Crash cushion selection criteria

by

Ashirwad Barnwal

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Transportation Engineering)

Program of Study Committee:
Peter Savolainen, Major Professor
Omar Smadi
Behrouz Shafei

Iowa State University

Ames, Iowa

2017

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BCR	Benefit-Cost Ratio
DOT	Department of Transportation
EFCCR	Equivalent Fatal Crash Cost Ratio
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FIPI	Finding in the Public Interest
HDPE	High-density Polyethylene
ISPE	In-Service Performance Evaluation
LCCA	Life Cycle Cost Analysis
MVKT	Million Vehicle Kilometers Traveled
MVMT	Million Vehicle Miles Traveled
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
RDG	Roadside Design Guide
ROR	Run-off-the-road
RSAP	Roadside Safety Analysis Program
VSL	Value of a Statistical Life

ACKNOWLEDGMENTS

This thesis study would not have been possible without my major professor, Dr. Peter Savolainen, who provided invaluable support and guidance, and the design engineer at the Iowa Department of Transportation, Khyle Clute, who assisted with gathering data for this research.

I would also like to extend my sincere thanks to my committee members, Dr. Omar Smadi, and Dr. Behrouz Shafei, for their insightful comments, which helped further refine the thesis.

I am also grateful to Dr. Indrajit Ghosh, who not only helped me build a strong foundation in transportation engineering during my undergraduate studies at IIT Roorkee, but also encouraged me to pursue higher education in the United States.

Finally, endless thanks to my parents, who have given me immense support and encouragement throughout my academic endeavors, and my two wonderful younger sisters, Aditi, and Anushka, for their unconditional love and motivation.

DISCLAIMER

The findings and conclusion of this study are those of the author and do not necessarily represent the views of the Iowa Department of Transportation, or Iowa State University.

ABSTRACT

Crash cushions are used as a roadside safety treatment alternative to protect errant vehicles from striking potentially hazardous roadside fixed 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. This research study aims to quantify the life cycle costs of different crash cushion systems installed across the state of 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, was used to estimate the frequency of run-off-the-road collisions under different scenarios for one-way, undivided, and divided highway facilities. The estimated impact frequency based on pertinent roadway and traffic characteristics was then used as a decision criteria to select the most appropriate cushion category 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 versus alternative cushions with lower installation and higher repair costs. The life cycle cost comparison indicated that the low-installation/high-repair category was optimum until an impact frequency of approximately 0.08 per year. Beyond that threshold, the high-installation/low-repair category tended to be more cost-effective.

CHAPTER 1: INTRODUCTION

1.1 Background

Roadway departure crashes, which involve vehicles leaving the traveled way and encroaching onto the roadside, have been a major highway safety concern in the United States for decades. According to a compilation of five years of motor vehicle crash data (2011–2015) from the Fatality Analysis Reporting System (FARS) database, roadway departure crashes accounted for approximately 62 percent of all traffic fatalities in Iowa and around 55 percent of all traffic fatalities across the U.S. (see Figure 1). A vast majority of such fatalities resulted from vehicles impacting one or more unyielding fixed roadside objects (e.g., trees and 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.

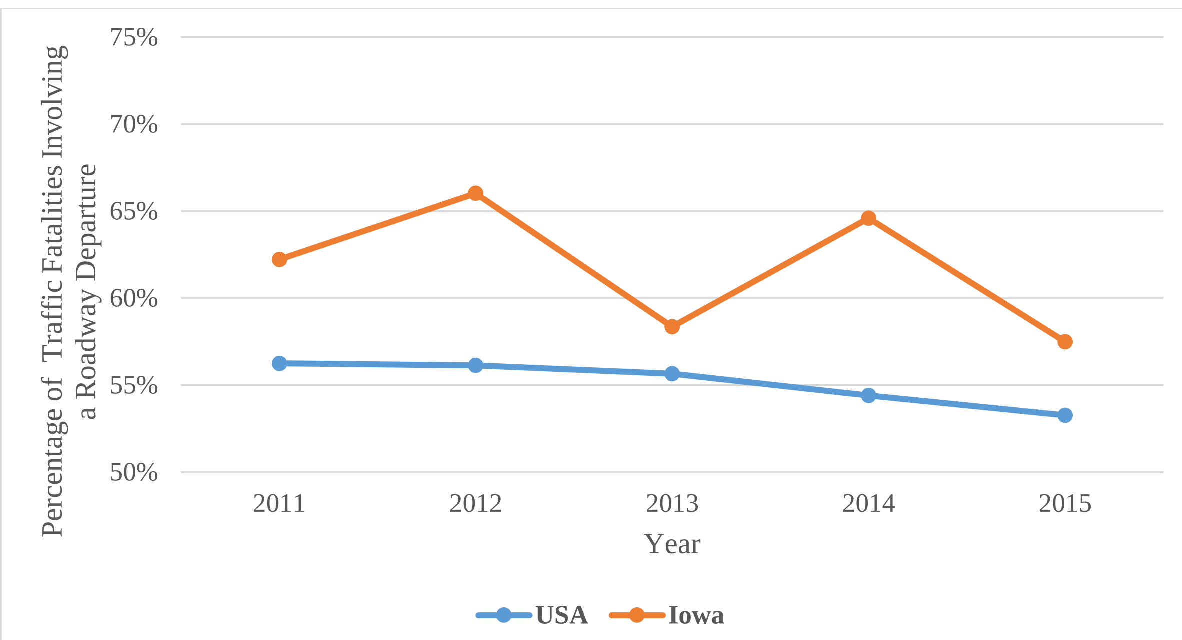


Figure 1. Role of Roadway Departure Crashes in Overall Traffic Fatalities in Iowa and across the U.S., 2011–2015 (NHTSA, 2017)

The first strategy involves the implementation of countermeasures to prevent vehicles from drifting onto the roadside, such as improved pavement friction, rumble strip installation, enhanced delineation along horizontal curves, and improved nighttime visibility. The second strategy includes the provision of wider shoulders, safe pavement edges, and adequate traversable clear zone areas to allow encroached vehicles to recover safely. Finally, the third strategy involves shielding fixed roadside objects located within the clear zone area that cannot be removed, redesigned for safe traversal, or relocated with a suitable safety hardware to minimize crash consequences.

Impact attenuators, commonly known as crash cushions, are one such safety hardware device that are designed to reduce the severity of impacts with fixed roadside hazards. The attenuators perform by absorbing the kinetic energy of a colliding vehicle and gradually decelerating it to a safe stop for frontal impacts, and by safely redirecting a vehicle toward the travel lane for lateral impacts. Short lengths, combined with the capability to accommodate both end-on 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 traffic barriers. Fixed roadside hazards that typically merit shielding with a crash cushion include bridge piers, bridge rails, sign trusses, exit gore ramps, and median barrier ends. 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 and 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 (see Figure 2):

- ***Non-redirecting sacrificial crash cushions*** are typically comprised of sand barrels which 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 sand masses, with lighter units being struck first. Repairs after each impact often require total replacement of the damaged units.
- ***Redirecting sacrificial crash cushions*** telescope backward during end-on impacts to crush energy-absorbing cartridges or rip specially designed internal parts to dissipate energy. For side-angle impacts, the system behaves similar to a guardrail and safely redirects a vehicle around the hazard. 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 body parts are constructed of more durable materials, such as high-density polyethylene (HDPE) cylinders, to withstand multiple impacts without requiring significant repair and maintenance. These cushions are preferred at highway locations which already experience or are expected to experience frequent impacts.

Non-redirecting Sacrificial | Redirecting Sacrificial | Severe Use

Figure 2. Crash Cushion Categories

1.2 Problem Statement

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 have not been thoroughly investigated. The existing data on repair and maintenance 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, repair, and maintenance costs and the choice of a single best cushion type that would optimize the safety benefits for a particular highway location is not readily apparent. Thus, research is needed to evaluate the field performance of cushion systems installed for use as safety devices, and estimate their life-cycle costs to use it as a factor in deciding where and when to install specific cushion types.

1.3 Research Objectives

The purpose of this research was to conduct an in-service performance evaluation (ISPE) of various crash cushion systems currently in use across the state of Iowa, allowing for more informed decision-making based upon empirical data. To that end, the following two primary objectives have been established:

- Quantify the cost-effectiveness of different crash cushion systems in consideration of various traffic, road geometry, and crash cushion characteristics.
- Develop guidance for selecting the most cost-effective crash cushion for any given highway scenario.

1.4 Thesis Overview

This thesis is organized into seven chapters, with this first chapter providing an introduction and background to the research, in addition to defining the problem statement and study objectives. A brief overview of the subsequent chapters is provided below.

Chapter 2 provides a review of existing literature on the efficacy and in-service safety performance of crash cushions. The review covers relevant research reports and journal articles, design guidelines, and best practices pertaining to the use of crash cushions by state departments of transportation (DOTs). Any economic analyses that examine the cost-effectiveness of crash cushions or other barrier systems were also reviewed and summarized.

Chapter 3 summarizes the data collection methodology and provides a description of different attributes which were collected for each installation, such as physical location (GPS coordinates), product type, placement in relation to the roadway and others, to develop a comprehensive inventory of crash cushions installed in Iowa.

Chapter 4 provides a detailed description of each of the 13 crash cushion systems used for permanent installations in Iowa. The information included in the description were gathered from various sources including product brochures, FHWA approval letters, and online publications on attenuator systems.

Chapter 5 outlines the methodology used to obtain installation and repair costs for different cushion systems, including details of an investigation of collisions involving permanent crash cushions.

Chapter 6 provides a description of the encroachment probability-based tool, Roadside Safety Analysis Program (RSAP), and the approach it uses for performing benefit-cost analyses on various roadside design alternatives. The design charts that can be used in selecting the optimum crash cushion category for different highway scenarios are also presented here.

Chapter 7 presents a summary of the research findings. This chapter also identifies limitations of this research, in addition to identifying prospective areas for future research that could address these limitations.

CHAPTER 2: LITERATURE REVIEW

2.1 Crash Cushion Efficacy

Several research studies have been conducted globally and in the U.S. to examine the efficacy of crash cushion installations. Elvik (1995) performed a meta-analysis to summarize the findings of 32 research studies that had focused on evaluating the safety benefits of installing guardrails, median barriers, and crash cushions. The weighted mean estimates of safety benefits derived from 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 crashes by 84 percent and 69 percent, respectively. Similar results were found in another meta-analysis conducted by Elvik and Vaa (2004), where the researchers concluded that crash cushions reduced property-damage-only (PDO) crashes by 46 percent, and both fatal and injury crashes by 69 percent. Further, according to the statistics reported in a report from the World Health Organization on road traffic injury prevention, installation of crash cushions in Birmingham, England, reduced fatalities by 53 percent and injury crashes by 40 percent at the treatment sites (WHO, 2004). Research in California indicated the installation of crash cushions along the highway network resulted in saving the lives of approximately 330 motorists over a 10-year period. The monetary savings derived from these cushion installations, which reduced the severity outcome for other crash-involved motorists in addition to reducing the number of fatalities, was estimated to be over $30 million (Stoughton, 1983).

Although crash cushion installations are effective in reducing the impact severity at gore areas, the increased crash frequency at such locations offsets the benefits to a degree. One potential countermeasure considered by highway agencies to address this problem was to use delineation treatments to increase conspicuity of gore areas, as well as the installed crash cushions. In this regard, four delineation treatments were developed and tested by Wunderlich (1982). 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. A total of the ten most frequently repaired gore crash cushion sites in Houston, Texas, were chosen for the study based on the past 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 left untreated and used as control sites. Repair records following the installation of delineation treatments were collected for a period of 17-22 months and compared against the repair records from the pre-installation period. Based on the short-term assessment, the level IV treatments were shown to be effective in reducing the repair frequency at treatment sites with high initial repair rates (9-12 repairs/year), while the static delineation treatments did not have any significant effect on repair rates at sites with moderate repair rates (4-6 repairs/year).

Creasey et al. (1989) conducted a survey of district officials in Texas to identify the delineation practices adopted for cushion installations at gore areas on urban freeways and attempted to evaluate the long-term effectiveness of the delineation treatments installed as part of the study described previously. Based on the survey responses, most of the districts used delineations on crash cushions, however the type and amount of delineation used varied considerably from object markers to nose/back panels and flashing lights. Contrary to the results of the study by Wunderlich, 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 in Houston, Texas, and 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 with regard to effective sight distance and horizontal curvature ahead of the gore location, a classification scheme was developed by researchers to aide in the selection of the most appropriate delineation treatment for a particular gore area.

2.2 In-service Performance Evaluation Studies

An early attempt to monitor the performance of fixed and portable steel drum crash cushions and sand inertia barriers, collectively called vehicle impact attenuators (VIAs), was carried out by Hirsch et al. (1975). At the time of this study, 147 VIAs were installed in Texas and had already sustained over 400 impacts since the first installation in October 1968. The researchers considered various aspects of VIAs including 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, foreman, and shop supervisors from seven districts within Texas to discuss the field experience with the attenuators and suggest improvements or changes they would like to see in the existing designs to increase safety and affordability of these countermeasures. Based on the discussions, the following changes were recommended: remove the redirection panels from steel drums at locations where frequent head-on impacts are expected to improve safety and reduce construction costs, encourage reuse of reconditioned steel drums to lower costs and save materials, improve the design of portable steel drums to lower fatigue failures and increase maneuverability, and regularly inspect inertia barriers to ensure they are in usable condition.

Another attempt was made by Pigman et al. (1984) to assess the performance and cost-effectiveness of crash cushion installations in Kentucky using a database that compiled 127 crashes involving crash cushions over a three-year analysis period from 1980 to 1982. For each crash, the researchers made efforts to obtain the corresponding police report form, photographs of the vehicle and cushion after the impact, and repairs needed to restore the cushion to working conditions. The crash database had information on six unique crash cushion types: Hi-Dro cell, Hi-Dro cluster, Great, Sand Barrels, and Streel Drums installed across Kentucky during the study period. Comparison of average repair cost data 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, performance of the cushion during the crash were also noted. The results indicated that cushions performed properly in 85 percent of the incidents. Improper performance was characterized by the cushion rebounding the striking vehicle into or across the adjacent roadway, or if the vehicle overturned after impacting the cushion. 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 at Davis aimed at developing 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 was the only expense considered while conducting economic analyses; however, the intent of this project was to include repair costs and routine maintenance information to refine the decision support tool. Actual repair data and impact frequency for each crash cushion was collected from the California Department of Transportation (Caltrans) Integrated Maintenance Management System (IMMS). The repair frequency was considered in the life cycle of the crash cushion rather than the impact frequency, as some impacts with the countermeasure may not require complete repairs. In order to collect an accurate estimate on the number of barrier strikes that did not require repairs, impact sensors and a site monitoring system were developed to maintain high resolution data on the life-cycle costs of these installations. These monitoring systems were installed at 3 test locations. The results from this life cycle tool development utilized estimates of impact frequency, repair costs, and access costs to develop the break-even points in cost for different classes of crash cushions. The developed decision support tool can be used to evaluate a wide variety of crash attenuator products based on their life cycle at a site-specific basis.

A research study was conducted by Schrum et al. (2015) to develop a guideline to assist highway engineers in selecting the most cost-effective crash cushion for installation on various highway locations differing in roadway, roadside and traffic characteristics. A total of eight different crash cushion systems: QuadGuard, Quest, TRACC, TAU-II, QuadGuard Elite, React 350, SCI and sand barrels were considered and their cost information (i.e., installation, repair, and maintenance costs) were obtained through manufacturer product sheets and surveys sent out to the state DOTs and manufacturers. Once the cost data was available, the cushion systems were grouped together to form three separate categories: redirecting with repair costs exceeding $1,000 (RGM), redirecting with repair costs less than $1,000 (RLM), and non-redirecting sacrificial (NRS). A threshold value of $1,000 was chosen as it was consistent with common practices in the industry. Letters G, L and M used in the designations refers to greater than, less than and the Roman numeral for 1,000 respectively.

This study also involved a sensitivity analysis to identify the roadway and traffic parameters which had the greatest influence on crash costs (Schrum et al. 2015). A parameter was considered significant if changing its value from the base condition caused a fluctuation of more than 20% in the crash cost. The analysis results indicated that only 3 parameters were significant: (1) crash cushion offset, (2) average daily traffic, and (3) horizontal curvature. Moreover, the analysis results were consistent across all functional classes considered in this study namely, freeways, arterials and local highways. The significant parameters were modified to model highway scenarios while the insignificant parameters were kept at their baseline values. Baseline values for insignificant parameter were different for different functional classes.

Following the estimation of crash costs and direct costs, benefit-cost analyses were conducted using two methods: (1) index method, and (2) incremental method. Index method compared the benefit-cost ratio of crash cushions relative to unprotected condition whereas incremental method compared two alternatives to ascertain the optimal option. Ultimately, a design chart was prepared where recommendations for a specific crash cushion category was based on the following parameters: (1) road facility type, (2) AADT, (3) crash cushion offset, (4) horizontal curvature, (5) benefit-cost ratio. These design charts indicated that RLM systems were cost-effective for locations experiencing high number of crashes while RGM systems were a feasible option for locations with moderate or low crash frequencies. The study results also suggested to leave the sites unprotected when lateral offset of fixed objects were very large or it carried a very low traffic volume (Schrum et al. 2015).

2.4 Computer Simulations for Crashworthiness Evaluation

Traditionally, full-scale crash tests have been the most popular method for assessing crashworthiness of safety hardware. However, in recent times, researchers have started experimenting with simulation software to perform such hardware crashworthiness evaluations. Miller & Carney (1997) performed an analysis to determine the fidelity and accuracy of computer simulated barrier impacts when compared to full-scale crash tests. 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). Testing involved nontracking, braking, and turning vehicles. Results determined that the computer simulations were extremely effective at modeling the impacts of full scale testing. Resultant graphs of physical barrier deformations as well as 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 their relative inexpensiveness.

CHAPTER 3: DATA COLLECTION

At the beginning of the project, geographic locations for 147 crash cushions installed along the road network under the jurisdiction of the Iowa Department of Transportation (Iowa DOT) were provided through the DOT list in a shape file format. In addition to location data, the shape file also included pertinent attribute information tied to each cushion installation, such as the name of the attenuator system, the type of hazard shielded by the cushion, etc. The map shown in Figure 3 identifies the primary road network in Iowa with red lines and crash cushions included in the DOT list are pinpointed using green circles.

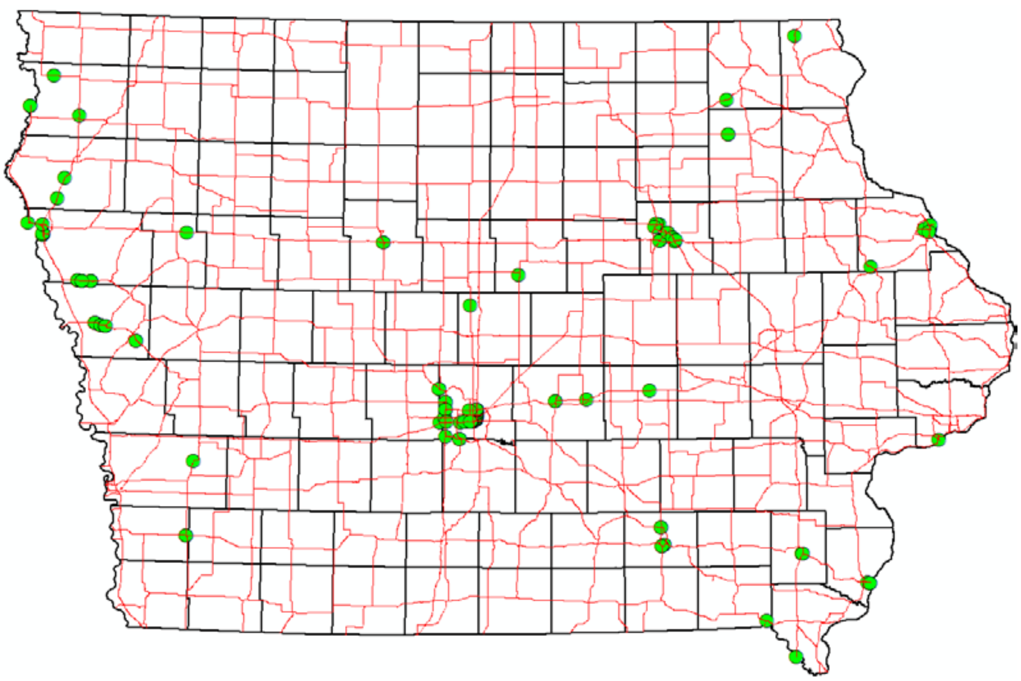


Figure 3. Installation Locations of Crash Cushions Included in The DOT List

Once the dataset was available, the first task involved reviewing the data to identify any potential discrepancies. To accomplish this task, the shape file was imported into the Google Earth software program and its aerial imagery and Street View functionalities were utilized to manually review each identified cushion location. After reviewing all the identified cushion locations, three installations identified in the shape file were found to have discrepancies. Two of these installations appeared to have been miscoded as there were no cushions installed at the identified locations, whereas the third case identified the cushion around 500 feet away from its true location. The miscoded locations were removed and geographic location of the misidentified cushion installation was updated to its true location. Once the discrepancies were fixed, the revised shape file had accurate information for 145 cushion installations.

The second task involved searching for additional cushion installations that were not included in the DOT list. Lyon County in the northwest corner of Iowa was used as a starting point and every interchange within the county was observed in Google Earth's aerial imagery to search for additional cushion installations. Interchanges were observed first because a wide variety of hazards including bridge piers, gore areas, sign trusses, and other obstacles are generally present in the interchange area within the clear zone distance and are potential candidates for a cushion installation. Once the interchanges were reviewed, the next step was to look for cushions that might have been installed to shield concrete barriers, bridge parapets, sign trusses, etc. along Iowa DOT-maintained road segments within the same county. This review process was then repeated for the remaining 98 counties to cover the entire state of Iowa.

A total of 135 additional cushion installations were identified over the course of this study and the updated database has location information for 280 cushion installation across Iowa. Moreover, the following sections detail the attribute information that was collected related to each crash cushion installation.

3.1 Product Type

A wide variety of crash cushion systems are available on the market; however, only 13 different product types have been installed across the state of Iowa. For each of the installations, the name of the corresponding product type was recorded in the database. A detailed description of each of these 13 crash cushion systems is provided in Chapter 4. Figure 4 shows the distribution of different cushion systems currently installed in Iowa.

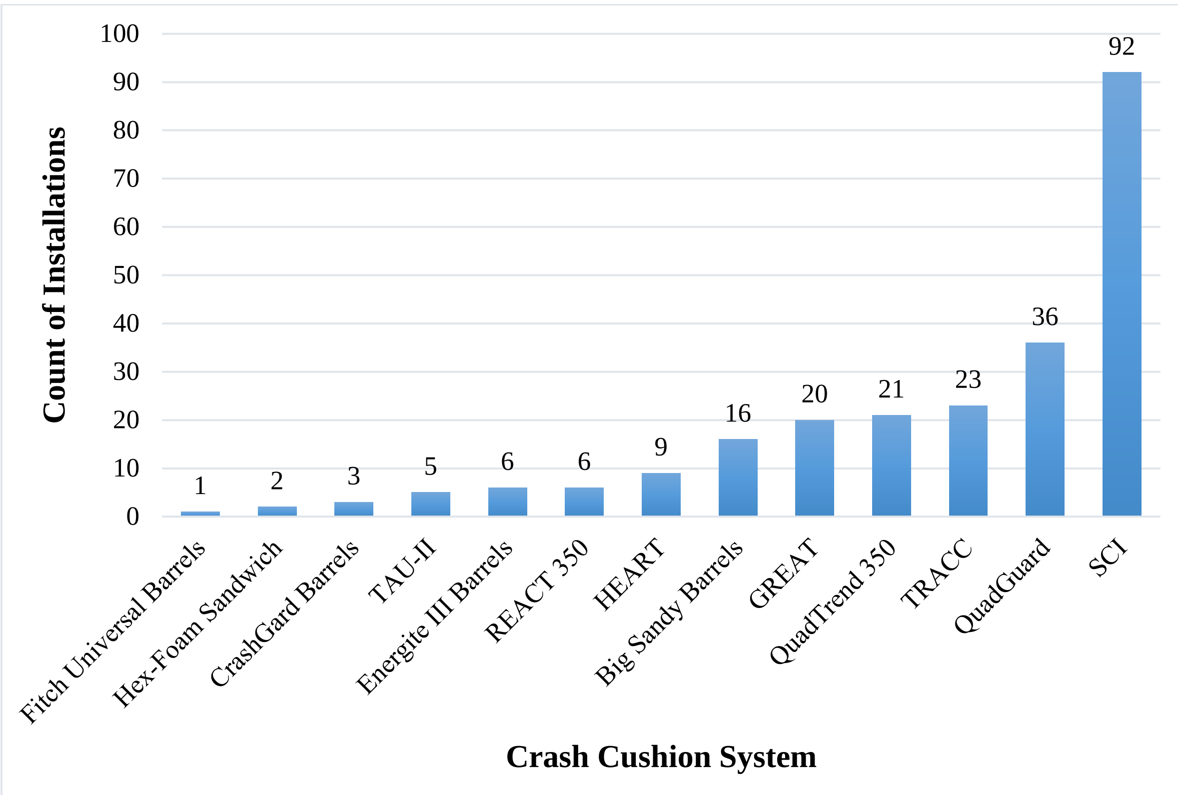
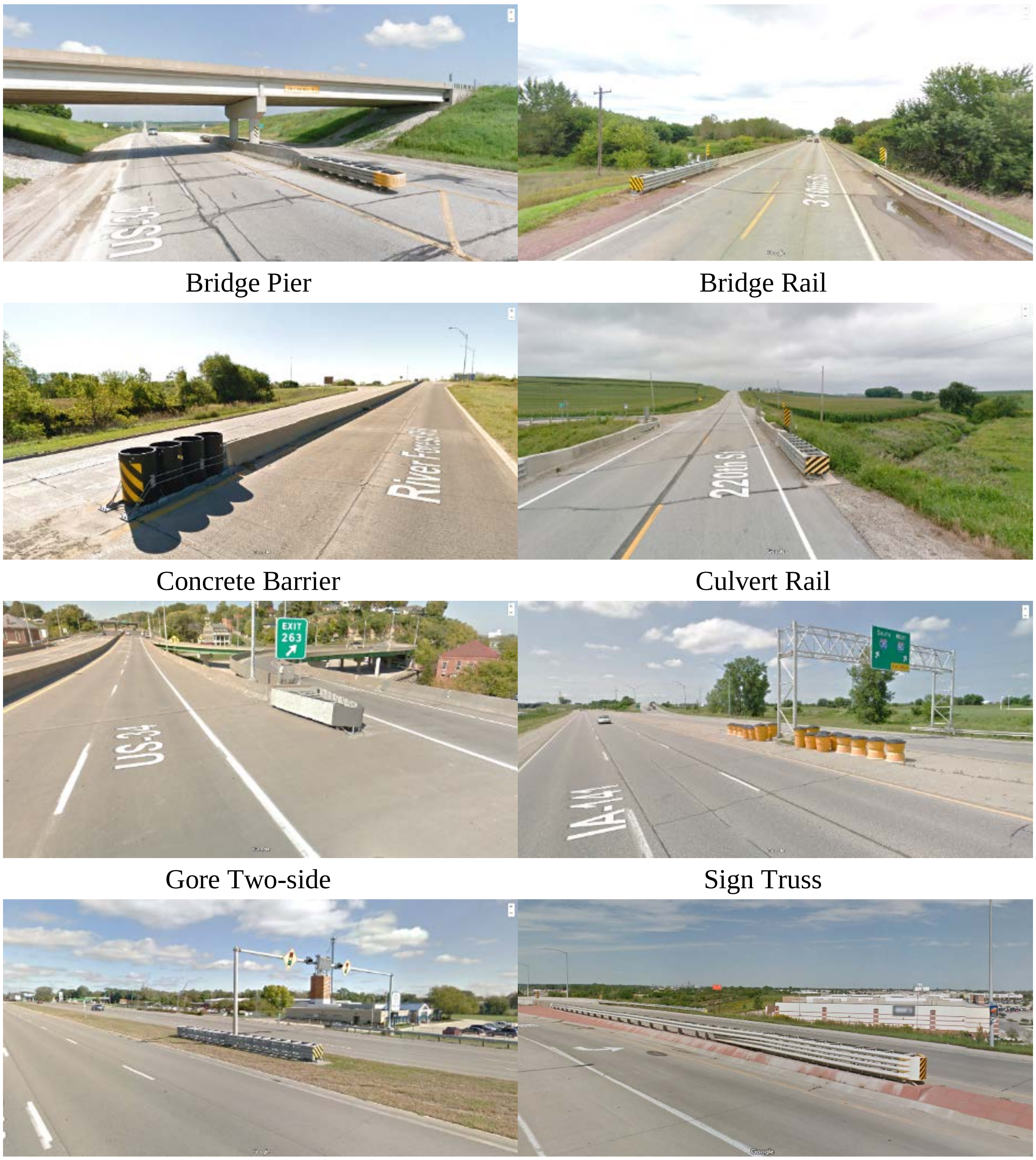


Figure 4. Distribution of Crash Cushion Installations by Product Type

3.2 Shielded Object

A variety of hazards located within the clear zone distance of a traveled way require shielding by a longitudinal barrier or crash cushion to mitigate the outcome when motorists crash into such hazards. Examples of roadside hazards which typically require a treatment include a bridge pier, bridge rail, concrete barrier, culvert rail, gore two-side, sign truss, signal post etc. Information on the type of hazard being shielded by the cushion was recorded for each installation and updated in the database. Figure 5 shows typical roadside hazards that are shielded using crash cushions in Iowa and their distribution is shown in Figure 6.



Bridge Pier | Bridge Rail

Concrete Barrier | Culvert Rail

Gore Two-side | Sign Truss

Signal Post | Guardrail End

Figure 5. Typical Fixed Roadside Hazards Shielded by Crash Cushions

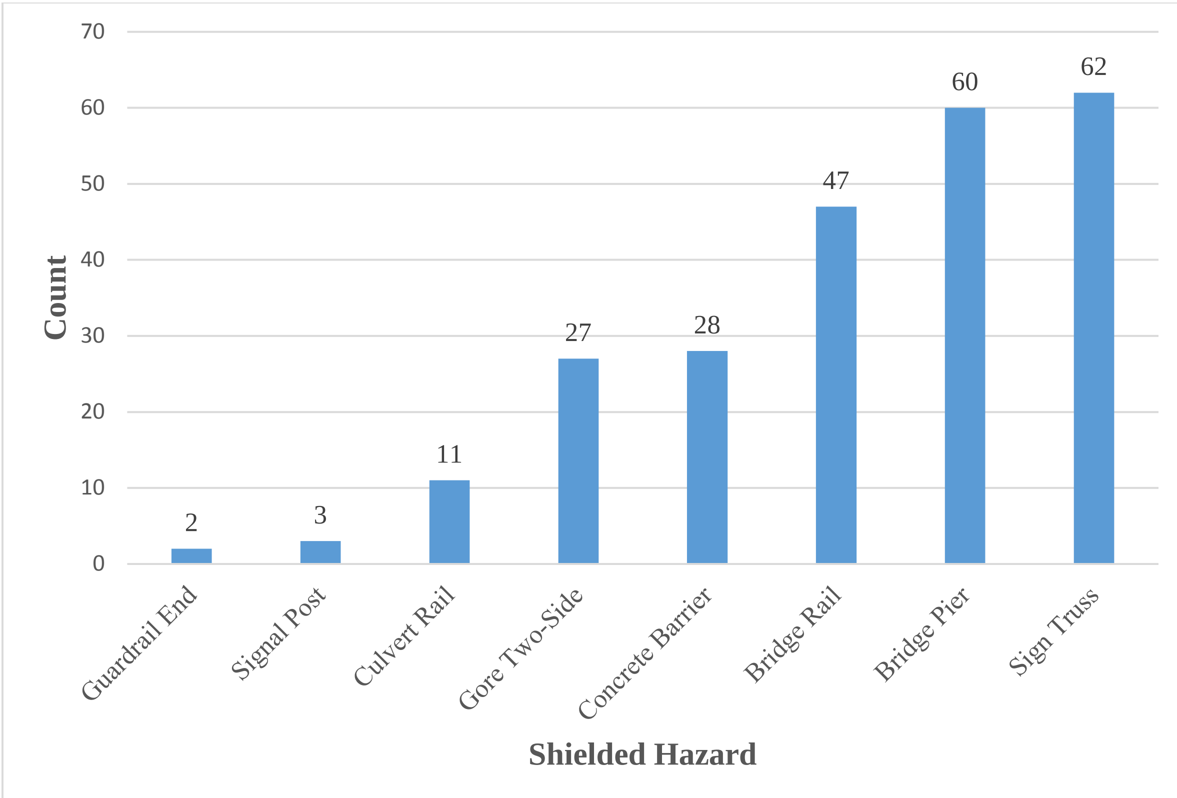


Figure 6. Distribution of Fixed Roadside Hazards Shielded by Crash Cushions

3.3 Route

The name of the mainline roadway and the direction of mainline traffic, which can potentially strike the cushion head-on, was collected for each installation and used as a double check for the geographic location. For cushions installed on ramps, the name of the mainline roadway and the direction of mainline traffic, which either branched out into or received traffic flow from, ramps were recorded as the route name and direction of travel, respectively. As shown in Figure 7, route name and direction of travel for cushions identified with CC_1 and CC_138 correspond to IA-141 E and IA-141 W, respectively, as the traffic moving along these directions can impact the cushions from the front. For cushions identified with CC_186 and CC_187, I-29 N was recorded as the route name and the direction of travel as traffic from I-29 N branches out into the Sioux highway where these cushions are installed.

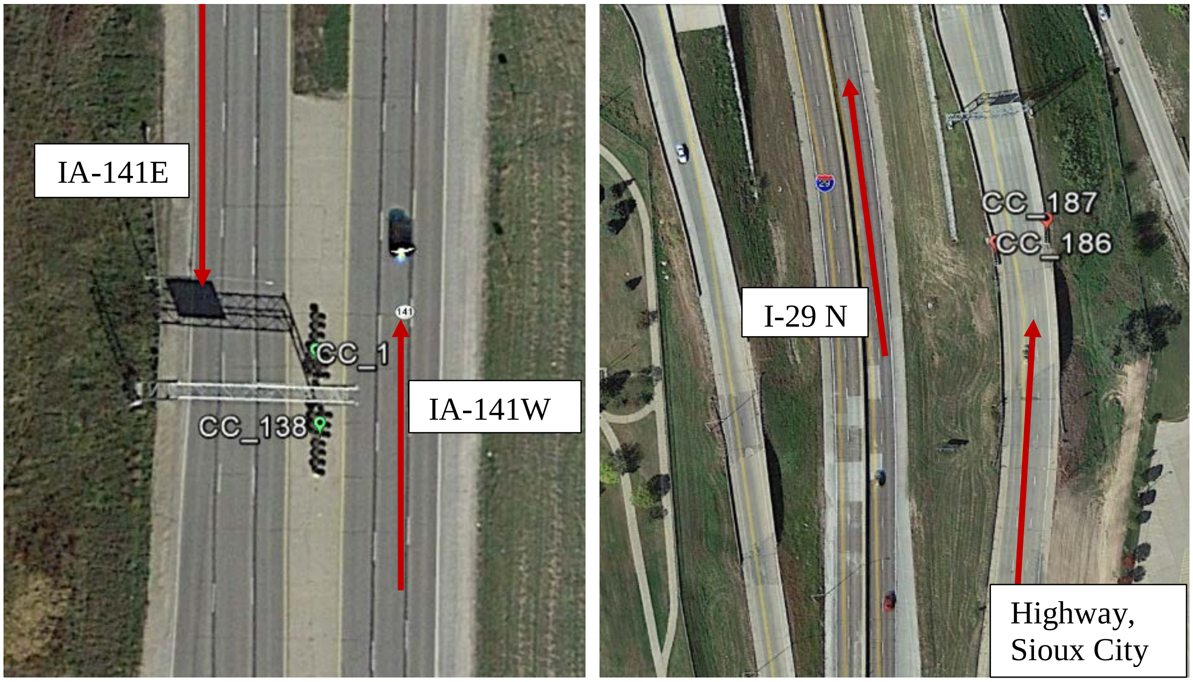


Figure 7. Identification of Route Name and Direction of Travel for Cushion Installations

3.4 Placement

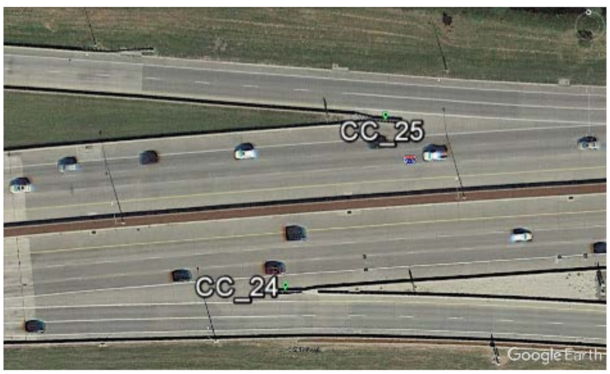
The placement of the cushion in relation to the roadway of the identified route was recorded for each installation. A total of five placement configurations have been defined and definition of each configuration is provided in the bulleted list that follows. Figure 9 and Figure 10 shows the distribution of cushion installations by placement configuration and the distribution of product types by placement configuration, respectively.

- **Mainline:** Cushion installation on the outside shoulder was flagged as a mainline placement.
- **Median:** Cushion installation in the median area or on the inside shoulder was flagged as a median placement.
- **Median*:** Cushion installation in the median area, which divides the traffic moving in the same direction, was flagged as a median* placement.
- **Ramp:** Cushion installation on the ramp was flagged as a ramp placement.

- **Gore:** Cushion installation in a gore area, which refers to the triangular piece of land between the mainline roadway and diverging or merging ramps, was flagged as a gore.

Mainline Placement

Median Placement



Gore Placement

Ramp Placement

Median* Placement

Figure 8. Placement Configurations for Crash Cushion Installations

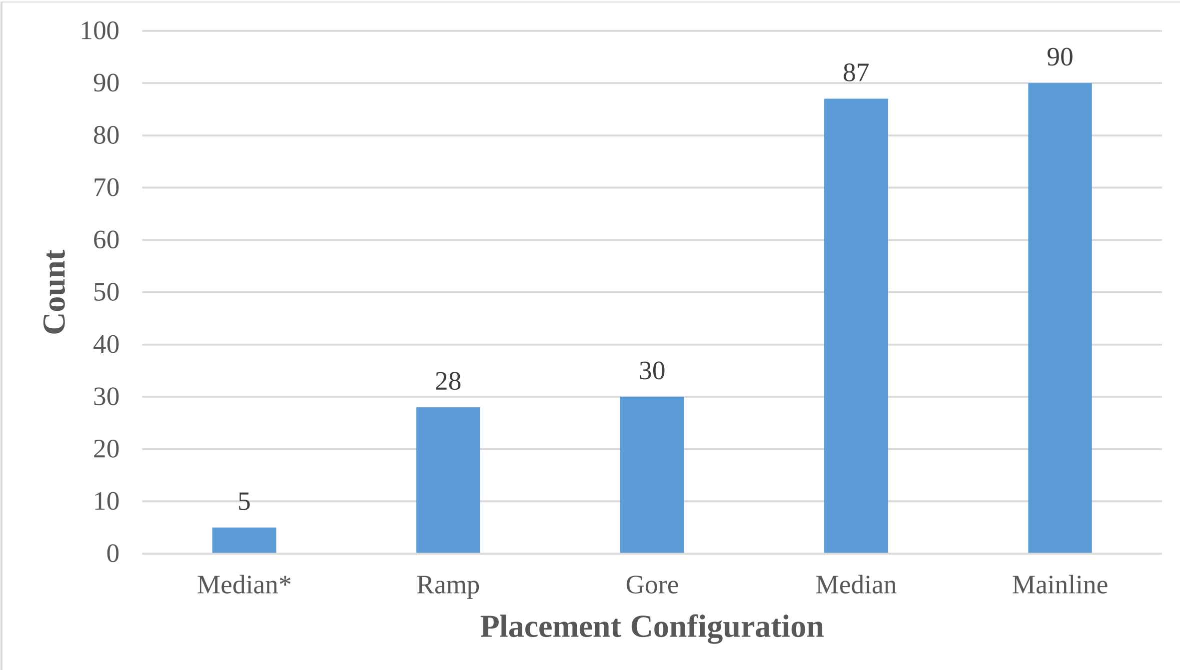


Figure 9. Distribution of Cushion Installations by Placement Configuration

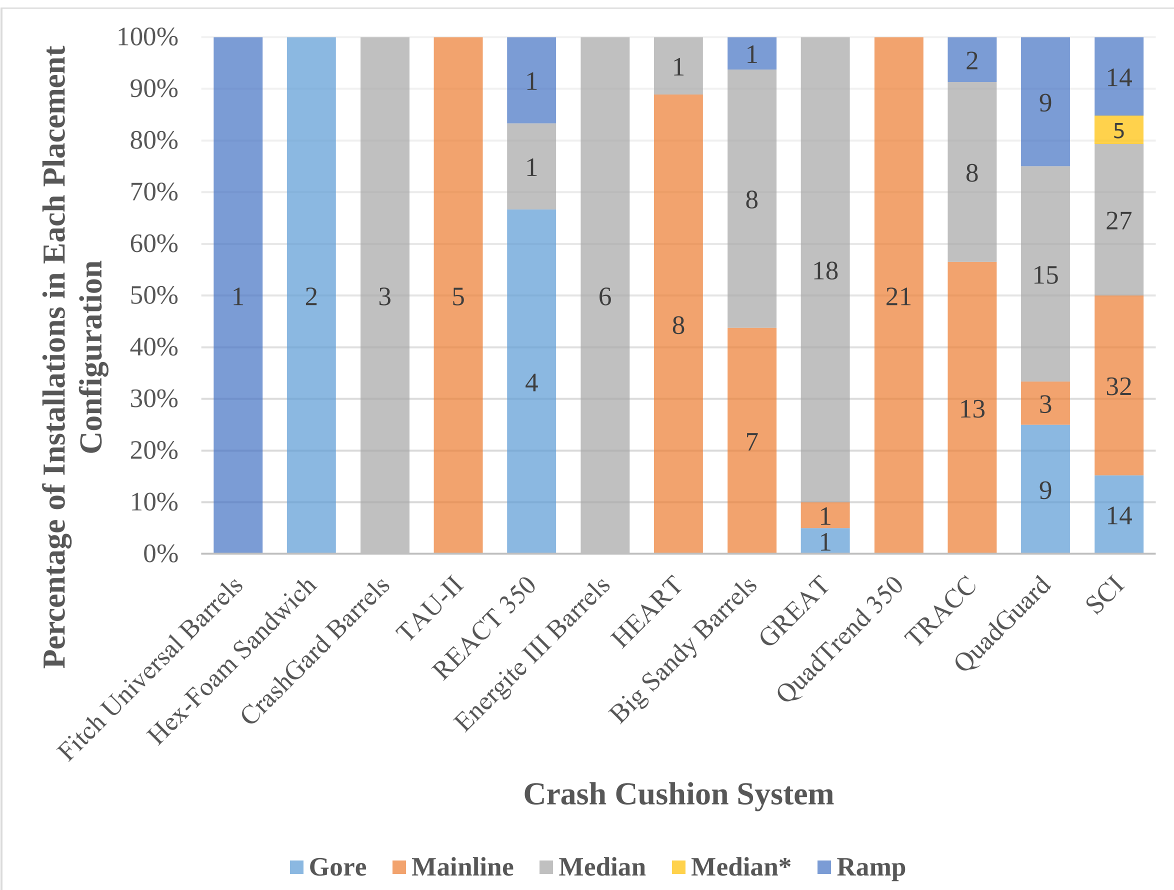


Figure 10. Distribution of Product Types by Placement Configuration

3.5 City

Bing Maps was used to identify whether a cushion installation is located within the city limits or lies outside of it. For cushions located within the city boundaries, corresponding city names were recorded, while those falling outside the city jurisdiction were designated to be in a rural area. Figure 12 provides an example where the county and city information are provided. The route and city information are combined to show the distribution of cushion installations by highway location in Figure 11.

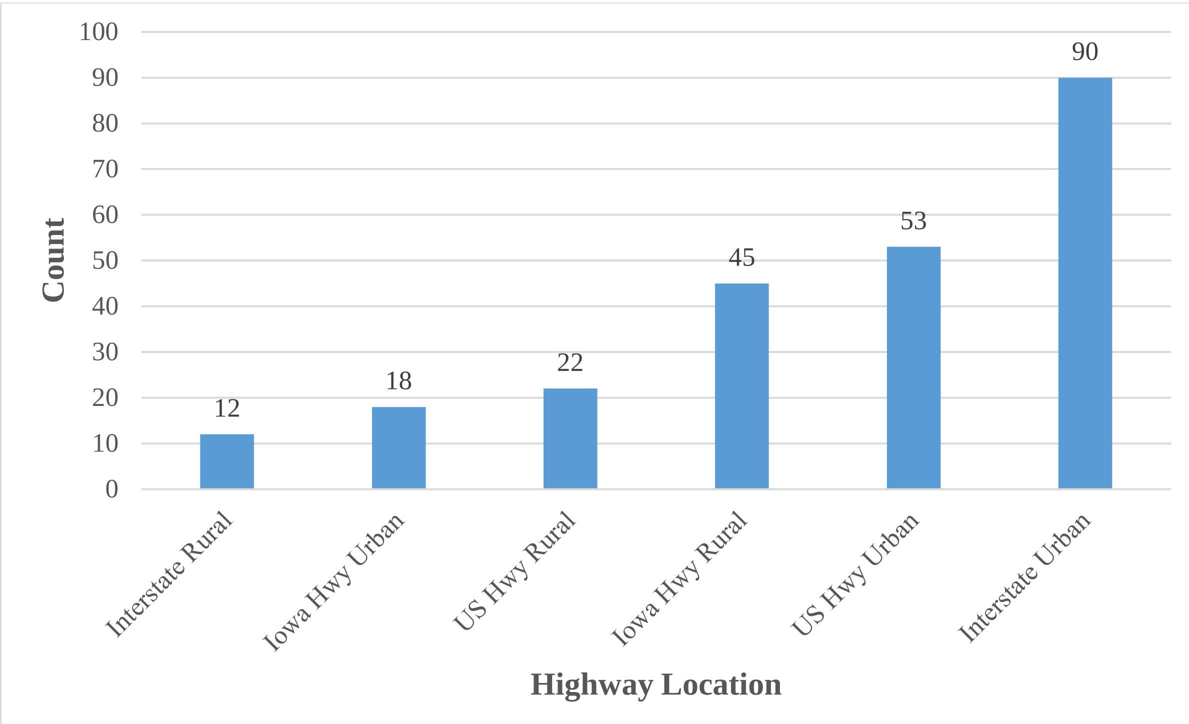


Figure 11. Distribution of Cushion Installations by Highway Location

3.6 County

County boundaries within which each of the cushion installations is located were obtained from the Bing Maps. Figure 12 highlights the location on Bing Maps which provides the County information for each installation.

Figure 12. Bing Maps Providing City and County Information for Cushion Installations

3.7 Status

Google Earth's imagery slider tool, which allows users to navigate through the historical imagery, was used concurrently with Street View to flag cushion installations as existing, replaced, or removed. The definition of the flagged items is provided in the bulleted list that follows, and the distribution of cushions by installation status is shown in Figure 13.

- **Existing:** Cushion installations that can be identified in the latest available imagery, either satellite imagery or Street View, were flagged as existing.
- **Replaced:** Crash cushions that were either replaced with different product types or other traffic barriers were flagged as replaced. Imagery slider bar, which is available in both Google Earth and Street View, was used to toggle satellite imagery and Street View back

and forth in time to look for such installations.

- **Removed:** Permanent crash cushions are typically not removed from the system unless roadway geometry changes to preclude the need for any attenuator at a given location. Google Earth's imagery slider tool was used to compare the historical imageries to identify such cases.

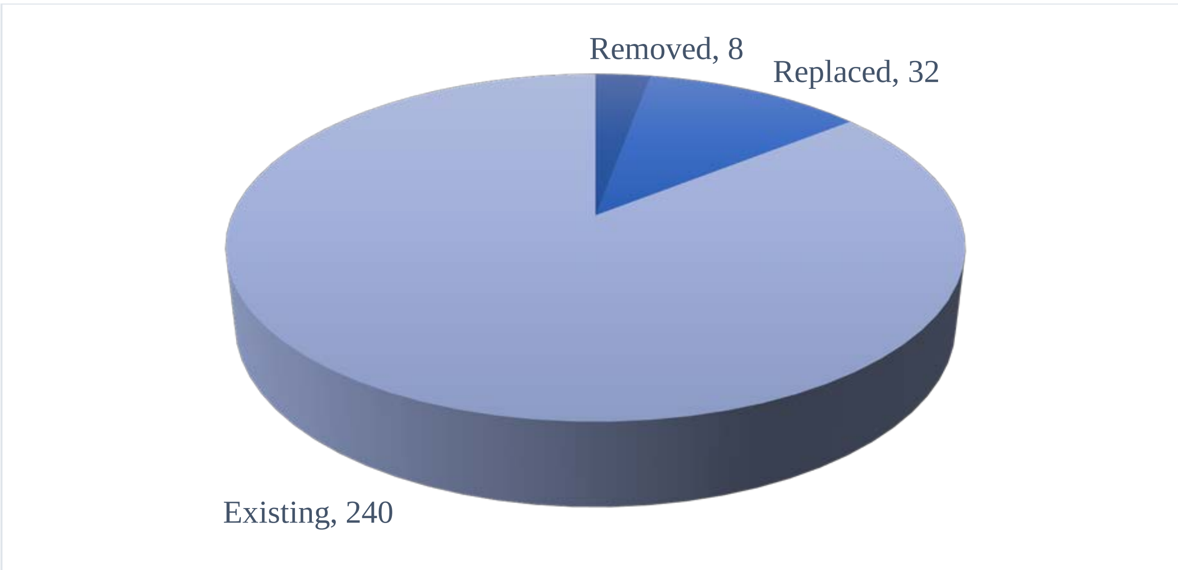


Figure 13. Distribution of Crash Cushions by Installation Status

3.8 Visibility

Cushion installations were also flagged based on their visibility in Google Earth's satellite imagery (or Aerial View) and Street View. Cushions can be visible only in Aerial View, only in Street View, or both imageries depending on the combination of imagery capture dates, cushion installation dates, and cushion removal dates. It gives users an idea of which imagery to look at to identify the cushion installation. Figure 14 shows the distribution of cushion installations by their visibility in Google imagery.

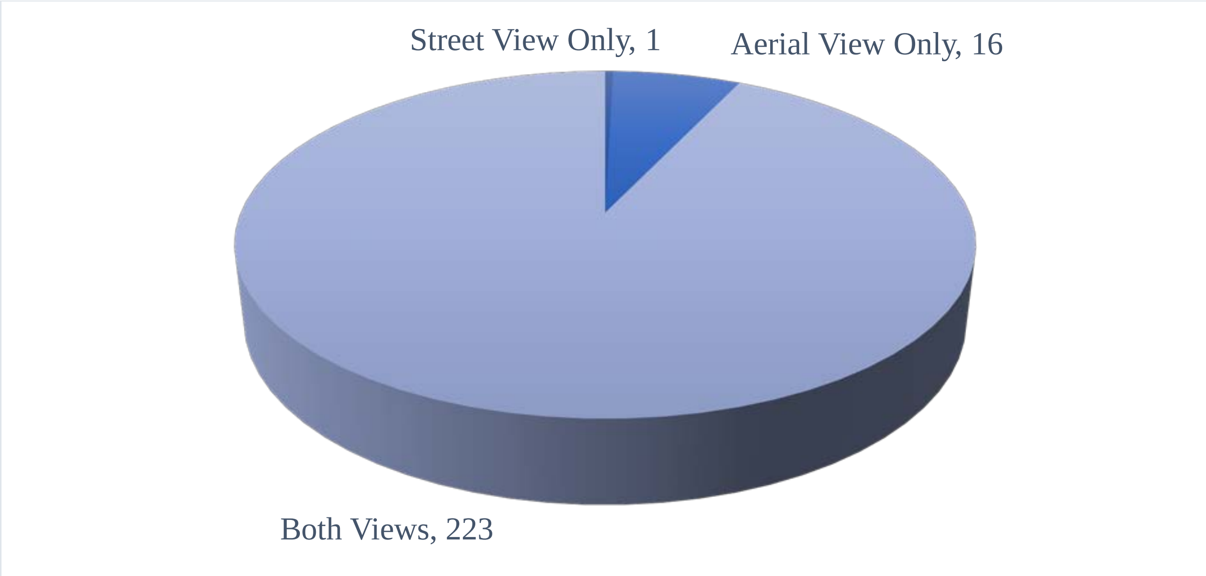
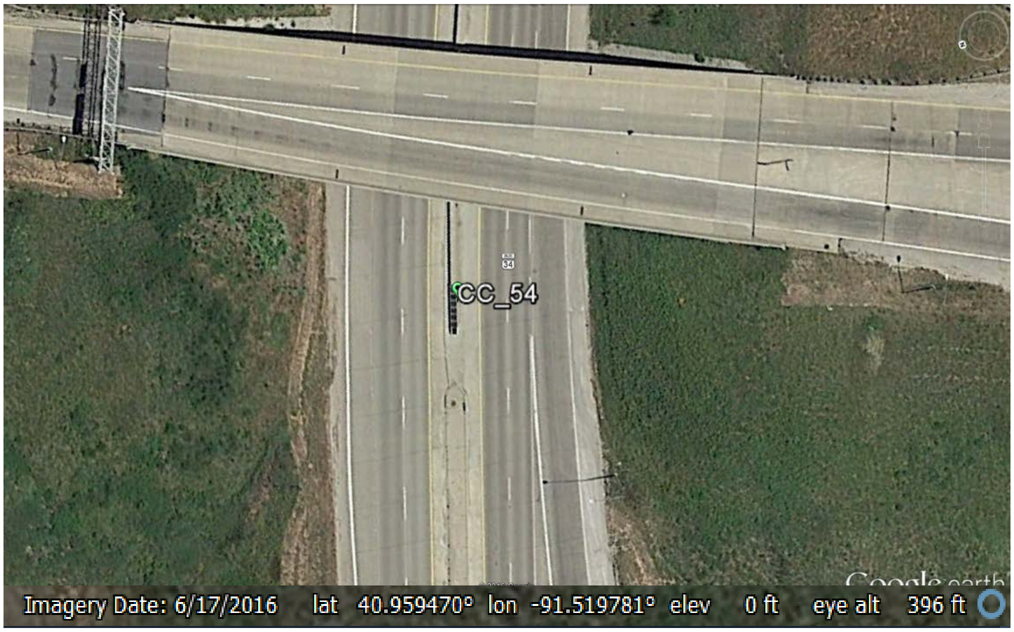


Figure 14. Distribution of Cushion Installations by Visibility in Google Imagery

3.9 Imagery Date

The most recent of the latest imagery capture dates for satellite imagery and Street View until which the crash cushion was visible was recorded as the imagery date. As shown in Figure 15, the latest satellite imagery and Street View dates until which the cushion identified with CC_54 is visible are June 17, 2016 and Sep, 2013, respectively. Thus, the most recent of these two dates (i.e., June 17, 2016 in this case) was recorded as the imagery date. In the absence of actual field data, differences between the imagery date and the installation date can be used to estimate the age of a cushion installation.



Satellite imagery showing a cushion identified with CC_54

Street View showing a cushion identified with CC_54

Figure 15. Illustration of Imagery Capture Dates

CHAPTER 4: CRASH CUSHION SYSTEMS

4.1 General Overview

A wide variety of crash cushion systems are available on the market, which differ from one another with regard to installation costs, energy-absorbing mechanisms, system performance, repair costs, and maintenance characteristics. This chapter provides a detailed description of 13 different crash cushion systems that have been permanently installed across the state of Iowa. Further, the examined systems have been broadly divided into two categories: redirective systems and non-redirective systems based on their re-direction capabilities.

4.2 Redirective Systems

Redirective crash cushion systems are designed to redirect errant vehicles toward the travel lane during side-angle impacts, and are further classified as gating and non-gating devices based on the extent of redirection capabilities available along the system length. Gating devices have redirection capabilities available only for a portion of the system length, also known as length of need (LON), and allow vehicles making side-angle impacts upstream of the beginning of the LON to pass through it, similar to a gate. Consequently, a sufficient clear zone area free of obstacles should be available behind the gating devices to allow impacting vehicles to regain control. Non-gating devices have redirection capabilities along the entire length of the system and in majority of cases, impacting vehicles do not pass through the system. Nine out of the 13 installed cushion devices are redirective systems and a description of each of these systems follows.

4.2.1 Guardrail Energy Absorbing Terminal (GREAT) System

The GREAT crash cushion is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is specifically designed to shield narrow hazards up to 3 feet wide and is compliant with the NCHRP Report 230 test requirements for a re-directive, non-gating crash cushion. The system is available in different configurations to accommodate a wide range of impact speeds up to 70 mph. 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 complete stop or a considerably low speed. Fender panels, chain anchors, and the guidance cable that runs along the length of the system provide the lateral restraint and redirect vehicles during side angle impacts. The dimensions and a picture of a typical GREAT cushion system are shown in Table 1 and Figure 16, respectively.

Table 1. Dimensions of GREAT Crash Cushion System (WSDOT)

	Min.	Max.
Length	15’ (4 bays)	33’ (10 bays)
Backup Width	24”	36”
Height	NA	NA

Figure 16. Typical GREAT Crash Cushion System (Google, 2016)

4.2.2 Hybrid Energy Absorbing Reusable Terminal (HEART) System

The HEART crash cushion is a trademarked attenuator system manufactured by Trinity Highway Products, LLC. It is compliant with the NCHRP Report 350 test level 3 (TL-3) requirements for a re-directive, non-gating crash cushion. The system consists of a series of steel diaphragms mounted on tubular steel tracks and surrounded within a framework of high density polyethylene (HDPE) side panels. During head-on impacts, tension cables attached to the second diaphragm from the nose are released and the assembly moves rearward crushing the HDPE panels to absorb the kinetic energy of the impacting vehicle. For side impacts, tubular steel tracks resist the lateral movement and help re-direct vehicles toward the travel lane. The dimensions and a picture of a typical HEART cushion system are shown in Table 2 and Figure 17, respectively.

Table 2. Dimensions of HEART Crash Cushion System (TxDOT, 2013)

	TL-2	TL-3	70 mph
Length	14’	26’–6”	29’
Backup Width	28”	28”	28”
Height	32”	32”	32”

Figure 17. Typical HEART Crash Cushion System (Google, 2016)

4.2.3 Hex-Foam Sandwich System

The Hex-Foam Sandwich crash cushion is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 230 test requirements for a re-directive, 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, while allowing for a controlled deceleration of the crashing vehicle. To accommodate side impacts, guidance cables provide the necessary lateral restraint and re-direct vehicles toward 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 18, respectively.

Table 3. Dimensions of Hex-Foam Sandwich Crash Cushion System (WSDOT)

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

Figure 18. Typical Hex-Foam Sandwich Crash Cushion System (Google, 2016)

4.2.4 QuadGuard System

The QuadGuard crash cushion is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 350 test requirements for a re-directive, non-gating crash cushion and is designed to accommodate a wide range of impact speeds ranging from 25 mph up to 70 mph. Moreover, the system is also available in various configurations to shield hazards as wide as 10 feet. The main system components include a monorail base, quad-beam panels, diaphragms, a backup and two types of energy-absorbing cartridges (Type-I and Type-II). 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 low speed or a complete stop. For side-angle impacts, the center monorail support structure resists the lateral movement and redirect vehicles towards the travel lane. The dimensions and a picture of a typical QuadGuard cushion system are shown in Table 4 and Figure 19, respectively.

Table 4. Dimensions of QuadGuard Crash Cushion System (FHWA)

	Min.	Max.
Length	9’ (25 mph)	27’ (70 mph)
Backup Width	24”	120”
Height	NA	NA

Figure 19. Typical QuadGuard Crash Cushion System (Google, 2016)

4.2.5 QuadTrend 350 System

The QuadTrend 350 crash cushion is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 350 test requirements for a re-directive, 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, since the attenuator allows gating, a minimum traversable clear zone is required behind the attenuator as per the FHWA recommendation. 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, steel cable running along the length of the system provide the necessary re-direction to the crashing vehicle. The dimensions and a picture of a typical QuadTrend 350 cushion system are shown in Table 5 and Figure 20, respectively.

Table 5. Dimensions of QuadTrend 350 Crash Cushion System (Energy Absorption Systems Inc)

Length	20’
Width	15”
Height	32”

Figure 20. Typical QuadTrend 350 Crash Cushion System (Iowa DOT, 2016)

4.2.6 Reusable Energy Absorbing Crash Terminal (REACT) 350 System

The REACT 350 is a trademarked crash cushion system manufactured by Trinity Highway Products, LLC. It is compliant with the NCHRP Report 350 test requirements for a re-directive, 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 High Density Polyethylene (HDPE) cylinders, re-directive cables anchored at both ends of the system and a backup structure. The backup structure is either self-contained in the system or a concrete backup is externally attached to it depending on the site requirements. The kinetic energy of the crashing vehicle making a head-on impact is absorbed by the HDPE cylinders which get crushed during the impact, although the cylinders get restored to their original shape after the impact. For side angle impacts, cables attached to both sides of the system provide the lateral restraint and re-direct the vehicles toward the travel lane. The dimensions and a picture of a typical REACT 350 cushion system are shown in Table 6 and Figure 21, respectively.

Table 6. Dimensions of REACT 350 Crash Cushion System (TxDOT, 2013)

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

Figure 21. Typical REACT 350 Crash Cushion System (Google, 2016)

4.2.7 Smart Cushion Innovations (SCI) System

The SCI 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 test requirements for a redirective, non-gating crash cushion at test level 2 (TL-2) and test level 3 (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 shock arresting cylinder to decelerate the vehicle to a considerably low speed. For side angle impacts, interlocking side panels and anchor bolts, which attach the system to the foundation, provide the necessary lateral restraint and re-direct the vehicle toward the travel lane. The dimensions and a picture of a typical SCI cushion system are shown in Table 7 and Figure 22, respectively.

Table 7. Dimensions of SCI Crash Cushion System (TxDOT, 2013)

	Narrow		Wide	
	TL-2	TL-3	TL-2	TL-3
Length	13’6”	21’6”	20’–42’	28’–50’
Backup Width	24”–36”	24”–36”	41”–133”	41”–133”
Height	33.4”	33.4”	33.4”	33.4”

Figure 22. Typical SCI Crash Cushion System (Google, 2016)

4.2.8 TAU-II System

The TAU-II is a trademarked crash cushion system manufactured by Barrier Systems, Inc. It is available for both low-speed and high-speed applications and is compliant with the NCHRP Report 350 test requirements for a re-directive, non-gating crash cushion. Moreover, the system is also designed in various configurations to shield hazard widths ranging from 30” up to 102”. 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 (Type-A and Type-B).

The assembly telescopes backward upon frontal impact, initially compressing the energy absorbing cartridge (EAC) in the first bay and then distributing the impact forces uniformly to all the remaining cartridges through diaphragms until the vehicle finally stops or decelerates to a considerably low speed. During a side angle impact, steel cables running along the length of the attenuator beneath the diaphragms provide the necessary lateral restraint and help redirect the vehicle toward the travel lane. The dimensions and a picture of a typical TAU-II cushion system are shown in Table 8 and Figure 23, respectively.

Table 8. Dimensions of TAU-II Crash Cushion System (TxDOT, 2013)

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

Figure 23. Typical TAU-II Crash Cushion System (Barrier Systems Inc.)

4.2.9 Trinity Attenuating Crash Cushion (TRACC) System

The 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, which all are compliant with the NCHRP Report 350 test requirements for a re-directive, non-gating crash cushion. The SHORTRACC model is used for low speed applications (TL-2), while TRACC and FASTRACC models are suited for high speed applications (TL-3). The FASTRACC model is an extended version of the TRACC model with an additional capacity and 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 either side or both sides to suit the 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 WIDETRACC model). During a head-on impact, 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 and redirect the impacting vehicle toward the travel lane. The dimensions and a picture of a typical TRACC cushion system are shown in Table 9 and Figure 24, respectively.

Table 9. Dimensions of TRACC Crash Cushion System (TxDOT, 2013)

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

Figure 24. Typical TRACC Crash Cushion System (Trinity Highway Products, Inc.)

4.3 Non-Redirective Systems

Non-redirective crash cushion systems do not have a redirection capability and are designed to allow a controlled penetration of vehicles impacting sideways, downstream from the nose of the system. Such systems mostly consist of sand barrels which can be arrayed in different geometric configurations to shield hazards of various shapes and sizes. A typical arrangement involves placing the lightest barrels at the front and weight of the barrels increases gradually as the array approaches the shielded hazard. Such arrangement facilitates the momentum transfer of vehicles making frontal impacts to variable sand masses while allowing for a controlled deceleration of the vehicle. Moreover, the number of units in each row of the array is also progressively increased to make the array wide enough at the obstacle to accommodate corner-rear angle 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 which can result in a rampaging effect on the impacting vehicle. Ideally, for the system to achieve its optimal performance, lighter barrels should be struck first followed by the heavier barrels. Consequently, in situations where reverse angle impacts are expected, lighter modules are placed along the fixed object to prevent vehicles from making initial impacts with the heavier barrels.

Initial installation cost of non-redirective systems is generally on the lower side, however, a total replacement of the impacted sand barrels is required after a crash, which significantly increases the repair costs. Such systems are most suited for locations which are expected to experience fewer side angle crashes and should be placed as far away from the travel lane as possible to minimize brush or nuisance hits. A total of four different sand barrel systems are installed across the state of Iowa and description of each of the systems is provided in the following paragraphs.

4.3.1 Energite III System

The Energite III sand barrel system is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 350 test level 3 (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 modules of 90, 180 and 320 kg 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 modules of 640 and 960 kg 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 25.

Figure 25. Typical Energite III Crash Cushion System (Energy Absorption Systems)

4.3.2 Big Sandy System

The Big Sandy sand barrel system is a trademarked attenuator system manufactured by TrafFix Devices, Inc. It is compliant with the NCHRP Report 350 test level 3 (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 model, also known as a combination barrel, utilizes a pedestal base and a top half barrel to configure the barrel in 90, 180 and 320 kg sizes to create a standard array. The combination barrels eliminate the use of cone inserts, thus prevent the leaking sand problem. A typical Big Sandy cushion system is shown in Figure 26.

Figure 26. Typical Big Sandy Crash Cushion System (Google, 2014)

4.3.3 CrashGard Sand Barrel System

The CrashGard sand barrel system is a trademarked attenuator system manufactured by Plastic Safety Systems, Inc. It is compliant with the NCHRP Report 350 test level 3 (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 of 90, 180 and 320 kg weights are configured by inserting a cone in the outer container first and then filling up the sand to the corresponding fill levels, while barrels weighing 640 and 960 kg are constructed by placing the corresponding amount of sand without the cone insert. A typical CrashGard sand barrel system is shown in Figure 27.

Figure 27. Typical CrashGard Sand Barrel System (Google, 2014)

4.3.4 Fitch Universal Barrel System

The Fitch Universal sand barrel system is a trademarked attenuator system manufactured by Energy Absorption Systems, Inc. It is compliant with the NCHRP Report 350 test level 3 (TL-3) requirements for a non-redirective, gating crash cushion when placed in a properly designed array. 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, four zip strips and a lid. The outer plastic container is made up of two identical half-cylinders which are fastened together using zip strips. Such multi-piece barrel design saves repair costs as it allows the replacement of only the impacted face and not the entire barrel, which is usually the case with other sand barrel systems. Moreover, overall weight of the barrels is configured in standard sizes of 90, 180, 320, 640 and 960 kg to create numerous array designs to meet the site specific needs. A typical Fitch Universal Barrel system is shown in Figure 28.

Figure 28. Typical Fitch Universal Barrel System (Energy Absorption Systems Inc.)

CHAPTER 5: EVALUATION OF CRASH DATA AND ESTIMATION OF INSTALLATION AND REPAIR COSTS

This chapter provides details of in-service data related to crash cushions installed in the state of Iowa. This includes a review of pertinent police-reported crash data from collisions involving permanent crash cushion installations throughout the state. Comparison data are provided for collisions involving other types of fixed hazards. The chapter also presents details as to installation and repair cost information related to in-service crash cushion systems that were obtained from the Iowa DOT over the course of this study.

5.1 Crash Data

The Iowa police-reported crash database was used to identify single-vehicle crashes involving permanent crash cushions over an eight-year period from 2007 through 2014. This time frame was chosen based upon the availability of crash report narratives from the Iowa DOT. In addition, Google satellite imagery and Street View can generally be traced back until 2007 without a significant loss in resolution. This allowed for verification as to whether crash reports 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 as a part of a manual review. These fields included the crash sequence of events, most harmful events, first harmful events, and type of fixed object struck. Table 10 provides a summary of the crash review, detailing whether the crash involved a collision with a permanent crash cushion system, a temporary (i.e., work zone-related) system, a cable barrier, or other coding error.

As shown in Table 10, only 32.4 percent of the crashes coded as striking an impact attenuator actually involved a permanent crash cushion and rest others were incorrectly coded, related to a work zone, or involved a cable barrier.

Table 10. Summary of Crashes Coded as Striking an Impact Attenuator (2007-2014)

	Count	Percentage (%)
Involved a permanent system	34	32.4
Involved a cable barrier	33	31.4
Coding error	15	14.3
Involved a temporary system	23	21.9
Total	**105**	**100.0**

For crashes where the most harmful event involved striking a permanent attenuator, the distribution of injury-severity outcomes is shown in Figure 29. These severity outcomes characterize the most severe level of injury sustained by a crash-involved occupant in this sample of crashes. Injury-severity levels are classified according to the KABCO scale, which is defined as follows:

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

These data are aggregated by the type of crash cushion system involved in each collision. The data presented in Figure 29 indicate that majority of the crashes involving impact attenuators resulted in minor injuries or property damage only.

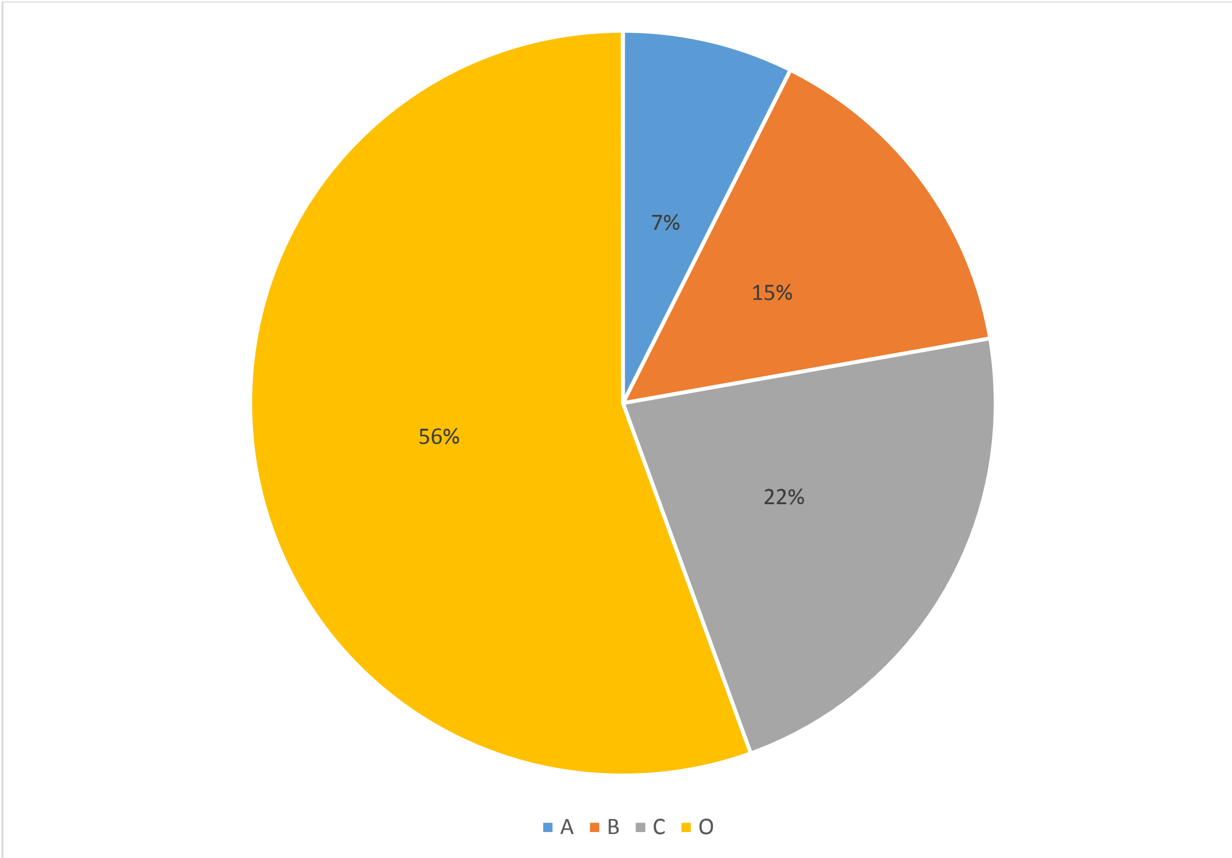


Figure 29. Distribution of Crash Severity for Impact Attenuator Crashes

For comparison purposes, Figure 30 shows the distribution of crashes by injury-severity level for crashes involving collisions with guardrail, concrete barrier, and various types of un-shielded fixed hazards, such as trees, poles, and unprotected structural supports (i.e., bridge piers). In general, the collisions with crash cushion systems tended to result in less severe injuries as compared to those collisions involving these more rigid roadside objects. However, it should be noted that only a limited sample of collisions involving crash cushion systems could be identified using the Iowa crash database. Consequently, this inhibited the ability to conduct a rigorous in-service comparison of the safety performance of the various types of crash cushion systems that have been installed throughout the state.

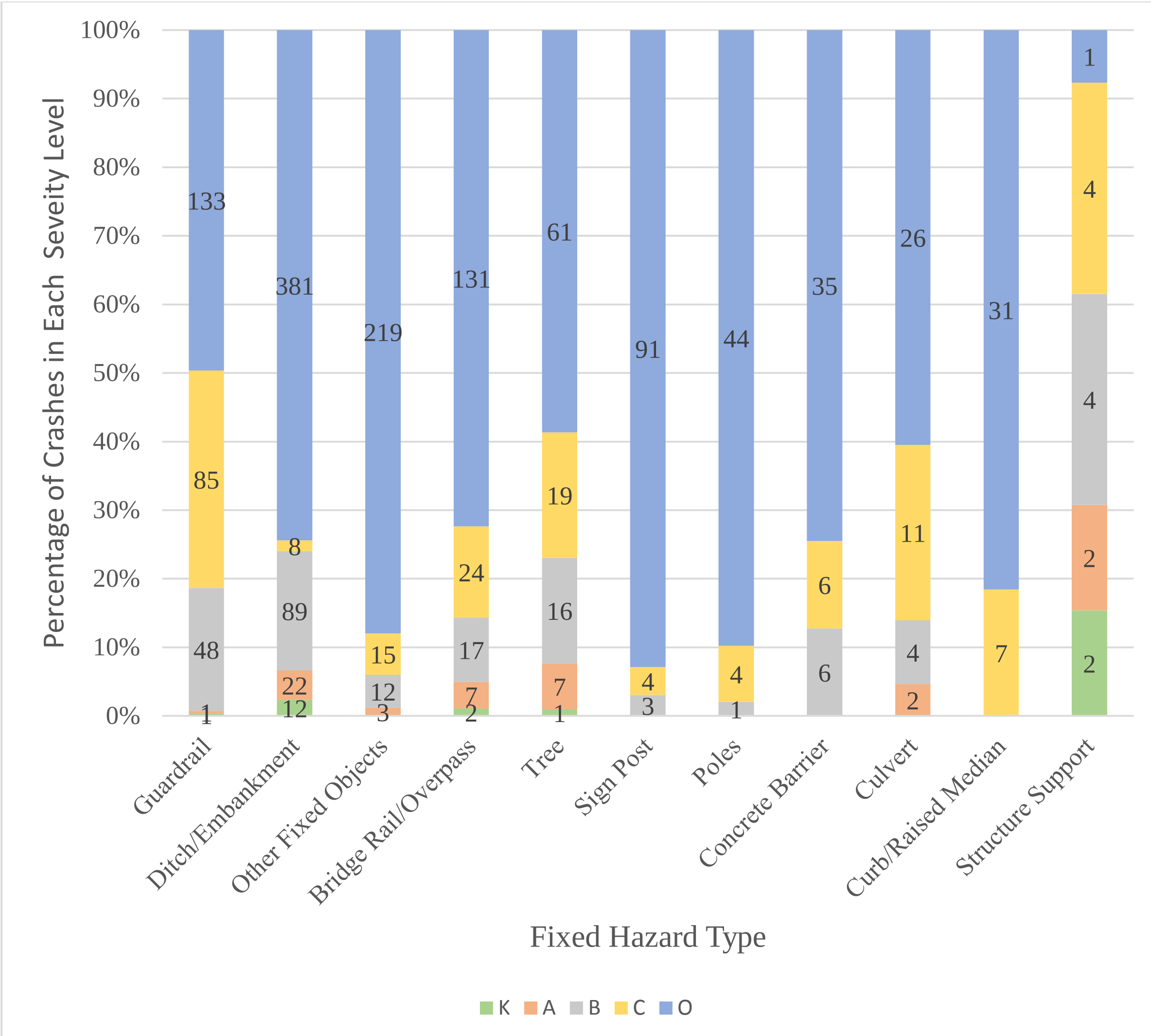


Figure 30. Crash Severity Distribution by Fixed Object Struck along Rural Interstates

While crash cushions are generally shown to minimize the consequences resulting from run-off-road crashes, additional data are necessary to discern differences in the performance of specific crash cushion systems. This highlights an important opportunity area to inform future installation decision, which is discussed in further detail as part of the conclusions in Chapter 7. In lieu of the availability of such data, the remainder of this chapter details the installation and repair costs associated with the systems that have been installed in Iowa to date.

5.2 Installation Cost

A collection of 89 plan sets, which contained information on plans of proposed improvements on the primary road system, was provided through the Iowa DOT. Each plan set was structured as a series of indexed sheets and a brief description for the index numbers was provided in the title sheet. As a beginning point, the table called Estimated Project Quantities (EPQ), usually located on the first page of the sheets indexed with the alphabet "C" (or C sheets), was searched to find whether the project involved the installation of permanent crash cushions. If the project did involve permanent cushion installations, the corresponding item number was recorded. The recorded item number was then searched in another table called Estimate Reference Information (ERI), located immediately following the EPQ table, to look for the reference information of the table called Crash Cushions, which contained location stations and other pertinent details for the installations, in the corresponding description field. For plan sets where the reference information for the Crash Cushions table was not tied to the item number of the permanent crash cushions, EPQ table was revisited to obtain the item number corresponding to the temporary crash cushions to again search for the required table reference information in the ERI table.

Subsequently, location stations for permanent cushion installations provided in the plan sets were used to locate additional permanent installations, which were not initially included in the database, and to match contract IDs, indicated on the plan sets, with the corresponding unique identifiers of the crash cushions which were installed as part of each project. Moreover, the DOT also provided a spreadsheet that linked the following information with each Contract ID: project number, project letting date, project start date, and project completion date, and another set of documents called Field Manager which were used to obtain installation costs and installation dates for permanent cushions installed under various projects using the corresponding Contract IDs.

Field Manager did not include installation cost information for all product types. Consequently, e-mails were sent to manufacturers requesting installation cost data for product types where such information was unavailable. Moreover, e-mails were also sent to manufacturers for product types where installation cost information was available through Field Managers for comparison purposes. Additional information was obtained from data available online from the Kansas and Mississippi DOTs. Table 10 provides a summary of installation costs for different crash cushion systems. These costs are shown to vary widely from a low of $2,735 for the low-cost, non-redirecting sacrificial systems to a high of $32,530 for the higher-cost redirecting sacrificial and severe use systems.

Table 11. Installation Costs for Different Test Level 3 (TL-3) Crash Cushion Systems

Product Types	Installation Cost
Energite III	$3,875[b]
Universal Fitch Barrels	$4,435[b]
CrashGard Sand Barrels	$3,580[b]
Big Sandy	$2,735[b]
SCI	$22,070[a]
Heart	$19,525[a]
TRACC	$14,430[b]
TAU-II	$19,500[a]
QuadTrend350	$5,220[b]
QuadGuard	$20,545[a]
React 350	$32,530[b]
Hex Foam Sandwich	$8,030[c]
Great	$10,511[c]

a: Iowa DOT Field Manager;
b: Kansas Department of Transportation's Contract Document (KDOT);
c: Mississippi Department of Transportation Agency Contract (MDOT)

5.3 Repair Cost

In an attempt to gather information pertaining to repairs that were performed on damaged permanent crash cushions along the primary roadway network, an e-mail was drafted and sent out to the district maintenance managers of all 6 Iowa DOT districts requesting for the following information concerning each repair: route and mile post of the repair location, date on which the attenuator was damaged, date on which the attenuator was repaired, total time required to perform the repair, number of workers involved in the repair, and overall cost of the damaged system parts that were replaced.

Based on the responses received from the district maintenance managers, districts 4 and 5 did not experience any significant damage to crash cushions, while the remaining four districts (i.e., Districts 1, 2, 3, and 6) did perform attenuator repairs and provided the requested information in a spreadsheet format. After receiving the spreadsheets, route and mile post information for each repair was used to link the repair data with the corresponding unique identifier of the permanent cushion on which the repair was performed. However, not all of the repair data could be linked to permanent crash cushions as some of these repairs were performed on truck-mounted attenuators, temporary crash cushions installed in work zones, or other safety devices such as guardrails and cable barriers and such cases were excluded from the dataset.

The repair data obtained through the Iowa DOT districts did not have information on all product types, possibly because some attenuator types were never struck or involved minor repairs that were not recorded. Consequently, another set of e-mails were drafted and sent out to the manufacturer of each crash cushion system requesting for the information on estimated average cost of damaged system parts and man-hours required to restore the cushion to working conditions after the attenuator system was subjected to various NCHRP 350 tests during the product approval process.

Once the repair data provided by the DOT districts and permanent crash cushion IDs were linked, and the missing information for certain product types were obtained from the manufacturers, the average repair cost and personnel hours required to repair different crash cushion systems were estimated. Table 12 provides a summary of the average cost and man-hours required to repair the damaged attenuators by product type. In cases where Iowa-specific information was unavailable, information was obtained from other sources as noted in Table 12.

Table 12. Average Material Cost and Average Work-Hours per Repair for Different Cushion Systems

Product Types	Avg. Material Cost	Avg. Repair Time	Avg. Total Repair Cost[d]
Energite III	$2,712.5[c]	21[c]	$3,762.50
Universal Fitch Barrels	$3,104.5[c]	21[c]	$4,154.50
CrashGard Sand Barrels	$2,506[c]	21[c]	$3,556.00
Big Sandy	$1,914.5[c]	21[a]	$2,964.50
SCI	$2,204[a]	12[a]	$2,804.00
Heart	$1,225[c]	16[c]	$2,025.00
TRACC	$8,700[b]	24[b]	$9,900.00
TAU-II	$5,550[b]	20[b]	$6,550.00
QuadTrend350	$6,565[c]	36.9[a]	$8,410.00
QuadGuard	$6,465[a]	39[a]	$8,415.00
React 350	$7,248[a]	14[b]	$7,948.00
Hex Foam Sandwich	$1,786[a]	38[a]	$3,686.00
Great	$7,323[a]	29[b]	$8,773.00

a: Iowa maintenance records;
b: Arizona Finding in the Public Interest (FIPI) submittal;
c: Engineering estimate;
d: Assuming labor charge as $50/hour, a value used in Arizona FIPI submittal

Based on the installation cost and average repair cost per crash for different cushion types, as provided in Table 11 and Table 12, a matrix of product installation costs and average repair costs was created as shown in Table 13.

Table 13. Matrix of Product Installation and Repair Costs

		Average Repair Costs per Crash ($)			
		2000-4000	**4000-6000**	**6000-8000**	**8000-10000**
Product Installation Costs ($)	**<5000**	Energite III, Big Sandy, CrashGard	Fitch Barrels	-	-
	5000-10000	Hex Foam Sandwich	-	-	QuadTrend 350
	10000-15000	-	-	-	Great, TRACC
	15000-20000	Heart	-	TAU-II	-
	20000-25000	SCI	-	-	QuadGuard
	>25000	-	-	React 350	-

Given the lack of maintenance data for sand barrels, only two crash cushion categories were created based on the installation and repair costs: redirective systems with high installation and low repair costs, and redirective systems with low installation and high repair costs. The cushions considered in high-installation/low-repair category had installation cost in $15,000-20,000 range and repair cost in $2000-4,000 range. An average installation cost of $17,500 and average repair cost of $3,000 was considered to generate the life cycle cost values. For low-installation/high-repair cushion category, cushions with installation cost in $10,000-15,000 range and repair cost in $8,000-10,000 range were included. Similar to high-installation/low-repair category, an average installation cost of $12,500 and average repair cost of $9,000 was used to estimate the life cycle cost values. Figure 31 shows the 15-year life cycle cost comparison between low-installation/high-repair and high-installation/low-repair cushion categories.

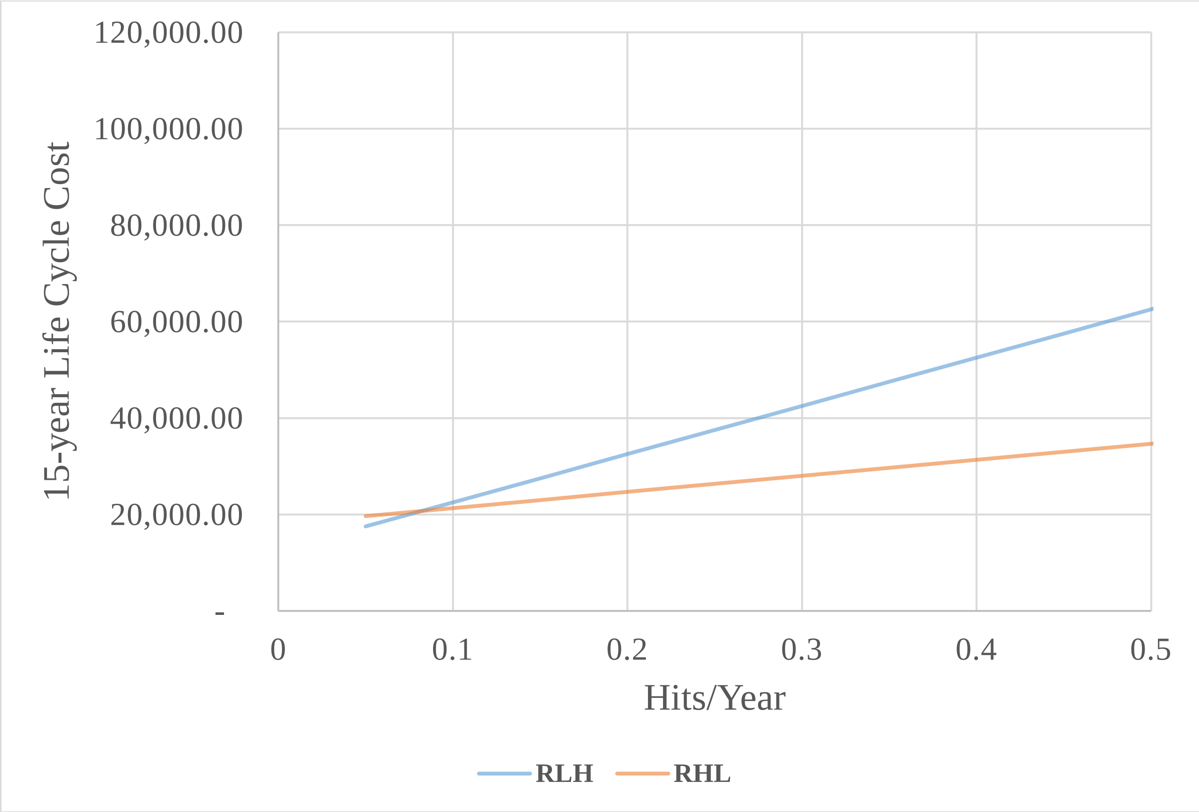


Figure 31. 15-Year Life Cycle Cost Comparison Between Low-Installation/High-Repair and High-Installation/Low-Repair Cushion Category

The graphs showing the variation of life-cycle costs for high-installation/low-repair and low-installation/high-repair cushion categories in Figure 31 intersect at an impact frequency of 0.08 per year. Thus, highway locations where the expected impact frequency with the crash cushions are less than 0.08/year, low-installation/high-repair category is the most cost-effective option, whereas at high impact locations with expected impacts greater than 0.08/year, high-installation/low-repair category is the optimal option.

CHAPTER 6: DATA ANALYSIS

6.1 RSAP Overview

The Roadside Safety Analysis Program (RSAP) is a software program used for cost-effectiveness evaluation of roadside safety treatment alternatives. It was originally developed under NCHRP Project 22-09(1) (Mak & Sicking, 1998) and was first distributed for public use with the 2002 edition of the AASHTO RDG (AASHTO, 2002). Subsequently, RSAP has undergone several upgrades over the years, some of which include improvements in the algorithms, updates to embedded default databases, and enhancements to the graphical user interface. RSAP version 3.0.0 (or RSAPv3) is the latest version of the software which was developed under NCHRP Project 22-27 (Ray, 2012) and has been used in this study to perform benefit-cost analyses on crash cushion systems currently in use across the state of Iowa.

The cost-effectiveness procedure incorporated within RSAPv3 uses an encroachment probability-based model built on a series of conditional probabilities which are computed using the following four modules: (1) Encroachment Probability Module, (2) Crash Prediction Module, (3) Severity Prediction Module, and (4) 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 road segment. Given an encroachment, the crash prediction module then evaluates the likelihood of the encroachment to result in a crash, P(Cr|Encr). For each predicted crash, severity prediction module assesses the severity outcome of the crash, P(Sev|Cr), which is then converted into dollar values using the crash cost figures. Ultimately, 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.

The conditional probability model used for each alternative on each segment is given as follows:

$E(CC)_{N,M} = ADT * L_N * P(Encr) * P(Cr|Encr) * P(Sev_s|Cr) * E(CC_s|Sev_s)$ (Ray, 2012)

Where:

$E(CC)_{N,M}$	=	Expected annual crash cost on segment N for alternative M,
ADT	=	Average Daily Traffic in vehicles/day,
L_N	=	Length of segment N in miles,
$P(Encr)$	=	The probability a vehicle will encroach on the segment,
$P(Cr\|Encr)$	=	The probability a crash will occur on the segment given that an encroachment has occurred,
$P(Sev_s\|Cr)$	=	The probability that a crash of severity s* occurs given that a crash has occurred and
$E(CC_s\|Sev_s)$	=	The expected crash cost of a crash of severity s in dollars.

* Note: Severity level is based on the KABCO scale, where "K" refers to a fatal crash proceeding in decreasing injury-severity to an "O" which is a property damage only crash.

A detailed description of each of the four analysis modules used in the encroachment probability model is provided in the sections that follow.

6.2 Encroachment Probability Module

The encroachment probability module estimates the expected number of encroachments on a road segment through a two-step process, consisting of generating baseline encroachment frequencies based on the highway type followed by modifications to the baseline encroachment frequencies using adjustment factors to account for deviations from the base conditions. The highway types defined in RSAPv3 include one-way, two-lane undivided and four-lane divided highways, and baseline encroachment frequencies for such highway types are developed using the encroachment data assembled in the late 1970s in Canada (Cooper, 1980). The Cooper encroachment data, which is based on the observation of tire-tracks on roadsides, has been preferred over another available data source developed by researchers in Illinois in the early 1960s (Hutchinson, 1962) as it offers better data quality and constitute a larger sample size.

The predictive models for generating baseline encroachment frequencies, in units of encroachments/mile/year, are developed using the negative binomial (NB) regression models and the following highway characteristics are chosen to represent the base condition: (a) posted speed limit of 65 mph, (b) flat ground, (c) relatively straight segment, (d) lane width greater than or equal to 12 ft., and (e) zero major access points per mile. Figure 33 shows the relationship between total encroachment frequency and AADT for different roadway types. The hump in the curves are purely because of the way the equations have been set up to develop these graphs. However, the results seem counterintuitive as encroachments are expected to increase with the increasing AADT. Consequently, the linear portion of the graphs shown in Figure 28 are assumed to start at the peak of the hump for each roadway type. The modified graphs used for estimating encroachment frequencies are shown in Figure 34. Further, in situations where analysis segments do not conform to the base conditions, various encroachment adjustment factors (EAFs) are incorporated within RSAPv3 to adjust for the effects of number of lanes, posted speed limit, access density, highway terrain, vertical grade, horizontal curvature, and lane width.

For both two-lane undivided and four-lane divided highways, four encroachment possibilities exist including two encroachments on the primary direction (i.e., the direction of increasing baseline stationing) and two encroachments on the opposing direction (see Figure 32). Encroachments on each direction are estimated using the product of total number of encroachments on the analysis segment, directional distribution of the traffic, and the left/right encroachment split. One-way highway facilities are assumed to have the functional characteristics of four-lane divided highways and total encroachment frequency on such facilities are estimated using the same equation as four-lane divided highways, however the resulting values are divided by two as only two encroachments are possible (i.e., primary left and primary right). Since there is no opposing traffic on one-way facilities, hundred percent of the traffic is moving in the primary direction and encroachments on each direction are estimated using only the product of total encroachment frequency and the encroachment split.

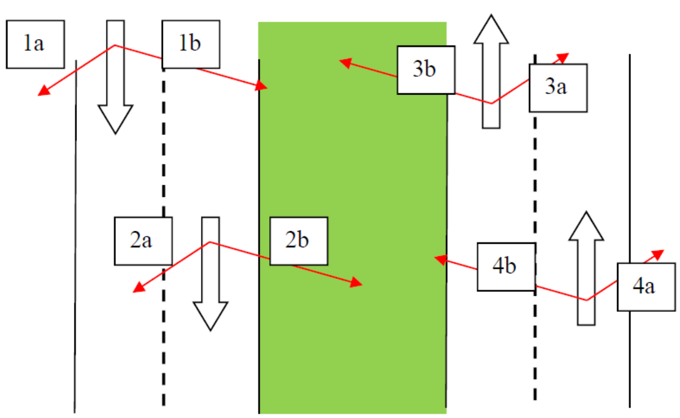


Figure 32. Possible Encroachments for Divided and Undivided Highways (Ray, 2012)

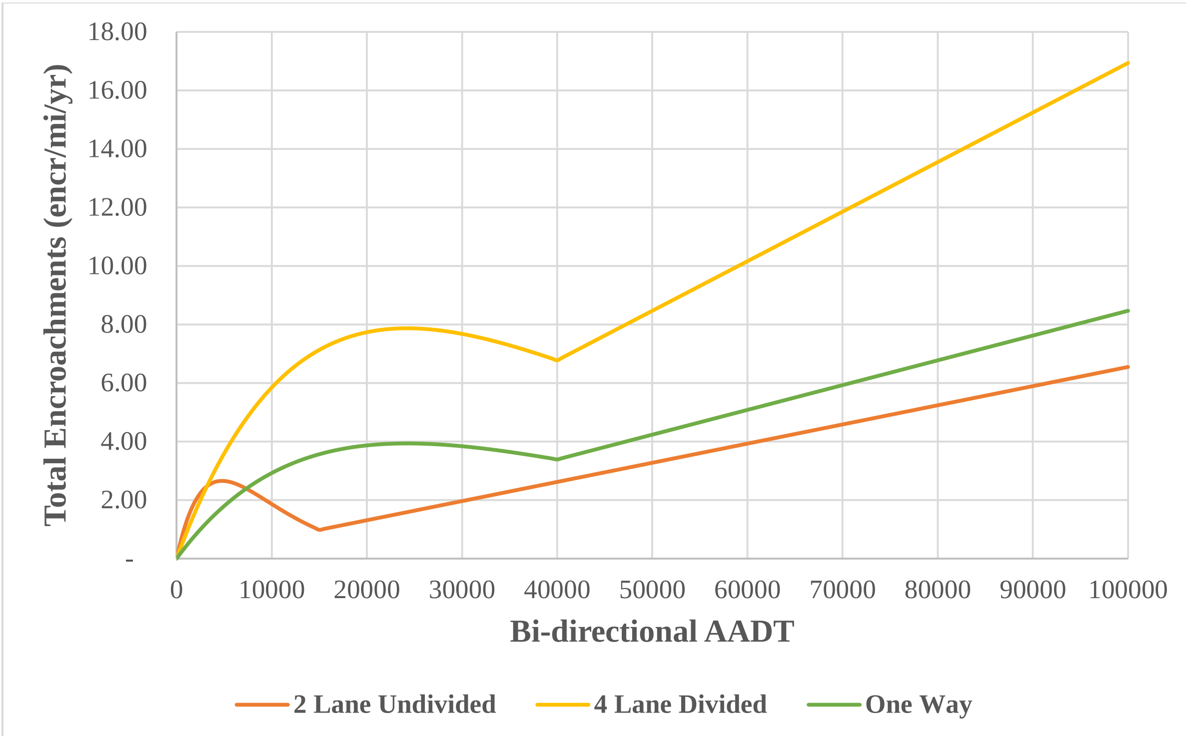


Figure 33. Total Encroachment Frequency by AADT and Highway Type (Ray, 2012)

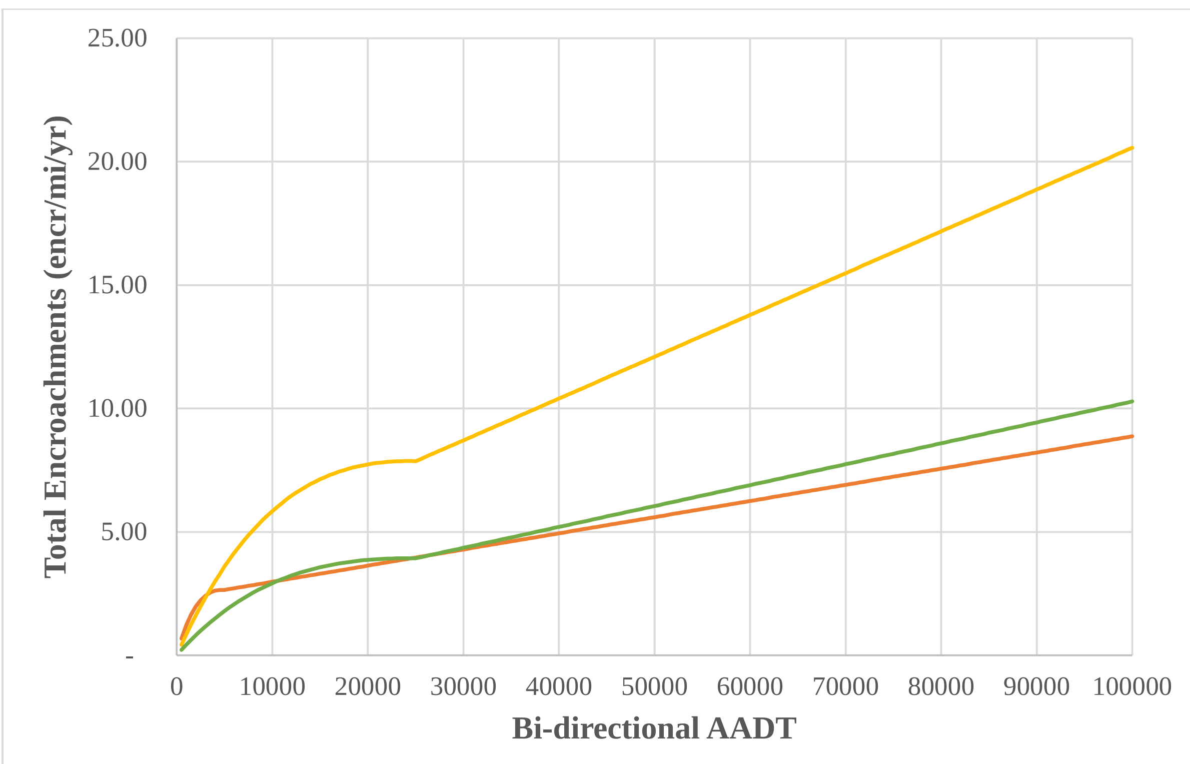


Figure 34. Modified Total Encroachment Frequency by AADT and Highway Type

6.3 Crash Prediction Module

After the encroachment probability module has predicted a vehicle encroachment, the next step is to assess if the encroachment would result in a crash. The crash prediction module begins the assessment by selecting appropriate vehicle trajectories for the analysis segment from the trajectory database incorporated within RSAPv3 to model vehicle paths during an encroachment. The trajectory database, also called crash reconstruction database, was developed under NCHRP Project 17-22 and contains trajectory information 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 critical roadway and roadside characteristics: roadside cross-section profile, horizontal curve radius, highway vertical grade and posted speed limit, to those in the user-defined road segment. The individual scores, where each score represents the degree of similarity between the analysis segment and the roadway for which the trajectory information was collected, 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 0.93 or higher (RSAPv3 default, can be changed by the user), or until the minimum number of desired trajectory cases, as defined by the user, are obtained.

Following trajectory selection, each trajectory is mapped onto the roadside and/or median at the beginning of the analysis segment and examined at pre-defined increments along the trajectory path to determine if a collision with a modeled hazard occurs, if a terrain rollover occurs, or the encroachment results in a non-crash event. For each detected collision, RSAPv3 estimates the probability of each of the following events that might result from striking the hazard: a complete stop, hazard penetration, or redirection. If the simulated vehicle encroachment penetrates the hazard, the trajectory is examined further to determine the possibility of collision with other hazards or terrain rollover. Further, if the vehicle is predicted to get redirected around the hazard, the redirection paths are evaluated. Once all the possibilities are exhausted, the trajectories are advanced along the segment at predetermined amounts to continue the analysis.

6.4 Severity Prediction Module

Given that a crash has occurred, 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 striking the hazard. The development of a severity model for each hazard involves the estimation of the following three parameters: (a) A dimensionless value, also called $EFCCR_{65}$, that represents the severity of crashes involving the hazard that did not result in PRV, or rollover after redirection on a scale of 0 to 1, where 0 represents a PDO and 1 represents a fatal injury, (b) percent of total crashes with the hazard which resulted in a penetration, rollover, or vault (PRV), and (c) percentage of total crashes with the hazard which resulted in a rollover after being redirected away from the hazard. The procedure for estimating $EFCCR_{65}$ comprises of the following five steps: (1) police-reported crash databases are used to identify crashes with each roadside hazard and are later segregated into different posted speed limit categories, (2) severity distribution of crashes which solely involved the hazards under evaluation and did not result in penetration or rollover is determined, (3) percentage of unreported crashes, all of which are assumed to have resulted in property damage only, are estimated and added to the reported crash severity distribution,

(4) crash cost of the severity distribution corresponding to each posted speed limit is calculated and subsequently, converted into equivalent fatal crash cost ratio (EFCCR) by dividing crash cost values with the cost for a fatal crash, (5) finally, EFCCR values are normalized to a baseline impact speed of 65 mph ($EFCCR_{65}$) to facilitate a direct comparison of hazard severity between roadside hazards.

6.5 Benefit/Cost Analysis Module

Once the severity estimate of a crash is determined in the severity prediction module, the societal or crash costs associated with the crash is computed using the economic value of a life, also called value of a statistical life (VSL), for direct comparison with agency costs. Here, VSL refers to the monetary costs that individuals are willing to pay to prevent a traffic fatality, and a value of $9.1 million, as established by FHWA in 2012, is currently set as the default value in RSAPv3. Further, the monetary values corresponding to various degrees of injury severity are set as a percentage of the VSL.

For each alternative, benefit-cost ratio is calculated as a proportion, with the numerator containing the project benefits, measured as the reduction in crash costs, and the denominator containing the agency costs. Agency costs include construction and maintenance associated with each alternative as well as repairs required as a result of crashes predicted on the segment. The following formula is used to calculate the benefit-cost ratio (BCR):

$$BCR_{i/j} = \frac{CC_i - CC_j}{DC_i - DC_i}$$

Where:

$BCR_{i/j}$	=	Incremental BCR of alternative j with respect to alternative I,
CC_i, CC_j	=	Annualized crash cost for alternatives i and j,
DC_i, DC_j	=	Annualized direct cost for alternatives i and j

6.6 Sensitivity Analysis

Sensitivity analyses were performed for each highway facility type (i.e., one-way, undivided, and divided) to identify the input parameters which have the greatest influence on ROR crash frequency in RSAPv3. The set of parameters included in the analyses were based on their likelihood to vary from one installation site to another. For example, crash cushions are typically installed on flat grounds, and thus percentage grade parameter was set at zero and was not included in the analyses. A 600-ft long segment was considered with a typical placement of fixed hazards on each roadway type (see Figure 35 through Figure 37) and each selected parameter was varied from its mean value to the lowest and highest values observed on the corresponding highway facility. The length of the analysis segment was set at the minimum recommended value of 600 ft., which includes 300 ft. upstream and 300 ft. downstream of the modeled hazards. Increasing the segment length beyond 600 ft. increased the simulation time without adding any significant improvements to the analysis results. The results of the sensitivity analyses for different facility types are provided in Table 14 through Table 16.

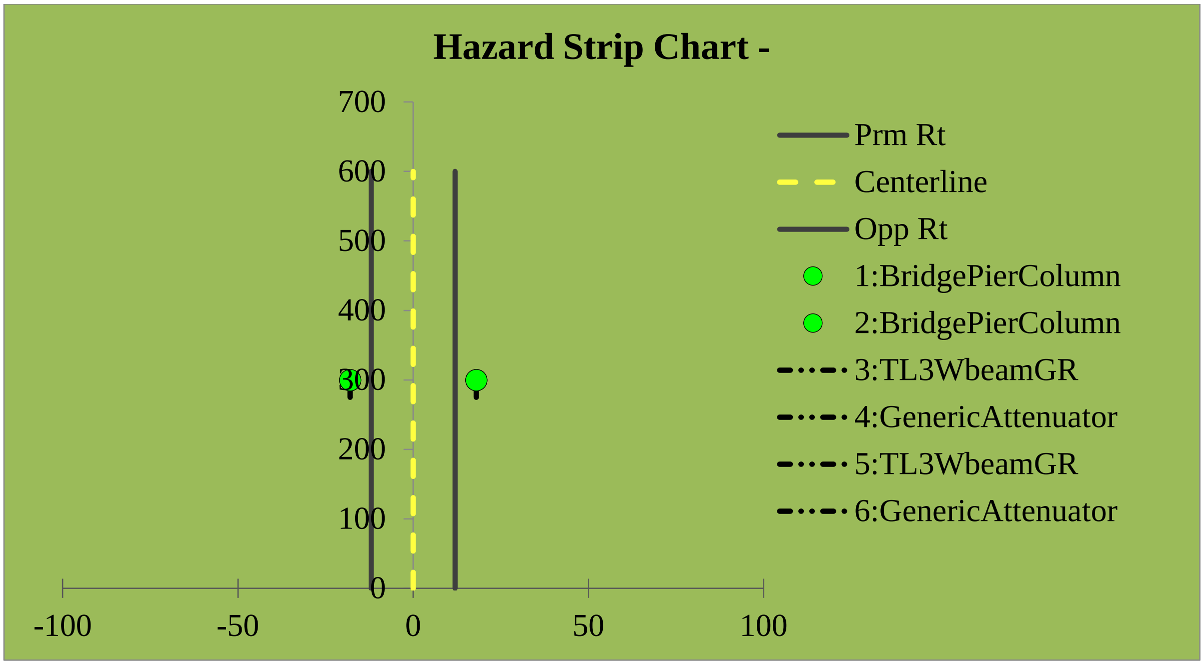


Figure 35. Typical Hazard Placement Configuration Considered on Undivided Highways

Table 14. Sensitivity Analysis Results for Undivided Highways

Parameter	Range	Impacts/year	Percent Difference
	2	0.07	0
Hazard Offset	6 (baseline)	0.07	n/a
	12	0.07	0
	650	0.03	-57.14
AADT	2,250 (baseline)	0.07	n/a
	12,500	0.10	42.86
	2	0.08	14.29
No. of Lanes	3 (baseline)	0.07	n/a
	4	0.05	-28.57
	10	0.09	28.57
Lane Width	12 (baseline)	0.07	n/a
	14	0.06	-14.29
	3	0.07	0
Shoulder Width	8 (baseline)	0.07	n/a
	10	0.07	0
	45	0.07	0
Speed Limit	50 (baseline)	0.07	n/a
	55	0.07	0
	500	0.08	14.29
Horizontal Curvature	1000 (baseline)	0.07	n/a
	Tangent	0.02	-71.43

The results of the sensitivity analysis presented in Table 14 indicate that the speed limit, hazard offset, and shoulder width had no influence on ROR crash frequency. The number of lanes and lane width did have some influence; however, in the majority of cases, crash cushions were installed on undivided roadways with two 12-ft wide travel lanes. Consequently, lane width and number of lanes were set at their baseline values and not modified in generating different highway scenarios. The only parameters that significantly influenced the impact frequency were AADT and horizontal curvature, which were modified to generate highway scenarios.

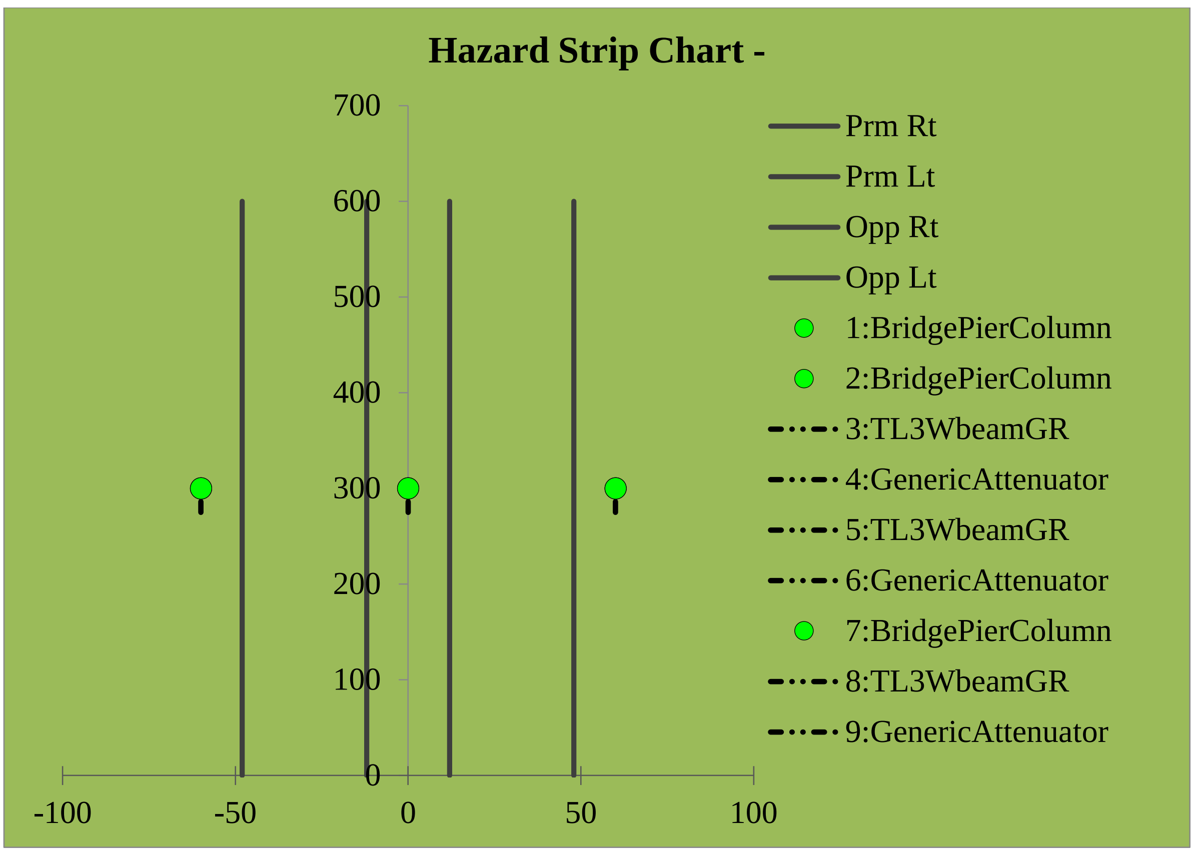


Figure 36. Typical Hazard Placement Configuration Considered on Divided Highways

Table 15. Sensitivity Analysis Results for Divided Highways

Parameter	Range	Impacts/year	Percent Difference (%)
Hazard Offset	2	0.38	0
	12 (baseline)	0.38	n/a
	26	0.18	-52.63
AADT	3,300	0.11	-71.05
	32,000 (baseline)	0.38	n/a
	115,000	1.01	165.75
No. of Lanes	2	0.42	10.53
	5 (baseline)	0.38	n/a
	9	0.33	-13.16
Lane Width	10	0.46	21.05
	12 (baseline)	0.38	n/a
	14	0.36	-5.26
Right Shoulder Width	0	0.38	0
	8 (baseline)	0.38	n/a
	12	0.38	0
Left Shoulder Width	0	0.38	0
	5 (baseline)	0.38	n/a
	11	0.38	0
Speed Limit	45	0.40	5.26
	55 (baseline)	0.38	n/a
	70	0.33	-13.16
Horizontal Curvature	500	0.39	2.63
	1000 (baseline)	0.38	n/a
	Tangent	0.11	-71.05

Sensitivity analysis results for divided highways as shown in Table 15 indicate that AADT, hazard offset, and horizontal curvature are the only three parameter which caused a fluctuation of more than 30 percent in the impact frequency. Consequently, only these three parameters were modified to generate highway scenarios while setting the other insignificant parameters to their default values. The highway scenarios modeled for divided highways are more than those for undivided highways as different hazard offsets are considered as well.

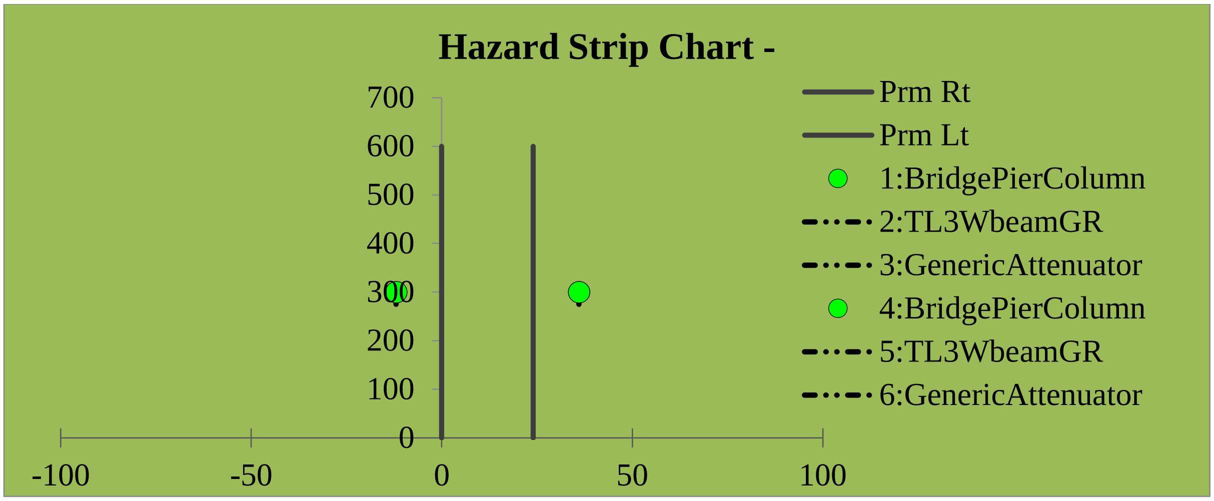


Figure 37. Typical Hazard Placement Configuration Considered on One-Way Highways

Table 16. Sensitivity Analysis Results for One-Way Highways

Parameter	Range	Impacts/year	Percent Difference
	3	0.11	0
Hazard Offset	12 (baseline)	0.11	n/a
	20	0.08	-27.27
	1400	0.02	-81.82
AADT	10,750 (baseline)	0.11	n/a
	66,100	0.27	145.45
	1	0.12	9.09
No. of Lanes	2 (baseline)	0.11	n/a
	5	0.11	0
	10	0.14	27.27
Lane Width	12 (baseline)	0.11	n/a
	16	0.11	0
	0	0.11	0
Shoulder Width	5 (baseline)	0.11	n/a
	10	0.11	0
	45	0.11	0
Speed Limit	50 (baseline)	0.11	n/a
	55	0.11	0
	500	0.12	9.09
Horizontal Curvature	1000 (baseline)	0.11	n/a
	Tangent	0.04	-63.64

RSAPv3 assumes that the one-way highways have the similar functional characteristics as that of divided highways, and consequently sensitivity analysis results shown in Table 16 are consistent with the results for divided highways.

6.7 Impact Frequency Estimation

Based on the sensitivity analyses results, those parameters which caused a fluctuation of more than 30 percent in annual impact frequency were considered in further detail while the remaining parameters were set at their baseline values. Previous research by Schrum et al. (2015) had chosen a threshold value of 20 percent; however, the range of parameters included in this study were wider and thus a relatively higher value of 30 percent was chosen as the decision criteria. The analysis results indicate that AADT, horizontal curvature, and hazard offset are the most sensitive parameters and were modified according to the schemes shown in Table 17 through Table 18 to model different highway scenarios for different facility types.

Table 17. Annual Impact Frequency under Different Highway Scenarios on Undivided Highways

		Horizontal Curvature		
		500	1000	100,000
AADT	1000	0.06	0.05	0.02
	2000	0.09	0.07	0.03
	3000	0.11	0.09	0.03
	4000	0.11	0.09	0.04
	5000	0.11	0.09	0.04
	10000	0.13	0.11	0.04
	15000	0.15	0.12	0.05
		All Offset		

Based upon the results of the sensitivity analysis for undivided highways, AADT and horizontal curvature were the only two parameters having significant influence on crash frequency and were modified as shown in Table 17 to generate numerous highway scenarios. On tangent sections, annual impact frequency did not exceed 0.05 hits, which shows that the chances of a cushion getting struck in the worst case scenario is once in a 20-year period. On sharper curves with radii up to 500 ft., impact frequency increases by about 2.5 times over the range of AADT. Similar trend is observed on milder curves, except that the magnitude of impact frequency is relatively low.

Table 18. Annual Impact Frequency under Different Highway Scenarios on Divided Highways

		Horizontal Curvature								
		500	1000	100,000	500	1000	100,000	500	1000	100,000
AADT	5000	0.16	0.14	0.05	0.13	0.12	0.04	0.08	0.07	0.03
	10000	0.25	0.21	0.07	0.20	0.19	0.07	0.12	0.11	0.05
	15000	0.29	0.25	0.09	0.24	0.22	0.08	0.14	0.13	0.06
	25000	0.34	0.29	0.10	0.28	0.26	0.09	0.17	0.15	0.07
	50000	0.53	0.45	0.16	0.43	0.40	0.15	0.26	0.24	0.11
	75000	0.72	0.62	0.22	0.59	0.55	0.20	0.36	0.33	0.15
	100000	0.92	0.79	0.27	0.75	0.70	0.25	0.45	0.42	0.19
	125000	1.11	0.95	0.33	0.91	0.85	0.31	0.55	0.51	0.23
		5			15			25		
		Offset								

Unlike undivided highways, where changing cushion offset over the pre-selected range did not have any influence on impact frequency, cushion offsets did influence impact frequency on divided highways. Consequently, more number of highway scenarios were modeled for divided highways considering different hazard offsets. As shown in Table 18, for any given offset and AADT value, impact frequency increases as the segment gets sharper. Similarly, for a given curve radius and AADT, as the hazard offset from the travel lane increases, the likelihood of impacting such hazards decreases. Further, for a segment with constant curve radius and hazard offset, the probability of impacting the hazard increases.

Table 19. Annual Impact Frequency under Different Highway Scenarios on One-way Highways

		Horizontal Curvature								
		500	1000	100,000	500	1000	100,000	500	1000	100,000
AADT	1000	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	2000	0.04	0.03	0.01	0.03	0.03	0.01	0.02	0.02	0.01
	3000	0.05	0.04	0.01	0.04	0.04	0.01	0.03	0.02	0.01
	4000	0.07	0.05	0.02	0.05	0.05	0.02	0.03	0.03	0.01
	5000	0.08	0.06	0.02	0.06	0.06	0.02	0.04	0.04	0.01
	15000	0.15	0.10	0.04	0.11	0.11	0.04	0.07	0.07	0.03
	25000	0.17	0.12	0.04	0.12	0.12	0.05	0.08	0.08	0.03
	50000	0.26	0.19	0.07	0.20	0.20	0.07	0.13	0.12	0.05
	75000	0.36	0.26	0.09	0.27	0.27	0.10	0.18	0.17	0.07
		5			15			25		
		Offset								

6.8 Design Charts

Based upon the results from the preceding section, 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 scenarios. Table 19, Table 20, and Table 21 provide design charts for undivided, divided, and one-way roadways, respectively. Based on the life cycle cost comparison (as shown in Figure 31), low-installation/high-repair category has lower life cycle cost than high-installation/low-repair category until 0.08 hits per year. In the design charts, cells colored with green indicate that the given highway scenario results in less than 0.08 impacts per year and low-installation/high-repair cushion category is the optimal option, while those colored with blue indicate that impact frequency is more than 0.08 per year and high-installation/low-repair cushion category is the optimal choice.

Table 20. Design Chart for Undivided Facility

		Horizontal Curvature		
		500	1000	100,000*
AADT	1000			
	2000			
	3000			
	4000			
	5000			
	10000			
	15000			
		All Offset		
*Note: In RSAPv3, tangent segments are represented with a curve radii of 100,000 ft. Green colored cells: low-installation/high-repair; Blue colored cells: high-installation/low-repair				

For undivided roadways, Table 20 shows that the low-installation/high-repair cushions are the optimal choice for segments located on sharper curves with radii less than 500 ft. and carrying fewer than 1,000 vehicles per day as cushions are less likely to get struck and won't require frequent repairs. However, on the segment with similar characteristics, as the traffic volume increases, expected number of impacts with cushions increases and high-installation/low-repair cushions become more cost-effective as these devices are relatively cheaper to repair. Further, as the curves get milder with radii up to 1,000 ft., frequency of impacts with cushions remain below the threshold value of 0.08 hits/year for even higher AADT of up to 2,000 vehicles/day and low-installation/high-repair cushions remain the optimal choice, beyond that high-installation/low-repair cushions become cost-effective. For tangent segments with the pre-selected range of AADT, impact frequency never exceeds the threshold value of 0.08 hits/year and low-installation/high-repair cushions remain the only cost-effective option.

Table 21. Design Chart for Divided Facility

		Horizontal Curvature								
		500	1000	100,000	500	1000	100,000	500	1000	100,000
AADT	5000									
	10000									
	15000									
	25000									
	50000									
	75000									
	100000									
	125000									
		5			15			25		
		Offset								

*Note: In RSAPv3, tangent segments are represented with a curve radii of 100,000 ft.
Green colored cells: low-installation/high-repair; Blue colored cells: high-installation/low-repair

For divided highways, Table 21 shows that for segments located on sharper curves with radii below 1000 ft., high-installation/low-repair cushions are the optimal choice to shield hazards located within an offset of up to 15 ft. from the traveled way irrespective of the traffic volume. However, on tangent segments, low-installation/high-repair cushions become the optimal choice to shield hazards located within 5 ft. offset and carrying traffic volumes of up to 10,000 veh/day as fewer impacts are expected. For hazards located even farther away up to 15 ft., low-installation/high-repair cushions remain cost-effective up to 15,000 veh/day. Further, for hazards located as far as 25 ft. away from the traveled way of the segment carrying up to 5,000 veh/day, the effect of horizontal curvature on impact frequency gets negated to a degree and the expected annual impacts fall below 0.08 hits and low-installation/high-repair cushions become cost-effective. This trend is observed on the tangent segments for even a larger AADT of up to 25,000 veh/day.

Table 22. Design Chart for One-Way Facility

		Horizontal Curvature								
		500	1000	100,000	500	1000	100,000	500	1000	100,000
AADT	1000									
	2000									
	3000									
	4000									
	5000									
	15000									
	25000									
	50000									
	75000									
		5			15			25		
		Offset								

*Note: In RSAPv3, tangent segments are represented with a curve radii of 100,000 ft.
Green colored cells: low-installation/high-repair; Blue colored cells: high-installation/low-repair

For one-way roadways, such as freeway ramps, Table 22 shows that for segments with traffic volumes less than 5,000 veh/day, low-installation/high-repair cushions are the optimal choice irrespective of the horizontal curvature and hazard offset. However, as the traffic volume increases on segments with sharper curves of up to 1000 ft. radii and hazards located up to 15 ft., expected annual impacts with cushions increases beyond 0.08 hits and high-installation and low-repair cushions become the optimal choice. For segments with similar characteristics but located on a tangent section, expected impact frequency exceeds 0.08 hits per year only beyond an AADT of 75,000 veh/day and high-installation/low-repair cushions become cost-effective. Further, for curved segments with hazards located as far as 25 ft., high-installation/low-repair cushions become effective only when AADT exceeds 50,000 veh/day and for remaining other scenarios low-installation/high-repair cushions are the optimal choice.

CHAPTER 7: CONCLUSIONS

7.1 Summary

This study examined the 13 unique crash cushion systems currently installed across the state of Iowa on a permanent basis. As a part of this in-service evaluation, the Iowa police-reported crash database was used to identify crashes that involved collisions with permanent crash cushions. Using data from 2007 through 2014, a detailed review was conducted of the narratives from police crash reports for those collisions in which an impact attenuator was indicated to have been struck by the investigating officer. Additional crash reports were reviewed for collisions occurring in close proximity to where crash cushions were installed. However, among 105 prospective crashes that were identified, only 34 were confirmed to have involved a collision with a permanent crash cushion. In these instances, the injury-severity outcome resulting for each crash was reviewed . The results indicated that approximately 78 percent of such crashes resulted in either a minor injury or property damage only, 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 for an extensive comparison of the in-service performance of various systems.

Consequently, in lieu of such data, the encroachment probability-based software program RSAPv3 was used to develop design guidance as to the most cost-effective crash cushion for several different highway scenarios. The facility types where cushions are installed were divided into three broad categories: one-way, undivided, and divided roadways. Sensitivity analyses were performed separately for each facility type to identify those parameters having the greatest influence on the frequency of run-off-road crashes.

The results indicated that annual average daily traffic (AADT), horizontal curvature, and hazard offset had the largest influence on the probability of a roadside hazard being struck as a result of a collision. Consequently, values of these parameters were modified over the range of values observed on each facility type based upon Iowa-specific field data to model a series of scenarios. RSAPv3 was subsequently used to estimate the number of impacts per year on the analysis segment for different scenarios on each facility type. The impact frequency was used as the decision criteria to identify the optimum cushion category. Based on the life-cycle cost comparison, the low-installation/high-repair cushion category had the lowest life cycle cost until a threshold of approximately 0.08 impacts per year. Beyond this threshold, the high-installation/low-repair category becomes more cost-effective.

7.2 Research Limitations

The accuracy of installation, repair, and maintenance costs for different cushion systems used in the life cycle cost analysis is the most important limitation of this research. Installation cost figures used in this analysis only include the material costs and disregard the additional costs associated with installation of different cushion systems under field settings. Such figures can vary depending on site-specific factors, such as whether the cushion system requires a paved concrete pad for installation or if it can be installed on unpaved surfaces. The average material costs and average work-hours per crash for different cushion systems were based on a very limited sample size obtained through the Iowa DOT district maintenance garages. Consequently, the accuracy of the repair cost data used for the analysis is unclear and additional data is warranted to better understand the long-term performance of different cushion devices. This study did not consider sand barrels as the repair and maintenance cost data for such cushion types were not available with greater accuracy. Further, monetary costs associated with other important variables such as exposure to maintenance crews during repairs, exposure 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 frequency under various different highway scenarios generated by RSAPv3 are based on the encroachment data developed by Cooper 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 grouped together and treated as a generic attenuator in RSAPv3, thus not accounting for differences in system performance across the product types. Consequently, a hazard severity model corresponding to each cushion type could be developed in future utilizing the police-reported crash database and later incorporated into RSAPv3 to perform incremental benefit-cost analyses between different cushion devices and identify the optimal cushion device for any given highway scenario.

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 repairs made to both permanent and temporary crash cushions by developing specific contract items for each situation. For the purposes of this study, extensive manual review of various resources was required in order to discern when and where crash cushion strikes occurred, along with the associated repair costs. Providing an improved inventory system for these items would expedite the ability to query repairs through contract item software. An additional opportunity to standardize repairs would involve the development of a standard form to be filled out by maintenance crews. This could include fields specific to the unique inventory identification number, which would tie it to location information, as well as the date of incident (if known), repair date, hours to repair, traffic control needed to repair, part-by-part listing of repairs, etc. While general forms may be available, it does not appear there is consistency among the maintenance garages of how this information is collected or stored in an easily accessible manner.

REFERENCES

AASHTO. (2002). *Roadside Design Guide.* Washington, D.C.: American Association of State Highway and Transportation Officials.

Barrier Systems Inc. (n.d.). *Crash Cushions | TAU-II | Barrier Systems.* Retrieved July 20, 2017, from Barrier Systems | Moveable Barrier and Crash Cushion Systems: http://www.barriersystemsinc.com/tau-ii-crash-cushion

Cooper, P. (1980). *Analysis of Roadside Encroachments--Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces.* Vancouver, British Columbia, Canada: B.C. Research Council.

Crash Cushions. (2013, November). Retrieved from https://safety.fhwa.dot.gov/roadway_dept/countermeasures/docs/CrashCushions_Nov2013Safelogo.pdf

Creasey, T., Ullman, G. L., & Dudek, C. L. (1989). Delineation of Urban Freeway Gore Area Crash Cushions in Texas. *Transportation Research Record*, 28-33.

Elvik, R. (1995). The Safety Value of Guardrails and Crash Cushions: A Meta-Analysis of Evidence from Evaluation Studies. *Accident Analysis and Prevention*, 523-549.

Elvik, R., Høye, A., Vaa, T., & Sørensen, M. (2004). *The Handbook of Road Safety Measures.* Bingley, UK: Emerald Group Publishing Limited.

Energy Absorption Systems Inc. (n.d.). *Energy Absorption . Quadtrend 350 End Treatment System.* Retrieved July 20, 2017, from Roadway Safety | Workzone Safety | Energy Absorption Systems: http://www.energyabsorption.com/products/PI%20Sheets/QuadTrend.pdf

Energy Absorption Systems Inc. (n.d.). *Energy Absorption . FITCH UNIVERSAL BARRELS Crash Cushion System.* Retrieved July 20, 2017, from Roadway Safety | Workzone Safety | Energy Absorption Systems: http://www.energyabsorption.com/products/PI%20Sheets/Fitch.pdf

Energy Absorption Systems, I. (n.d.). *Energy Absorption . ENERGITE III Crash Cushion System.* Retrieved July 20, 2017, from Roadway Safety | Workzone Safety | Energy Absorption Systems: http://www.energyabsorption.com/products/PI%20Sheets/Energite.pdf

FHWA. (n.d.). Retrieved July 20, 2017, from https://safety.fhwa.dot.gov/roadway_dept/countermeasures/docs/CrashCushions_Nov2013Safelogo.pdf

Hex-Foam Sandwich. (n.d.). Retrieved from http://www.wsdot.wa.gov/publications/fulltext/design/RoadsideSafety/HexFoamSand.pdf

Hirsch, T. J., Nixon, J. F., Hustace, D., & Marquis, E. L. (1975). *Summary of Crash Cushion Experience in Texas.* College Station, Texas: Texas Transportation Institute.

Hutchinson, J. W. (1962). *The significance and nature of vehicle encroachment on medians of divided highways.* Urbana, IL: University of Illinois.

JR., H. E., Sicking, D. L., & Ziimmer, R. A. (1993). *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.* Washington, D. C.: Transportation Research Board, National Research Council.

KDOT. (n.d.). *Additional Files for Procurement Contracts.* Retrieved July 19, 2017, from Home - Kansas Department of Administration: http://admin.ks.gov/docs/default-source/ofpm/procurement-contracts---adds/evt0004716-contractors-and-pricing.docx?sfvrsn=4

Mak, K. K., & Sicking, D. L. (1998). *NCHRP Project 22-09: Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features.* Washington, D. C.: Transportation Research Board, National Research Council.

MDOT. (n.d.). *Contract Details - Buying and Selling to Government of Mississippi.* Retrieved July 20, 2017, from Home Page - Buying and Selling to Government of Mississippi: https://srm.magic.ms.gov/SAP/EBP/DOCSERVER?PHIOGET&KPID=0600E80500261EE582DE1F8C93B02794&KPCLASS=BBP_P_DOC&SAP-CLIENT=100/GULF%20INDUSTRIES%20ATTENUATOR%20PARTS.PDF

Michie, J. D. (1981). *NCHRP Report 230: Recommended Procedures for Safety Performance Evaluation of Highway Appurtenances.* Washington, D. C.: Transportation Reserarch Board, National Research Council.

Miller, P., & Carney III, J. F. (1997). Computer Simulations of Roadside Crash Cushion Impacts. *Journal of Transportation Engineering*, 370-376.

NHTSA. (2017, July 17). *FARS Encyclopedia.* Retrieved from NHTSA| National Highway Traffic Safety Administration: https://www-fars.nhtsa.dot.gov/Main/index.aspx

Pigman, J. G., Agent, K. R., & Creasey, T. (1984). Analysis of Accidents Involving Crash Cushions. *Kentucky Transportation Center Research Report*, 625.

QuadTrend Product Information Sheet. (n.d.). Retrieved from http://www.energyabsorption.com/products/PI%20Sheets/QuadTrend.pdf

Ravani, B., Burkett, G., Leong, B., & Bennett, D. (2014). *Crash Attenuator Data Collection and Life Cycle Tool Development.* Davis, Calif.: AHMCT.

Ray, M. H. (2012). *NCHRP Project 22-27: Roadside Safety Analysis Program (RSAP) Update.* Washington, D. C.: Transportation Research Board, National Research Council.

Schrum, K. D., de Albuquerque, F. D., Sicking, D. L., Lechtenberg, K. A., Faller, R. K., & Reid, J. D. (2015). Cost-Benefit Analysis of Crash Cushion Systems. *Journal of Transportation Safety & Security*, 1-19.

Sicking, D. L. (2009). *NCHRP Project 17-22: Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes.* Washington, D. C.: Transportation Research Board, National Research Council.

TxDOT. (2013, June 4). Retrieved from https://agctx.org/private/cushions.pdf

World Health Organization. (2004). *World Report on Road Traffic Injury Prevention.* Geneva: World Health Organization.

WSDOT. (n.d.). Retrieved July 20, 2017, from http://www.wsdot.wa.gov/publications/fulltext/design/RoadsideSafety/HexFoamSand.pdf

WSDOT. (n.d.). Retrieved July 20, 2017, from http://www.wsdot.wa.gov/publications/fulltext/design/RoadsideSafety/Great.pdf

Wunderlich, R. C. (1985). Evaluation of Freeway Crash Cushion Delineation Treatments. *Transportation Research Record*, 14-19.