31	$1,320	2.5	$1,445	$1,933.33
	33	$2,420	2.5	$2,545	
	37	$1,710	2	$1,810	
TAU II	31	$3,480	0.5	$3,505	$2,518.83
	33	$3,960	1.83	$4,052	
	37	$0	0	$0	
QG	31	$4,475	1	$4,525	$3,909.67
	33	$5,519	1.5	$5,594	
	37	$1,560	1	$1,610	
QUEST	31	$9,000	3	$9,150	$9,683.33
	33	$9,800	3	$9,950	
	37	$9,800	3	$9,950	

*Assuming a labor cost of $50 per hour

Appendix F. Freeway Accident Costs

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
5,000	0	5	74927.40	55999.12	58001.10	58222.93	58724.09	57483.27	58222.93	57813.41	76658.68
		15	57620.53	39542.42	40197.86	40366.13	41747.01	40760.67	40366.13	40917.36	58478.28
		25	47724.43	33163.46	33987.74	34153.87	34783.65	33853.63	34153.87	34605.98	49149.41
		35	39594.11	26513.70	28292.87	28400.52	28262.78	27504.11	28434.15	28905.29	40562.79
	2	5	74927.40	55999.12	58001.10	58222.93	58724.09	57483.27	58222.93	57813.41	76658.68
		15	57620.53	39542.42	40197.86	40366.13	41747.01	40760.67	40366.13	40917.36	58478.28
		25	47724.43	33163.46	33987.74	34153.87	34783.65	33853.63	34153.87	34605.98	49149.41
		35	39594.11	26513.70	28292.87	28400.52	28262.78	27504.11	28434.15	28905.29	40562.79
	4	5	74927.40	55999.12	58001.10	58222.93	58724.09	57483.27	58222.93	57813.41	76658.68
		15	57620.53	39542.42	40197.86	40366.13	41747.01	40760.67	40366.13	40917.36	58478.28
		25	47724.43	33163.46	33987.74	34153.87	34783.65	33853.63	34153.87	34605.98	49149.41
		35	39594.11	26513.70	28292.87	28400.52	28262.78	27504.11	28434.15	28905.29	40562.79
10,000	0	5	96789.04	73342.93	75895.84	76177.73	76813.90	75237.02	76177.73	75657.17	98848.59
		15	75411.75	51814.72	52688.75	52912.95	54749.59	53438.26	52912.95	53646.78	76501.99
		25	62632.08	43248.19	44360.91	44584.98	45433.81	44179.99	44584.98	45194.43	64493.96
		35	51883.69	34218.93	36642.99	36789.48	36602.04	35568.98	36835.25	37476.12	53174.84
	2	5	96789.04	73342.93	75895.84	76177.73	76813.90	75237.02	76177.73	50168.06	98848.59
		15	75411.75	51814.72	52688.75	52912.95	54749.59	53438.26	52912.95	37992.32	76501.99
		25	62632.08	43248.19	44360.91	44584.98	45433.81	44179.99	44584.98	32652.03	64493.96
		35	51883.69	34218.93	36642.99	36789.48	36602.04	35568.98	36835.25	24998.05	53174.84
	4	5	96789.04	73342.93	75895.84	76177.73	76813.90	75237.02	76177.73	75657.17	98848.59
		15	75411.75	51814.72	52688.75	52912.95	54749.59	53438.26	52912.95	53646.78	76501.99
		25	62632.08	43248.19	44360.91	44584.98	45433.81	44179.99	44584.98	45194.43	64493.96
		35	51883.69	34218.93	36642.99	36789.48	36602.04	35568.98	36835.25	37476.12	53174.84

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
25,000	0	5	179201.30	147476.22	150436.33	150770.27	151529.03	149661.39	150770.27	150154.70	182512.93
		15	149866.18	117613.92	119157.12	119548.55	122686.81	120458.65	119548.55	120817.12	151156.11
		25	134731.39	101079.61	103368.02	103823.90	105535.61	102998.73	103823.90	105055.33	137228.24
		35	117736.66	81051.76	86675.26	87009.47	86581.70	84205.21	87113.76	88567.33	120003.52
	2	5	179201.30	147476.22	150436.33	150770.27	151529.03	149661.39	150770.27	114632.67	182512.93
		15	149866.18	117613.92	119157.12	119548.55	122686.81	120458.65	119548.55	89729.00	151156.11
		25	134731.39	101079.61	103368.02	103823.90	105535.61	102998.73	103823.90	77325.45	137228.24
		35	117736.66	81051.76	86675.26	87009.47	86581.70	84205.21	87113.76	58175.05	120003.52
	4	5	179201.30	147476.22	150436.33	150770.27	151529.03	149661.39	150770.27	150154.70	182512.93
		15	149866.18	117613.92	119157.12	119548.55	122686.81	120458.65	119548.55	120817.12	151156.11
		25	134731.39	101079.61	103368.02	103823.90	105535.61	102998.73	103823.90	105055.33	137228.24
		35	117736.66	81051.76	86675.26	87009.47	86581.70	84205.21	87113.76	88567.33	120003.52
50,000	0	5	477888.67	354624.48	367811.86	369273.12	372574.06	364400.64	369273.12	366575.42	488839.11
		15	365304.84	248163.48	252262.54	253317.87	262020.92	255796.75	253317.87	256783.04	370955.02
		25	300401.43	209440.30	214303.73	215289.75	219044.33	213509.23	215289.75	217982.42	309677.31
		35	248486.01	172332.49	181833.11	182419.20	181669.48	177576.81	182602.58	185183.60	254552.67
	2	5	477888.67	354624.48	367811.86	369273.12	372574.06	364400.64	369273.12	240508.65	488839.11
		15	365304.84	248163.48	252262.54	253317.87	262020.92	255796.75	253317.87	187280.13	370955.02
		25	300401.43	209440.30	214303.73	215289.75	219044.33	213509.23	215289.75	166403.72	309677.31
		35	248486.01	172332.49	181833.11	182419.20	181669.48	177576.81	182602.58	140111.84	254552.67
	4	5	477888.67	354624.48	367811.86	369273.12	372574.06	364400.64	369273.12	366575.42	488839.11
		15	365304.84	248163.48	252262.54	253317.87	262020.92	255796.75	253317.87	256783.04	370955.02
		25	300401.43	209440.30	214303.73	215289.75	219044.33	213509.23	215289.75	217982.42	309677.31
		35	248486.01	172332.49	181833.11	182419.20	181669.48	177576.81	182602.58	185183.60	254552.67

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
75,000	0	5	817624.45	677115.53	691921.26	679226.17	683720.59	673707.56	679226.17	684583.05	828298.40
		15	686726.21	512226.51	538317.90	535699.17	544911.25	526633.73	535699.17	546512.75	690884.10
		25	607105.38	431048.85	450024.24	452187.58	451421.30	441311.33	452187.58	453486.05	617598.25
		35	525553.01	343765.24	369080.19	370827.01	368647.95	356968.75	372856.24	381576.39	536182.76
	2	5	817624.45	677115.53	691921.26	679226.17	683720.59	673707.56	679226.17	490251.20	828298.40
		15	686726.21	512226.51	538317.90	535699.17	544911.25	526633.73	535699.17	374364.48	690884.10
		25	607105.38	431048.85	450024.24	452187.58	451421.30	441311.33	452187.58	316420.21	617598.25
		35	525553.01	343765.24	369080.19	370827.01	368647.95	356968.75	372856.24	244618.57	536182.76
	4	5	817624.45	677115.53	691921.26	679226.17	683720.59	673707.56	679226.17	684583.05	828298.40
		15	686726.21	512226.51	538317.90	535699.17	544911.25	526633.73	535699.17	546512.75	690884.10
		25	607105.38	431048.85	450024.24	452187.58	451421.30	441311.33	452187.58	453486.05	617598.25
		35	525553.01	343765.24	369080.19	370827.01	368647.95	356968.75	372856.24	381576.39	536182.76
100,000	0	5	1345889.39	1022222.63	1060750.88	1032589.86	1043581.25	1019034.58	1032589.86	1045270.01	1367705.72
		15	1049703.14	759635.25	791648.55	789534.79	800589.17	777473.20	789534.79	802340.81	1058141.26
		25	894711.82	686569.02	698504.58	700822.43	711316.32	700482.41	700822.43	711720.48	910190.07
		35	785468.20	597348.46	624906.11	627127.17	624388.47	609497.12	630583.09	641676.19	798270.64
	2	5	1345889.39	1022222.63	1060750.88	1032589.86	1043581.25	1019034.58	1032589.86	730461.76	1367705.72
		15	1049703.14	759635.25	791648.55	789534.79	800589.17	777473.20	789534.79	623840.93	1058141.26
		25	894711.82	686569.02	698504.58	700822.43	711316.32	700482.41	700822.43	549055.18	910190.07
		35	785468.20	597348.46	624906.11	627127.17	624388.47	609497.12	630583.09	436969.91	798270.64
	4	5	1345889.39	1022222.63	1060750.88	1032589.86	1043581.25	1019034.58	847521.27	1045270.01	1367705.72
		15	1049703.14	759635.25	791648.55	789534.79	800589.17	777473.20	672260.32	802340.81	1058141.26
		25	894711.82	686569.02	698504.58	700822.43	711316.32	700482.41	603004.01	711720.48	910190.07
		35	785468.20	597348.46	624906.11	627127.17	624388.47	609497.12	630583.09	641676.19	798270.64

Appendix G. Divided Rural Arterial Accident Costs

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
1,000	0	5	18314.05	13232.97	14163.25	13742.08	13470.25	12993.97	13535.29	14346.85	19102.47
		10	15680.29	12278.16	12201.10	12479.20	12426.13	12810.48	12288.07	11891.22	16939.19
		15	14894.43	10963.65	11029.36	11552.42	10712.13	10875.78	10819.68	11224.16	15624.22
		20	12711.32	9888.93	10210.30	10738.28	10170.05	9889.53	9935.83	10767.47	14428.90
		35	11363.23	7965.67	7959.40	7865.32	8689.75	7857.71	8106.20	7937.96	12012.66
	3	5	17596.59	13635.44	13964.61	12870.45	13671.62	13030.80	13908.28	13785.66	11177.40
		10	16187.69	12004.28	12255.59	12496.01	12227.10	11788.64	12234.75	12354.09	9940.94
		15	15456.33	11108.59	10957.79	10696.01	11307.98	11193.53	10878.32	11185.00	8589.46
		20	13620.88	10479.17	10346.09	9592.84	10439.95	9451.14	10321.71	10172.52	14428.90
		35	11541.73	8339.52	8170.37	8081.39	7816.94	8135.24	8141.50	8061.18	12012.66
	6	5	17802.75	13277.52	14038.59	14164.63	14063.50	13977.44	13468.13	13977.61	15868.79
		10	16845.27	12162.81	11908.59	12268.37	11983.96	11810.54	12304.25	11671.67	14572.38
		15	14788.82	11303.83	11306.78	11059.73	11122.28	9838.54	10717.28	11282.00	13180.63
		20	13515.69	10712.68	9389.24	9773.31	9794.81	10153.10	10531.93	9537.92	14428.90
		35	11469.11	8070.03	8294.14	8372.27	8200.72	8038.08	8198.81	8104.55	12012.66
5,000	0	5	60004.31	41777.86	41782.54	40594.39	39441.87	37585.69	40666.19	38400.78	63701.63
		10	51010.30	34352.27	36760.40	33736.09	34292.54	35328.69	35823.61	36261.42	54763.71
		15	44178.41	30488.18	29730.39	29099.71	29571.89	29093.67	29464.73	30851.49	49211.08
		20	39429.92	27334.42	27010.48	27014.35	26606.36	25094.39	24916.88	27211.17	44103.53
		35	30555.27	21658.29	19887.40	21491.02	21607.54	20815.20	21264.30	22154.77	33683.08
	3	5	60535.91	40632.33	41342.60	41963.51	40521.46	41504.45	42879.23	42382.47	30131.85
		10	55216.43	37754.73	34343.91	35611.93	34732.06	35474.04	34743.02	36380.67	26520.45
		15	45449.21	28536.59	30254.16	29974.11	30804.24	29196.93	32017.24	30034.77	22753.06
		20	38692.54	26416.02	26174.20	26602.00	27492.01	25294.59	25825.24	27449.97	44103.53
		35	32048.68	21248.81	21592.34	21732.92	21701.76	20336.49	20897.13	21463.05	33683.08
	6	5	60813.46	39954.79	40372.59	40597.33	38544.14	38307.97	39207.66	40706.49	50249.62
		10	51514.57	33557.00	35514.56	35296.33	35957.75	32818.84	34183.24	36313.75	44719.06
		15	43854.36	29484.17	29266.09	29301.42	29842.37	29072.62	30317.16	29559.86	38728.30
		20	41378.71	27034.77	25249.30	26886.14	26406.55	26242.24	27220.42	28260.57	44103.53
		35	29966.49	20712.25	21112.83	22078.28	20654.62	20195.96	20737.60	20144.49	33683.08

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
10,000	0	5	78841.53	49671.90	57370.95	55881.53	53818.12	52591.68	55084.09	54736.80	83075.85
		10	69330.38	44295.34	46244.33	43610.49	46250.90	44829.76	46084.49	46545.94	71759.77
		15	57360.33	38662.59	39905.55	40373.24	35966.78	38075.53	37442.58	38329.92	64574.38
		20	52274.00	34765.42	34490.68	36813.09	33756.26	34014.23	35674.36	34349.28	57870.66
		35	39922.84	26864.43	27258.00	26178.01	27762.63	25995.24	27332.17	29594.32	43949.82
	3	5	77115.92	54313.60	54832.63	51588.01	53968.22	50320.52	54194.91	52818.47	39142.61
		10	66928.17	48151.35	45872.86	46301.23	45593.85	45857.30	47556.73	50032.47	34228.16
		15	59239.53	39821.14	39472.72	38995.37	38050.24	37849.32	39261.79	39951.74	29080.27
		20	51187.64	33025.96	35171.38	34218.43	34452.51	33867.04	34741.75	35069.59	57870.66
		35	39138.46	29547.47	27146.15	27726.43	28617.56	27029.61	25812.46	27470.08	43949.82
	6	5	79259.94	53013.11	54286.32	54052.17	55656.40	51862.36	52248.52	53268.66	65926.72
		10	72053.50	46482.48	48630.31	46085.65	47053.74	44390.65	46377.10	44049.15	58683.05
		15	55442.63	39678.24	39753.65	41005.63	38158.99	38625.55	38815.15	36268.04	50727.41
		20	53748.94	34696.50	36167.74	34518.64	32802.59	33047.94	33317.74	37337.10	57870.66
		35	42093.51	25856.89	24787.08	27416.28	28100.05	25636.62	25805.31	29197.53	43949.82
20,000	0	5	130399.78	96427.19	100603.64	100629.74	94735.75	94192.83	95170.09	90280.67	137077.56
		10	116594.78	77111.33	79984.80	81616.85	80854.97	75405.65	81375.57	82438.18	123685.81
		15	107175.18	70433.44	69880.04	70525.65	72367.15	69364.35	71365.57	71945.66	113836.67
		20	90342.48	60368.72	63817.07	65842.54	61948.43	60131.87	64986.31	64771.66	103797.81
		35	69901.56	46829.25	48631.89	53468.06	48649.35	47588.15	49651.15	53262.27	80604.02
	3	5	134868.94	92286.72	97814.33	97619.53	95295.48	93170.19	100481.63	103900.28	71934.63
		10	120436.55	82305.47	82565.17	80288.87	80005.93	83894.43	86475.21	87052.42	62762.24
		15	105047.48	71161.42	70233.87	73815.50	70444.50	69798.50	66976.37	73262.28	52852.60
		20	94095.87	64997.29	64303.69	66476.37	63179.91	63731.34	65414.99	64485.64	103797.81
		35	74196.15	49503.17	51436.54	49550.21	47548.60	49518.08	46764.97	51026.46	80604.02
	6	5	130762.73	101581.89	96647.79	91815.19	99460.38	97154.26	95052.87	94693.59	115764.68
		10	120105.79	83236.20	82319.64	77378.74	80549.28	83154.02	84164.85	88098.09	105055.84
		15	104351.16	72043.12	67774.33	74362.83	70368.13	72196.21	69039.43	75940.53	92270.03
		20	99530.49	67045.04	67272.71	63249.35	64592.72	62239.35	64011.57	67048.38	103797.81
		35	76747.21	48330.05	49147.55	49448.98	51303.13	47571.88	50664.09	50562.26	80604.02

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
30,000	0	5	208697.52	141538.26	136974.03	137116.21	141857.74	140864.39	144135.86	157576.86	189876.89
		10	185094.90	124685.37	131955.27	122477.55	124462.89	119972.07	131313.30	127621.65	169032.43
		15	162269.92	115730.88	111952.77	117569.27	120295.76	110344.02	109099.90	116513.68	157274.42
		20	140606.13	104363.55	107526.79	100148.16	98410.38	101124.31	101589.38	102726.50	147347.03
		35	116644.61	79388.98	80079.53	80177.63	83597.62	71600.67	78109.86	78701.30	124285.22
	3	5	211115.34	135431.20	158162.38	140094.47	142902.79	136783.11	142007.29	155550.93	113477.72
		10	176761.18	125208.42	128585.89	127052.77	123165.12	119574.57	130249.53	135726.71	100942.89
		15	157146.18	111774.34	110904.10	108880.46	111458.78	110921.12	114788.49	117295.62	86276.68
		20	134797.72	103245.05	101448.39	99303.17	104451.24	97143.28	104259.07	101012.89	147347.03
		35	119374.88	79251.04	81100.24	79732.37	81191.09	77946.02	77067.46	85383.59	124285.22
	6	5	229565.43	141635.05	139971.66	140327.89	155151.95	142885.69	141418.36	142987.89	159399.82
		10	185681.78	125028.60	131300.20	127609.37	128309.36	126277.16	127804.87	127686.20	148495.41
		15	159001.37	114547.54	113347.43	109344.02	109910.84	106594.39	113279.55	112115.74	136989.74
		20	136910.73	104542.91	108227.83	103202.39	106259.19	101558.33	102125.39	107811.70	147347.03
		35	114624.69	82035.47	81009.00	74238.39	75488.87	77959.58	82150.81	81303.33	124285.22

Appendix H. Undivided Rural Arterial Accident Costs

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
1,000	0	5	12935.33	11223.65	11221.96	11214.56	10692.72	11141.83	11205.82	11227.18	13050.90
		10	9856.77	7898.59	7921.50	7904.83	7542.11	5925.10	7905.04	7826.51	9941.38
		15	7078.86	5485.53	5489.75	5483.72	5197.90	3966.39	5484.15	5495.60	7194.68
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	3	5	6522.28	5618.26	5615.47	5615.94	5296.75	5649.57	5617.89	5718.56	6924.53
		10	4966.73	4289.91	4280.11	4289.20	4058.25	4290.04	4289.53	4320.41	5094.63
		15	3500.56	2995.22	2987.26	2992.16	2841.63	2983.69	2992.91	3006.63	3582.59
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	6	5	10929.76	9254.48	9243.35	9240.30	8853.75	9249.60	9243.34	9443.47	11532.91
		10	7798.05	6898.66	6841.71	6894.94	6711.09	7018.97	6899.48	7013.52	8179.81
		15	5619.15	5084.61	5069.60	5072.77	4721.92	5025.05	5075.40	5107.03	5910.85
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
5,000	0	5	35912.52	28921.91	28915.02	2709.83	27426.80	28681.53	28861.77	28936.32	36385.13
		10	25141.21	20064.44	20121.45	708.62	19185.55	19971.34	20080.48	19885.55	25369.48
		15	18065.65	14417.07	14426.28	3755.73	13793.72	14433.59	14414.03	14439.09	18343.26
		20	3917.78	2710.53	2719.24	965.39	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	965.39	709.36	704.36	816.86	713.04	963.68
	3	5	16754.54	14708.45	14702.31	14703.35	14006.69	14777.54	14707.66	14930.21	17698.27
		10	13300.96	11901.22	11881.45	11899.78	11437.21	11901.49	11900.44	11962.89	13572.69
		15	9948.96	8512.71	8490.12	8504.01	8076.20	8479.97	8506.16	8545.16	10182.09
		20	3917.78	2710.53	2719.24	3755.73	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	965.39	709.36	704.36	816.86	713.04	963.68
	6	5	28086.80	23536.76	23507.45	23499.42	22489.91	23523.93	23507.44	24036.26	30181.80
		10	19815.08	17636.99	17502.35	17628.18	17194.99	17922.75	17638.95	17909.74	20768.06
		15	14710.41	13551.32	13519.33	13526.08	12787.19	13424.58	13531.70	13599.17	15359.07
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
10,000	0	5	24191.04	19897.36	19893.14	19874.71	18981.51	19750.08	19860.51	19906.19	24482.34
		10	17581.94	14469.52	14504.55	14479.05	13929.21	14412.32	14479.38	14359.60	17721.72
		15	13239.65	10874.84	10883.18	10871.23	10304.59	10889.80	10872.07	10894.78	13410.70
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	3	5	12430.39	11137.94	11132.42	11133.36	10500.57	11200.03	11137.23	11299.77	13013.12
		10	9846.31	8504.56	8485.14	8503.14	8045.30	8504.81	8503.79	8565.02	10099.88
		15	6939.71	5937.87	5922.13	5931.81	5633.40	5915.04	5933.31	5960.52	7102.32
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	6	5	19385.75	16599.29	16581.34	16576.42	15957.80	16591.43	16581.33	16905.27	20669.56
		10	14316.29	12975.32	12892.25	12969.89	12702.52	13151.55	12976.53	13143.54	14901.63
		15	11139.71	10080.02	10050.25	10056.54	9361.00	9961.95	10061.77	10124.48	11566.11
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
20,000	0	5	33655.50	27179.50	27173.12	27145.29	25795.74	26957.00	27123.83	27192.83	34093.75
		10	23680.95	18984.65	19037.38	18998.99	18171.52	18898.51	18999.48	18819.15	23892.14
		15	17135.27	13757.00	13765.54	13753.32	13179.31	13772.31	13754.19	13777.40	17392.16
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	3	5	15921.77	14026.97	14021.28	14022.25	13376.70	14090.98	14026.24	14232.42	16795.29
		10	12722.48	11423.97	11405.61	11422.63	10893.19	11424.21	11423.25	11481.21	12974.41
		15	9396.24	8039.78	8018.46	8031.57	7627.52	8008.86	8033.59	8070.43	9616.42
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	6	5	26406.55	22196.70	22169.59	22162.16	21228.34	22184.83	22169.58	22658.77	28345.85
		10	18753.95	16738.58	16613.96	16730.41	16329.48	17003.02	16740.39	16991.00	19635.55
		15	14028.79	12954.62	12924.95	12931.21	12246.03	12837.11	12936.42	12998.97	14629.65
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
30,000	0	5	43972.10	35173.02	35164.32	35126.32	33282.76	34869.29	35097.03	35191.22	44564.28
		10	30388.69	23947.68	24020.05	23967.37	22831.87	23829.48	23968.03	23720.55	30677.94
		15	21410.27	16784.62	16796.27	16779.59	15996.05	16805.52	16780.77	16812.48	21762.63
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	3	5	19746.65	17153.46	17145.68	17147.00	16265.38	17240.94	17152.46	17434.27	20944.02
		10	15373.20	13607.24	13582.34	13605.43	13023.10	13607.57	13606.27	13684.94	15716.60
		15	11660.92	10141.69	10114.78	10131.33	9621.65	10102.68	10133.88	10180.35	11857.30
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68
	6	5	34117.51	28354.52	28317.35	28307.15	19718.24	28338.24	28317.33	28988.00	36763.87
		10	23631.09	20866.27	20695.40	20855.08	14949.95	21228.91	20868.75	21212.40	24840.94
		15	17155.95	15689.61	15649.16	15657.70	11460.03	15529.42	15664.80	15750.08	17977.50
		20	3917.78	2710.53	2719.24	2709.83	2719.04	2711.48	3297.14	2699.44	3900.73
		35	966.31	709.37	709.20	708.62	709.36	704.36	816.86	713.04	963.68

Appendix I. Local Highway Accident Costs

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
200	0	5	2623.38	2155.46	1978.23	2022.93	1981.52	1964.87	2023.14	1983.55	2647.23
		10	1955.44	1596.25	1478.98	1476.77	1482.19	1456.03	1476.96	1470.71	1962.81
		15	1466.24	1186.72	1088.76	1090.82	1095.22	1078.10	1091.01	1085.66	1480.62
		20	1017.68	729.06	732.35	733.44	732.10	722.49	732.32	969.68	1015.11
		35	268.01	189.99	190.28	190.98	190.28	187.78	189.35	242.30	265.18
	5	5	2623.38	1891.59	1978.23	2022.93	1772.45	1964.87	2023.14	1983.55	2647.23
		10	1955.44	1340.24	1478.98	1476.77	1482.19	1456.03	1476.96	1470.71	1962.81
		15	1466.24	999.14	1088.76	1090.82	951.35	1078.10	1091.01	1085.66	1480.62
		20	1017.68	729.06	732.35	733.44	732.10	722.49	732.32	969.68	1015.11
		35	268.01	189.99	190.28	190.98	190.28	187.78	189.35	242.30	265.18
	10	5	2623.38	1306.98	1978.23	2022.93	1172.75	1964.87	2023.14	1983.55	2647.23
		10	1955.44	1027.74	1478.98	1476.77	951.87	1456.03	1476.96	1470.71	1962.81
		15	1466.24	698.12	1088.76	1090.82	661.03	1078.10	1091.01	1085.66	1480.62
		20	1017.68	729.06	732.35	733.44	732.10	722.49	732.32	969.68	1015.11
		35	268.01	189.99	190.28	190.98	190.28	187.78	189.35	242.30	265.18
500	0	5	6558.45	5388.67	4945.57	5057.31	4953.80	4912.17	5057.85	4958.87	6618.07
		10	4888.61	3990.62	3697.46	3691.92	3705.47	3640.07	3692.40	3676.80	4907.01
		15	3665.58	2966.80	2721.88	2727.06	2738.06	2695.26	2727.50	2714.15	3701.56
		20	2544.20	729.06	1830.87	1833.59	1830.23	1806.24	1830.80	2424.18	2537.78
		35	670.03	189.99	475.70	477.45	475.70	469.45	473.39	605.74	662.94
	5	5	6558.45	4728.96	4945.57	5057.31	4431.15	4912.17	5057.85	4958.87	6618.07
		10	4888.61	3350.60	3697.46	3691.92	3705.47	3640.07	3692.40	3676.80	4907.01
		15	3665.58	2497.87	2721.88	2727.06	2378.38	2695.26	2727.50	2714.15	3701.56
		20	2544.20	729.06	1830.87	1833.59	1830.23	1806.24	1830.80	2424.18	2537.78
		35	670.03	189.99	475.70	477.45	475.70	469.45	473.39	605.74	662.94
	10	5	6558.45	3267.46	4945.57	5057.31	2931.88	4912.17	5057.85	4958.87	6618.07
		10	4888.61	2569.34	3697.46	3691.92	2379.68	3640.07	3692.40	3676.80	4907.01
		15	3665.58	1745.30	2721.88	2727.06	1652.57	2695.26	2727.50	2714.15	3701.56
		20	2544.20	729.06	1830.87	1833.59	1830.23	1806.24	2308.32	2424.18	2537.78
		35	670.03	189.99	475.70	477.45	475.70	469.45	591.36	605.74	662.94

ADT	Curvature (deg)	Offset (ft)	Unprotected	QuadGuard	Quest	TRACC	QG Elite	REACT 350	SCI	TAU II	Sand Barrels
		5	12092.82	10238.48	9396.57	9608.89	9412.22	9333.11	9609.93	9421.85	12173.98
		10	9288.35	7582.17	7025.17	7014.65	7040.42	6916.13	7015.57	6985.91	9323.31
	0	15	6964.60	5636.93	5171.58	5181.41	5202.31	5120.98	5182.26	5156.90	7032.96
		20	4833.99	484.14	3478.66	3483.81	2321.31	3431.84	4385.79	4605.95	4821.80
		35	1273.06	189.99	903.83	907.15	597.73	891.95	1123.59	1150.91	1259.59
		5	12092.82	8985.03	9396.57	9608.89	8419.18	9333.11	9609.93	2863.71	12173.98
		10	9288.35	6366.16	7025.17	7014.65	7040.42	6916.13	7015.57	1995.46	9323.31
1,000	5	15	6964.60	4745.95	5171.58	5181.41	4518.92	5120.98	5182.26	1377.44	7032.96
		20	4833.99	729.06	3478.66	3483.81	3477.43	3431.84	4385.79	4605.95	4821.80
		35	1273.06	189.99	903.83	907.15	903.83	1120.90	1123.59	1150.91	1259.59
		5	12092.82	6208.16	9396.57	9608.89	5570.58	8366.58	9609.93	2863.71	12173.98
		10	9288.35	4881.75	7025.17	7014.65	4521.39	6712.29	7015.57	1995.46	9323.31
	10	15	6964.60	3316.08	5171.58	5181.41	3139.89	4721.82	5182.26	1377.44	7032.96
		20	4833.99	729.06	3478.66	3483.81	3477.43	4552.02	4385.79	4605.95	4821.80
		35	1273.06	189.99	903.83	907.15	903.83	1120.90	1123.59	1150.91	1259.59
		5	26787.01	21823.64	20039.33	20484.04	20071.98	29166.49	20486.22	2863.71	27049.15
		10	19814.02	16391.65	15329.53	15309.74	15358.21	20031.18	15311.45	1995.46	19886.72
	0	15	15215.72	12808.67	12005.76	12022.51	12058.11	14318.85	12023.96	1377.44	15344.18
		20	11437.04	729.06	8299.98	8312.26	5538.58	10860.97	10464.35	10989.64	11416.72
		35	3037.47	189.99	2156.49	2164.44	1426.17	2674.42	2680.85	2746.03	3005.34
		5	26787.01	19187.68	20039.33	20484.04	18039.59	25098.79	20486.22	2863.71	27049.15
		10	19814.02	14109.88	15329.53	15309.74	15358.21	17916.43	15311.45	1995.46	19886.72
3,000	5	15	15215.72	11290.65	12005.76	12022.51	10781.99	13124.88	12023.96	1377.44	15344.18
		20	11437.04	729.06	8299.98	8312.26	8297.04	10860.97	10464.35	10989.64	11416.72
		35	3037.47	189.99	2156.49	2164.44	2156.49	2674.42	2680.85	2746.03	3005.34
		5	26787.01	13823.57	20039.33	20484.04	12692.87	17934.23	20486.22	2863.71	27049.15
		10	19814.02	11516.78	15329.53	15309.74	10787.87	14745.40	15311.45	1995.46	19886.72
	10	15	15215.72	7912.03	12005.76	12022.51	7491.67	11250.65	12023.96	1377.44	15344.18
		20	11437.04	729.06	8299.98	8312.26	8297.04	10860.97	10464.35	10989.64	11416.72
		35	3037.47	189.99	2156.49	2164.44	2156.49	2674.42	2680.85	2746.03	3005.34

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