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Abstract

Crash cushions vary in geometry and cost. In this study, crash cushions were categorized in three different categories: redirecting with repair costs greater than \$1,000 (RGM), redirecting with repair costs less than \$1,000 (RLM), and nonredirecting sacrificial (NRS). Typically, RGM systems are less expensive initially, but life-cycle costs are high. RLM systems typically reciprocate this trend. NRS crash cushions (e.g., sand barrels) are generally less expensive but require total replacement after a crash has occurred, which may be impractical at high-traffic volume locations. Due to limited funding, there is often a need to identify the most cost-effective crash cushion category for highway scenarios with different roadway, traffic, and roadside characteristics. This study was commissioned to determine benefit-cost ratios for each crash cushion category in a wide range of roadway and roadside characteristics using the probability-based encroachment tool, Roadside Safety Analysis Program. Only RGM and RLM systems were cost effective for freeways and divided rural arterials, but all three categories competed against the unprotected condition on undivided rural arterials and local roads.

Keywords: roadside, crash cushions, benefit-cost, RSAP

1. Introduction

1.1. Background

Crash cushions are used to reduce the severity of an impact with a fixed, narrow object. This is usually accomplished using energy absorption to reduce the vehicle's kinetic energy and, ultimately, its speed at a safe deceleration rate. Crash cushions are ideal for fixed objects that cannot be removed, relocated, or shielded by longitudinal barriers (American Association of State Highway and Transportation Officials [AASHTO], 2011b). The need for a crash cushion is partially dependent on the clear zone distance, which is the minimum distance at which a fixed object may be placed and still leave enough recovery area for the driver to avoid that fixed object.

Crash cushions were defined according to their average repair costs. A distinction between systems in the redirecting family was made by selecting \$1,000 as the descriptive cost, which provided consistent grouping of the systems with respect to common practices in the industry, such as those in the *Roadside Design Guide (RDG)* (AASHTO, 2011b). For simplicity, the Roman numeral for 1,000 (M) was used in the designations. The resulting categories were Redirecting with repair costs less than or equal to \$1,000 (RLM), Redirecting with repair costs Greater than \$1,000 (RGM), and Non-Redirecting Sacrificial (NRS).

The repair costs of the RLM category were relatively low because of concept of restorability and, given a design impact, the cost of the parts needed to repair the system are inexpensive. However, there is a trade-off for these low repair costs. They require a higher up-front investment in installation.

In contrast, the repair costs of the RGM category are higher per impact event because these systems generally make use of permanent deformation or damage to dissipate energy. As a result, the cost of the parts needed to repair the system can be expensive. However, the trade-off is that these systems present lower installation costs. RLM and RGM systems are able to redirect vehicles when hit on their side, which is a significant advantage over NRS crash cushions.

Ultimately, NRS crash cushions primarily comprise 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. In a design impact, the lighter barrels are hit first, and the heavier barriers are struck as the vehicle continues through the crash cushion. The absorption of the vehicle's kinetic energy makes the vehicle slow down at a safe deceleration rate until it brings the vehicle's energy low enough that "bulldozing" through the sand will be enough to stop the vehicle (i.e., a velocity less than 10 mph or 16.1 km/h) (AASHTO, 2011b). Because any impacted barrel typically suffers significant permanent deformation, the repair costs for these systems can approach the initial installation costs because they may have to be completely replaced. Also, because these systems are nonredirecting crash cushions, they may allow vehicles to gate through them, potentially inducing a more harmful event. On the other hand, these systems typically had the lowest installation costs.

1.2. Problem Statement

Guidelines contained in the *RDG* list crash cushions as a safety treatment for fixed objects that cannot be removed, relocated, or shielded by longitudinal barriers (AASHTO, 2011b). However, the use of a crash cushion may not be economically justifiable under certain traffic and roadside characteristics. For example, the installation of a high-cost crash cushion may not be economically justifiable on a road with low-traffic volumes and large lateral offsets because the crash frequency will tend to be very low. As a result, the use of different crash cushions may depend on varying roadway, roadside, and traffic characteristics, making the selection of a specific crash cushion type challenging for transportation safety engineers.

Therefore, there is a need to develop crash cushion selection guidelines that can be used to assist engineers in selecting the crash cushion that results in the highest accident cost reduction per unit of direct cost (i.e., installation and repair cost) associated with the chosen crash cushion. However, to provide flexibility in design options available to the engineer, crash cushion categories (e.g., RLM, RGM, or NRS) needed to be compared such that selection guidelines pertained to broad categories rather than specific systems.

1.3. Objective

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

1.4. Scope

The objective of this research study was achieved through various tasks. First, crash cushion systems were examined to understand dimensions and associated costs for each system via manufacturer product sheets and surveys sent out to State Departments of Transportation (DOTs) and manufacturers. 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 highway scenarios were modeled to evaluate the benefit-cost (BC) ratios of each crash cushion. Next, direct costs were determined based on mobilization, labor, installation, maintenance, and repair costs. Societal costs were determined based on the 2010 Federal Highway Administration (FHWA) comprehensive costs. Finally, BC analyses were conducted to determine whether the placement of a type of crash cushion was economically justifiable. Example applications of the results were included to assist engineers in the selection process.

2. Crash Cushion Systems

The QuadGuard is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC (Energy Absorption Systems, Inc., 2013b). It utilizes crushable cartridges that need to be replaced after an impact event. These cartridges are placed within a structure of quad beams that are designed to “fishscale” backward as a vehicle strikes the end. The length of the QuadGuard was 15 ft (4.6 m), and the width was 2.5 ft (0.8 m).

The QUEST crash cushion is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC (Energy Absorption Systems, Inc., 2013c). It telescopes backward to dissipate kinetic energy. The length of the QUEST was 19 ft (5.8 m) and the width was 2.0 ft (0.6 m).

The Trinity Attenuating Crash Cushion (TRACC) is a proprietary crash cushion manufactured by Trinity Highway Products, LLC (Trinity Highway Products, 2013). It telescopes backward while tearing through metal plates. The length of the TRACC crash cushion was 21.25 ft (6.5 m) and the width was 2.0 ft (0.6 m).

The TAU II is a proprietary crash cushion manufactured by Barrier Systems, Inc. (Barrier Systems, 2013). It absorbs the kinetic energy of

the vehicle using disposable energy absorbing cartridges. The length of the TAU II was 23 ft (7.0 m) and the width was 4.0 ft (1.2 m).

The QuadGuard Elite is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc., a subsidiary of Trinity Highway Products, LLC (Energy Absorption Systems, Inc., 2013a). It utilizes self-restoring cylinders made from high-density polyethylene (HDPE). 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 the QuadGuard Elite was 27 ft (8.2 m), and the width was 2.0 ft (0.6 m).

The Reusable Energy-Absorbing Crash Terminal (REACT 350) is a proprietary crash cushion manufactured by Energy Absorption Systems, Inc. (Energy Absorption Systems, Inc., 2013d), 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 the REACT 350 was 28.75 ft (8.8 m) and the width was 3.0 ft (0.9 m).

The Smart Cushion is a proprietary crash cushion manufactured by Smart Cushion Innovations (SCI) Products, Inc. (SCI Products, 2013). The length of the SCI was 21.5 ft (6.6 m), and the width was 2.0 ft (0.6 m).

NRS systems are typically represented by sand barrels that can be arrayed in numerous designs. Sand barrels can be arrayed to shield almost any fixed object. Further, sand barrels are inexpensive and easy to design and construct. However, repair costs can be high because the system usually requires total replacement of the impacted barrels. Sand barrels cannot redirect vehicles in the event of a side impact, do not guarantee that lighter barrels are struck first, and perform poorly in coffin corner impacts. Higher-speed highways generally require sand barrel configurations that contain more barrels. The masses of the barrels increase as the system approaches the hazard. This provides a relatively safe deceleration rate for the vehicle until it slows to a safe velocity, which was specified in the *RDG* to be 10 mph (16.1 km/h) (AASHTO, 2011b).

3. Survey of Crash Cushion Costs

To estimate the cost of installation of all crash cushions used in this study, a survey questionnaire was sent to the following Midwest States Pooled Fund States Departments of Transportation (DOTs): Illinois,

Iowa, Kansas, Minnesota, Missouri, Nebraska, Ohio, South Dakota, Wisconsin, and Wyoming. The State DOTs were asked to provide information pertaining to each crash cushion that they currently implement. This information included the average installation cost, the average crash repair cost, and the average regular maintenance cost per year. Additional information included inventory need and costs for each crash cushion type, repair time needed once the system has been involved in a crash, and information on the test level and speed limit of each particular crash cushion used.

Only a few States replied to the survey. Also, not all responders answered the questions adequately, which decreased the number of survey responses even further. Responses from Kansas, Minnesota, and Wisconsin were used in the study.

A summary of costs and dimensions of each crash cushion type evaluated in this study is shown in Table 1. Dimensions were taken from manufacturer product sheets for typical Test Level 3 (TL-3) designs. The cost of the sand barrels in this table was the average of three online distributors for the same design configuration (Transportation Safety & Equipment Co., 2011; Transportation Supply, 2011; Twin Discovery Systems, Inc., 2011). Crash cushion size was directly associated with the safety performance of the crash cushion. Costs were independent of the crash cushion size because the States did not provide detailed cost information as a function of crash cushion size or safety performance level.

Table 1. Costs and dimensions used in the benefit-cost analysis

<i>Crash Cushion</i>	<i>Installation Cost</i>	<i>Length, ft (m)</i>	<i>Width, ft (m)</i>
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)

Table 2. Average repair costs in U.S. dollars for standard National Cooperative Highway Research Program (NCHRP) Report No. 350 crash tests

<i>System</i>	<i>Avg Repair Cost For Mutual Tests</i>
SCI	\$67.33
REACT 350	\$66.67
QuadGuard Elite	\$638.33
TRACC	\$1,933.33
TAU II	\$2,518.83
QuadGuard	\$3,909.67
QUEST	\$9,683.33

4. Repair Cost Estimation

Manufacturers of the systems described herein were solicited for repair cost estimations for each of the NCHRP Report No. 350 crash tests conducted for the given system. Crash test numbers 3-31, 3-33, and 3-37 were conducted for all of the redirecting systems in this article. For each of these tests, the manufacturers provided the estimated cost for repair parts and the estimated time to repair the system. Assuming a labor cost of \$50 (USD) per hour, the average repair costs for each system from the three mutual tests were determined and are shown in Table 2.

The target velocity of each of the three mutual tests was specified to represent the 85th percentile speed in real-world accidents. Therefore, the average repair costs in Table 2 were adjusted for each of the three functional classes considered in this article according to the average impact velocity of those functional classes. Previous research has shown that the average impact velocity for freeways, arterials, and local highways were 45.3 mph (73.0 km/h), 39.3 mph (63.2 km/h), and 34.9 mph (km/h), respectively (Albuquerque et al., 2009). Impact severity (IS) is a function of the square of this velocity. By determining the IS for the two different speeds, the IS for the real-world accident velocity for the given functional class can be estimated according to Equation 1.

$$\overline{IS} = \left(\frac{V_{50}}{V_{85}} \right)^2 (IS) \quad (1)$$

where

$\overline{IS}$ = reduced impact severity

IS = impact severity of the test conditions

v_{50} = velocity of an average impact

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. Because 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 3.

5. New Categories Based on Repair Costs

As aforementioned, three new categories were developed for the purpose of conducting a comparative study between similar groups of systems. These categories were based entirely on the repair costs data supplied by manufacturers and in no way are meant to classify a system according to performance, ease of installation, or any other subjective method of description. Based on the \$1,000 threshold, the crash cushions were categorized according to Table 4.

6. Highway Scenario Modeling

6.1. Arbitrary Unprotected Roadside Condition

Hundreds of highway scenarios were modeled using RSAP, which is a probability-based encroachment tool used to estimate the cost-effectiveness of roadside safety treatment alternatives (Mak & Sicking,

Table 3. Reduced average repair costs based on functional class

<i>System</i>	<i>Freeway Avg Repair Cost</i>	<i>Arterial Avg Repair Cost</i>	<i>Local Avg Repair Cost</i>
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

Table 4. Crash cushion categories

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

2003). Different crash cushions were used on each modeled scenario to determine the B/C ratio of each system relative to the do-nothing alternative as well as relative to the other systems.

Different highway scenarios were created by varying values of traffic, roadway, and roadside parameters used to characterize a specific scenario. A hypothetical highway scenario was modeled in RSAP. This scenario is shown in Figure 1 and shows 4×2 -ft bridge piers placed on the roadside and in the median of divided highways (as shown in Figure 1a) and on the roadside of undivided highways (as shown in Figure 1b).

6.2. Sensitivity Analysis

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.

Fig. 1. Crash cushion placement on (a) divided and (b) undivided highways.

The parameters that were analyzed in the sensitivity analysis were crash cushion offset, average daily traffic, horizontal curvature, number of traffic lanes, lane width, and shoulder width. These parameters were then programmed into RSAP and their corresponding values were chosen based on typical ranges (i.e., low, medium, and high values) observed on freeways and local roads. In other words, values varied based on the functional roadway class. The traffic volume ranges were determined with assistance from AASHTO (2011a) *Geometric Design of Highways and Streets*. Curvature was chosen based on a summary of State standards given in NCHRP Report No. 638 (Sicking et al., 2009). Offsets were set out as far as 35 ft (10.7 m). According to the RDG, clear zones of 30 ft can allow as much as 80% of the vehicles enough room to recover (AASHTO, 2011b). 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.

This significance of a parameter was determined based on the assumption that fluctuations of less than 20% were insignificant. The significant parameters included were (1) crash cushion offset, (2) average daily traffic, and (3) horizontal curvature. Because the sensitivity results for freeways and local highways indicated the same dependencies, the analysis was not required for arterial highways. The resulting sensitivity of the aforementioned variables for freeways and local highways are given in Tables 5 and 6, respectively.

6.3. Parameter Values

Parameters with a sensitivity of more than 20% were selected for a detailed analysis in RSAP. Three parameters met this requirement and are shown in Table 7.

Constant, but reasonable values were chosen for parameters deemed insensitive in this analysis. The lane width was 12 ft (3.66 m) and the shoulder width was 8 ft (2.44 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.

Table 5. Sensitivity results for a freeway

<i>Parameter</i>	<i>Range</i>	<i>Annual Accident Cost (\$)</i>	<i>Percent Difference (%)</i>
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%

Table 6. Sensitivity results for a local highway

<i>Parameter</i>	<i>Range</i>	<i>Annual Accident Cost (\$)</i>	<i>Percent Difference (%)</i>
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	11.81	0.0%
	6 (baseline)	411.81	na
	8	411.81	0.0%

Table 7. Roadside Safety Analysis Program 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)

7. Societal and Direct Cost Estimation

7.1. Societal Costs

According to the Federal Highway Administration (FHWA), the average cost of a human life was \$2.6 million dollars in 1994 (AASHTO, 1996). 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 (Bureau of Economic Analysis, 2011). 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 Equation 2. Using this approach, the KABCO costs were scaled to the values shown in Table 8.

$$\text{AccCost} = P \left[\frac{\text{GDP}_{2010}}{\text{GDP}_{1994}} \right] \quad (2)$$

where

$$\text{GDP}_{2010} = 111.141$$

$$\text{GDP}_{1994} = 80.507$$

P = the principal in 1994 dollars.

Using this scale and the predicted accident frequency, RSAP was able to determine an accident cost for each crash cushion at each location. Simulated accident costs are contained in *Guidelines for Crash Cushion Selection* (Schrum et al., 2013).

Table 8. Societal costs for each injury level

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

7.3. *Direct Costs*

7.3.1. *Mobilization and Labor Costs.*

Mobilization costs were not included in this study because mobilization is highly variable and dependent on the site location. Costs could be high if the distance to the site was great or low if the distance was minimal. However, because these costs to mobilize would be equal for the all systems being compared in the analysis, they cancel out of the analysis.

Installation costs ascertained from the State of Wisconsin were used for RGM and RLM crash cushions, as shown in Table 1. However, Wisconsin did not list inertial sand barrels (NRS 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 \$2,540 (Transportation Safety & Equipment Co., 2011; Transportation Supply, 2011; Twin Discovery Systems, Inc., 2011).

Labor and utility truck costs were assumed to be \$50 and \$125 per hour based on correspondence with the State of Wisconsin. A difference was observed when comparing each crash cushion type in the time required to make repairs. Labor costs included labor for a two-man crew to make repairs. Labor cost estimates submitted by the Wisconsin DOT assumed a setup and takedown time, including travel time, to be one hour each. This time was considered separately for NRS crash cushions. According to survey response submitted by the Minnesota DOT, the approximate time for repairs of Energite III (i.e., setup and takedown time) was an average of 4 h.

A two-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, resulting in a total of four man hours and a labor cost of \$200. The truck was rented for one hour at \$125. Summing each fixed cost resulted in a total hourly fixed labor and utility truck cost of \$325.

Because each crash cushion had a different repair time, each system also had a different variable repair cost. Repair time and associated labor and utility truck costs for each crash cushion system are summarized in Table 9 and were determined using Equation 3. Based on the reported time to repair a system following a standard NCHRP Report No. 350 crash test (Ross et al., 1993), the cost of labor and utility truck use was determined and is shown in Table 9.

Table 9. Summary of labor costs

<i>System</i>	<i>Man Hours for Repairs</i>	<i>Labor Cost*</i>
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.

$$L_{\text{cost}} = \text{Hourly}_{\text{cost}} (\text{RepairTime}_{\text{avg}}) \quad (3)$$

where

L_{cost} = Total labor and truck rental costs

$\text{Hourly}_{\text{cost}}$ = Hourly rate to repair the system (\$225)

$\text{RepairTime}_{\text{avg}}$ = Average time required to repair the system.

7.3.2. Regular Maintenance Costs.

Responses from State DOTs indicated either a total maintenance cost for all crash cushions (i.e., 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.

8. Benefit-Cost Analysis

Once all direct and societal costs have been estimated, they can be used in Equation 4 to calculate the BC ratio for each safety alternative, including the “do-nothing” option.

$$BC_{2-1} = \frac{(AC_1 - AC_2)}{(DC_2 - DC_1)} \quad (4)$$

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 tabulated in *Guidelines for Crash Cushion Selection* (Schrum et al., 2013). The costs were annualized using a design life of 25 years and a discount rate of 4%. This parameter represents the difference between interest rates and the annual inflation rate and is commonly accepted as the appropriate value for use in economic analyses for government-funded projects (Mak & Sicking, 2003).

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 transportation investment practices, this would not be worth the effort. Instead, a minimum ratio of 2.0 is usually suggested, with a ratio of 4.0 being preferred.

Benefit-cost analyses were 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

One goal of this project was to determine cost-effective crash cushion categories 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 that are also 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 toward implementing a crash cushion. This system was best explained through an example, as shown in Figure 2. The given BC ratios shown in Figure 2 were generated arbitrarily and do not reflect any of the tested scenarios.

Fig. 2. Example of weighted average system. B/C = benefit/cost.

In the hypothetical example illustrated by Figure 2, 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 (rRGM and rRLM). The average BC ratio of each type of crash cushion was determined (BCRGM and BCRLM), including the ones that did not exceed the BC threshold. An index was used to rank the crash cushion categories (IRGM and IRLM). This index was the product of the ratio, r_i , and the average BC ratio, BC_i . Equations 5–10 show the calculations for the example shown in Figure 2.

$$r_{RGM} = 4/4 = 1.0 \quad (5)$$

$$r_{RLM} = 2/3 = 0.667 \quad (6)$$

$$BC_{RGM} = (3.100 + 3.050 + 2.850 + 2.150)/4 = 2.788 \quad (7)$$

$$BC_{RLM} = (3.200 + 2.050 + 1.850)/3 = 2.367 \quad (8)$$

$$I_{RGM} = r_{RGM} BC_{RGM} = 1.000 \times 2.788 = 2.788 \quad (9)$$

$$I_{RLM} = r_{RLM} BC_{RLM} = 0.667 \times 2.367 = 1.579 \quad (10)$$

Because I_{RGM} and I_{RLM} were greater than 0, both categories in this arbitrary example were cost-effective. However, if a transportation agency adopts a minimum BC ratio of 2, only RGM crash cushions would be recommended in this case.

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 compared 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’s,” 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 done 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 4 could be applied to determine all possible BC ratios.

8.3. Understanding the Design Charts

Symbolic representations of the recommendations that follow are given in Table 10. The alphabetic codes in Table 10 were also used in Figure 6. Figures 3–5 show design charts that were created to assist engineers in selecting the most cost-beneficial option, based on an incremental benefit-cost analysis, for a specific highway scenario. Figures 6–8 show not only the most cost-beneficial crash cushion category, but also all other categories that were cost beneficial based on a B/C ratio of at least 2. To use these charts, the engineer must know the traffic volume (average daily traffic [ADT]), the degree of curvature of the road (degrees), and the offset of the crash cushion from the roadway (ft). For Figures 3–5, blank cells refer to RGM systems, “*” cells refer to Do-Nothing option, and “**” cells refer to RLM systems. For Figures 6–8, “A” cells refer to all systems, “B” cells refer to RGM and RLM systems, “E” cells refer to RGM systems only, and “N” cells refer to Do-Nothing option.

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

Table 10. Legend of graphical recommendations

<i>Legend</i>			
*	Do Nothing	A	All Systems
	RGM	B	RGM and RLM
**	RLM	E	RGM only
		N	Do Nothing

		Curvature (Degrees)			
		0	2	4	
AADT	5,000				B/C > 2
	10,000				
	25,000				
	50,000				
	75,000	**	**	**	
	100,000	**	**	**	
	5,000				B/C > 4
	10,000				
	25,000				
	50,000				
	75,000				
	100,000	**	**	**	
5, 15, 25, and 35					
Offset (ft)					

Fig. 3. Optimal recommendations for freeways. B/C = benefit/cost.

- Highway Class = Freeway
- AADT = 75,000 vehicles per day (vpd)
- Offset = 15 ft (4.6 m)
- Degree of Curvature = 2 degrees
- Minimum BC ratio = 2.0

Solution:

- Refer to Figure 3

Select a RLM Crash Cushion Other Cost-Effective Solutions:

- Refer to Figure 6
- RGM is also cost-effective

9. Conclusions and Recommendations

Based on the incremental BC analysis, it was found that RGM crash cushions were the optimal cost-beneficial category of crash cushions, when a BC ratio of 2 was adopted, on freeways and divided rural arterials with traffic volumes lower than 75,000 and 20,000 vpd, respectively, as shown in Figures 3 and 4. However, RLM systems appeared to be the most cost-beneficial category on freeway scenarios with traffic volumes of 75,000 and 100,000 vpd, as well as on divided arterial

			Curvature (Degrees)												
			0	3	6	0	3	6	0	3	6	0	3	6	
Divided	AADT	1,000													B/C > 2
		5,000													
		10,000													
		20,000	**	**	**	**	**	**	**	**	**	**	**	**	
		30,000	**	**	**	**	**	**	**	**	**	**	**	**	
		1,000										*	*	*	B/C > 4
		5,000													
		10,000													
		20,000													
		30,000													
Undivided	AADT	1,000	*	*	*	*	*	*	*	*	*	*	*	*	B/C > 2
		5,000						*	*	*	*	*	*		
		10,000						*	*	*	*	*	*		
		20,000						*	*	*	*	*	*		
		30,000			**			*	*	*	*	*	*		
		1,000						*	*	*	*	*	*	B/C > 4	
		5,000						*	*	*	*	*	*		
		10,000						*	*	*	*	*	*		
		20,000						*	*	*	*	*	*		
		30,000						*	*	*	*	*	*		
			5		10-15			20			35			Offset (ft)	

Fig. 4. Optimal recommendations for rural arterials. B/C = benefit/cost.

scenarios with traffic volumes of 20,000 and 30,000 vpd. RLM crash cushions were not found to be cost-effective on divided arterial highways when a BC ratio of 4 was adopted as shown in Figure 4. The do-nothing alternative option was not a cost-effective alternative on freeway scenarios as shown in Figure 3. The RGM and do-nothing options competed on undivided arterials and local highways as shown in Figures 4 and 5. In these cases, do-nothing alternative was preferable on scenarios with larger offsets and/or low traffic volumes.

Therefore, RLM systems would be cost-effective at locations that experience higher crash frequencies, while RGM crash cushions would be a more feasible option at locations with moderate or low crash frequencies. The do-nothing alternative would only be recommended on locations where there is very large crash cushion offset and/or very low traffic volume. This finding was attributed to the fact that

		Curvature (Degrees)									
		0	5	10	0	5	10	0	5	10	
AADT	200	*	*	*	*	*	*	*	*	*	B/C > 2
	500	*	*		*	*	*	*	*	*	
	1,000							*	*	*	
	3,000							*	*	*	
	200	*	*	*	*	*	*	*	*	*	B/C > 4
	500	*	*	*	*	*	*	*	*	*	
	1,000	*			*	*	*	*	*	*	
	3,000							*	*	*	
		5			10-20			35			
		Offset (ft)									

Fig. 5. Optimal recommendations for local highways. B/C = benefit/cost.

		Curvature (Degrees)			
		0	2	4	
AADT	5,000	B	B	B	B/C > 2 & 4
	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	
		5, 15, 25, and 35			
		Offset (ft)			

Fig. 6. All cost-effective options for freeways. B/C = benefit/cost.

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. These findings indicate the optimal cost-effective solution for each highway scenario, for use when funding is a limiting agent.

However, often times, other options may provide the minimum BC ratio threshold of 2. Results referring to these alternatives were presented in Figures 6–8. It was found that RLM and RGM presented BC ratios greater than 4 on freeways. On divided arterials, all systems were cost-effective, except on scenarios with small lateral offsets and/or traffic volumes. On scenarios with offsets less than 20 feet, nonredirecting sacrificial crash cushions could not be economically

			Curvature (Degrees)															
			0	3	6	0	3	6	0	3	6	0	3	6	0	3	6	
Divided	AADT	1,000	B	B	B	B	B	B	B	B	B	A	A	A	B	B	B	B/C > 2
		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	
	AADT	1,000	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	B/C > 4
		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	
Undivided	AADT	1,000	E	E	E	E	E	E	E	E	E	N	N	N	N	N	N	B/C > 2
		5,000	B	B	B	B	B	B	B	B	B	N	N	N	N	N	N	
		10,000	B	B	B	B	B	B	B	B	B	N	N	N	N	N	N	
		20,000	B	B	B	B	B	B	B	B	B	N	N	N	N	N	N	
		30,000	B	B	B	B	B	B	B	B	B	N	N	N	N	N	N	
	AADT	1,000	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	B/C > 4
		5,000	B	B	B	B	B	B	E	E	E	N	N	N	N	N	N	
		10,000	B	B	B	B	B	B	E	E	E	N	N	N	N	N	N	
		20,000	B	B	B	B	B	B	E	E	E	N	N	N	N	N	N	
		30,000	B	B	B	B	B	B	E	E	E	N	N	N	N	N	N	
			5		10		15		20		35							
			Offset (ft)															

Fig. 7. All cost-effective options for divided and undivided rural arterials. B/C = benefit/cost.

		Curvature (Degrees)															
		0	5	10	0	5	10	0	5	10	0	5	10	0	5	10	
AADT	200	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	B/C > 2
	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	E	B	E	E	E	
	200	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	B/C > 4
	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		
		5			10			15			20			35			
		Offset (ft)															

Fig. 8. All cost-effective options for local highways. B/C = benefit/cost.

justifiable, as shown in Figure 7. On divided arterials with traffic volumes of 1,000 vpd and when a BC threshold of 4 was adopted, only RGM crash cushions were cost-effective, as shown in Figure 7. Figure 8 shows that the do-nothing option and redirecting crash cushions competed on local roads.

It is also important to stress that other factors, which may not have been considered in this study, may play a role in selecting a crash cushion system. For example, the time between the impact event and the time to repair the system should be taken in consideration. If there is a significant time gap, this could indicate that motorists would be exposed to unprotected hazards or less effective crash cushion systems. These conditions could potentially pose unacceptable risks to motorists. This could ultimately increase the benefits of reusable crash cushion systems, in a risk-adjusted basis, for certain roadway scenarios.

10. Limitations and Future Work

Installation, repair, and maintenance costs were based on limited data from the State DOTs and manufacturers. These costs may vary from region to region and from system to system. If the variation in cost is significant, a site-specific analysis would be required.

Posted speed limits along many highways, especially freeways, are above 55 mph (88.5 km/h). However, RSAP cannot accurately treat higher posted speed limits because the speed distributions were based on a study that investigated impact conditions in accident reports in the 1970s (Mak et al., 1986), which was prior to the repeal of the national speed limit of 55 mph (88.5 km/h). However, these speed distributions do allow for impact speeds above 55 mph (88.5 km/h).

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 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.

This article focuses on the modeled scenarios in the RSAP benefit-cost analysis, which represented generic roadside configurations. “Black spots” and other anomalies, such as gore areas, were not considered due to the impracticality of modeling the decision making process of a human being, among other difficulties. Therefore, if the impact frequency is known, and is relatively high, then a severe-duty crash cushion may be viable for impact frequencies as low as one impact every 2.44 years (Schrum et al., 2013).

The economic analysis contained herein was limited to quantifiable parameters pertaining directly to the crash cushions themselves. However, there may be other life cycle costs that could be applicable to the analysis that were not incorporated, such as delay time while a lane of traffic is closed, disposal costs of damage systems, and the risk to human life associated with the task of repairing these systems. Where these costs may constitute a significant portion of the life cycle costs, an in-depth case-by-case approach for conducting a benefit-cost analysis should be adopted.

For future studies, States should consider recording not only repair times for each system, but also 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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