Crash Cushion Selection Criteria

Final Report
September 2017

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16. Abstract

Crash cushions are used as a roadside safety treatment alternative to protect errant vehicles from striking potentially hazardous fixed roadside objects. A variety of crash cushion designs, with varying characteristics, are available for use by transportation agencies. The choice of an optimum cushion type in consideration of safety performance and economic viability at any given highway location depends on several factors, including roadway geometry and traffic characteristics, among others.

This research study aimed to quantify the life cycle costs of 13 different crash cushion systems installed in Iowa and to develop guidance to help decide where and when to install specific types of cushions. A probability-based tool, the Roadside Safety Analysis Program (RSAP), was used to estimate the frequency of run-off-the-road (ROR) crashes under a variety of roadway characteristics for three separate facility types, including two-lane undivided, four-lane divided, and one-way highways. The estimated impact frequency based on pertinent roadway and traffic characteristics was then used as a decision criterion to select the most appropriate crash cushion system in consideration of installation and maintenance costs.

Two general categories of redirective crash cushion systems were compared. These included crash cushions with higher installation and lower repair costs (RHL) and crash cushions with lower installation and higher repair costs (RLH). The life cycle cost comparison indicated that the RLH category was the optimal crash cushion type until an impact frequency of approximately 0.08 countermeasure strikes per year. Beyond this threshold, the RHL crash cushion category tended to be more cost-effective. Design guidelines based on hazard offset, annual average daily traffic (AADT), and curve radius are provided for each facility type of interest.

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CRASH CUSHION SELECTION CRITERIA

Final Report
September 2017

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EXECUTIVE SUMMARY

Some of the most severe roadway crashes occur when motorists depart from their intended lane of travel and strike a fixed (i.e., rigid and non-crashworthy) object. These crashes, known as roadway departure or run-off-the-road (ROR) crashes, represent a large portion of traffic fatalities on higher classification roadways, especially highways with fixed roadside objects that cannot be displaced. Recently, roadway departure crashes have accounted for up to 55 percent of all traffic fatalities nationally and approximately 62 percent of roadway fatalities in Iowa. Because there are a variety of objects within the roadside clear zone that cannot be removed (e.g., utility poles, bridge piers, or sign trusses), the American Association of State Highway and Transportation Officials (AASHTO) has established three strategies to mitigate the detrimental impacts of roadway departure crashes, one of which is the installation of crash cushions.

Crash cushions are used as a roadside safety treatment alternative to protect errant vehicles from striking potentially hazardous fixed roadside objects. The goal of a crash cushion is to intercept a vehicle before it impacts a rigid hazard. Therefore, crash cushions are designed to withstand both head-on and angle collisions with the intent of slowing down the striking vehicle over a short duration of time and space. Crash cushions are commonly designed with internal mechanisms specifically designed to withstand high impact forces and strategically fail in order to slow an errant vehicle. Based on this concept, there are a wide variety of crash cushions that perform appropriately according to testing requirements established by the National Cooperative Highway Research Program (NCHRP). Currently, there are 13 unique crash cushion systems installed along roadways within Iowa. This project aimed to assess the safety performance of these crash cushion systems based on historical crash information through an in-service performance evaluation. Additionally, the cost-effectiveness of each system was documented by collecting the installation, maintenance, and repair costs for each crash cushion from a wide variety of sources. Lastly, guidance was provided regarding the type of crash cushion to install based on prevalent roadway geometry and traffic characteristics.

In order to measure the safety performance of the installed crash cushion systems, a list of existing crash cushion installations provided by the Iowa Department of Transportation (DOT) was manually reviewed and updated based on Google Earth imagery. To ensure that a comprehensive analysis of the entire state network was completed, all Interstates and Iowa DOT-owned roadways were manually searched for further installations of crash cushions. Ultimately, 280 crash cushions were identified representing 13 unique types of systems. After collecting the relevant attributes for the installations, including the shielded object and the spatial location of the system in relation to the roadway, the cushions were grouped into two categories: redirective and non-redirective. Redirective countermeasures are designed to maneuver the striking vehicle back into the travel lane from which it departed, while non-redirective cushions are designed to be strategically penetrated by the striking vehicle.

Using law enforcement-reported crash information from the Iowa DOT crash database, a brief analysis of the resultant crash severities indicated that vehicles that collided with crash cushions experienced less severe crashes than vehicles that struck fixed objects. Unfortunately, due to the limited sample size of the crash cushion systems, an accurate safety performance analysis could not be conducted for each system independently. After collecting financial information from the Iowa DOT, district maintenance managers, and crash cushion manufacturers, the life cycle cost for each system was computed based on the initial installation costs as well as the average total repair cost for each system. Due to the lack of available maintenance data for the non-reactive barrier cushions, reactive barrier types were further split into two categories: high installation with low repair costs (RHL) and low installation with high repair costs (RLH). From this, a threshold of 0.08 crash cushion strikes per year was determined as the significant cutoff point between the RHL and RLH categories. RLH crash cushions were more cost-effective below this threshold due to their decreased likelihood of being struck by an errant vehicle, while RHL crash cushions were the better financial option in locations where barrier strikes were more prevalent.

Lastly, a probability-based software tool (the Roadside Safety Analysis Program) was consulted to estimate the frequency of ROR crashes under various roadway parameters and traffic characteristics based on the three facility types of interest: two-lane undivided, four-lane divided, and one-way highways. From this software, the offset of the hazard, the annual average daily traffic (AADT), and the curve radius of the segment were all significantly correlated with the likelihood of a crash occurring. Using these parameters with the life cycle cost categories, three individual design charts were crafted based on the derived cost-effectiveness of each crash cushion category. The RLH cushions were typically better for tangent facilities, roadways with lower AADT volumes, and hazards offset further from the roadway. Conversely, the RHL cushions were more cost-effective on shaper curves and roadways with higher AADT volumes and closely spaced hazards.

1. INTRODUCTION

Roadway departure crashes, which involve vehicles leaving the paved travel surface and encroaching onto the roadside, have been a major highway safety concern in both Iowa and the United States for decades. According to a compilation of five years (2011–2015) of motor vehicle crash data from the Fatality Analysis Reporting System (FARS) database managed by the National Highway Traffic and Safety Administration (NHTSA 2015), roadway departure crashes accounted for approximately 62 percent of all traffic fatalities in Iowa and about 55 percent of all traffic fatalities within the United States. Figure 1 displays this trend graphically for the five years of data.

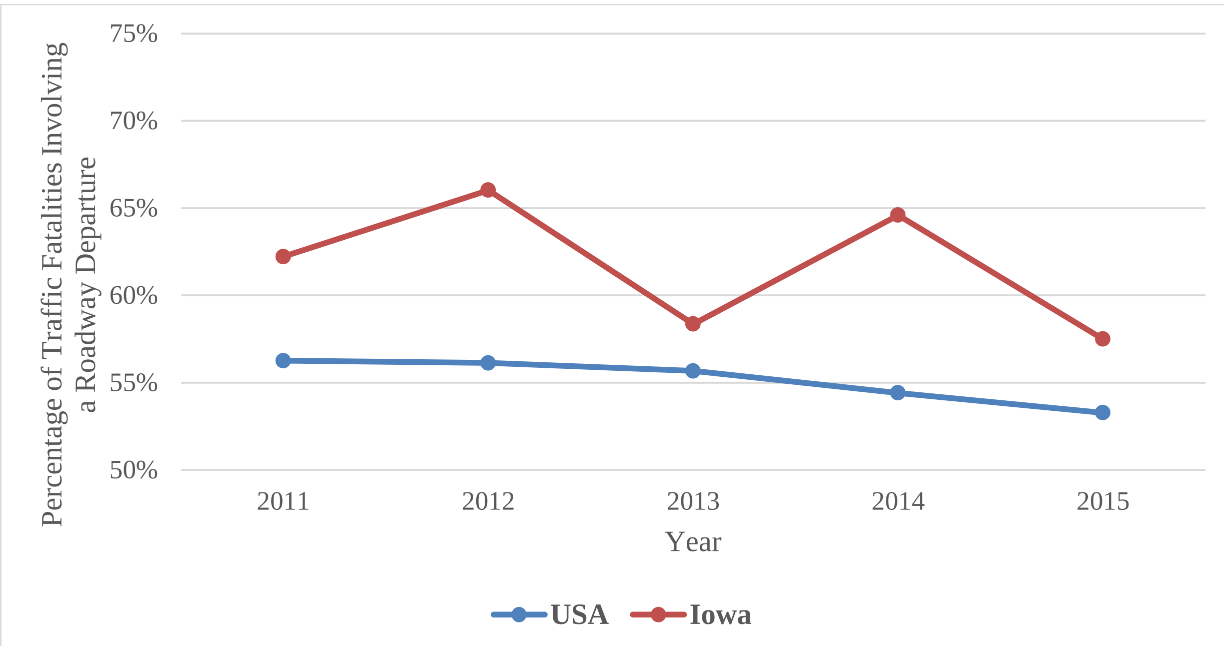


Figure 1. Role of roadway departure crashes in overall traffic fatalities in Iowa and the United States

A vast majority of such fatalities resulted from vehicles impacting one or more unyielding fixed roadside objects (e.g., trees or utility poles), colliding with opposing traffic, or overturning. In response to these concerns, the American Association of State Highway and Transportation Officials (AASHTO) has established three major roadside strategies that could be deployed to reduce the frequency and severity of roadway departure crashes, one of which includes the installation of crash cushions to shield fixed roadside objects within the clear zone that cannot be removed, redesigned, or relocated.

Crash cushions are designed to reduce the severity of impacts with fixed roadside hazards. The cushions absorb the kinetic energy of a colliding vehicle and gradually decelerate it to a lesser speed for frontal impacts and safely redirect a vehicle toward the travel lane for angular impacts. Short installation lengths, combined with the capability to accommodate both front-end and angled impacts, make crash cushions ideally suited for highway locations where such impacts are expected and roadway geometric constraints preclude the use of other types of traffic barriers. Fixed roadside hazards that typically merit shielding using a crash cushion include bridge piers, bridge rails, sign trusses, exit gore ramps, and median barrier ends, among others. Crash cushions are either directly attached to or placed in front of roadside hazards and are available in a variety of designs, each of which has a unique energy-absorbing mechanism that can be tailored to meet site-specific requirements. The crash cushion systems that are currently included in the Iowa DOT-approved product list are divided into the following three broad categories based on the system capabilities:

- ***Non-redirecting sacrificial crash cushions*** are typically comprised of sand barrels that can be arranged in various configurations to shield fixed objects of different shapes and sizes. These cushion types are mostly designed for head-on impacts and should not be used at locations where frequent angle impacts are expected. When impacted head-on, the barrels dissipate the kinetic energy of a vehicle through incremental momentum transfer to the contained sand masses, with lighter units being struck first within the configuration. Repairs after each impact often require total replacement of the damaged units.

- ***Redirecting sacrificial crash cushions*** telescope in the same direction as the striking vehicle during head-on impacts and crush energy-absorbing cartridges or rip specially designed internal parts to strategically dissipate energy. For side-angle impacts, the system behaves similarly to a guardrail and safely redirects a vehicle around a hazard and back onto the roadway. Maintenance is generally required to reset the cushion and replace any damaged system parts.

- ***Severe use crash cushions*** are functionally similar to redirecting sacrificial crash cushions, except that the internal mechanisms are constructed of more durable materials, such as high-density polyethylene (HDPE) cylinders, which can withstand multiple impacts without requiring significant repair and maintenance. These cushions are preferred at highway locations that already experience or are expected to experience frequent impacts.

The three system categories are visually depicted in Figure 2.

Non-Redirecting Sacrificial | Redirecting Sacrificial | Severe Use

Energy Absorption Systems, Inc. 2008a (left), Trinity Highway Products n.d.(a) (center), Trinity Highway Products n.d.(b) (right)

Figure 2. Iowa DOT crash cushion categories

Although several crash cushion systems have been successfully crash tested and deemed acceptable for use on the National Highway System (NHS), their efficacy and performance after installation in the field has not been thoroughly investigated. The existing data on maintenance and repair costs for different cushion systems, which form the basis of a benefit-cost analysis procedure, are largely based on these crash test results and may not be reflective of the true costs associated with real-world crash scenarios. Further, the approved cushion systems offer different trade-offs among installation, maintenance, and repair costs. Therefore, research is needed to evaluate the field performance of cushion systems installed for use as safety devices and to estimate their total life cycle costs to properly estimate their financial effectiveness.

This report is organized into seven chapters, with this first chapter providing an introduction and background to the research, in addition to defining the study objectives. A brief overview of the subsequent chapters is as follows:

- Chapter 2 provides a review of the existing literature on the efficacy and in-service safety performance of crash cushions. Best practices among state departments of transportation (DOTs) are considered, as well as any economic analyses that examine the cost-effectiveness of the systems.

- Chapter 3 summarizes the data collection strategies and methodology utilized during this study. Various attributes were collected for each installation, including product type and placement in relation to the roadway surface, among others.

- Chapter 4 outlines the estimated performance and use cases for all 13 crash cushion systems installed in Iowa. Design charts are provided where applicable, as well as figures that display the cushion in use.

- Chapter 5 presents the safety performance of the crash cushion installations based on historical crash data, as well as the maintenance and repair costs associated with each type of barrier. A brief cost analysis examines the life cycle cost of two barrier categories.

- Chapter 6 explains the inclusion of the Roadside Safety Analysis Program (RSAP), which was consulted to determine the probability of a vehicular encroachment based on a variety of roadside design factors. Crash severity and cost-effectiveness were also computed with the RSAP software.

- Chapter 7 provides a summary of the research findings and conclusions based on the results.

2. LITERATURE REVIEW

Several research studies have been conducted internationally and in the United States to examine the efficacy of crash cushion installations. A meta-analysis of 32 research studies focused on evaluating the safety benefits of installing guardrails, median barriers, and crash cushions (Elvik 1995). The weighted mean estimates of the safety benefits derived from the crash cushion installations were computed, and the results indicated that crash cushions were effective in reducing both the crash rate (per million vehicle kilometers traveled) and fatal injury crash frequency by 84 percent and 69 percent, respectively. Similar results were found in another meta-analysis, which concluded that crash cushions reduced property damage-only crashes by 46 percent and reduced both fatal and injury crash frequency by 69 percent (Elvik et al. 2004). Further, according to international statistics on traffic injury prevention, the installation of crash cushions in Birmingham, England, reduced fatalities by 53 percent and injury crashes by 40 percent (WHO 2004). Research in California indicated that the installation of crash cushions along the highway network within the state resulted in saving the lives of approximately 330 motorists over a 10-year period (Caltrans 1983). The monetary savings derived from these cushion installations, which reduced the severity outcome for most crash-involved motorists, was estimated to be over $30 million.

2.1 Crash Cushion Delineation

Although crash cushion installations are effective at reducing the impact severity of crashes near gore areas, the increased crash frequency at such locations may offset the benefits. One potential countermeasure considered by highway agencies to address this problem has been to use delineation treatments to increase the conspicuity of gore areas and the installed crash cushions. To determine the effectiveness of the delineation treatments, one research study analyzed four unique delineation schemes (Wunderlich 1985). Three of the four treatments, designated as Level I through Level III, consisted of varying levels of reflective static elements, while the fourth treatment (Level IV) was a combination of static elements and flashing lights. The 10 most frequently repaired gore crash cushion sites in Houston, Texas, were chosen for the study based on three years of repair records. Each of the four treatments was installed at two sites; thus, eight sites received delineation treatments, while the remaining two sites were utilized as control locations. Repair records following the installation of the delineation treatments were collected for a period of 17 to 22 months and compared against the repair records from the pre-installation period. Based on a short-term assessment, the Level IV treatments were shown to be effective at reducing the repair frequency at treatment sites with high initial repair rates (9 to 12 repairs/year), while the static delineation treatments did not have any significant effect on repair rates at sites with moderate repair rates (4 to 6 repairs/year).

A survey of district officials in Texas was conducted to identify the delineation practices adopted for crash cushion installations at gore areas on urban freeways (Creasey et al. 1989). The intent of this survey was to evaluate the long-term effectiveness of the delineation treatments installed as part of the study by Wunderlich (1985) described above. The survey responses indicated that most of the district officials used delineation treatments with their crash cushions; however, the type and amount of delineation used varied considerably in terms of object markers, nose/back panels, and flashing lights. Contrary to the results of Wunderlich (1985), the long-term effectiveness evaluation indicated that all of the gore area crash cushion delineations were effective in reducing crash cushion repair rates at the eight study sites. This resulted in an estimated $174,000 savings in crash and repair costs over a four-year analysis period. Moreover, given the differences among gore areas in regard to physical roadway attributes, such as sight distance and horizontal curvature, a classification scheme was developed to aide in the selection of the most appropriate delineation treatment for a particular gore area.

2.2 In-Service Performance Evaluation

An early attempt to monitor the performance of fixed and portable steel drum crash cushions and sand inertia barriers was conducted in Texas (Hirsch et al. 1975). A total of 147 steel drum cushions and sand inertia barriers were installed in Texas and had already sustained over 400 impacts since the first installations occurred in October 1968. The performance analysis considered various aspects of the barrier types, including relative safety to motorists, safety to highway maintenance crew, initial costs, maintenance and repair costs, durability and reliability, and overall cost-effectiveness. The research methodology involved interviewing traffic engineers, construction foreman, and shop supervisors from seven districts within Texas to discuss their field experience with the cushions. From this, the participants suggested improvements or changes they would like to see in the existing designs of the cushions to increase the safety and affordability of these countermeasures. Based on these discussions, the following changes were recommended: remove the redirection panels from steel drums at locations where frequent head-on impacts are expected, encourage the reuse of reconditioned steel drums, improve the design of portable steel drums, and regularly inspect inertia barriers to ensure they are in usable condition.

Additional research focused on the performance and cost-effectiveness of crash cushion installations in Kentucky using a database that compiled 127 crashes between 1980 and 1982 (Pigman et al. 1984). For each crash, an effort was made to obtain the corresponding police report form, photographs of the vehicle and crash cushion after the impact, and repairs needed to restore the cushion to working condition. The crash database had information on six unique crash cushion types: Hi-Dro cell, Hi-Dro cluster, guardrail energy absorbing terminal (G-R-E-A-T), G-R-E-A-T – temporary, sand barrels, and steel drum cushions. A comparison of the data on average repair costs among the product types indicated that the Hi-Dro cell cushion was the cheapest to repair ($392), while the highest average repair cost was associated with the Hi-Dro cell clusters ($2,839). Moreover, when available, the performance of a cushion during a crash was also noted. The results indicated that cushions performed properly in 85 percent of the 127 crashes. Improper performance was characterized by the cushion rebounding the striking vehicle into or across the adjacent roadway and overturning the vehicle after impact. Ultimately, the installation of each of the cushion devices resulted in a benefit-cost ratio between 1.0 and 2.0, thus validating the cost-effectiveness of the installations.

2.3 Life Cycle Cost Analysis

A research study performed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California-Davis aimed to develop a decision support tool to estimate the life cycle costs of crash cushion systems (Ravani et al. 2014). Traditionally, the installation cost of a crash cushion had been the only expense considered while conducting economic analyses; however, the intent of this project was to also include routine maintenance and repair cost information to refine the life cycle cost estimation process. Actual repair and impact frequency data for each crash cushion were collected from the California Department of Transportation (Caltrans) Integrated Maintenance Management System (IMMS). The repair frequency rather than the impact frequency was considered in the life cycle of the crash cushion because some impacts with the countermeasure did not require repairs. In order to collect an accurate estimate of the number of barrier strikes that did not require repairs, impact sensors and a site monitoring system were developed to collect high-resolution impact data. These monitoring systems were installed at three test locations. The results from this life cycle tool utilized estimates of impact frequency, repair costs, and access costs to develop the break-even point in cost for the different classes of crash cushions. The developed decision support tool can be used to evaluate a wide variety of crash cushion products based on their assumed life cycles on a site-specific basis.

Further research was conducted to develop guidelines to assist highway engineers in selecting the most cost-effective crash cushion for installation at various highway locations that differ in terms of roadway, roadside, and traffic characteristics (Schrum et al. 2015). A total of eight different crash cushion systems were considered, including QuadGuard, Quest, TRACC, TAU-II, QuadGuard Elite, React 350, SCI, and sand barrels. The cost information (i.e., installation, repair, and maintenance costs) was obtained from available manufacturer product sheets and surveys sent out to both state DOTs and manufacturers. Once the cost data were available, the cushion systems were grouped together to form three separate categories: redirecting with repair costs exceeding $1,000 (Group 1), redirecting with repair costs less than $1,000 (Group 2), and non-redirecting sacrificial (Group 3). A threshold value of $1,000 was chosen because it was consistent with common practice based on the surveys.

Schrum et al. (2015) also involved a sensitivity analysis to identify the roadway and traffic parameters that had the greatest influence on crash costs. A parameter was considered significant if changing its value from the base condition caused a fluctuation of more than 20 percent in the crash cost. The analysis results indicated that only three parameters were significant: crash cushion offset, average daily traffic, and curve radius. Moreover, the analysis results were consistent across all functional classes considered in this study (freeways, arterials, and local highways). The significant parameters were modified based on various highway scenarios, while the insignificant parameters were kept at their baseline values. Following the estimation of crash costs and direct costs, benefit-cost analyses were conducted using the index method and the incremental method. The index method compared the benefit-cost ratio of the crash cushions relative to an unprotected hazard, whereas the incremental method compared two crash cushion alternatives to ascertain an optimum scenario. Ultimately, a design chart was prepared that recommended a specific crash cushion category based on the following parameters: road facility type, annual average daily traffic (AADT), crash cushion offset, curve radius, and benefit-cost ratio. These design charts indicated that Group 2 systems were cost-effective for locations experiencing a high number of crashes, while Group 1 systems were a feasible option for locations with moderate or low crash frequencies. The study results also suggested that sites be left unprotected when the lateral offsets of fixed objects are large or if the site carries a very low traffic volume.

2.4 Crashworthiness Evaluation

Traditionally, full-scale crash tests have been the most popular method for assessing the crashworthiness of safety hardware. However, in recent years researchers have started experimenting with simulation software to perform such hardware crashworthiness evaluations. As such, an analysis was performed to determine the fidelity and accuracy of computer-simulated barrier impacts compared to full-scale crash tests (Miller and Carney 1997). The study utilized finite element computer simulations to model the physical impacts of a vehicle striking a roadside crash cushion. The Narrow Connecticut Impact Attenuation System was the crash cushion of interest, while the DYNA3D software provided an accurate simulation of the energy-dissipating response of the barrier. Both heavy and light vehicles were tested and simulated striking the cushion at 97 km/h (60 mph). The testing involved nontracking, braking, and turning vehicles. The results indicated that the computer simulations were extremely effective at modeling the impacts of full-scale testing. The resultant graphs of physical barrier deformations and impact displacements were almost identical. Due to the symmetric nature of the analyses, it was recommended that simulation tools be utilized much more extensively than full-scale evaluations due to the former's relative inexpensiveness.

3. DATA COLLECTION AND INTEGRATION

The geographic locations of 147 crash cushions installed along the roadway network in Iowa were provided by the Iowa DOT in a spatial shape file format. In addition to location data, the shape file also included pertinent attribute information for each installation, including the name of the crash cushion system and the type of hazard shielded by the cushion, among others. The map shown in Figure 3 identifies the primary road network in Iowa with red lines and the 147 crash cushion installations with green circles.

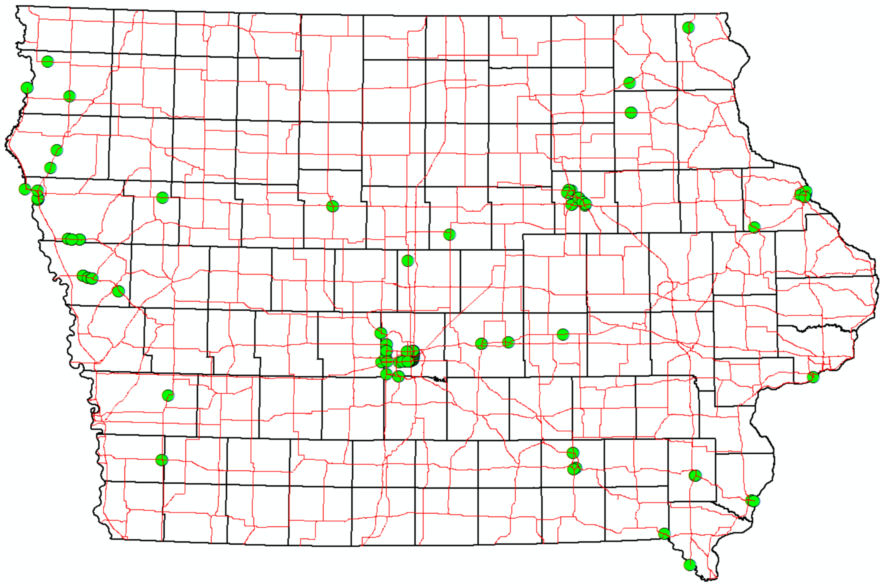


Figure 3. Installation locations of crash cushions per Iowa DOT resources

In order to ensure the accuracy of the data, each location was reviewed to identify any potential discrepancies. To accomplish this task, Google Earth aerial and Street View imagery was consulted to manually review each identified location. After reviewing all 147 cushion locations, three installations identified in the shape file were found to have discrepancies based on the provided imagery. Two of these installations were miscoded in that no cushion was installed, whereas the third identified the cushion around 500 ft away from its actual location. The miscoded locations were removed from the analysis, and the geographic information was updated for the remaining installation. After this quality assurance, the geographic shape file contained accurate information for 145 crash cushions.

After confirmation of the provided crash cushion installations, a manual search was conducted to identify any additional crash cushion installations that were not documented by the Iowa DOT. Every interchange within the state was observed using Google Earth aerial imagery to search for additional cushion installations. Interchanges were observed specifically because a wide variety of hazards, including bridge piers, gore areas, sign trusses, and other obstacles, are generally present within the clear zones of these facility types. Once the interchanges were reviewed, the entirety of the Iowa DOT-maintained highway network was also manually reviewed for crash cushions. These locations often have concrete barriers, bridge parapets, and sign trusses, which need to be shielded due to their rigidity. Ultimately, 135 additional cushion installations were identified and included in the database, increasing the total number of crash cushion installations to 280. The following sections include a detailed breakdown of the attributes collected for each identified crash cushion.

3.1 Product Type

To date, there are 13 unique crash cushion systems that have been installed along roadways in Iowa. A detailed description of each of these 13 crash cushion systems is provided in Chapter 4, including manufacturer design specifications. Figure 4 shows the frequency of the various crash cushion installation types within Iowa.

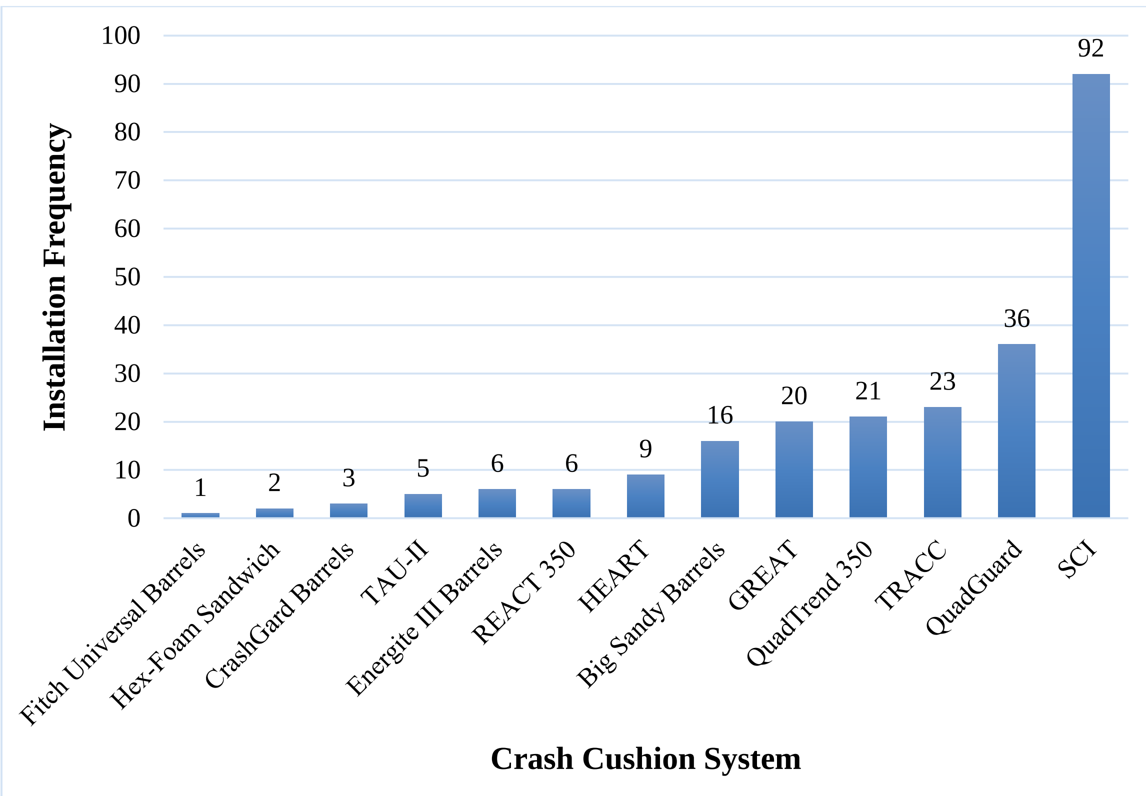


Figure 4. Installation frequency of crash cushion systems

3.2 Shielded Object

A variety of hazards located within the clear zone of a roadway require shielding by a crash cushion in order to reduce the potential injury severity. Examples of roadside hazards include bridge piers, bridge rails, the end points of concrete barriers, culvert rails, gores at ramps, sign trusses, signal posts, and guardrail ends. Information on the type of hazard being shielded by the cushion was recorded for each installation and updated in the spatial database, as mentioned above. Figure 5 contains the typical roadside hazards that are shielded using crash cushions, while Figure 6 documents the frequency of each roadside hazard as determined by the manual review.

Bridge Pier

Bridge Rail

Concrete Barrier

Culvert Rail

Gore at Ramp

Sign Truss

Signal Post

Guardrail End

Figure 5. Roadside hazard types

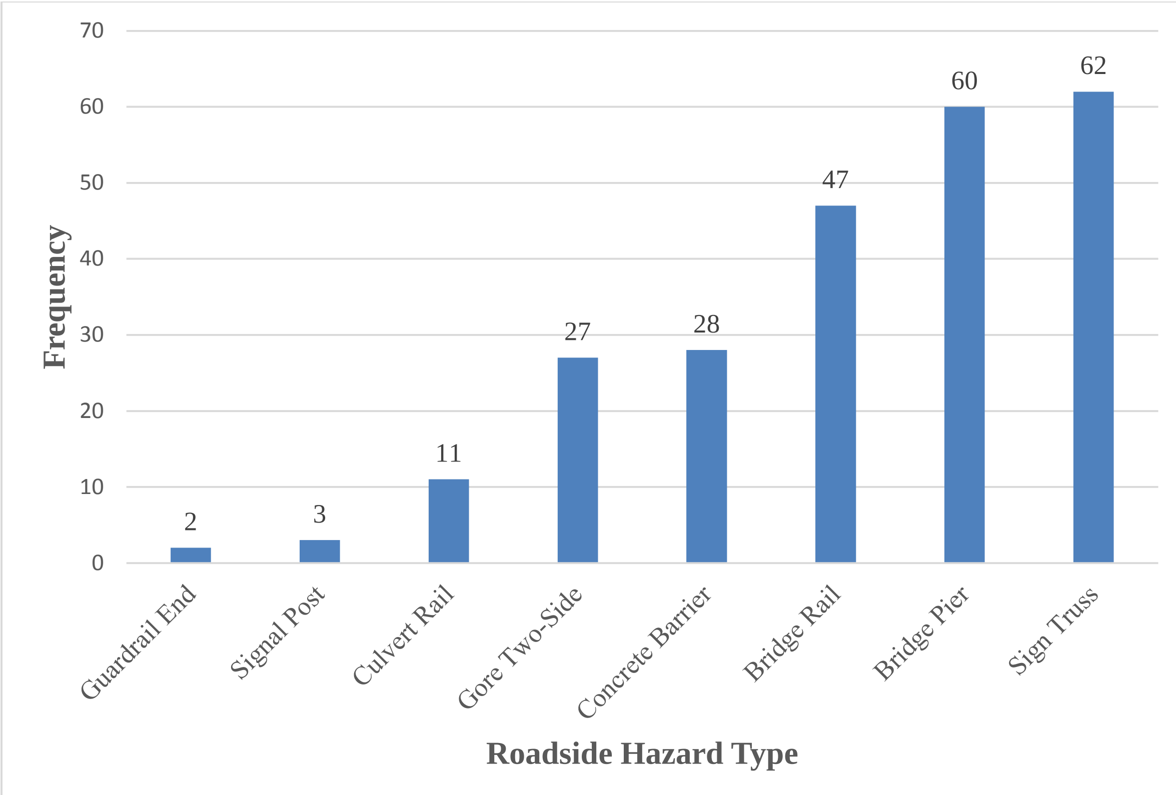
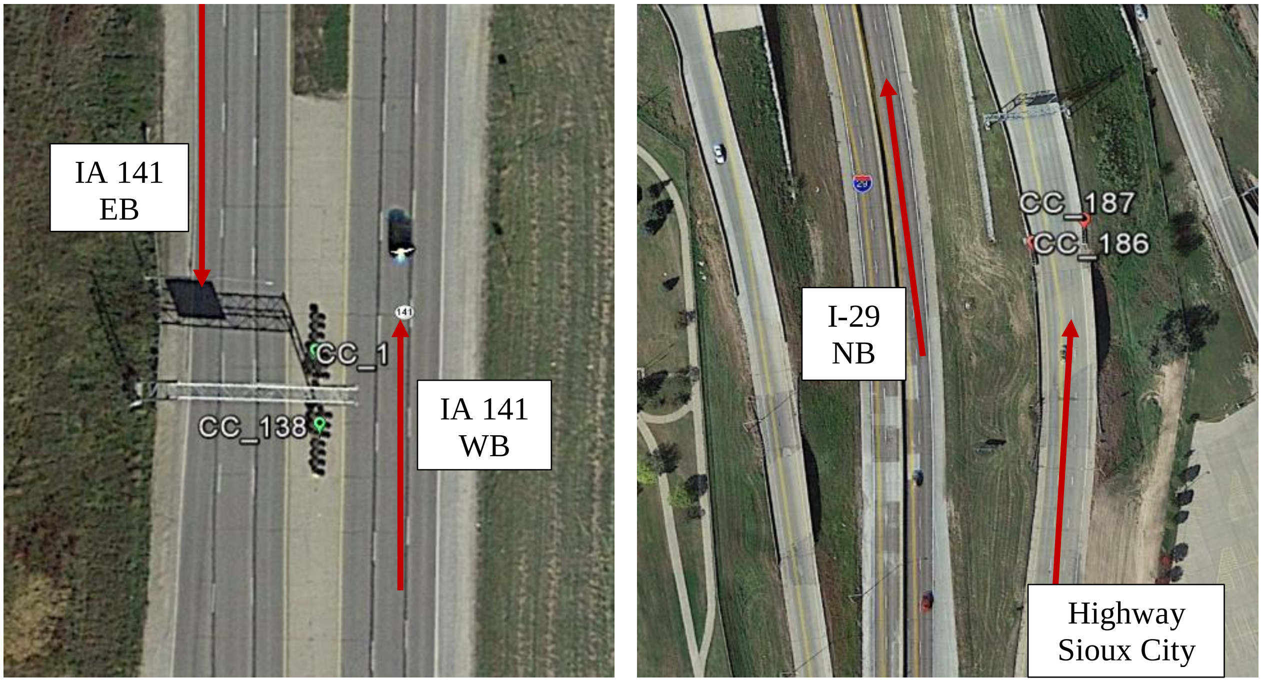


Figure 6. Frequency of roadside hazard types

3.3 Route and Relevant Direction of Travel

The name of the mainline roadway and the direction of travel was collected for each crash cushion installation. For cushions installed on ramps, the name of the mainline roadway and the direction of mainline traffic were both noted. As shown in the left portion of Figure 7, the route and direction of travel for the cushions identified as CC_1 and CC_138 corresponded to IA 141 eastbound (EB) and IA 141 westbound (WB). In the right portion of Figure 7, the cushions identified as CC_186 and CC_187 both had I-29 recorded as the route and northbound (NB) as the direction of travel.



Images © 2016 Google (from Google Earth)

Figure 7. Route and direction of travel identification

Figure 8 contains the frequency of cushion installations by functional roadway classification. The relevant city and county information was also recorded for each crash cushion installation.

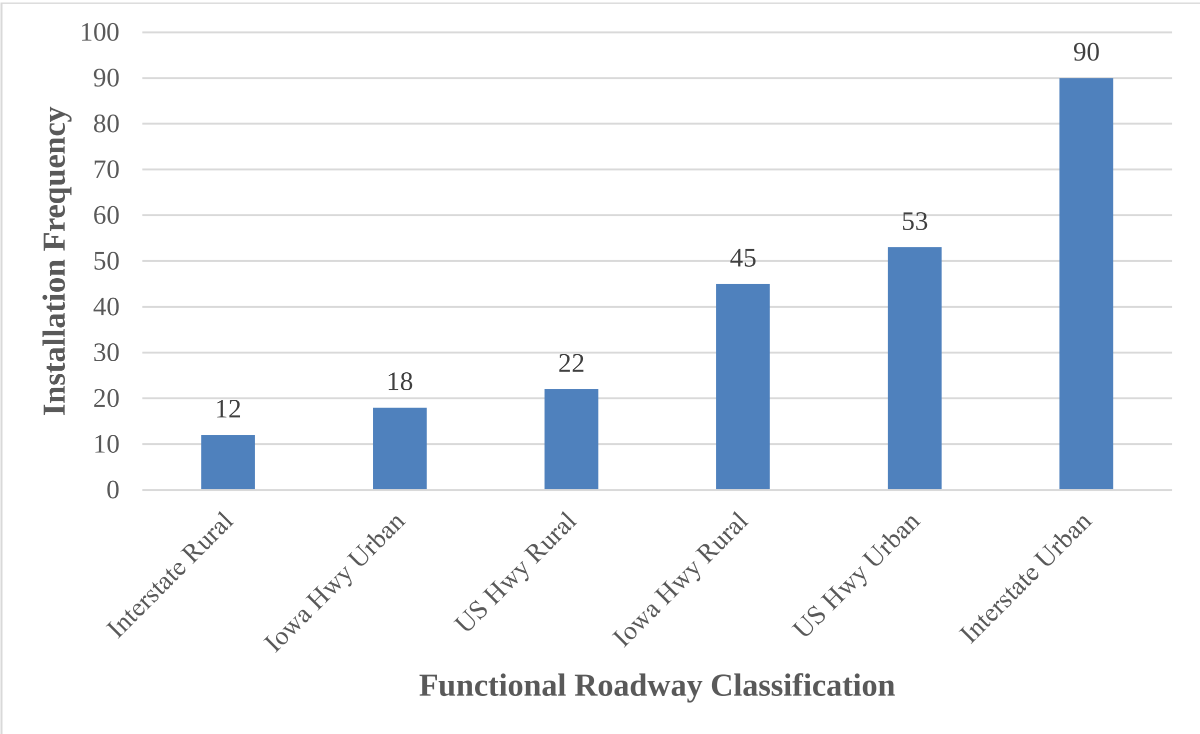


Figure 8. Frequency of cushion systems by roadway classification

3.4 Relevant Spatial Location

The placement of the cushion in relation to the roadway was also recorded for each installation. For this analysis, five placement configurations were utilized:

- **Mainline:** Cushion installation on the outside shoulder of the roadway.

- **Median 1:** Cushion installation in the median area or on the inside shoulder separating two directions of travel.

- **Median 2:** Cushion installation in the median area between the same direction of travel, commonly between the mainline roadway and access ramps.

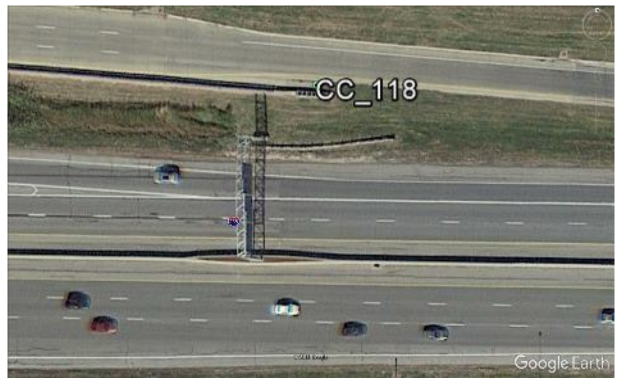
- **Ramp:** Cushion installation on an entrance or exit ramp.

- **Gore:** Cushion installation in a gore area, which refers to the triangular piece of land between the mainline roadway and the diverging or merging ramps. Figure 9 visually displays the placement configurations, while Figure 10 contains the frequency of the identified configuration patterns across the roadway network.

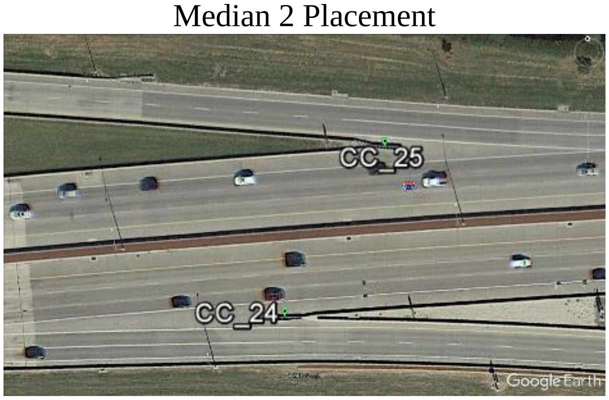
Mainline Placement

Median 1 Placement

Median 2 Placement



Ramp Placement



Gore Placement

Figure 9. Placement configuration types

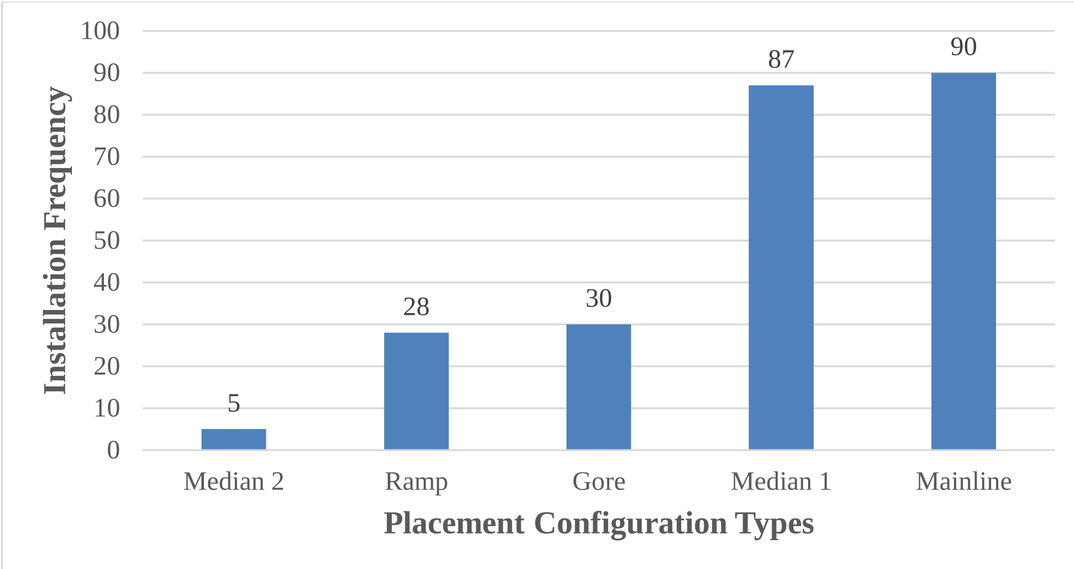


Figure 10. Frequency of placement configuration types

Figure 11 outlines the entire crash cushion system as well as the percentage of installations per placement configuration. The frequency of each installation is also included within Figure 11 for each crash cushion system.

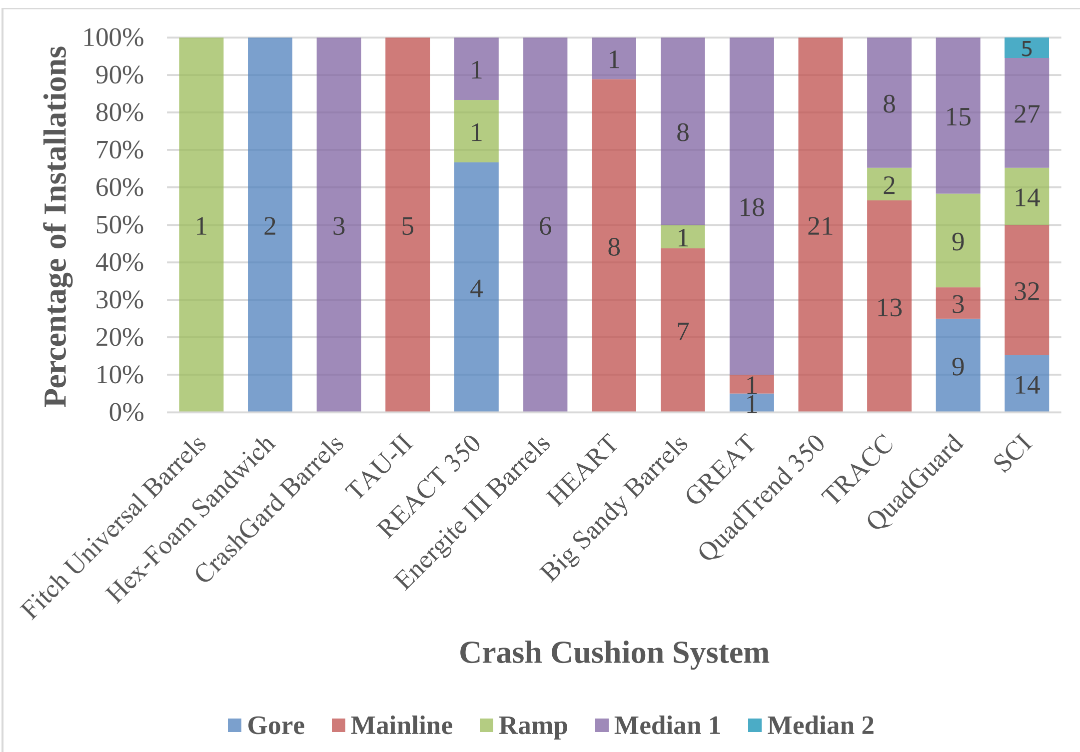


Figure 11. Percentage of placement configurations by crash cushion system

4. CRASH CUSHION SYSTEMS

A wide variety of crash cushion systems are available to date, each of which differs from one another in regard to installation costs, energy-absorbing mechanisms, system performance, maintenance characteristics, and repair costs. Because of this, a detailed description of the 13 different crash cushion systems that have been installed along roadways within Iowa is provided. Further, the examined systems have been broadly divided into two categories: redirective systems and non-redirective systems.

4.1 Redirective Systems

Redirective crash cushion systems are designed to maneuver errant vehicles back toward the travel lane during side-angle impacts. These systems are further classified as gating and non-gating devices based on the extent of their redirection capabilities. Gating devices have redirection capabilities available for a portion of the system length, which allows vehicles making side-angle impacts upstream of this portion to pass through it, similar to a gate. Consequently, a sufficient clear zone area should be available behind the gating devices to allow impacting vehicles to regain control after passing through the barrier. Non-gating devices have redirection capabilities along the entire length of the system, disallowing impacting vehicles from passing through the system. Nine out of the 13 installed cushion devices are redirective systems. A description of each of these systems follows.

4.1.1 Guardrail Energy Absorbing Terminal (G-R-E-A-T) System

The G-R-E-A-T crash cushion is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is specifically designed to shield narrow hazards up to 3 ft wide and is compliant with the NCHRP Report 230 (Michie 1981) test requirements for a redirective, non-gating crash cushion. The system is available in different configurations to accommodate a wide range of impact speeds. Its main components include a base support, a guidance cable, interlocking fender panels, steel diaphragms, and hex-foam cartridges. When hit head-on, the assembly telescopes rearward, crushing the energy-absorbing cartridges and simultaneously decelerating the vehicle to a considerably lower speed. Fender panels, chain anchors, and the guidance cable that runs along the length of the system provide lateral restraint and redirect vehicles during side-angle impacts. The dimensions and a picture of a typical G-R-E-A-T cushion system are shown in Table 1 and Figure 12, respectively.

Table 1. Dimensions of G-R-E-A-T crash cushion system

	Minimum	Maximum
Length	15 ft (4 bays)	33 ft (10 bays)
Backup Width	24 in.	36 in.

Source: Energy Absorption Systems, Inc. n.d.(a)

© 2016 Google (from Google Street View)

Figure 12. Typical G-R-E-A-T crash cushion system

4.1.2 Hybrid Energy Absorbing Reusable Terminal (HEART) System

The hybrid energy absorbing reusable terminal (HEART) crash cushion is a trademarked attenuator system manufactured by Trinity Highway Products, LLC. It is compliant with the NCHRP Report 350 (Ross et al. 1993) test level 3 (TL-3) requirements for a redirective, non-gating crash cushion. The system consists of a series of steel diaphragms mounted on tubular steel tracks and surrounded within a framework of HDPE side panels. During head-on impacts, tension cables attached to the second diaphragm are released and the assembly moves rearward, crushing the HDPE panels to absorb the kinetic energy of the impacting vehicle. For side impacts, the tubular steel tracks resist the lateral movement and help maneuver vehicles back towards the travel lane. The dimensions and a picture of a typical HEART cushion system are shown in Table 2 and Figure 13, respectively.

Table 2. Dimensions of HEART crash cushion system

	Test Level 2 (TL-2)	TL-3	70 mph
Length	14 ft	26 ft 6 in.	29 ft
Backup Width	28 in.	28 in.	28 in.
Height	32 in.	32 in.	32 in.

Source: TxDOT 2013

© 2016 Google (from Google Street View)

Figure 13. Typical HEART crash cushion system

4.1.3 Hex-Foam Sandwich System

The Hex-Foam Sandwich crash cushion is a trademarked system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 230 (Michie 1981) test requirements for a redirective, non-gating crash cushion and is particularly used to shield wide hazards. The main system components include crushable hex-foam cartridges, steel diaphragms, fender panels, and guidance cables. During a head-on crash, the kinetic energy of the impacting vehicle is absorbed by a series of hex-foam cartridges, which allow for a controlled deceleration of the crashing vehicle. To accommodate side impacts, the guidance cables provide the necessary lateral restraint and maneuver vehicles back towards the travel lane. The system is designed to accommodate a wide range of impact speeds, and a design table is provided by the manufacturer to tailor the system to site-specific requirements. The dimensions and a picture of a typical Hex-Foam Sandwich cushion system are shown in Table 3 and Figure 14, respectively.

Table 3. Dimensions of Hex-Foam Sandwich crash cushion system

	Min.	**Max.**
Length	9 ft 4.5 in. (4 bays)	28 ft 11.5 in. (10 bays)
Backup Width	36 in.	90 in.
Height	NA	NA

Source: Energy Absorption Systems, Inc. n.d.(b)

Figure 14. Typical Hex-Foam Sandwich crash cushion system

4.1.4 QuadGuard System

The QuadGuard crash cushion is a trademarked system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 350 (Ross et al. 1993) test requirements for a redirective, non-gating crash cushion and is designed to accommodate a wide range of impact speeds. Moreover, the system is available in various configurations to shield hazards as wide as 10 ft. The main system components include a monorail base, quad-beam panels, diaphragms, and two types of energy-absorbing cartridges. During head-on impacts, the assembly telescopes rearward, compressing the energy-absorbing cartridges located between the diaphragms while simultaneously decelerating the vehicle to a considerably lower speed. For side-angle impacts, the center monorail support structure resists the lateral movement and maneuvers the vehicle back towards the travel lane. The dimensions and a picture of a typical QuadGuard cushion system are shown in Table 4 and Figure 15, respectively.

Table 4. Dimensions of QuadGuard crash cushion system

	Min.	**Max.**
Length	9 ft (25 mph)	27 ft (70 mph)
Backup Width	24 in.	120 in.
Height	NA	NA

Source: FHWA 2013

© 2016 Google (from Google Street View)

Figure 15. Typical QuadGuard crash cushion system

4.1.5 QuadTrend 350 System

The QuadTrend 350 crash cushion is a trademarked system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 350 (Ross et al. 1993) test requirements for a redirective, gating end treatment. Its main components include base supports, interlocking Quad-Beam panels, redirecting cable anchored at both ends of the system, a back strap, sand containers, and six steel posts resting on the slip base supports. Moreover, because the cushion allows gating, a minimum traversable clear zone is required behind the attenuator as per Federal Highway Administration (FHWA) recommendations. During head-on impacts, the Quad-Beam panels telescope rearwards, crushing the sand containers attached to posts 1, 3, and 4 to dissipate the kinetic energy of the impacting vehicle. To accommodate side-angle impacts, the steel cable running along the length of the system provides the necessary redirection for the crashing vehicle. The dimensions and a picture of a typical QuadTrend 350 cushion system are shown in Table 5 and Figure 16, respectively.

Table 5. Dimensions of QuadTrend 350 crash cushion system

	Dimensions
Length	20 ft
Width	15 in.
Height	32 in.

Source: Energy Absorption Systems, Inc. 2008b

Iowa DOT (field photo)

Figure 16. Typical QuadTrend 350 crash cushion system

4.1.6 Reusable Energy Absorbing Crash Terminal (REACT) 350 System

The Reusable Energy Absorbing Crash Terminal (REACT) 350 crash cushion is a trademarked system manufactured by Trinity Highway Products, LLC. It is compliant with the NCHRP Report 350 (Ross et al. 1993) test requirements for a redirective, non-gating crash cushion and is available in different configurations to accommodate a wide range of impact speeds. The cushion system mainly consists of an array of HDPE cylinders, redirective cables anchored at both ends of the system, and a backup structure. The backup structure is self-contained within the system or a concrete backup is externally attached. The kinetic energy of the crashing vehicle is absorbed by the HDPE cylinders, which are crushed during the impact, although the cylinders are restored to their original shape after the impact. For side-angle impacts, the cables attached to both sides of the system provide the lateral restraint necessary to maneuver the vehicles back towards the travel lane. The dimensions and a picture of a typical REACT 350 cushion system are shown in Table 6 and Figure 17, respectively.

Table 6. Dimensions of REACT 350 crash cushion system

	TL-2		**TL-3**		**70 mph**	
	Self-Contained Backup	**Concrete Backup**	**Self-Contained Backup**	**Concrete Backup**	**Self-Contained Backup**	**Concrete Backup**
Length	15 ft 3 in.	13 ft 9 in.	21 ft 3 in.	19 ft 5 in.	30 ft 3 in.	28 ft 9 in.
Backup Width	24 in.	30–36 in.	24 in.	30–36 in.	24 in.	30–36 in.
Height	51.5 in.	51.5 in.	51.5 in.	51.5 in.	51.5 in.	51.5 in.

Source: TxDOT 2013

Figure 17. Typical REACT 350 crash cushion system

4.1.7 Smart Cushion Innovations (SCI) System

The Smart Cushion Innovations (SCI) system is a trademarked crash cushion system manufactured by Work Area Protection Corp. It is available in two different models, SCI-70GM and SCI-100GM, both of which are compliant with the NCHRP Report 350 (Ross et al. 1993) test requirements for a redirective, non-gating crash cushion at TL-2 and TL-3, respectively. The cushion system mainly consists of a base, support frame assemblies, a front sled assembly, side panels attached to collapsing support frames, a steel cable, sheaves, and a shock-arresting cylinder. During a head-on impact, the assembly telescopes backward and a resistive force, which varies with the mass and speed of the impacting vehicle, is generated by the cylinder to decelerate the vehicle to a considerably lower speed. For side-angle impacts, the interlocking side panels and anchor bolts, which attach the system to the foundation, provide the necessary lateral restraint to maneuver the vehicle back towards the travel lane. The dimensions and a picture of a typical SCI cushion system are shown in Table 7 and Figure 18, respectively.

Table 7. Dimensions of SCI crash cushion system

	Narrow		**Wide**	
	TL-2	**TL-3**	**TL-2**	**TL-3**
Length	13 ft 6 in.	21 ft 6 in.	20–42 ft	28–50 ft
Backup Width	24–36 in.	24–36 in.	41–133 in.	41–133 in.
Height	33.4 in.	33.4 in.	33.4 in.	33.4 in.

Source: TxDOT 2013

Figure 18. Typical SCI crash cushion system

4.1.8 TAU-II System

The TAU-II family of crash cushion systems are from Lindsay Corporation (Lindsay 2017). The TAU-II is available for both low-speed and high-speed applications and is compliant with the NCHRP Report 350 (Ross et al. 1993) test requirements for a redirective, non-gating crash cushion. Moreover, the system is designed in various configurations to shield hazard widths ranging from 2.5 ft to 8.5 ft. Its main components include a back support, a front cable anchor, guidance cables, steel diaphragms dividing the assembly into collapsible bays, sliding panels, and two types of energy-absorbing cartridges. The assembly telescopes backwards upon frontal impact, initially compressing the energy-absorbing cartridges in the first bay and then distributing the impact forces uniformly to all the remaining cartridges through the diaphragms until the vehicle finally decelerates to a considerably lower speed. During a side-angle impact, the steel cables running along the length of the system beneath the diaphragms provide the necessary lateral restraint to maneuver a vehicle back towards the travel lane. The dimensions and a picture of a typical TAU-II cushion system are shown in Table 8 and Figure 19, respectively.

Table 8. Dimensions of TAU-II crash cushion system

	Narrow			**Wide**		
	TL-2	**TL-3**	**70 mph**	**TL-2**	**TL-3**	**70 mph**
Length	12 ft 7 in. – 14 ft 3 in.	26 ft 10 in. – 28 ft 6 in.	29 ft 7 in. – 31 ft 3 in.	11 ft 5 in. – 14 ft 4 in.	25 ft 7 in. – 28 ft 5 in.	25 ft 7 in. – 31 ft 3 in.
Width	30 or 36 in.	30 or 36 in.	30 or 36 in.	42–102 in.	42–102 in.	42–102 in.
Height	32 in.	32 in.	32 in.	32 in.	32 in.	32 in.

Source: TxDOT 2013

Lindsay 2017, © Lindsay Corporation

Figure 19. Typical TAU-II crash cushion system

4.1.9 Trinity Attenuating Crash Cushion (TRACC) System

The Trinity Attenuating Crash Cushion (TRACC) family of crash cushion systems is manufactured by Trinity Highway Products, LLC. The attenuator family consists of four different models (TRACC, SHORTRACC, FASTRACC, and WIDETRACC), all of which are compliant with the NCHRP Report 350 (Ross et al. 1993) test requirements for a redirective, non-gating crash cushion. The SHORTRACC model is used for low-speed applications (TL-2), while the TRACC and FASTRACC models are suited for high-speed applications (TL-3). The FASTRACC model is an extended version of the TRACC model that can accommodate head-on impacts at speeds up to 70 mph. The WIDETRACC model is specifically designed to shield wide hazards and is available for both TL-2 and TL-3 applications. It can be flared on one side or both sides to suit site-specific needs. The main components of the TRACC family include a guidance track, crossties, a front sled, intermediate support frames, W-beam fender panels, a backup frame, and steel cables (used only in the WIDETRACC model). During a head-on impact, the kinetic energy of the impacting vehicle is dissipated as the hardened steel plate contained in the front sled cuts through the rip plates attached to the top of the base assembly. To accommodate side impacts, crossties, which attach the system to the foundation, provide the necessary lateral restraint to maneuver the impacting vehicle back towards the travel lane. The dimensions and a picture of a typical TRACC cushion system are shown in Table 9 and Figure 20, respectively.

Table 9. Dimensions of TRACC crash cushion system

	TRACC	SHOR TRACC	FAS TRACC	WIDE TRACC	WIDE SHORTRACC	WIDE FASTRACC
Length	23 ft	16 ft	27 ft 9 in.	23 ft – 46 ft 4 in.	17 ft – 39 ft 3 in.	27 ft 11 in.– 51 ft 1 in.
Backup Width	24 in.	24 in.	24 in.	58–127 in.	39–108 in.	71–141 in.
Height	32 in.	32 in.	32 in.	32 in.	32 in.	32 in.

Source: TxDOT 2013

Trinity Highway Products n.d.(a)

Figure 20. Typical TRACC crash cushion system

4.2 Non-Redirective Systems

Non-redirective crash cushion systems do not have a redirection capability and are designed to allow for a controlled penetration of vehicles impacting at an angle downstream from the nose of the system. Such systems mostly consist of sand barrels, which can be arranged in different geometric configurations to shield hazards of various shapes and sizes. A typical arrangement involves placing the lightest barrels at the front, with the weight of each barrel increasing as the array approaches the shielded hazard. Such arrangement facilitates the smooth momentum transfer of the impact forces to the variable sand masses while allowing for a controlled deceleration of the vehicle. Moreover, the number of units in each row of the array also increases as the shielded hazard is approached in order to make the array wide enough at the obstacle to accommodate corner impacts. A sufficient gap between the last row of sand modules and the fixed object is also provided to prevent the confinement of sand and debris. Ideally, for the system to achieve its optimal performance, lighter barrels should be struck first, followed by the heavier barrels just before the hazard. Consequently, in situations where reverse angle impacts are expected, lighter modules are placed along the fixed object to prevent vehicles from making initial impact with the heavier barrels.

The initial installation cost of non-redirective systems is generally lower than that of their redirective counterparts; however, total replacement of the impacted sand barrels is required after almost every crash, which significantly increases the repair costs in certain situations. Such systems are most suited for locations that are expected to experience fewer side-angle crashes and should be placed as far away from the travel lane as possible to minimize nuisance strikes. Four different sand barrel systems are installed across roadways within Iowa, and a description of each system is provided in the following sections.

4.2.1 Energite III System

The Energite III sand barrel system is a trademarked system from Energy Absorption Systems, Inc., a Trinity Industries Company. It is compliant with the NCHRP Report 350 (Ross et al. 1993) TL-3 requirements for a non-redirective, gating crash cushion. A typical array consists of sand modules available in 90, 180, 320, 640 and 960 kg sizes. The 90, 180, and 320 kg modules include a model 640 outer container, a cone insert to adjust the center of mass and overall weight of the barrel, and a lid. The 640 and 960 kg modules do not require a cone insert and consist of model 640 and model 960 outer containers, respectively. A typical Energite III cushion system is shown in Figure 21.

Energy Absorption Systems, Inc. 2008c

Figure 21. Typical Energite III crash cushion system

4.2.2 Big Sandy System

The Big Sandy sand barrel system is a trademarked cushion array manufactured by TrafFix Devices, Inc. It is compliant with the NCHRP Report 350 (Ross et al. 1993) TL-3 requirements for a non-redirective, gating crash cushion. The system mainly consists of three models of outer plastic containers, sand, and a lid. The largest barrel accommodates 960 kg of sand, the second largest holds 640 kg, and the third largest model (also known as a combination barrel) utilizes a pedestal base and a top half-barrel to configure the system into 90, 180, and 320 kg sizes within a standard array. The combination barrels do not use cone inserts. A typical Big Sandy cushion system is shown in Figure 22.

Figure 22. Typical Big Sandy crash cushion system

4.2.3 CrashGard Sand Barrel System

The CrashGard sand barrel system is a trademarked cushion array manufactured by Plastic Safety Systems, Inc. It is compliant with the NCHRP Report 350 (Ross et al. 1993) TL-3 requirements for a non-redirective, gating crash cushion. Its main components include an outer plastic container, a cone insert, sand, and a lid. The CrashGard sand barrels are available in standard weights of 90, 180, 320, 640, and 960 kg to create appropriate array designs to shield hazards. Sand barrels weighing 90, 180, and 320 kg are configured by inserting a cone into the outer container first and then filling the container with sand to the corresponding fill levels, while barrels weighing 640 and 960 kg are constructed by placing the necessary amount of sand without the cone insert. A typical CrashGard sand barrel system is shown in Figure 23.

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Figure 23. Typical CrashGard sand barrel system

4.2.4 Fitch Universal Barrel System

The Fitch Universal sand barrel system is a trademarked cushion array from Energy Absorption Systems, Inc., Trinity Industries Company. It is compliant with the NCHRP Report 350 (Ross et al. 1993) TL-3 requirements for a non-redirective, gating crash cushion. Each sand-filled unit of the array consists of an outer plastic container, one unicore insert to adjust the center of mass and overall weight of the barrel, and a lid. The outer plastic container is made up of two identical half-cylinders that are fastened together. Such multi-piece barrel design saves repair costs because it allows the replacement of only the impacted face and not the entire barrel. Moreover, the overall weights of the barrels are configured in standard sizes of 90, 180, 320, 640, and 960 kg to create numerous array designs to meet site-specific needs. A typical Fitch Universal barrel system is shown in Figure 24.

Energy Absorption Systems, Inc. 2008a

Figure 24. Typical Fitch Universal barrel system

5. PRELIMINARY ANALYSIS

5.1 Crash Data

The statewide crash database (from the Iowa DOT Motor Vehicle Division) was consulted to identify single-vehicle crashes involving permanent crash cushions over an eight-year period from 2007 through 2014. This analysis period was chosen based upon the availability of crash report narratives from the Iowa DOT. Additionally, high-resolution Google Earth aerial and Street View imagery is generally available from 2007 onward. This imagery allowed for manual verification as to whether crashes coded as attenuator strikes actually involved a vehicle colliding with a permanent crash cushion installation. Crashes that were coded as striking attenuators in any relevant field of the crash report form were included in the manual review. Relevant fields included the crash sequence of events, the most harmful events, and the type of fixed object struck. Table 10 summarizes the results of the crash review for collected target crashes.

Table 10. Summary of target crashes

Type of Device Struck	Frequency	Percentage (%)
Permanent crash cushion	34	32.4
Temporary crash cushion	23	21.9
Median cable barrier	33	31.4
Coding error	15	14.3
Total	**105**	**100.0**

Crashes were grouped into four categories: crashes that involved a vehicle striking a permanent crash cushion system, crashes in which a vehicle struck a temporary (i.e., work zone-related) crash cushion system, crashes that involved median cable barriers, and crashes that were incorrectly coded based on a detailed review of the crash form.

As noted in Table 10, only 32.4 percent of the crashes coded as striking a crash cushion actually involved a permanent system. The other 67.6 percent of vehicular crashes coded as such were coded incorrectly; they either involved a temporary crash cushion system erected for work zone protection or a median cable barrier or were miscoded based on other identifying information available within the crash report form. Because of this, only 34 target crashes were available for analysis purposes.

Using these data, crash rates were estimated for the eight-year analysis period from 2007 to 2014. These rates were determined per million vehicle miles traveled (MVMT) considering the traffic volume of the roadway on which the cushion was located and the cushion’s length. Table 11 summarizes the rates for each of three facility types, which include two-lane undivided highways, multi-lane divided highways, and one-way roadways/ramps. In addition to these rates, the average number of crashes per cushion per year are presented for this same period.

Table 11. Rate of crashes involving permanent crash cushions by facility type, 2007–2014

Facility Type	Crashes per MVMT	Crashes per cushion per year
Two-lane undivided highway	0.000	0.000
Multi-lane divided highway	0.261	0.017
One-way roadway/ramp	1.209	0.021

During these eight years, no collisions were identified among the crashes occurring on two-lane, two-way highways. On multi-lane divided highways, an average of 0.017 collisions occurred per crash cushion per year. This translates to a crash rate of 0.261 impacts per MVMT. Interestingly, this rate is slightly higher than the rate of reported crashes involving median cable barriers, which have been shown to experience approximately 0.238 impacts per MVMT (based on police-reported crashes). The collision rate for crash cushions was expected to be higher because these devices are generally installed closer to the traveled way than cable barriers. Lastly, the crash rate was significantly higher on one-way roadways/ramps. The rate of collisions with crash cushions was 1.209 per MVMT, nearly five times higher than the rate on divided highways. However, the rate of collisions per crash cushion was reasonably similar within the two facility types, with crash cushions on ramps experiencing approximately 0.021 collisions per year.

For the 34 crashes identified as involving a vehicle striking a permanent crash cushion, the distribution of injury severity outcomes at the crash level (i.e., where the highest injury severity sustained in all involved vehicles is representative of the entire crash) is displayed in Figure 25.

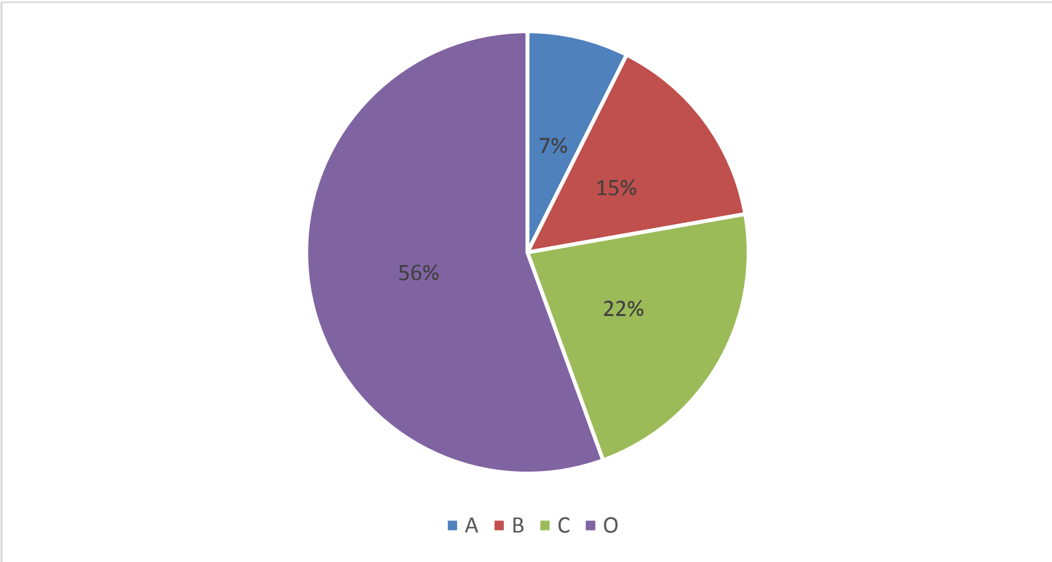


Figure 25. Crash severity distribution of target crashes

For each of these crashes, the most harmful event (as coded by the responding law enforcement officer) was striking the crash cushion. The injury levels were classified according to the KABCO scale:

- K = fatal injury
- A = incapacitating injury
- B = non-incapacitating injury
- C = possible injury
- O = no injury (i.e., property damage only)

Note that a majority of the crashes (78 percent) during the eight-year analysis period resulted in possible injury or property damage-only crashes. Of the target crashes, only 15 percent involved a non-incapacitating injury, and even fewer (7 percent) had an occupant sustain an incapacitating injury. Also, no fatal injury target crashes occurred between 2007 and 2014, providing a general indication as to the overall effectiveness of these crash cushion installations in preventing more severe injuries resulting from strikes with the fixed object shielded by these devices.

For comparison, crashes involving guardrails, concrete barriers, and various unprotected fixed hazards were collected during the same eight-year analysis period from the Iowa DOT crash database. The purpose of this task was to document the distribution of injury severity at the crash level. This would provide an equivalent comparison to the results displayed in Figure 25. The percentage of crashes within each KABCO threshold per fixed hazard type is shown in Figure 26. The counts for each severity level are also included.

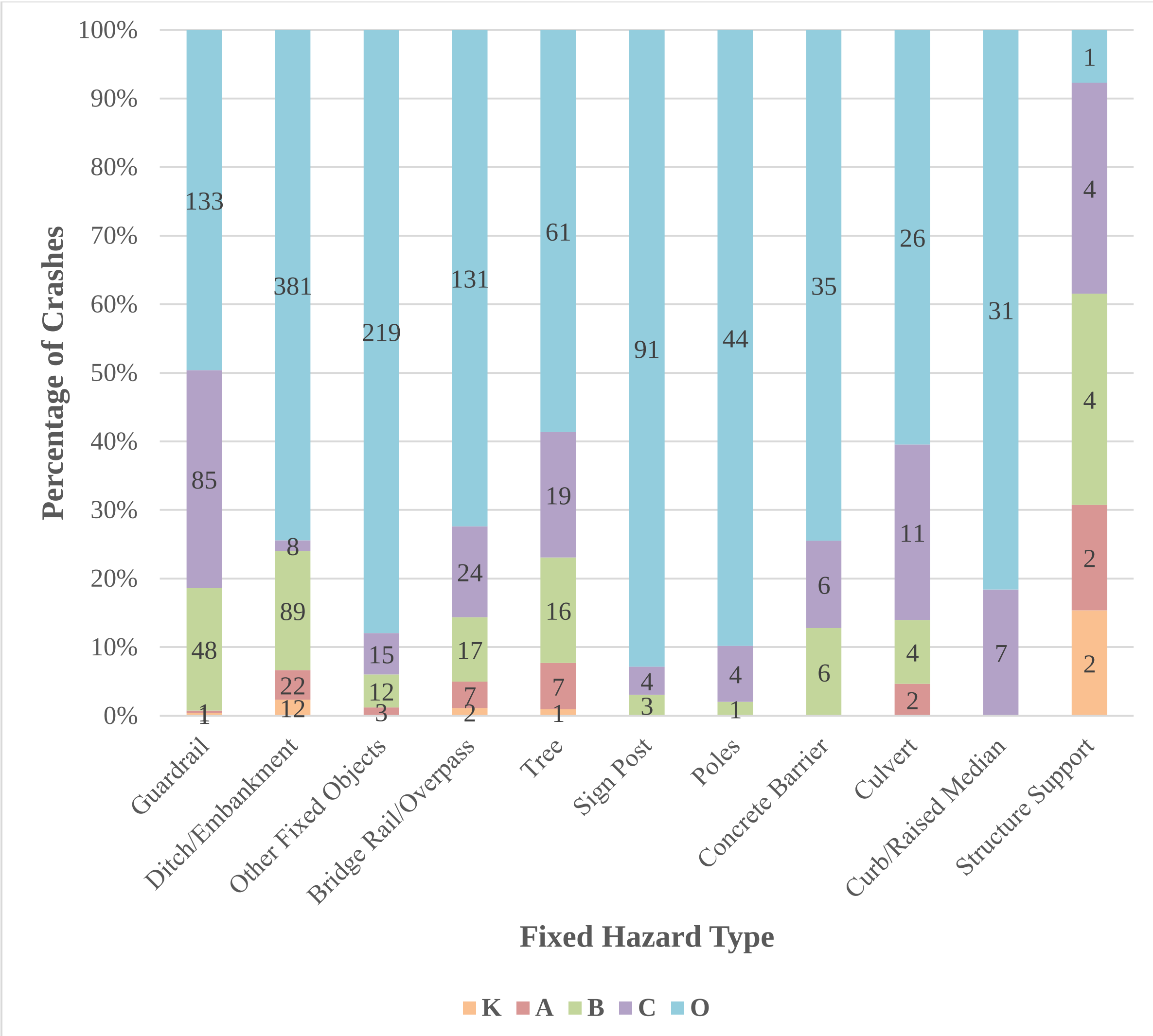


Figure 26. Crash severity distribution of crashes with unprotected fixed objects

Note that the comparison crashes involving unprotected fixed objects during the analysis period tended to be more severe. Of the 1,601 crashes, 17 (1.1 percent) resulted in a fatal injury. Among all of the fixed object crashes considered, 43 incapacitating injury crashes occurred between 2007 and 2014. A majority of these crashes were due to vehicles entering a ditch or embankment. Lastly, crashes involving a structural support were rarely property damage-only crashes in nature, with a majority of crashes involving some form of occupant injury. This finding indicates that it is important to protect such rigid structures with crash cushions in order to reduce the severity of a crash.

When examining the injury severity distributions from the collisions involving permanent crash cushions, it should be noted that the sample of only 34 crashes limits the ability to conduct product-specific comparisons across the various devices currently in use throughout the state. Ideally, the selection of a specific crash cushion would be informed by a comparison among several devices in terms of the relative effectiveness of each based upon the probability of specific injury outcomes occurring (conditioned on a crash having occurred). However, a much larger sample size would be needed to allow for such comparisons. Given the relative infrequency of crashes involving permanent installations, this represents an important research need that could best be served by a collaborative effort, such as a pooled-fund study, involving multiple states.

In the absence of such data, no distinction can be made between the performance characteristics of competing crash cushion systems. Consequently, for the purposes of the subsequent analyses, it is presumed that all approved devices provide a similar level of performance. As such, the selection of a device is primarily driven by differences in installation and maintenance costs, as well as the expected frequency with which each device would be struck while in service.

5.2 Installation Costs

To estimate the installation costs for each of the 13 crash cushion types, a collection of 89 plan sets was provided by the Iowa DOT. Each plan set was structured as a series of indexed sheets. First, the Estimated Project Quantities table was consulted to determine whether the project included the installation of permanent crash cushions. For every project that included crash cushions, the corresponding item number was recorded. This item number was then queried in the Estimate Reference Information table to locate additional reference information in the Crash Cushions table. This latter table contained location stations and other pertinent details for the installations of interest. For plan sets that did not properly link to the Crash Cushions table, the search was restarted, but this time the installation of temporary crash cushions was included to identify miscoded information.

Subsequently, the location stations were used to locate additional permanent installations that were initially not included in the database. Furthermore, the provided Contract IDs (indicated on the plan sets) were collected to find additional information. The Iowa DOT also provided a spreadsheet that linked Contract IDs with the following information: project number, project letting date, project start date, and project completion date. From this information, the Field Manager documents were consulted to obtain the installation costs and installation dates for permanent cushions installed under various projects.

Unfortunately, the Field Manager documents did not include the installation cost information for all product types. Consequently, emails were sent to manufacturers requesting installation cost data on product types for which Iowa DOT information was not available. Emails were also sent to manufacturers of product types whose installation cost information was available through the Field Manager documents for comparison purposes. Additional information was obtained from data available online from both the Kansas DOT (KDOT) and Mississippi DOT (MDOT). Table 12 provides a summary of the installation costs for the 13 different crash cushion systems.

Table 12. Installation costs for 13 crash cushion systems

Product	Installation Cost
Redirective Systems	
G-R-E-A-T	$10,511[c]
HEART	$19,525[a]
Hex-Foam Sandwich	$8,030[c]
QuadGuard	$20,545[a]
QuadTrend 350	$5,220[b]
REACT 350	$32,530[b]
SCI	$22,070[a]
TAU-II	$19,500[a]
TRACC	$14,430[b]
Non-Redirective Systems	
Energite III	$3,875[b]
Big Sandy	$2,735[b]
CrashGard sand barrels	$3,580[b]
Fitch Universal barrels	$4,435[b]

a. Iowa DOT Field Manager
b. Kansas DOT Contract Document (KDOT 2017)
c. Mississippi DOT Agency Contract (MDOT 2015)

As Table 12 shows, these costs vary widely, from as low as $2,735 (Big Sandy) for the low-cost non-redirecting sacrificial systems to as high as $32,530 (REACT 350) for the high-cost redirecting sacrificial and severe use systems. Based on the installation costs alone, the most expensive non-redirective system was the Fitch Universal barrels ($4,435), while the cheapest redirective system was the QuadTrend 350 ($5,220).

5.3 Repair Cost

In order to obtain accurate repair information for permanent crash cushions along the roadway network, an email was distributed to all district maintenance managers in each of the six Iowa DOT districts. Besides the total number of repairs, the following information was also requested: route and mile point of repair, date on which the crash involving the cushion occurred, date on which the cushion was repaired, time taken to perform the repair, number of workers needed for the repair, and the overall cost and replacement fees.

Based on the responses received from the district maintenance managers, Districts 4 and 5 did not experience any significant damage to crash cushions installed within their jurisdictions, while the remaining four districts performed crash cushion repairs. The responding districts provided the requested information in spreadsheet format. After the spreadsheets were received, the route and mile post information for each repair was used to link the appropriate repair data to the corresponding unique identifier for each permanent cushion.

The repair data obtained from the responding districts did not include information on all product types because some cushion systems were never struck or required only minor repairs. Consequently, another email was crafted and distributed to the manufacturers of each crash cushion system requesting an estimate for the average costs of damaged system parts and the personnel hours required to restore the cushion to working condition after the system had been subjected to various NCHRP 350 (Ross et al. 1993) tests during the product approval process.

Once the repair data were received from the Iowa DOT districts and the manufacturers, the average repair costs and personnel hours required to repair different crash cushion systems were estimated. Table 13 provides a summary of the average costs and personnel hours required to repair the damaged cushions by product type.

Table 13. Average repair costs for 13 crash cushion systems

Product	Avg. Material Cost	Avg. Repair Time (Hours)	Total Avg. Repair Cost[g]
Redirective Systems			
G-R-E-A-T	$7,323.00[a]	29.0[b]	$8,773.00
HEART	$1,225.00[f]	16.0[f]	$2,025.00
Hex-Foam Sandwich	$1,786.00[a]	38.0[a]	$3,686.00
QuadGuard	$6,465.00[a]	39.0[a]	$8,415.00
QuadTrend 350	$6,565.00[c]	36.9[a]	$8,410.00
REACT 350	$7,248.00[a]	14.0[b]	$7,948.00
SCI	$2,204.00[a]	12.0[a]	$2,804.00
TAU-II	$5,550.00[b]	20.0[b]	$6,550.00
TRACC	$8,700.00[b]	24.0[b]	$9,900.00
Non-Redirective Systems			
Energite III	$2,712.50[d]	21.0[e]	$3,762.50
Big Sandy	$1,914.50[d]	21.0[a]	$2,964.50
CrashGard sand barrels	$2,506.00[d]	21.0[e]	$3,556.00
Fitch Universal barrels	$3,104.50[d]	21.0[e]	$4,154.50

a. Iowa maintenance records
b. Arizona Finding in the Public Interest (FIPI) submittal
c. Assuming full replacement cost
d. Assuming 70% system replacement after each crash
e. Assuming same average repair time as Big Sandy system
f. Approximate values based on the NCHRP 350 test results
g. Assuming labor charge of $50/hour, a value used in Arizona FIPI submittal

In cases where Iowa-specific information was unavailable, information was obtained from other sources, as detailed in the note under Table 13. Based on the total average repair cost alone, the cheapest crash cushion system was the HEART redirective cushion ($2,025). Conversely, the most expensive crash cushion to repair was the TRACC redirective system ($9,900). Of the non-redirective systems, the Big Sandy had the lowest total average repair cost ($2,965), while the Fitch Universal barrels had the greatest average repair cost ($4,155).

Based on the installation and average repair costs noted in Table 12 and Table 13, respectively, a matrix was created to display the information simultaneously, as shown in Table 14.

Table 14. Matrix of installation and total average repair costs

Installation Costs	Total Average Repair Costs			
	$2,000–4,000	**$4,000–6,000**	**$6,000–8,000**	**$8,000–10,000**
< $5,000	Energite III, Big Sandy, CrashGard	Fitch Universal barrels	-	-
$5,000–10,000	Hex-Foam Sandwich	-	-	QuadTrend 350
$10,000–15,000	-	-	-	G-R-E-A-T, TRACC
$15,000–20,000	HEART	-	TAU-II	-
$20,000–25,000	SCI	-	-	QuadGuard
> $25,000	-	-	REACT 350	-

Given the lack of maintenance data for non-redirective cushions, the subsequent analyses focus exclusively on redirective systems. Two crash cushion categories were created based on the available installation and repair costs: redirective systems with high installation costs and low repair costs (RHL) and redirective systems with low installation costs and high repair costs (RLH). The cushions in the RHL category had installation costs in the $15,000 to $20,000 range and repair costs in the $2,000 to $4,000 range. An average installation cost of $17,500 and an average repair cost of $3,000 were used to generate the life cycle cost values. The RLH category included cushions with installation costs in the $10,000 to $15,000 range and repair costs between $8,000 and $10,000. Similar to the previous category, an average installation cost of $12,500 and average repair cost of $9,000 were used to estimate the life cycle cost values.

Based upon these estimates, a direct comparison could be made between the RHL and RHL systems through a life cycle cost comparison. Figure 27 provides a comparison between the two categories for a 15-year service life based on the expected number of crash cushion strikes per year.

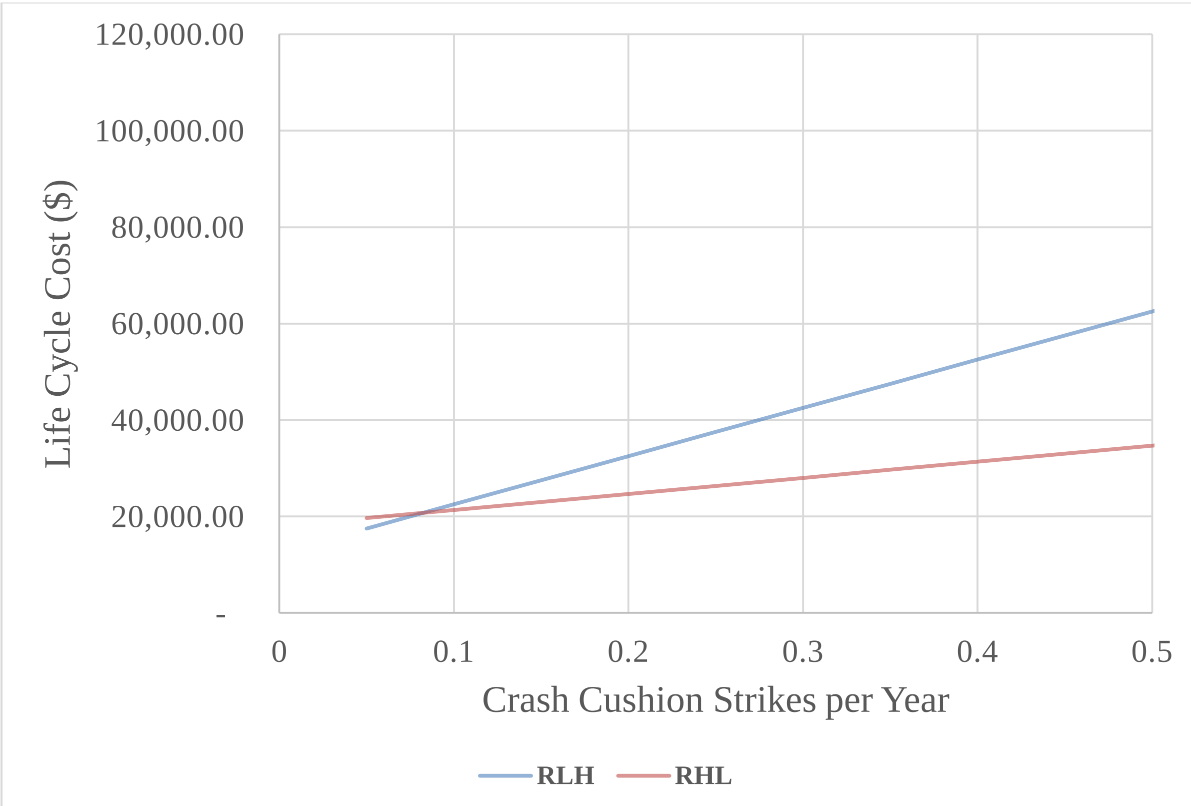


Figure 27. Life cycle costs based on crash cushion strikes per year

These data show that the RLH systems provide a more cost-effective solution at sites where the expected crash frequencies are low. In contrast, beyond the point where the life cycle cost curves intersect, the RHL systems become a more viable alternative economically.

Note that the RHL and RLH categories intersect at a crash frequency of about 0.08 crash cushion strikes per year. Therefore, highway locations with an expected crash frequency of less than 0.08 strikes per year should utilize a crash cushion system with a lower installation cost and higher repair costs (RLH), while the opposite is true for locations experiencing more than 0.08 strikes per year, as displayed in Figure 27. Ultimately, the cost per repair is the driving factor in this relationship. As the number of expected strikes per year increases, a cushion type with a higher installation cost and lower repair costs becomes the more cost-effective option.

It should be noted this rate of 0.08 strikes per cushion per year is significantly higher than the rates presented previously in Table 11. However, it is important to note that the Iowa-specific collisions rates presented previously are likely to be low for at least two reasons. First, the research literature includes several studies that have assessed the degree to which traffic crashes are underreported to law enforcement agencies. Blincoe et al. (2002) examined data from various federally maintained databases and estimated that 21 percent of injury crashes and half of property-damage only (PDO) crashes are unreported. While these underreporting rates are likely to vary by facility type and other factors, the 34 crashes identified in this study are likely to include only a subset of all collisions involving permanent crash cushions. Second, this study involved the utilization of specific fields from police crash report forms in combination with a review of the narrative sections of these reports. Table 10 illustrates the significant issues associated with crash report fields for identifying various types of collisions, and, as such, it is expected that some reported crashes may also have not been appropriately identified. Given these issues, the subsequent analyses consider both a lower range for the expected number of crashes (based on the Iowa data) and a higher rate in consideration of the expected underreporting.

6. EVALUATION USING ROADSIDE SAFETY ANALYSIS PROGRAM (RSAP)

Given the limited number of crashes involving permanent crash cushion installations throughout the state, the use of simulation software was required to estimate the impacts of various design factors, such as traffic volume, horizontal curvature, and device offset, on the likelihood of a crash occurring. This investigation utilized RSAP.

6.1 Overview

RSAP is a software tool used specifically to determine the cost-effectiveness of various roadside safety treatment alternatives. RSAP was originally developed in 1988 under NCHRP Project 22-09 and was initially available for public use with the 2002 edition of the AASHTO *Roadside Design Guide* (AASHTO 2002). Subsequently, RSAP has undergone several upgrades, some of which include improvements to the algorithms, updates to embedded default databases, and enhancements to the graphical user interface. RSAP Version 3 (RSAPv3) is the latest version of the software, which was developed under NCHRP Project 22-27, and was used in this study to perform various analyses on crash cushion systems currently in use across the state.

The cost-effectiveness procedure incorporated within RSAPv3 uses an encroachment probability-based model that is built on a series of conditional probabilities, which are computed using the following four modules: encroachment probability module, crash prediction module, severity prediction module, and benefit/cost analysis module. First, the encroachment probability module uses roadway geometric characteristics and traffic information to estimate the expected encroachment frequency on a user-defined roadway segment. Given an encroachment, the crash prediction module then evaluates the likelihood of the encroachment resulting in a crash. For each predicted crash, the severity prediction module estimates the crash severity, which is then converted into dollar values using the internal crash cost estimations. Finally, the benefit/cost analysis module utilizes the crash cost estimates and the user-assigned agency costs to calculate the benefit-cost ratio for each alternative.

6.2 Encroachment Probability Module

The encroachment probability module estimates the expected number of encroachments on a road segment through a two-step process. First, a baseline encroachment frequency is developed based on the facility type. Next, the baseline frequency is modified with adjustment factors to account for deviations from the baseline conditions. The highway types defined in RSAPv3 include two-lane undivided, four-lane divided, and one-way highways. The baseline encroachment frequencies for these highway types are based on encroachment data collected in the late 1970s in Canada (Cooper 1980). These encroachment data, which were based on the observations of tire tracks on the traveled roadway, provide rates of encroachment for various facility types and traffic volume ranges. Figure 28 shows the relationship between the total encroachment frequency and AADT for the three different roadway facilities using the default data. These include two-lane undivided highways, four-lane divided highways, and one-way roadways (e.g., ramps).

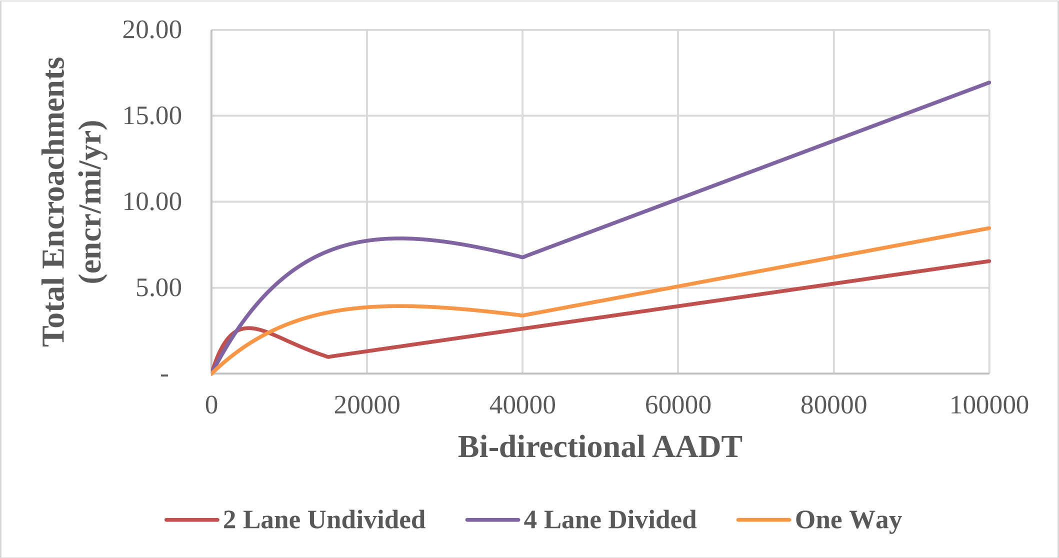


Figure 28. Total encroachment frequency by AADT using unadjusted RSAP data

As shown in Figure 28, this relationship between total encroachment frequency and AADT is somewhat counterintuitive because encroachments are expected to increase as AADT increases; however, a range of AADT values show a decrease in encroachments for each facility. This trend has been observed by prior research on collisions with roadside objects, including an Iowa DOT study on median cable barriers.

Consequently, the default data set in RSAPv3 was modified, as was the associated statistical model based on these data. As a part of this modification, two scenarios were considered (hereafter referred to as the "high crash rate" and "low crash rate" scenarios). In the high crash rate scenario, the linear portion of the graph shown in Figure 28 was assumed to start at the peak of the hump for each roadway type. In the low crash rate scenario, the linear portion of the graph shown in Figure 28 was assumed to start from the origin for each facility type. The latter graph was calibrated such that the average rate of collisions (as estimated in RSAP) involving permanent crash cushions was equal to the statewide averages shown in Table 11. Because no collisions were observed on two-lane undivided highways, the low crash rate scenario assumed a similar rate per MVMT as for four-lane divided highways. This rate was adjusted downward to account for the fact that fewer cushions would be required for the default scenario (i.e., protection of bridge piers) on two-lane undivided highways (i.e., two cushions are assumed in the two-lane case and three cushions in the four-lane case). The modified relationships between encroachment frequency and AADT corresponding to the high crash rate and low crash rate scenarios are shown in Figure 29 and Figure 30, respectively.

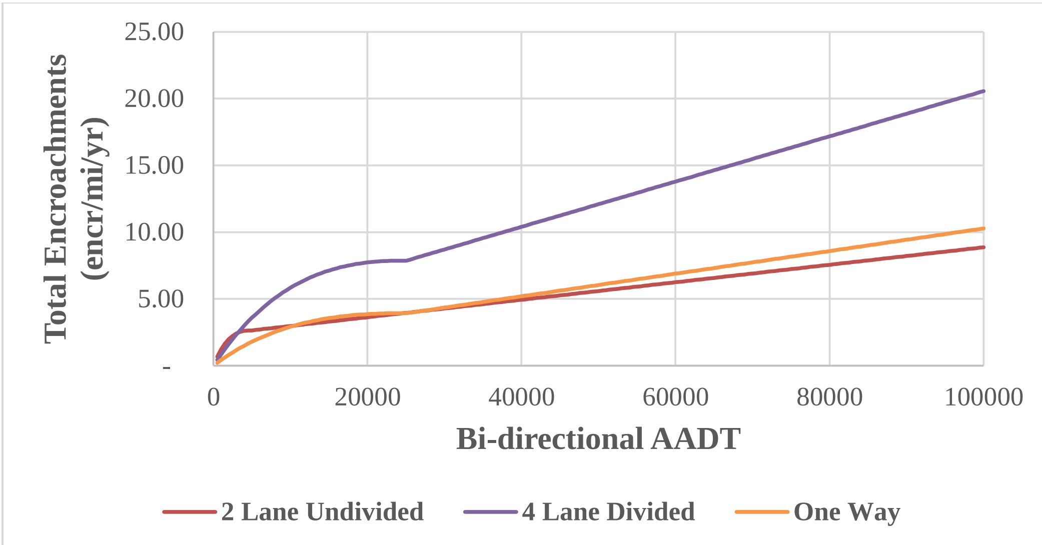


Figure 29. Total encroachment frequency by AADT for high crash rate scenario

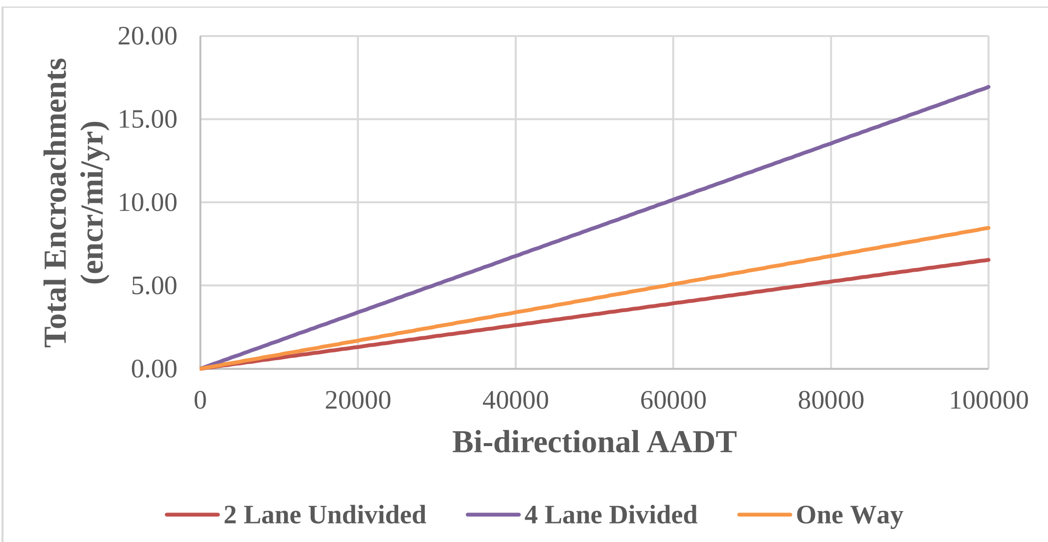
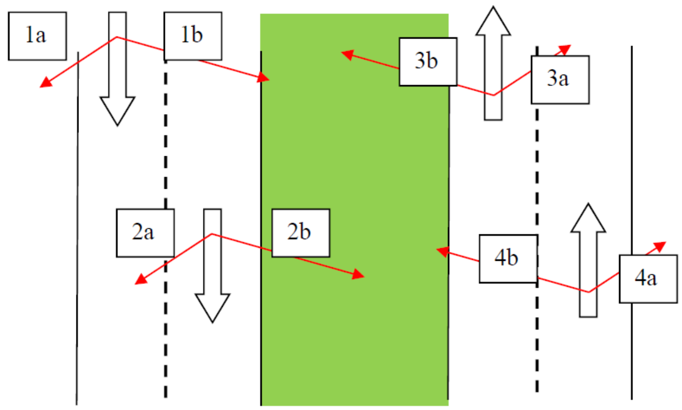


Figure 30. Total encroachment frequency by AADT for low crash rate scenario

The predictive models for generating the baseline encroachment frequencies use negative binomial regression models. A highway with the following characteristics is considered as the baseline condition: posted speed limit of 65 mph, flat surface, tangent in orientation, lane width of at least 12 ft, and an average of zero major access points per mile.

For both two-lane undivided and four-lane divided highways, four pairs of encroachment possibilities exist, including two encroachment pairs in one direction of travel and two encroachment pairs in the opposite direction of travel (as shown in Figure 31).



Ray et al. 2012, Roadsafe LLC

Figure 31. Two-lane undivided and four-lane divided encroachment possibilities

Encroachments in each direction are estimated using the product of the total number of encroachments on the analysis segment, the directional distribution of the traffic, and the left/right encroachment split. RSAPv3 assumes that one-way facilities have the same functional characteristics and total encroachment frequency as four-lane divided highways; however, the resulting encroachments are divided by two because only two encroachment possibilities exist (left or right) on one-way facilities given that there is no opposing direction of travel.

6.3 Crash Prediction Module

After the encroachment probability module has predicted the probability of a vehicle encroachment, the next step is to assess whether the encroachment would result in a crash. The crash prediction module selects the appropriate vehicle trajectories based on the user-defined analysis segment. The trajectory database was developed under NCHRP Project 17-22 and contains trajectory information for vehicles, along with the corresponding roadway and roadside characteristics for 890 run-off-the-road (ROR) crashes. In order to select suitable vehicle trajectories, each trajectory case included in the database is examined and assigned four individual scores based on a quantitative comparison of the following four roadway and roadside characteristics: roadside cross-section profile, horizontal curve radius, highway vertical grade, and posted speed limit. The individual scores are then combined using a weighted average formula to develop a composite score for each trajectory case. Ultimately, RSAPv3 arranges the trajectory cases in descending order using the composite scores and selects those with scores of 0.93 or higher until only those trajectory cases remain.

Following the trajectory selection, each trajectory is mapped onto the user-defined roadway at the beginning of the analysis segment and examined at pre-defined increments along the roadway to determine the probability of a collision resulting from an encroachment. For each predicted encroachment, RSAPv3 estimates the probability of each of the following events based on the provided roadway characteristics: a complete stop, a hazard penetration, or a vehicular redirection. If the simulated vehicle encroachment penetrates the hazard, the trajectory is examined further to determine the possibility of colliding with other hazards or vehicular rollover. Further, if the vehicle is predicted to be redirected around the hazard, the redirection paths are evaluated.

6.4 Severity Prediction Module

Given that a crash has occurred based on the predefined trajectory database, the severity prediction module then assesses the resulting crash severity to appropriately apportion the crash costs. In RSAPv3, a crash severity model unique to each roadside hazard is used to represent the severity of the crash that occurs when the hazard is struck. The development of a severity model for each hazard involves the estimation of the following parameters: a value that indicates the severity of the crash, a percentage of the total crashes that result in a penetration or rollover event due to the barrier, and a percentage of crashes for which a rollover event occurs after barrier redirection.

6.5 Benefit/Cost Analysis Module

Once the severity estimate for each crash is determined in the severity prediction module, the crash costs associated with each crash are computed using the FHWA economic value of life. The economic value of life is a monetary estimate of the costs that individuals are willing to pay to prevent a traffic fatality. According to the FHWA, this is approximately $9.1 million per fatality. This cost is the default parameter for fatal injuries in RSAPv3. For the other severity categories, a percentage of the fatal estimate is utilized.

For each alternative, the benefit-cost ratio is calculated as a proportion that compares the measured reduction in crash costs due to a reduction in crash severity to the agency costs associated with the specific countermeasure. The agency costs include the construction and maintenance costs associated with each alternative, as well as the cost of the repairs required as a result of crashes predicted on the segment.

6.6 Sensitivity Analysis

Sensitivity analyses were performed for each highway facility type to identify the input parameters that had the greatest influence on ROR crash frequency in RSAPv3. As a part of this investigation, the baseline conditions (e.g., hazard offset, AADT, lane width, speed limit, horizontal curvature) were varied to determine the sensitivity of run-off-road crash frequency to each of these parameters. A 600 ft long segment was considered with a typical placement of fixed hazards on each roadway type (see Figure 32 through Figure 34).

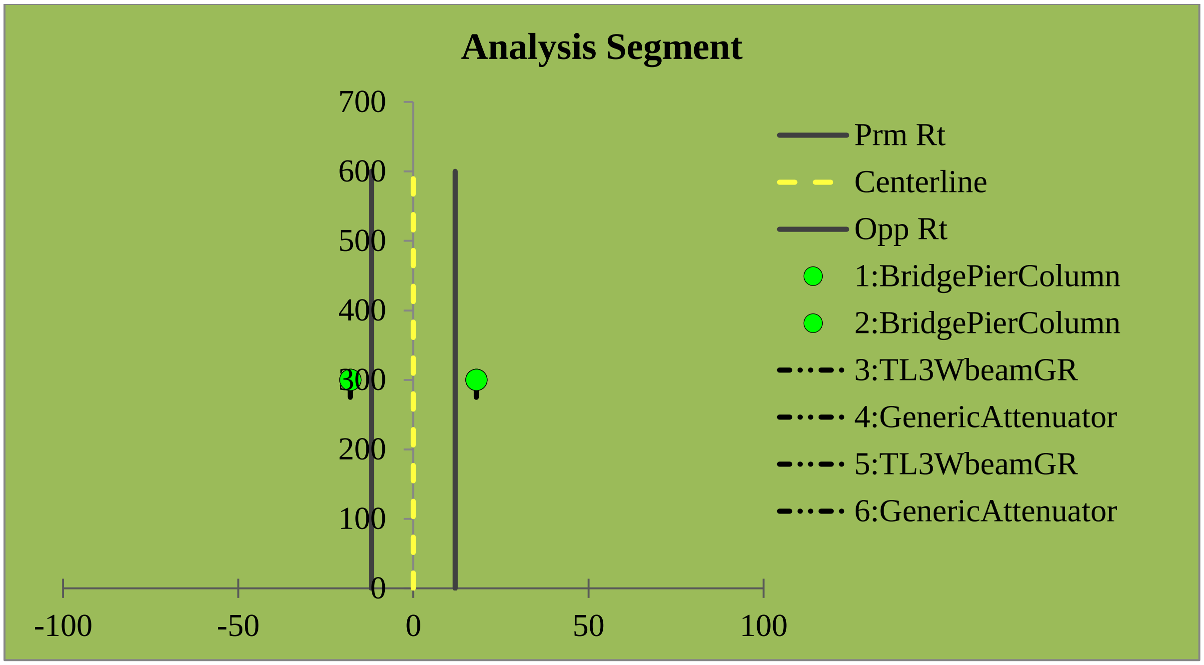


Figure 32. Hazard placement configuration on two-lane undivided highways

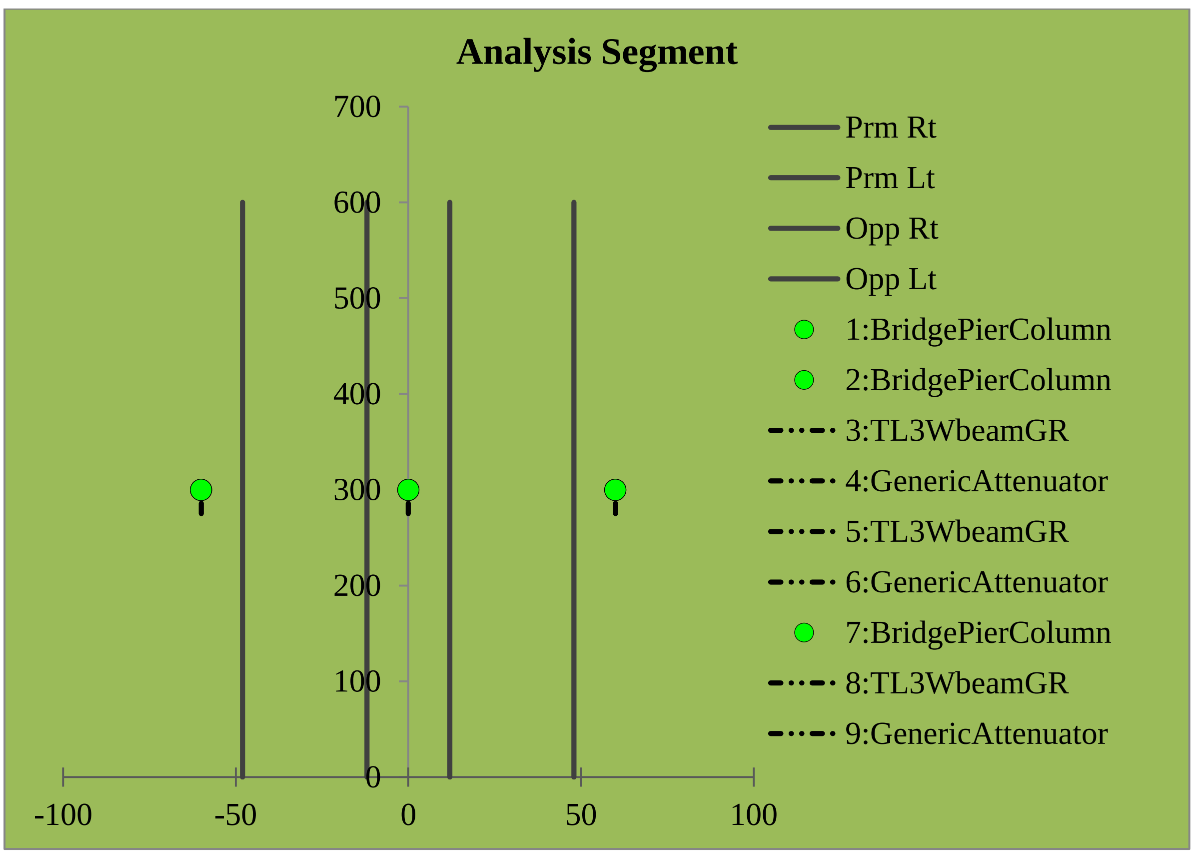


Figure 33. Hazard placement configuration on four-lane divided highways

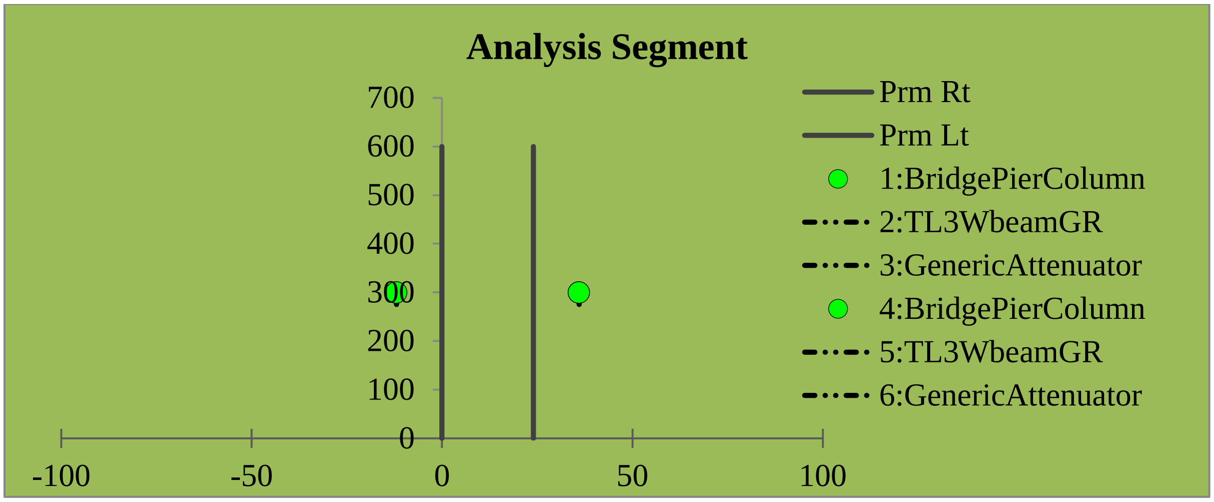


Figure 34. Hazard placement configuration on one-way highways

Each segment included 300 ft upstream and 300 ft downstream of the hazard for consistency purposes. To estimate a wide variety of alternatives, each included parameter was varied between its lowest value, mean value, and greatest value based upon data identifying the locations of crash cushions. This was true for each parameter except for curve radius. The horizontal curve adjustment factors in RSAP show no significant impacts on encroachment rate beyond a radius of 2,000 ft, which is treated as the tangent condition. The results of the sensitivity analyses for the different facility types are provided in Table 15 through Table 17.

Table 15 indicates that the hazard offset, shoulder width, and posted speed limit had negligible influence on run-off-road crash frequency. It is important to note that these results are primarily a function of the underlying data in RSAP. For example, hazard offset is shown to have negligible impacts from 2 ft to 12 ft for all three facility types. For two-lane facilities, all crash cushions were used to protect bridge rails, which were all within this range of values. Likewise, right and left shoulder widths were not found to have an impact on any of the facility types. Further research is warranted to understand the impacts of these parameters, particularly offset, on the frequency of run-off-road events.

The number of lanes and lane width did have some influence; however, in a majority of cases, crash cushions were installed on undivided roadways with two 12 ft wide travel lanes. Consequently, the number of lanes and lane width were set at their baseline values when generating different highway alternatives. The only parameters that significantly influenced the impact frequency were AADT and curve radius.

Table 15. Sensitivity analysis results for two-lane undivided highways

Parameter	Range	Impacts/ Year	Percent Difference
Hazard offset (ft)	2	0.07	0%
	6 (baseline)	0.07	NA
	12	0.07	0%
AADT	650	0.03	-57.14%
	2,250 (baseline)	0.07	NA
	12,500	0.10	42.86%
No. of lanes	2	0.08	14.29%
	3 (baseline)	0.07	NA
	4	0.05	-28.57%
Lane width (ft)	10	0.09	28.57%
	12 (baseline)	0.07	NA
	14	0.06	-14.29%
Shoulder width (ft)	3	0.07	0%
	8 (baseline)	0.07	NA
	10	0.07	0%
Speed limit (mph)	45	0.07	0%
	50 (baseline)	0.07	NA
	55	0.07	0%
Curve radius (ft)	Horizontal curve	0.07	NA
	Tangent (baseline)	0.02	-71.43%

The sensitivity analysis results for divided highways (as shown in Table 16) indicate that hazard offset, AADT, and curve radius are the only three parameters that caused a fluctuation of more than 30 percent in the resultant impact frequency. Consequently, only these three parameters were modified to generate highway scenarios, while the other, insignificant parameters were set to their default values.

Table 16. Sensitivity analysis results for four-lane divided highways

Parameter	Range	Impacts/ Year	Percent Difference
Hazard offset (ft)	2	0.38	0%
	12 (baseline)	0.38	NA
	26	0.18	-52.63%
AADT	3,300	0.11	-71.05%
	32,000 (baseline)	0.38	NA
	115,000	1.01	165.75%
No. of lanes	2	0.42	10.53%
	4 (baseline)	0.38	NA
	6	0.33	-13.16%
Lane width (ft)	10	0.46	21.05%
	12 (baseline)	0.38	NA
	14	0.36	-5.26%
Right shoulder width (ft)	0	0.38	0%
	8 (baseline)	0.38	NA
	12	0.38	0%
Left shoulder width (ft)	0	0.38	0%
	5 (baseline)	0.38	NA
	11	0.38	0%
Speed limit (mph)	45	0.40	5.26%
	55 (baseline)	0.38	NA
	70	0.33	-13.16%
Curve radius (ft)	Horizontal curve	0.38	NA
	Tangent (baseline)	0.11	-71.05%

As mentioned above, RSAPv3 assumes that one-way highways have similar functional characteristics as divided highways. Because of this, the sensitivity analysis results shown in Table 17 are consistent with the estimated results for four-lane divided highways (Table 16).

Table 17. Sensitivity analysis results for one-way highways

Parameter	Range	Impacts/ Year	Percent Difference
Hazard offset (ft)	3	0.11	0%
	12 (baseline)	0.11	NA
	20	0.08	-27.27%
AADT	1,400	0.02	-81.82%
	10,750 (baseline)	0.11	NA
	66,100	0.27	145.45%
No. of lanes	1	0.12	9.09%
	2 (baseline)	0.11	NA
	3	0.11	0%
Lane width (ft)	10	0.14	27.27%
	12 (baseline)	0.11	NA
	16	0.11	0%
Shoulder width (ft)	0	0.11	0%
	5 (baseline)	0.11	NA
	10	0.11	0%
Speed limit (mph)	45	0.11	0%
	50 (baseline)	0.11	NA
	55	0.11	0%
Curve radius (ft)	Horizontal curve	0.11	NA
	Tangent (baseline)	0.04	-63.64%

6.7 Impact Frequency Estimation

Based on the results of the sensitivity analyses, those parameters associated with an increase or decrease of over 30 percent in annual crash cushion impact frequency were considered in further detail. The analysis results indicate that hazard offset, AADT, and curve radius have the greatest influence on annual cushion strike frequency. Because of this, each of these parameters was modified based on the various facility types. These results are shown in Table 18 through Table 23 for different highway alternatives based on these three parameters. Annual crash cushion strike frequencies were computed using the relationships between encroachment frequency and AADT shown in Figure 29 and Figure 30.

Table 18. Annual crash cushion strike frequency on two-lane undivided highways, high crash rate scenario

	Horizontal Alignment	
AADT	**Curve**	**Tangent**
1,000	0.05	0.02
2,000	0.06	0.03
3,000	0.08	0.03
4,000	0.08	0.04
5,000	0.08	0.04
10,000	0.10	0.04
15,000	0.11	0.05

Table 19. Annual crash cushion strike frequency on two-lane undivided highways, low crash rate scenario

	Horizontal Alignment	
AADT	**Curve**	**Tangent**
1,000	0.01	0.01
2,000	0.01	0.01
3,000	0.01	0.01
4,000	0.01	0.01
5,000	0.01	0.01
10,000	0.02	0.01
15,000	0.03	0.02

Table 20. Annual crash cushion strike frequency on four-lane divided highways, high crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
5,000	0.13	0.05	0.08	0.05	0.06	0.04
10,000	0.20	0.08	0.13	0.08	0.09	0.06
15,000	0.23	0.10	0.16	0.09	0.10	0.07
25,000	0.27	0.11	0.18	0.10	0.12	0.08
50,000	0.42	0.18	0.28	0.16	0.19	0.13
75,000	0.58	0.24	0.39	0.22	0.26	0.18
100,000	0.73	0.31	0.49	0.28	0.33	0.22
125,000	0.89	0.37	0.59	0.34	0.39	0.27
	5		**15**		**25**	
	Hazard Offset (ft)					

Table 21. Annual crash cushion strike frequency on four-lane divided highways, low crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
5,000	0.03	0.01	0.02	0.01	0.01	0.01
10,000	0.06	0.03	0.04	0.02	0.03	0.02
15,000	0.09	0.04	0.06	0.04	0.04	0.03
25,000	0.15	0.07	0.10	0.06	0.07	0.05
50,000	0.31	0.13	0.21	0.12	0.14	0.09
75,000	0.46	0.20	0.31	0.18	0.21	0.14
100,000	0.62	0.26	0.41	0.24	0.28	0.19
125,000	0.77	0.33	0.52	0.29	0.34	0.24
	5		**15**		**25**	
	Hazard Offset (ft)					

Table 22. Annual crash cushion strike frequency on one-way highways, high crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
1,000	0.01	0.01	0.01	0.01	0.01	0.01
2,000	0.03	0.01	0.02	0.01	0.01	0.01
3,000	0.04	0.01	0.03	0.01	0.02	0.01
4,000	0.05	0.02	0.03	0.02	0.02	0.01
5,000	0.05	0.02	0.04	0.02	0.03	0.01
15,000	0.10	0.04	0.07	0.04	0.05	0.03
25,000	0.12	0.04	0.08	0.05	0.06	0.03
50,000	0.18	0.07	0.13	0.07	0.10	0.05
75,000	0.25	0.09	0.18	0.10	0.14	0.07
	5		**15**		**25**	
	Hazard Offset (ft)					

Table 23. Annual crash cushion strike frequency on one-way highway, low crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
1,000	0.01	0.01	0.01	0.01	0.01	0.01
2,000	0.01	0.01	0.01	0.01	0.01	0.01
3,000	0.01	0.01	0.01	0.01	0.01	0.01
4,000	0.01	0.01	0.01	0.01	0.01	0.01
5,000	0.01	0.01	0.01	0.01	0.01	0.01
15,000	0.04	0.02	0.03	0.02	0.02	0.01
25,000	0.07	0.03	0.05	0.03	0.04	0.02
50,000	0.13	0.05	0.10	0.05	0.07	0.04
75,000	0.20	0.08	0.14	0.08	0.11	0.05
	5		**15**		**25**	
	Hazard Offset (ft)					

Based upon the results of the sensitivity analysis for two-lane undivided highways, AADT and curve radius were the only two parameters that had a significant influence on crash frequency. As shown in Table 18, annual impact frequency on tangent sections, generated assuming the relationship between encroachment and AADT as per the high crash rate scenario, did not exceed 0.05 strikes. Based on this result, a crash cushion would only be struck once during a 20-year period. On horizontal curves, the impact frequency is approximately double that of tangent sections. Moreover, as shown in Table 19, the annual impact frequency, generated assuming the encroachment-AADT relationship as per the low crash rate scenario, did not exceed 0.03 for any combination of AADT and horizontal curvature.

Unlike on two-lane undivided highways, the hazard offset influenced the cushion strike frequency on four-lane divided highways. As shown in Table 20, for any given offset and AADT, the strike frequency is higher on curves than on tangents. Similarly, for a given facility type (curve or tangent) and AADT, as the hazard offset from the travel lane increases, the likelihood of a vehicle impacting the crash cushion decreases. Further, for a segment with a constant hazard offset, the probability of a vehicle impacting the cushion increases with AADT. A similar trend is evident for the annual impact frequency shown in Table 21.

The offset of the hazard was also significant on one-way highways (as shown in Table 22 and Table 23). The results from the analysis demonstrate that as the hazard offset distance and the AADT are held constant, cushion strikes are more likely to occur on curved segments rather than tangent segments. Furthermore, as AADT is held constant, cushion strikes are less likely to occur as the hazard offset increases. Moving the hazard further from the roadway decreases the likelihood of strike occurrence. This result is also demonstrated on four-lane divided highways (Table 20), again confirming the assumption that four-lane divided and one-way highways have similar operational characteristics.

6.8 Design Charts

Based upon the generated results from the crash cushion strike frequency estimations, a series of design charts were developed to provide guidance as to which crash cushion category is the most cost-effective option for different facility types and highway geometries.

These charts were developed based upon the life cycle cost comparison (as shown in Figure 27), which showed that the RLH (redirective with low installation and higher maintenance costs) crash cushion category has a lower life cycle cost than the RHL (redirective with high installation and low maintenance costs) category up to a rate of approximately 0.08 strikes per year.

In the design charts provided, cells marked RLH indicate that the given roadway geometry and traffic characteristics result in less than 0.08 strikes per year. Therefore, the RLH category of crash cushions provides the optimal countermeasure. Conversely, those cells marked RHL indicate that the impact frequency is greater than 0.08 strikes per year. Therefore, a crash cushion from the RHL category is the financially appropriate design choice.

Table 24 and Table 25 present design guidelines for two-lane undivided highways under the high crash rate and low crash rate scenarios, respectively. Table 26 and Table 27 provide similar guidance for four-lane divided highways, while Table 28 and Table 29 provide guidance for one-way highways.

Table 24. Design chart for two-lane undivided highways, high crash rate scenario

	Horizontal Alignment	
AADT	**Curve**	**Tangent**
1,000	RLH	RLH
2,000	RLH	RLH
3,000	RHL	RLH
4,000	RHL	RLH
5,000	RHL	RLH
10,000	RHL	RLH
15,000	RHL	RLH

Table 25. Design chart for two-lane undivided highways, low crash rate scenario

	Horizontal Alignment	
AADT	**Curve**	**Tangent**
1,000	RLH	RLH
2,000	RLH	RLH
3,000	RLH	RLH
4,000	RLH	RLH
5,000	RLH	RLH
10,000	RLH	RLH
15,000	RLH	RLH

Table 26. Design chart for four-lane divided highways, high crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
5,000	RHL	RLH	RHL	RLH	RLH	RLH
10,000	RHL	RHL	RHL	RHL	RHL	RLH
15,000	RHL	RHL	RHL	RHL	RHL	RLH
25,000	RHL	RHL	RHL	RHL	RHL	RLH
50,000	RHL	RHL	RHL	RHL	RHL	RHL
75,000	RHL	RHL	RHL	RHL	RHL	RHL
100,000	RHL	RHL	RHL	RHL	RHL	RHL
125,000	RHL	RHL	RHL	RHL	RHL	RHL
	5		**15**		**25**	
	Hazard Offset (ft)					

Table 27. Design chart for four-lane divided highways, low crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
5,000	RLH	RLH	RLH	RLH	RLH	RLH
10,000	RLH	RLH	RLH	RLH	RLH	RLH
15,000	RHL	RLH	RLH	RLH	RLH	RLH
25,000	RHL	RLH	RHL	RLH	RLH	RLH
50,000	RHL	RHL	RHL	RHL	RHL	RHL
75,000	RHL	RHL	RHL	RHL	RHL	RHL
100,000	RHL	RHL	RHL	RHL	RHL	RHL
125,000	RHL	RHL	RHL	RHL	RHL	RHL
	5		**15**		**25**	
	Hazard Offset (ft)					

Table 28. Design chart for one-way highways, high crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
1,000	RLH	RLH	RLH	RLH	RLH	RLH
2,000	RLH	RLH	RLH	RLH	RLH	RLH
3,000	RLH	RLH	RLH	RLH	RLH	RLH
4,000	RLH	RLH	RLH	RLH	RLH	RLH
5,000	RLH	RLH	RLH	RLH	RLH	RLH
15,000	RHL	RLH	RLH	RLH	RLH	RLH
25,000	RHL	RLH	RHL	RLH	RLH	RLH
50,000	RHL	RLH	RHL	RLH	RHL	RLH
75,000	RHL	RHL	RHL	RHL	RHL	RLH
	5		**15**		**25**	
	Hazard Offset (ft)					

Table 29. Design chart for one-way highways, low crash rate scenario

	Horizontal Alignment					
AADT	**Curve**	**Tangent**	**Curve**	**Tangent**	**Curve**	**Tangent**
1,000	RLH	RLH	RLH	RLH	RLH	RLH
2,000	RLH	RLH	RLH	RLH	RLH	RLH
3,000	RLH	RLH	RLH	RLH	RLH	RLH
4,000	RLH	RLH	RLH	RLH	RLH	RLH
5,000	RLH	RLH	RLH	RLH	RLH	RLH
15,000	RLH	RLH	RLH	RLH	RLH	RLH
25,000	RLH	RLH	RLH	RLH	RLH	RLH
50,000	RHL	RLH	RHL	RLH	RLH	RLH
75,000	RHL	RHL	RHL	RHL	RHL	RLH
	5		**15**		**25**	
	Hazard Offset (ft)					

For two-lane undivided roadways, Table 24 shows that RLH cushions are the optimal choice for segments located on sharper curves with radii less than 1,000 ft and carrying fewer than 1,000 vehicles per day. This is intuitive because cushions are less likely to be struck due to the lower vehicle exposure rate; therefore, a system with a low installation cost is the preferred type. However, on segments with similar curve radii, as the traffic volume increases the expected number of impacts with the cushion system also increases, and a RHL cushion becomes more cost-effective. Because these devices have a lower repair cost, the increase in damage due to increased vehicle strikes can be offset by the inexpensive repair costs. Further, as the curves become less sharp with radii up to 1,500 ft, the frequency of impacts with crash cushions remains below the threshold value of 0.08 strikes per year for an AADT of up to 2,000. Beyond this AADT threshold, the RHL cushions become the most cost-effective option. For tangent segments, the impact frequency never exceeds the threshold value of 0.08 strikes per year, and therefore the RLH crash cushions are the only cost-effective option. Another design chart, shown in Table 25, developed based on the impact frequencies shown in Table 19, indicates that annual impact frequency never crosses the threshold value of 0.08 for any combination of AADT and horizontal curvature, and therefore a RLH cushion is the optimal cushion category for all highway scenarios on two-lane undivided roadways.

For four-lane divided highways, Table 26 shows that for segments located on sharper curves with radii below 1,500 ft, RHL cushions are the optimal choice to shield hazards located within an offset of up to 15 ft from the traveled way irrespective of traffic volume. However, on tangent segments, RLH cushions become the optimal choice to shield hazards located within 5 ft of the roadway with traffic volumes of up to 5,000 vehicles per day because fewer impacts are expected. For hazards located 15 ft from the roadway, RLH cushions remain cost-effective for AADT values less 5,000 vehicles per day. Lastly, for hazards located 25 ft away from the roadway with an AADT of 5,000 vehicles per day, the effect of the milder curve radius is insignificant because the number of expected annual impacts is always below the 0.08 strikes per year threshold. Another design chart developed, shown in Table 27, assuming the encroachment-AADT relationship as per the low crash rate scenario, shows a more even distribution of RLH and RHL cushion categories across the modeled highway scenarios.

For one-way highways, Table 28 demonstrates that for segments with traffic volumes less than 5,000 vehicles per day, RLH cushions are the optimal choice irrespective of the hazard offset and curve radius present. However, as the traffic volume increases on segments with 1,000 ft curve radii and hazards located up to 15 ft away, the number of expected annual impacts with crash cushions increases beyond 0.08 strikes per year. Because of this, RHL cushions become the most cost-effective choice. For segments that have similar characteristics but that are tangent in nature, the expected impact frequency exceeds 0.08 strikes per year only beyond an AADT of 75,000 vehicles per day. Further, for curved segments with hazards located 25 ft from the roadway, RHL cushions only become cost-effective when the AADT exceeds 50,000 vehicles per day. The design chart shown in Table 29 indicates that a RLH cushion is the optimal choice for an even larger number of scenarios on one-way highways because the annual impact frequencies are relatively lower, even at higher AADTs.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This study examined the 13 unique crash cushion systems currently installed in Iowa. As a part of this in-service evaluation, the Iowa statewide crash database was used to identify target crashes that involved collisions with permanent crash cushion systems. Using data from 2007 through 2014, a detailed review of crash reports was conducted to identify those collisions in which the investigating officer indicated that a crash cushion was struck. After further examination of the target crashes, only 34 were confirmed to have involved a collision with a permanent crash cushion.

When considering crash cushion length and the traffic volume of the adjacent roadway, these crashes result in an estimated crash rate of 0.261 per MVMT for divided highways and 1.209 for one-lane roadways/ramps. No collisions were identified involving crash cushions on undivided two-lane highways. For each of the 34 crashes that were identified, the worst injury severity outcome among occupants in each crash-involved vehicle was reviewed. The results indicated that approximately 78 percent of such crashes resulted in either a minor injury or a property damage-only crash (i.e., non-injury crash), providing general evidence as to the effectiveness of the crash cushion installations. Unfortunately, this limited sample size and the general difficulty in identifying this target set of crashes limited the ability to conduct an extensive comparison of the in-service performance of the various systems utilized in the state.

Consequently, an encroachment probability-based software program (RSAPv3) was used to develop design guidance regarding the most cost-effective crash cushion type for several different combinations of roadway geometries and traffic characteristics. The facility types of interest were divided into three broad categories: two-lane undivided, four-lane divided, and one-way. Sensitivity analyses were performed separately for each facility type to identify those parameters having the greatest influence on the frequency of ROR crashes. Ultimately, two scenarios were considered for each facility type. These included a low crash risk scenario, which was based upon the Iowa-specific crash rates noted previously, and a high crash risk scenario, which was based upon a modified regression model using the default RSAP data.

The results indicated that hazard offset, AADT, and the curve radius of the roadway had the largest influence on the probability of a roadside hazard being struck in a crash. The values of these parameters were modified and evaluated based on known Iowa-specific field data. After adjusting the underlying RSAPv3 data (to ensure a consistent increase in crashes with respect to traffic volumes), the program was used to estimate the number of crash cushion strikes per year on an analysis segment for different combinations of factors on each facility type. The annual strike frequency was used as the decision criteria to identify the optimal crash cushion category based on cost-effectiveness for various alternatives of hazard offset, AADT, and curve radius. From the life cycle cost comparison, the RLH cushion category had the lowest life cycle cost when the expected strikes per year were less than 0.08. Beyond this threshold, the RHL crash cushion category was demonstrated to be more cost-effective.

7.2 Limitations

The accuracy of the installation, repair, and maintenance costs for different cushion systems used in the life cycle cost analysis is the most important limitation of this research. The installation cost figures used in this analysis only include the material costs and disregard the additional costs associated with the installation of different cushion systems under field conditions. Such figures can vary depending on site-specific factors, such as whether the cushion system requires a paved concrete pad for installation or whether it can be installed on unpaved surfaces. Moreover, the average material costs and average work-hours per crash for different cushion systems were based on a very limited sample size obtained from the Iowa DOT district maintenance garages. Consequently, the accuracy of the repair cost data used for the analysis is unclear, and the use of additional data is warranted to better understand the long-term performance of different cushion devices. This study did not consider sand barrels because the repair and maintenance cost data for such cushion types were not available with sufficient accuracy. Further, monetary costs associated with other important variables, such as the exposure of maintenance crews to traffic during repairs, exposure of the fixed hazard to traffic during the time a crash cushion is non-functional, and others, were not considered due to their unavailability.

The run-off-road crash frequencies under different highway scenarios generated by RSAPv3 are based on encroachment data collected by Cooper (1980) in the late 1970s, and the accuracy of these data for current roadway conditions is uncertain. Forthcoming NCHRP research aims to reevaluate these fundamental encroachment models. These results may also be validated with actual run-off-road crash frequency data observed on roadway segments with similar characteristics.

7.3 Future Work

Currently, different crash cushion systems are aggregated together and treated as a generic attenuator in RSAPv3, which does not account for differences in system performance across product types. Consequently, hazard severity models corresponding to each cushion type should be developed in the future utilizing the database of police-reported crashes and then incorporated into RSAPv3 to perform incremental benefit-cost analyses between different cushion devices and identify the optimal cushion device for any given highway scenario. However, given the relative infrequency of collisions involving crash cushions, such research would likely require a large-scale, multi-state pooled-fund study.

One important area where short-term improvements could be made is in regard to the manner in which crash cushion strike and repair data are inventoried. Transportation agencies could standardize reporting for repairs made to both permanent and temporary crash cushions by developing specific contract items for each situation. For the purposes of this study, an extensive manual review of data on various resources was required to discern when and where crash cushion strikes occurred and the associated repair costs. An improved inventory system for these items would expedite the ability to query repairs through contract item software.

An additional opportunity to standardize repair data would involve the development of a standard form to be completed by maintenance crews. This form could include fields specific to the unique inventory identification number, which would tie the repair to location information, as well as the date of the incident (if known), the repair date, the hours spent on the repair, the traffic control needed for the repair, a part-by-part listing of repairs, etc. While general forms may be available, it does not appear that there is consistency among the maintenance garages in terms of how this information is collected or stored in an easily accessible manner.

Another area of future work could be to improve the manner in which installation costs for permanent crash cushions are recorded in the Iowa DOT's Field Manager documents. In the documents' current form, it is unclear whether the installation costs include just the material costs or include other expenses associated with the field installation, such as shipping costs (i.e., cost to transport cushion devices from the warehouse to the installation site), labor costs and truck rental charges, cost of installation equipment, etc. Consequently, installation costs should be recorded as the costs associated with each step during the installation process rather than as a single figure.

Moving forward, it is also important for the Iowa DOT to keep track of the time that elapses between when a cushion strike occurs and when the repair is performed to reset the cushion. More detailed recordkeeping of such information will help to quantify the monetary costs associated with the fixed object's exposure to traffic during the time the crash cushion is non-functional. Further, during the repair and maintenance work, it may be important to keep track of the extent of the disruption caused to traffic, such as the number of lanes closed, the reduction in travel speeds, etc., because this information could help stakeholders decide which cushions to install at high-traffic locations to cause minimal disruption.

Finally, additional comments may be included in the crash narratives that detail the redirective performance of the cushion devices involved in crashes, characterized by the rebound angle, and whether the vehicle overturned after impacting the cushion. Such information can help improve cushion design to increase the overall efficacy. Moreover, photographs of the vehicle(s) and the cushion after the impact could also be captured so that the crash can be visually inspected and other pertinent information can be extracted that might have been missed by the reporting officer.

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