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Effectiveness of median cable barrier in Iowa

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Effectiveness of median cable barrier in Iowa

by

Ellen E. Nightingale

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
Shauna Hallmark
Say Kee Ong

The student author and the program of study committee are solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2017

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NOMENCLATURE

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACRP	Airport Cooperative Research Program
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials (known by abbreviation only)
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SHRP	Strategic Highway Research Program
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board

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ABSTRACT

Median-crossover crashes involve a vehicle departing the travel lane, traversing the median, and striking either a fixed object or an oncoming vehicle in the opposing direction of traffic. These types of crashes present the highest risk of fatal and severe injuries among all collision types on freeways. Median-crossover crashes are caused by a variety of factors, including driver distraction, impaired driving, mechanical failure, and loss of control. Median barriers are the primary countermeasure to reduce the opportunity for multi-vehicle cross-median crashes. Due to the lower installation costs, as compared to more rigid systems, high-tension median cable barrier has become a popular countermeasure for reducing such crashes. The Iowa Department of Transportation (Iowa DOT) began installing high-tension median cable barriers in 2003 and will have approximately 330 miles of such barrier installed on freeways statewide by the end of 2018. While anecdotal evidence suggests that cable barriers are functioning as desired, no in-depth analysis of performance or cost-effectiveness has been conducted to date. This project aims to determine the cost-effectiveness of median cable barrier systems based on crash cost savings resulting from reductions in fatal and injury crashes as compared to the costs associated with increased property-damage-only crashes, installation costs, and ongoing maintenance costs. An in-depth analysis of the frequency and severity of crashes occurring in the freeway median was conducted.

This research identified general trends in crash frequency and severity between the pre- and post-installation periods. Following an extensive manual review of crash narratives, a before-and-after study design showed the overall impact of the median cable barrier program was a 51.3% reduction in fatal crashes. The barrier program also showed an 80.4% increase in total crashes, which was driven by an increase in property-damage-only crashes

of 118.1%. Installation and maintenance repair costs on the barrier were investigated and discussed. The design life of the median cable barrier was recommended to be 20 years with a benefit-cost ratio of 9.153. Geometric characteristics such as median width, shoulder width, and barrier offset were investigated, but no significant trends were identified. Future research as to the relationship between roadway geometric characteristics and median cable barrier effectiveness is recommended in order to plan for subsequent installations of median cable barrier in Iowa.

Keywords: median cable barrier, design criteria, cable guardrail, cross-median crashes, Iowa, benefit-cost, maintenance, safety

CHAPTER 1. OVERVIEW

1.1 Introduction

Cross-median crashes occur when a vehicle departs the inside travel lane of a divided highway, crosses the median, and strikes a roadside object or a vehicle traveling in the opposing direction. While various countermeasures, such as rumble strips, have been installed on roadways to prevent vehicles from leaving the road, additional devices can be used to reduce the likelihood of a vehicle crossing over the median or to mitigate the impact of crashes involving diverging vehicles. Particularly for cross-median lane-departure crashes, barriers made out of various materials have been used to protect traffic in the opposing lanes from cross-median crashes. Concrete, steel beam, and cable barriers have been installed along medians for this reason. Each type of barrier has varying lists of considerations that dictate the appropriateness of installation at a given location. Among these, median cable barrier on average has the lowest installation cost, in addition to allowing for installation on more severe slopes. Median cable barrier can also be installed further from the travel way and is better able to contain vehicles as compared to more rigid barrier types. For this reason, high-tension median cable barrier has rapidly been installed around the United States of America over the last two decades. Iowa began installing this barrier in 2003 and by the end of 2018, will have 330.5 miles of barrier installed along its Interstate system. This research studies the performance of the system in Iowa. As a part of this study, an in-depth analysis of the cost-effectiveness of the high-tension median cable barrier systems is conducted to evaluate Iowa's investment in multivehicle cross-median crash mitigation. Observations of the crash experience before and after the installation of the barrier system is evaluated. The cost-effectiveness is determined through a benefit-cost analysis considering installation costs,

annual maintenance costs, and the costs associated with changes in the annual frequency of crashes at varying injury severity levels.

1.2 Thesis Objectives

The objective of this thesis is to discern the efficacy of the median cable barrier systems in Iowa through an examination of impacts on crash frequency and severity, as well as the cost-effectiveness of these systems in consideration of road user and agency costs. The project involves an in-depth analysis of median cable barrier system performance, including an evaluation of effectiveness in preventing multi-vehicle cross-median crashes, as well as a comprehensive benefit-cost analysis considering costs related to barrier installation and maintenance, as well as costs associated with changes in the number of crashes by injury level.

Research Question 1: What effects do median cable barriers have on crashes?

This question will be answered through the estimation of a series of negative binomial regression models at different crash severity levels to compare the safety performance of segments before and after median cable barrier installation across the Iowa Interstate system. The results of this analysis will be used for the cost-effectiveness evaluation. While the effects of cable barrier installation have been quantified in prior research in other states, Iowa has substantive differences in topography, weather conditions, and other salient factors that motivate the need for additional research. Based on the results of this analysis, decisions about future investment in expanding the median cable barrier network can be examined by looking at control segments with no barriers currently present.

An increase in total crashes is anticipated to occur on a segment after median cable barrier is installed. This anticipation is based on the idea that the presence of a roadside

object, in contrast to it not being present, increases crash risk to the driver. Median encroachments that may otherwise be correctable in the absence of a barrier, may now result in a crash. Design manuals generally dictate to minimize the number of roadside objects along a corridor and to provide barrier only when there is a risk of cross-median events or when a non-crashworthy obstacle in the median could be hit by an errant vehicle (AASHTO 2011). By strategically installing barrier along a road segment, a trade-off must be made between the increased risk of a less severe crash versus the existing risk of a more severe crash that was mitigated through the installation of the barrier. Overall, it is expected that the severity of crashes will decrease on segments with a cable median barrier installed; however, the overall number of crashes will increase.

Research Question 2: What common characteristics are associated with those road segments that are the optimum candidates for median cable barrier?

In order to prioritize the segment locations for subsequent median cable barrier installation, the safety analysis also involves the identification of common roadway characteristics found to increase the risk of cross-median crashes (in the absence of barrier) along each study segment. Patterns as to the effectiveness among those segments where median cable barrier has been installed can be used to help select ideal locations for future installation.

Research Question 3: Are median cable barrier systems cost-effective?

The third objective of this study is to assess the cost-effectiveness of the median cable barrier system. By gathering the installation and maintenance information on the barrier system, the total investment by the Iowa DOT can be assessed. In this study, the design life of a median cable barrier system will be discussed with a sensitivity analysis considering

various lifespans. As median cable barrier continues to be installed in the state, some locations will not yield an effective benefit-cost ratio as the increase in non-injury crashes may outweigh the benefit of the reduction in severe crashes. As maintenance costs rise with the total number of crashes, installing barrier on segments without a sufficient positive trade-off may cost more to the Iowa DOT than intended. Utilizing funds on non-cost effective safety measures reduces the DOT's ability to invest in projects more effective at helping the general public. Through the assessment made in this research, the Iowa DOT can determine how to proceed with future safety-related investments.

1.3 Thesis Scope

In this project, median cable barrier generally refers to high-tension cable barrier installed in the median in continuous runs at least one mile long, excluding brief breaks for turn-arounds. The median cable barrier analyzed in this study focuses on longer runs installed in the median with the intent of preventing cross-median crashes. Unique to Iowa, the same type of cable barrier system is used to protect roadside hazards such as bridge piers and sign supports. Small segments of median cable barrier installed for the purpose of roadside object protection are ignored. In cases with both a median cable barrier and a steel barrier present along the roadway, the longer continuous barrier took precedence as the predominant type of barrier on the roadway segment. Segments with concrete barrier and steel beam guardrail only were completely removed from the dataset, including installations near overpasses.

While median cable barrier has been installed in other states on divided and undivided state routes (Monsere et al. 2005), these were not included in this study, and their exclusion is not meant to imply exclusion of their eligibility for this safety treatment. As of

2015, Iowa does not have high-tension median cable barrier installed on their road network outside of the Interstate system.

1.4 Thesis Organization

The thesis is broken into five chapters, each of which focuses on the various research questions outlined previously. Brief synopses of the contents of each chapter are summarized below.

Chapter 2. Literature Review – Existing literature is summarized in relation to the topics covered in this thesis. While median cable barrier has been thoroughly researched by various prior studies in other states, this literature review focuses only on those relevant to the specific focus of this thesis, excluding the structural components of the barrier system, the cable height on the barrier system, etc.

Chapter 3. Data – All of the data utilized and collected throughout this study are described in this chapter, along with their limitations. These data included information regarding barrier installation location and offset, roadway geometric characteristics, traffic volumes, weather history, maintenance costs, and crash report information. The chapter describes how these data were collected, integrated, and investigated for the purposes of this research, along with which data were used in the analysis.

Chapter 4. Results – This portion of the report is broken into two major parts evaluating safety and cost-effectiveness. The first part compares the effects before-and-after the barrier installations with a time frame from 2007 to 2014, during which police crash report narratives were available. A discussion on an alternate target crash selection method and an inconclusive geometric character investigation is included. The second portion examines the costs associated with the median cable barrier program utilizing the observed

crash experience. This includes both an overview of the general cost components, as well as the factors contributing to the cost on a crash-to-repair basis.

Chapter 5. Conclusions – This section restates and summarizes the key findings of this report, in addition to discussing the practical impacts of the results within the context of the extant literature. Limitations encountered throughout the study are detailed, as well recommendations for future research. Many of these issues can be investigated with the data currently available in Iowa.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Median Cable Barrier

One-cable wire guardrail was installed as early as the 1960's to prevent illegal median U-turns in California and New York (Ray, 2010). Subsequently, modern cable barrier system have been installed along thousands of miles of medians across the United States with a different purpose entirely (Ray, 2010). Modern day median cable barrier, which is known by various other names (i.e., cable median barrier, high-tension cable barrier, median guard cable, cable guardrail, wire rope safety barrier), is used to prevent errant vehicles departing the roadway from being involved in a multi-vehicle cross-median crash. Due to the high severity associated with these crashes, the barrier has the potential to prevent a multi-vehicle crash, instead resulting in a less severe, single-vehicle collision with the barrier. Median cable barrier generally falls into one of two categories, including low-tension and high-tension systems, each of which have differing design constraints and performance characteristics. Figure 1 (Chandler et al. 2007) illustrates simply from a visual standpoint the difference between the two types of barrier, with the low-tension on top showing slack, while the bottom image shows high-tension with no slack in the cables. Beyond appearance, the deflection when hit is generally 4' less for high-tension cable than low-tension (Marzougui et al., 2012). The procedure for untangling trapped cars is reportedly less damaging to the barrier system for high-tension barrier when compared with low (Marzougui et al., 2012). For the purpose of this study, all mention of median cable barrier will refer to high-tension cable barrier.



Figure 1: Low-Tension Cable Barrier (top); High-Tension Cable Barrier (bottom)

2.2 Safety Effectiveness

Several prior projects have examined the effectiveness of cable barrier across the United States since its widespread installation. In a study by Ray (2010), a synthesis of research and news articles on cable median barrier was presented. This synthesis was based primarily on aggregate statistics and surveys of road agencies. Subsequently, a series of more rigorous analyses have been conducted. Looking only at these empirically-based studies

using more robust datasets, the key findings from each are summarized in Table 1. In the table, the KABCO scale is used. This scale is used in safety studies to code the severity of the damage: ‘K’ meaning fatal, means that a person involved in the crash died from reasons directly related to the crash, tracked for up to 30 days after the crash; ‘A’ meaning incapacitating injury, or an injury where the person is alive but is permanently affected; ‘B’ meaning a reported injury that was not incapacitating; ‘C’ meaning a possible injury, or that no injury was identified at the time of the police report but it was possible that the people involved in the crash were injured; and ‘O’ meaning only the vehicles and property was damaged, no injuries or fatalities occurred. This scale can be applied to both individuals involved and the crash itself. If the scale is applied to the scale, generally the most severe injury is represented at the severity of the crash. In Table 1, when the study represents the severity of each person involved in a crash, the word “injury” follows the scale rating. Otherwise, the scale represents the severity of the crash. For this thesis, the severity of crashes is found for the safety effectiveness, and for maintenance the severity of injury for each individual is used.

Table 1: Summary of Empirically-Based Studies on Median Cable Barrier

State	Year	Methodology	No. Miles	No. Crashes	Evaluation Results*
Tennessee (Chimba et al. 2013)	2016	Empirical Bayes	14	270	K crashes -94%, A crashes -92%
Michigan (Savolainen et al. 2014)	2014	Empirical Bayes	300	9640	PDO/C crashes +163% (+151%) K/A crashes -53% (-24%)
Wisconsin (Noyce 2005)	2014	Before-After Frequency	82	692	Total crashes +112% K/A crashes -59%
Washington (Olson et al. 2013)	2013	Before-After Rates	238	4600	Total crashes +91% A injury -61%; K injury -52%
Florida (Alluri et al. 2012)	2012	Before-After Rates	101	8818	Total crashes +37% K crashes -42%; A crashes -20%
*K- Fatal, A- Major Injury, B- Minor Injury, C- Potential Injury, and PDO- Property-Damage-Only					

The Florida study analyzed information from 549 police crash reports at 23 locations on limited access facilities, which occurred from 2003 to 2010 (Alluri et al. 2012). The crash reports were verified for accuracy and reviewed for further details as to the sequence of events leading up to the crash. Of the 549 identified target crashes, 84 percent were contained by the cable barrier. Of the 90 crashes that penetrated the barrier, only 14 ultimately reached the opposite direction of travel. The cable median barrier installations reduced the fatal crash rate by 42 percent, the severe injury crash rate by 20 percent, and the minor injury crash rate by 12 percent.

A summation of the cable median barrier installation program in Washington discovered similar safety benefits (Olson et al. 2013). Due to the low initial cost, cable

median barrier was installed between 2000 and 2011 in Washington along 238 miles of roadway. During this time period, there was a dramatic decline in both fatal and serious injury collisions among target crashes. The results showed a 58 percent decrease in the rate of injury collisions after cable median barrier was installed. This represents a decline from 28 fatal and serious injury crashes per year to 15. A 58 percent decline was also evident in cross-median crashes; cable installations reduced cross-median collisions from 62 per year to 26 after the countermeasure was implemented.

Another large-scale evaluation of median cable barrier installation was conducted in Michigan, where 317 miles of cable barrier was installed between 2008 and 2013 (Savolainen et al. 2014). A comprehensive evaluation determined that fatal and serious injuries were reduced by 33 percent after installation while cross-median crash rates were reduced by 87 percent. With road and weather conditions having a profound impact on the severity and frequency of crashes, the researchers also noted that cable barriers were 97 percent effective in preventing barrier penetration.

One of the most recent in-service evaluations of median cable barrier was conducted in Tennessee, where barrier was installed on 14 miles of divided highway (Chimba et al. 2013). At least three years of crash data before and after barrier installation were utilized for the analysis from each location. The safety impacts of the barrier were examined through an Empirical Bayes evaluation. On these limited sections, fatal and incapacitating injury crashes were both reduced by more than 90 percent.

In every study, a marked decrease in the number of fatal crashes can be seen with the installation of the median cable barrier. The increase in total crashes was more pronounced in snowier regions such as Michigan, Wisconsin, and Washington State when compared to

states with more temperate climates such as Tennessee and Florida. While each study echoed that these barriers were an effective way to prevent cross-median crashes, the regional differences warrant state-specific studies.

2.3 Guidelines and Specifications

Various states have installations guidelines for median barrier, including high-tension cable barrier. The AASHTO Roadside Design Guide recommends barriers when the median is less than 30 feet in tandem with an average daily traffic in excess of 20,000 vehicles (AASHTO 2011). The Roadside Design Guide suggests barrier be considered when medians are between 30 and 50 feet, as seen in Figure 2. Barrier is optional when median widths are greater than 50 feet and volumes are lower than 20,000 vpd.

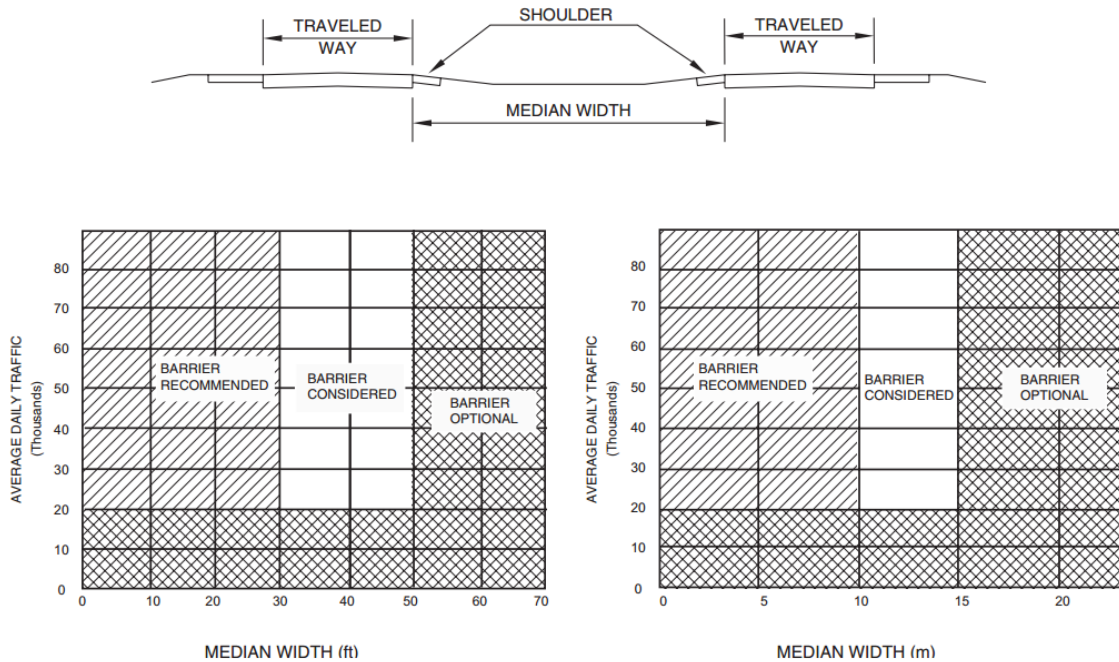


Figure 2: AASHTO 2011 Guidelines for Median Barriers on High-Speed, Controlled Access Roadways

The AASHTO guidelines have been in place for many years, and in the 1990's some states considered a revised guideline based not only on median width, but also average daily

traffic volumes and cross-median crashes per year, as well as just an update to reflect improvements in modern barriers (Bligh et al. 2006). A Wisconsin study sought to establish more refined installation recommendations (Noyce 2006). Data were analyzed from 631 median crossover crashes during a three-year study period, which led to more than 600 injuries and 53 fatalities. As 82 percent of these crashes occurred on roadways where median barriers were not recommended based on previous warrants, it was recommended that the past national barrier standards be refined for state use in Wisconsin to prevent these crash types. A similar Pennsylvania study found that cross-median crashes still occurred on roadways in which a median treatment was not recommended by the existing installation policy. Consequently, additional policy guidelines were recommended following a survey and Delphi focus group (Donnell et al. 2002).

Similar recommendations were proposed based on a Texas study following the development of cross-median crash risk models (Bligh et al. 2006). Similar to the recommendation from the Roadside Design Guide, the guidelines are a function of AADT and median width. Because cable median barrier is much more flexible than traditional barrier types, a wider median is required for installation in order to prevent vehicles from striking the barrier and still reaching the opposing lanes of traffic. However, the results from the Texas study were a recommendation and not incorporated in the current practitioners' guidelines. In Figure 3, the current Texas guidelines are presented for reference.

Table 2: Cost of Barrier Types

Barrier Type	Cost/ft	Cost/mi
Cable median barrier	\$8.33/ft	\$44,000/mi
W-beam guardrail	\$13.65/ft	\$72,000/mi
Precast concrete barrier	\$24.64/ft	\$130,000/mi
Single slope concrete barrier	\$44.94/ft	\$237,000/mi
Cast in Place concrete barrier	\$79.36/ft	\$419,000/mi
*Cost does not include mobilization, traffic control, or engineering.		

While the installation costs are shown to be the lowest among other options, concern over the maintenance costs could be a potential setback from continued wide-spread use of median cable barrier. All of the previously mentioned studies saw an increase in property-damage-only crashes (Savolainen et al., 2014; Noyce, 2006; Cooner, et al. 2009).

2.5 Life Span of Median Cable Barrier

One question of interest regarding cable barrier is its lifespan, particularly since few barrier systems in the United States have been in place long enough to have reached the end of their service lives. In New Zealand, the Transport Agency adopted high-tension median cable barrier in the early 1990's and have shared comments on the issue. Their two biggest issues with the longevity of the barrier system are the connections holding the cable to the posts and the anchor/terminals locations. Both of these pieces are likely to corrode, especially near coastal regions. Given such concerns, a design life of 20 to 25 years is recommended (Chinsall, 2017).

To estimate the design life of the wire rope, other historical uses of the steel wire rope can be used. While the wire rope is more recently used in its application in the median cable

barrier, it has been manufactured for other uses since the 1880's (US Navy, 1979). Gibraltar, a major manufacturer of the median cable barrier, recommends using the life of the cable as a means of estimating the life of the system. Models have been developed to estimate the life of steel based on environmental factors (American Galvanizers Association, 2017). Factors like zinc coating thickness, salinity, sulfur dioxide, and precipitation, humidity, and temperature are all factored into the design life.

2.6 Median Cable Barrier in Iowa

NCHRP Report 711 (Marzougui, 2012) on median cable barrier notes, "High-tension cable barriers are most commonly used in freeway medians to prevent crossover crashes. However, freeway facilities generally include median bridge piers and twin bridge overpasses that can only be shielded with semi-rigid or rigid barriers." As shown in Figure 4, the Iowa DOT has begun utilizing high-tension cable barrier in these settings, as well.



Figure 4: Cable barrier used to protect fixed objects (top); non-median cable barrier (bottom)

Also shown in Figure 4 is high-tension cable barrier placed on the side of the roadway. While the device is the same as median cable barrier, the purpose of preventing multi-vehicle cross-median crashes differs in these locations. Both of the installations in Figure 4 are excluded from the scope of this study.

Median cable barrier has been on the rise in Iowa. As seen from Figure 5, installations rapidly increased in 2010. The median barrier is located on I-35, I-80, I-29, and I-380 in four Iowa DOT Districts. Several installations are planned in the near future out to 2018. With the results of this study, the Iowa DOT can make a more informed decision about the future of the median cable barrier program.

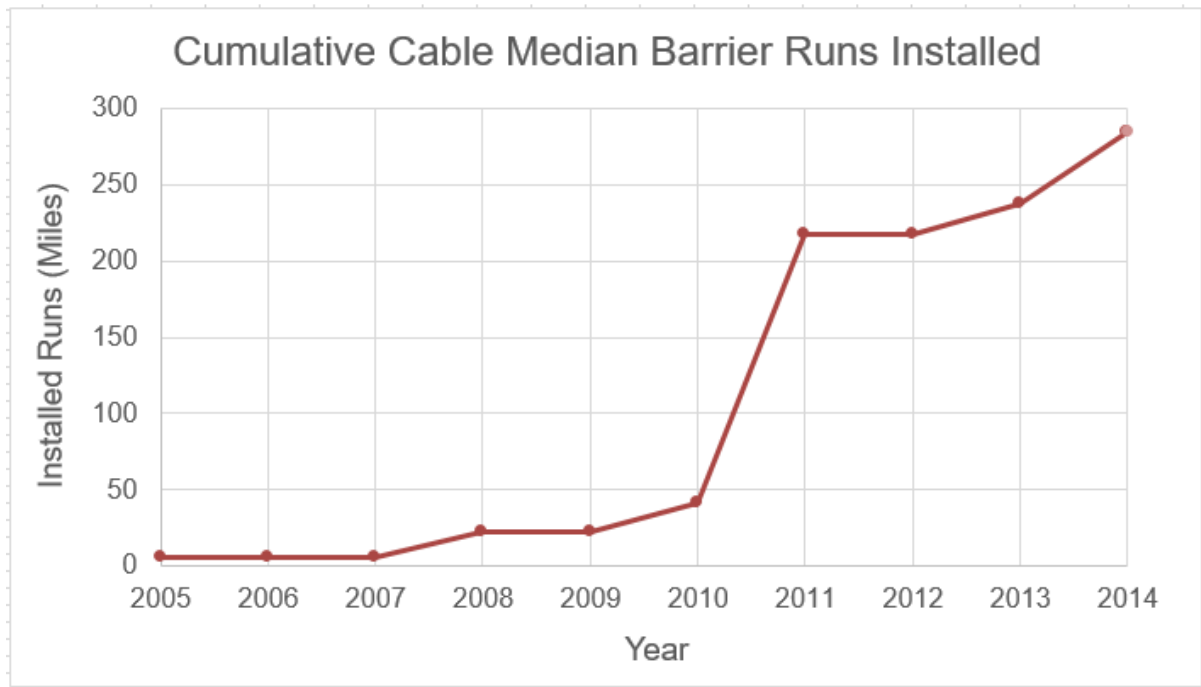


Figure 5: Installation of Median Cable Barrier in Iowa 2005-2014

CHAPTER 3. DATA

This project involved the collection and integration of a diverse range of data. Significant work on this project focused on synthesizing data in various forms into a usable format. These data were either provided in database format by the Iowa DOT or collected from various resources by members of the project team. This chapter outlines each of the data sources utilized as a part of this study, in addition to detailing the specific variables used in this study.

3.1 GIMS Roadway Information

The baseline road network information was provided by the Iowa DOT through the Geographical Information Management System (GIMS). This database contains georeferenced segments, which serve as an underlying framework for integrating a variety of asset inventory files. Each line represented a small section, varying in length, that corresponded with the coordinates of a real section of roadway for each year. Each line also bore attributes that reflected the characteristics of the roadway it represented. Work utilizing these segments was done in ArcGIS with characteristics like annual average daily traffic (AADT), percent truck traffic, number of lanes, lane width, and speed limit. All crash points are placed along the corresponding year's alignment.

One limitation with this particular dataset was that GIMS does not uniquely distinguish the characteristics between opposing directions of a divided roadway. As seen in Figure 6, a singular centerline is used to represent both directions of the roadway. This impacts the project as median cable barrier is typically installed closer to one side of the road than the other, so direction may impact the effects seen when modeling geometric factors with the effects of the barrier.

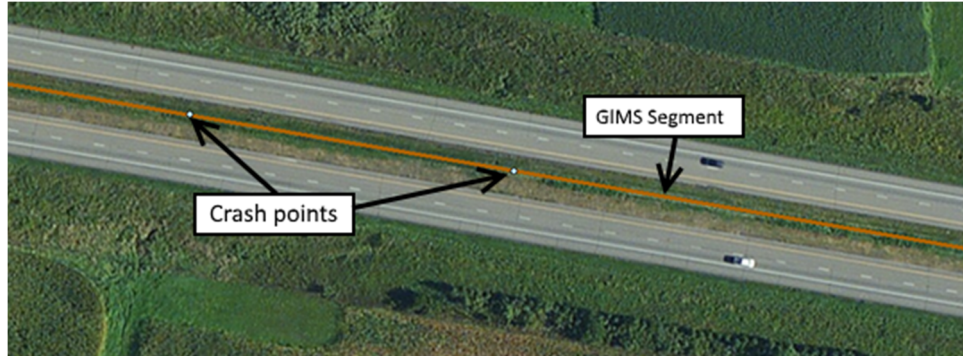


Figure 6: Non-directional GIMS Segment with Crash Points

While the segments could be generated to represent directions of the roadway, the crash points would remain in the median and need additional work to assign to each direction.

Another concern with the GIMS pertains to minor changes in the alignment data that occur from year-to-year. The crashes for each year were placed along the roadway alignment file of the same year. In order to create uniform segments for the statistical analysis, a consistent buffer generated with the 2012 roadway alignment was used to collect the crashes and combine the smaller GIMS segments. Segments were spot checked for any problematic sections, like seen in Figure 7, and manually joined to the buffer. A buffer for each year could have been created, however this method alleviated concerns about having consistent segment identification numbers across the years.

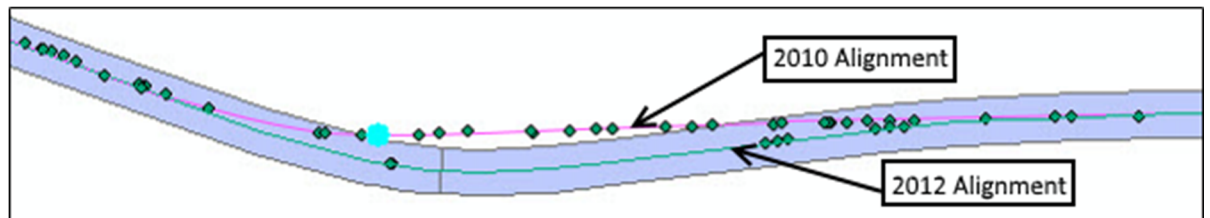


Figure 7: Variations in GIMS roadway alignment by year

3.2 Crash Database: Codes and Narratives

The Iowa DOT maintains a database detailing all crashes reported to law enforcement statewide updated on a continuous basis. These databases included the crash codes based on the crash report form filled out by a police officer at the time of a crash, or from a self-reported crash completed at a later time. Information like time of crash, vehicle type, first major event, etc. can be linked as an attribute to the georeferenced data point representing the crash, as represented in Figures 6 and 7 above. While the crash database provided by the Iowa DOT offers extensive detail based on the standard fields from the Iowa crash report form, this information is somewhat limited in terms of the detailed circumstances related to the crash. For example, the crash report form also includes sections for a drawing and narrative from the officer, neither of which is included in the default Iowa DOT crash database generally made available to researchers. The narrative section of the crash report form occasionally contains sensitive information about the investigating officers and drivers involved in the crash, including names, dates of birth, and insurance policy numbers. In the interest of privacy, the Iowa DOT withholds these two fields to protect the privacy of the drivers involved in the crash. However, the crash codes can be limited in reconstructing the circumstances contributing to the crash. By having the crash narratives along with the other descriptive fields from the crash codes, target crashes can be better identified and verified; target crashes identified as those involving a vehicle which enters the median.

For the purposes of this project, a memorandum of understanding was developed and accepted by the Iowa DOT, which allowed for the use of the crash narrative information after it was digitized and confidential information was redacted. Crash narratives were provided for the interstate system from April 2007 to June 2016. Narratives were not available for

every crash. Narratives were provided for 402,379 of 481,939 total crashes (83.4%). The final scope of the project was limited to 2007 to 2014 due to the availability of the median cable barrier installation spreadsheet and the modified crash report form implemented in 2015. Since the method of target crash selection in this study utilized narratives, 16.6% of potential target crashes were automatically excluded from being used. From the crashes without a narrative, the only common trend identified among these crashes were that the many were self-reported crashes coded as report type 6. Self-reported crashes are not held in the same database as the other narratives, but are counted and georeferenced. The automatic exclusion of self-reported crashes is a limitation in the dataset.

3.3 Median Cable Barrier Installations Spreadsheet

At the start of the project, the Iowa DOT had provided a spreadsheet detailing the installation locations and cost of 31 projects totaling 330.5 miles. These projects span from 2003 to planned projects yet-to-be bid as of 2015. Fields in this data included county, route, mile point, project number, cable cost, anchor cost, project cost, letting date, bid order, proposal ID, system, proposed offset, contractor, construction start, operational date, construction end, and additional notes. This information provided the cable installation date in order to classify whether crashes had occurred before or after installation. The year(s) where the roadway was under construction were excluded from the analysis. The cost from this spreadsheet was also used in the benefit-cost analysis for the installation cost. Some of the projects included more than only median cable barrier installation. For example, one project costing \$13 million included 1.87 miles of reconstruction. A field in the spreadsheet called out the specific cost of the cable barrier unit item, as well as another field calling out

all related cable barrier pay items such as the anchor and turnbuckles in addition to the cable barrier pay item. The latter field was used in the benefit-cost analysis.

3.4 Manual Median, Shoulder, Manufacturer, and Offset Information

A full review of barrier locations was completed on the statewide Interstate network using Google Earth. While conducting this review, information regarding median width, shoulder width, barrier offset and manufacturer was captured as well. This review was completed for the purpose of verifying the median cable barrier locations installed, to capture geometric information for subsequent analyses, and to identify open median sections with no barrier installed. This review captured all barrier types including steel, concrete, and median cable barrier used to protect bridge piers (in median only). Figure 8 offers an insight into the level of detail collected with the example of roadway and bridge over a river. The green section represents the cable median barrier, the yellow shows a mix of barrier types, and the pink shows concrete barrier. As the roadway approaches the bridge, the barrier type changes to a steel system over the piers and then concrete on the deck, and repeats the process as the bridge terminates and resumes to transition into median cable barrier. Any crashes occurring on the bridge deck were excluded from the study. This review can also aid future research focused on medians by providing precise road network information pertaining to barrier presence.

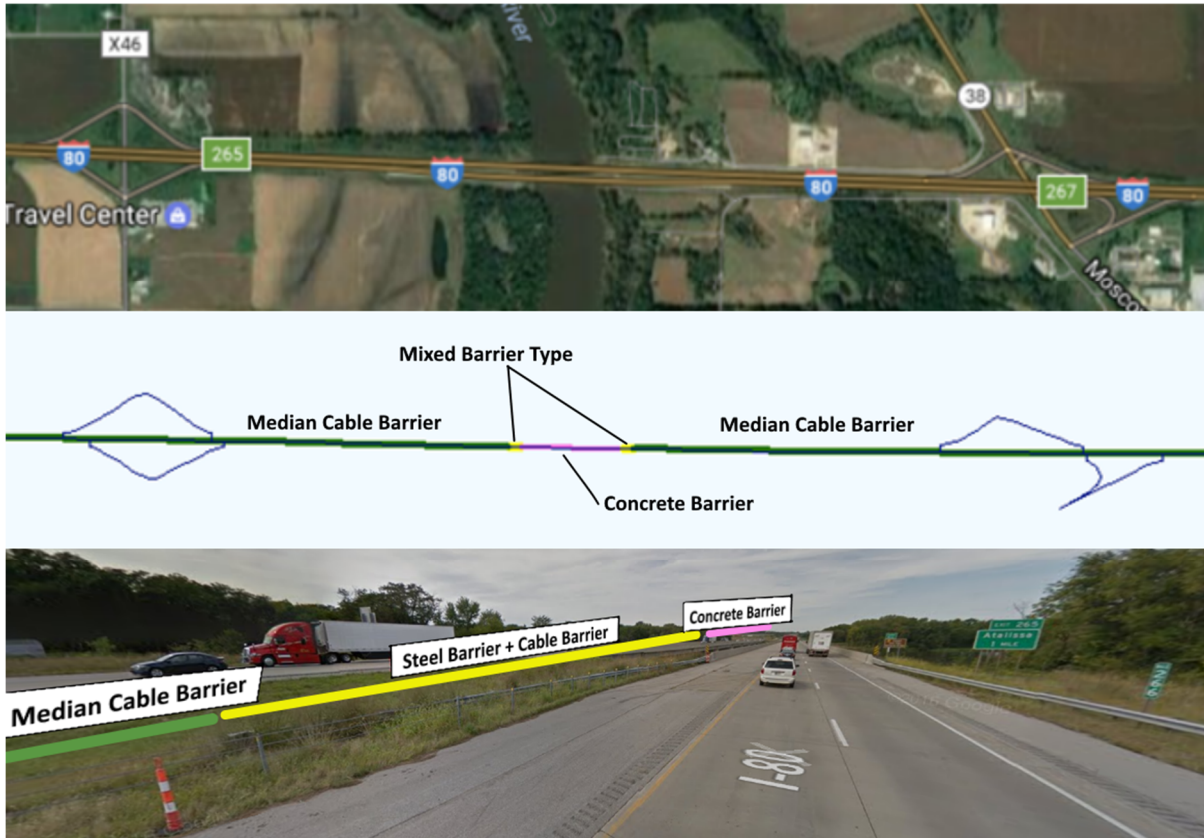


Figure 8: Manual Barrier Identification

3.5 Repair Data

The four Iowa DOT maintenance districts with median cable barrier in their jurisdiction were contacted for information about their repairs. Districts 1, 5, and 6 responded with data of different time periods between the years 2011 and 2015. Each repair detailed the number of posts repaired, cost of the posts, anchor cost (if applicable), turnbuckle cost (if applicable), mobilization costs, and total cost of repair. The date of the repair and a nearby mile point were provided, which were useful in attempting to identify the crash associated with each repair. While it is assumed that the majority of repairs are due to crashes, both reported and unreported, no details were provided as to whether the repair was due to faulty

construction, an animal, a crash, or routine maintenance. Data from a total of 2,682 repairs were used in this study.

The price of the repairs annually stemmed not only from the number of repairs but also from the unit prices in the contract's bid. Only District 1 explicitly provided each unit price from each annual contract, the other districts' unit prices were calculated by identifying patterns in the repair costs for the discussion in the analysis. It should also be noted that each year's contract does not change at the end of the calendar year, but approximately in mid-November to early December, depending on the district.

3.6 Additional Datasets

The following sections describe datasets developed and explored through the course of this project, but not utilized in the final analysis presented in this thesis.

Median Cable Barrier Installations Spreadsheet - Locations

While cost and date of construction was utilized in the final results, the locations in this file were not used in the results of this thesis. The 31 projects were drawn in ArcGIS using the mile point information and used for the preliminary analysis earlier in the study. With this spreadsheet, the barrier type field in GIMS was evaluated and found to be significantly incorrect. In Figure 9, both the barrier field from GIMS as well as the manually plotted installation locations are compared side-by-side.

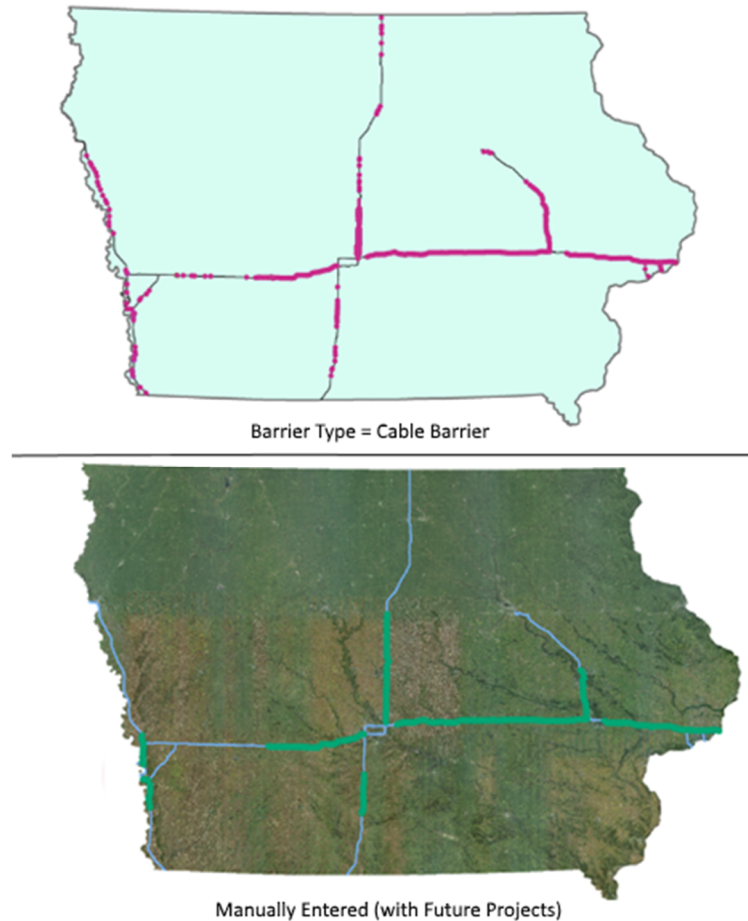


Figure 9: Top - Map of Median Cable Barrier via GIMS (top); Bottom Median Cable Barrier through Installation Spreadsheet (bottom)

The installation locations from the spreadsheet were added in ArcGIS using the mile point information from the installation spreadsheet. The future installations, project designed but yet-to-be-bid as of 2015, were also added to the bottom map in Figure 9 for a total of 330.5 miles. The large difference in the GIMS database compared to the installation map is due to the small runs used for roadway object protection such as overpass bridge piers. A secondary, but less impactful reason of the imprecision, is due to the length of the GIMS segment. Where the median cable barrier is used for this purpose, the entire segment, ranging from less than .05 miles to 3 miles, is flagged as containing median cable barrier, over representing the extents of cable barrier installation. The bottom map, with manually added lines where

median cable barrier can start or end regardless of the GIMS segments start and end, avoided this problem. While the locations as per the installations spreadsheet were utilized for preliminary results earlier in the project, the entire Interstate was reviewed manually via Google Earth with even higher precision and used in the final project.

As-Built Drawings and Letting Plans

Of the 31 projects, 28 drawing sets were provided by the Iowa DOT. The plans vary in level of detail provided about the median cable barrier system; however, special details like anchor connections and installations around fixed objects are provided. The intention with this dataset was to obtain slope information and also identify other factors influencing project costs on certain installations. However, many of the plans contained limited information about the installation, many times containing only a generic detail for the median cable barrier. Some of the drawings had information about existing low-tension barrier, but this information typically only provide quantity but neither locations nor year of installation of low-tension barrier. Due to the missing and vague information, slope was excluded from this study and offset collected via manual review. This dataset was not used to obtain the final results.

Weather Data

The National Weather Service provides a platform where volunteer weather stations can report precipitation and temperature data throughout the years (Mesonet 2017). Through this cooperative program, the data from 1893 to the current date is available in certain locations. The temperature, rainfall, and snowfall data were obtained for the time period from 2007 to 2014 from various stations near the Interstate system. The map in Figure 10 illustrate the stations buffers used for annual precipitation and snowfall. If a segment of

roadway fell in more than one buffer radius, then the precipitation values from both overlapping buffers were averaged.

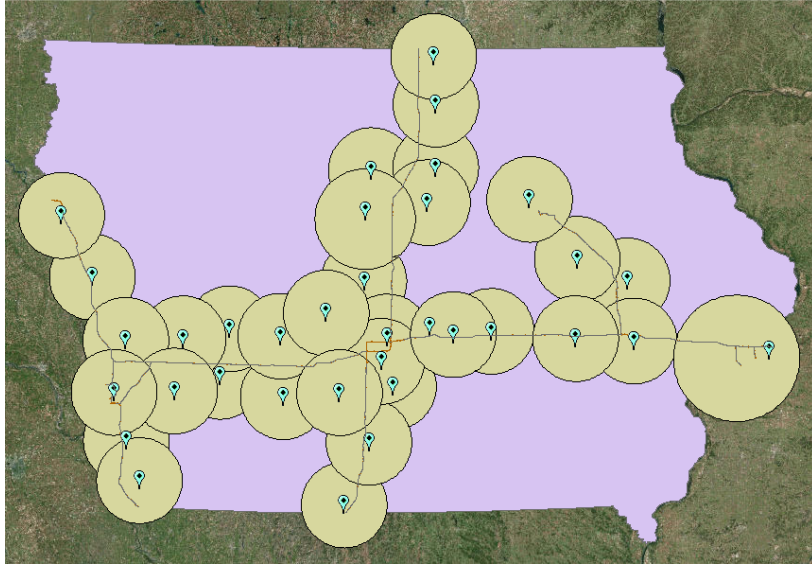


Figure 10: Weather Stations near Interstate

Crash-to-Repair List

Each repair was matched, using ArcGIS, to those crashes occurring within one month prior to the crash and within a distance of one mile of the mile point stated in the repair file. The repairs-to-crashes were then reviewed based on the crash narratives to find any information about hitting the barrier. Examples included number of posts knocked down, if the anchor was hit, or details alluding to the extent of the damages (multiple cars involved going into the median, if the car rode the barrier, or details of the car pulling the cable to the other side.) Problems in this process included instances of one repair with many reported crashes meeting the time and distance thresholds, as well as the converse (i.e., many repairs, each of which were associated with only one reported crash) with little detail in the narratives. The majority of narratives did not include number of posts damage with only

10.7% containing a number. In some cases, maintenance reports listed a location that did not at any point in history contain median cable barrier. In the repair data from the maintenance districts, there were 41 repairs total that contained more than 30 posts. In no crash narrative was a repair containing more than 30 posts reported, while the largest repair in terms of posts was 117. These instances were assumed to involve cases where maintenance crews fixed multiple damaged sections along the same run of barrier. It is unknown how many crashes or locations are contained in these larger repairs. Overall, many crashes and repairs could not be paired together, but 896 instances were found as potential one-to-one crash-to-repair matches.

Some of the repairs were not applicable because they occurred on high-tension cable barrier segments not in the scope of the study. For example, this would include repairs to barrier located past the outside (i.e., right-side) shoulder of the roadway or limited installations where barrier was in place to shield a specific object, but not as a part of a longer run of median cable barrier. Repairs on these sections were removed where possible to locate. In instances where cable barrier was installed both in the median and the right side of the road, it was impossible to distinguish which barrier was repaired, and the repair data was retained in the dataset.

3.7 Data Integration Methods

The various dataset were combined in both ArcGIS and Microsoft Excel using primarily the near table and join functions in ArcGIS and the vlookup function in Excel. Target crashes identified by narrative, GIMS roadway information, manually collected data, weather data, and maintenance information were joined into 917 segments between 0.25 and

1 mile long in ArcGIS. Installation information was joined later in Excel using a unique ID per installation.

Formatting and collecting the data took a substantial amount of time during this project. Challenges from the data methods include communication and establishing a procedure for the manual collection for the target crash selection via the crash narratives as well as the manual road review collecting median information and barrier type. Spot checks were performed on both datasets after their creation to ensure quality before using the data in the final analyses. It is recommended for future research to perform quality assurance checks earlier in the database creation process to avoid time-consuming corrections.

CHAPTER 4. RESULTS

The results of this study are broken into four major parts. The first section includes a before-and-after study looking at the effect on target crashes. Target crashes were identified through a manual review of crash narratives along manually reviewed barrier locations and used in this analysis.

The second section details an investigation of geometric and weather-related variables on the safety impact. This analysis did not find any conclusive results to suggest future implications in the median cable barrier installation program. It is included in this thesis for completeness.

The third section summarizes and discusses the maintenance data provided by the Iowa DOT districts. This section also provides context for the benefit-cost analysis by illustrating the recurring costs of the median cable barrier.

The final results detail the results of a benefit-cost analysis of the median cable barrier. This analysis contrasts the crash cost savings, due to reductions in the frequency of fatal and severe injury crashes, with the costs due to increases in less severe crashes, along with agency costs for installation, maintenance, and repair. A sensitivity analysis is conducted to discern how various assumptions for crash cost values and design life affect the results.

4.1 Before-and-After Cross-Sectional Analysis

After an extensive manual review of the crash narratives, the set of target crashes were identified and used to estimate a series of negative binomial models. This set of target crashes were selected based on the movements of the vehicles as described by the police officer in the crash narrative in combination with crash codes when the descriptions

were unclear. Vehicles leaving the roadway towards the center median were captured.

Overall, the number of crashes from 2007 to 2014 were 6,163. A summary of the target crashes can be seen in Table 3. The target crashes included in this table only include crashes on segments of roads that have median cable barrier installed or is slated to be installed.

Table 3: Summary Statistics for Cross-Sectional Analysis

	Min	Max	Mean	Std	Count
AADT	11700.00	82784.62	31128.4	10594.6	2888
Cable Presence (1 if yes; 0 otherwise)	0.00	1.00	0.26	0.44	747
Length (Miles)	0.23	0.94	0.76	0.13	2199.7
Total	0.00	13.00	1.44	1.55	4169
K (Fatal)	0.00	1.00	0.02	0.14	62
A (Major Injury)	0.00	2.00	0.05	0.22	132
B (Minor Injury)	0.00	3.00	0.13	0.36	368
C (Possible Injury)	0.00	4.00	0.18	0.44	513
O (Property-Damage Only)	0.00	11.00	1.07	1.35	3094

Table 4: Before-and-After Model Results

By Crash Severity				
Severity	Parameter	Estimate	Std Error	P-Value
K (Fatal)	Intercept	-9.363	4.4270	0.034
	LN(AADT)	0.578	0.4306	0.179
	Cable Present	-0.719	0.3554	0.043
A (Major Injury)	Intercept	-10.893	3.0159	<0.001
	LN(AADT)	0.790	0.2928	0.007
	Cable Present	-0.275	0.2137	0.198
B (Minor Injury)	Intercept	-9.821	1.8081	<0.001
	LN(AADT)	0.784	0.1756	<0.001
	Cable Present	-0.221	0.1265	0.081
C (Possible Injury)	Intercept	-10.481	1.5877	<0.001
	LN(AADT)	0.867	0.1541	<0.001
	Cable Present	0.251	0.1013	0.013
O (Property-Damage Only)	Intercept	-8.554	0.7638	<0.001
	LN(AADT)	0.834	0.0742	<0.001
	Cable Present	0.780	0.0448	<0.001
Total Crashes				
	Intercept	-8.085	0.6551	<0.001
	LN(AADT)	0.825	0.0637	<0.001
	Cable Present	0.590	0.0394	<0.001

As seen in Table 4, there is an overall increase in PDO crashes and a decrease in K&A crashes. The reduction in A crashes is not statistically significant at the 95 percent confidence level, but were included for completeness. When aggregated, the reduction in K and A crashes is statistically significant. In any case, the coefficient for the A crashes shows a clear trend that fits in relative to the rest of the severities. Significant increase in C crashes is also present. A summary of the percent change in crashes between the pre- and post-installation is presented in Table 5.

Table 5: Cable Presence Effects Summarized

Cable Presence Effect on Crashes	
Severity	Change in Crashes
K	-51.3%
A	-24.0%
B	-19.8%
C	28.5%
PDO	118.1%
Total	80.4%

4.2 Investigation in Median, Offset, Shoulder Widths, and Snowfall

An effort to compare the relationship between the median, offset, shoulder widths, and snowfall data was undertaken. As seen in previous literature, these variables are likely to play a role in the effectiveness of the barrier. If a relationship could be established between the median width, shoulder width, barrier offset, and annual snowfall with the effects of AADT and the median cable presence, then potentially sites without median cable barrier with the same characteristics could be recommended for future installation. A negative binomial model using binary categories at various ranges of these variables was estimated.

However, after several iterations, no combinations of these variables were found to have a strong relationship, as indicated by the statistical significance through the model's p-value and the lack of pattern. Figure 11 illustrates the distribution of median widths compared to K and A crashes and C and O crashes. The charts were truncated to better show the trends around the 50ft mark, though segments from each category had segments with medians greater than 90ft. The general trend for both charts in all categories is a pyramid-like shape. The average median width was 57ft with a minimum of 28ft and a maximum of 327ft.

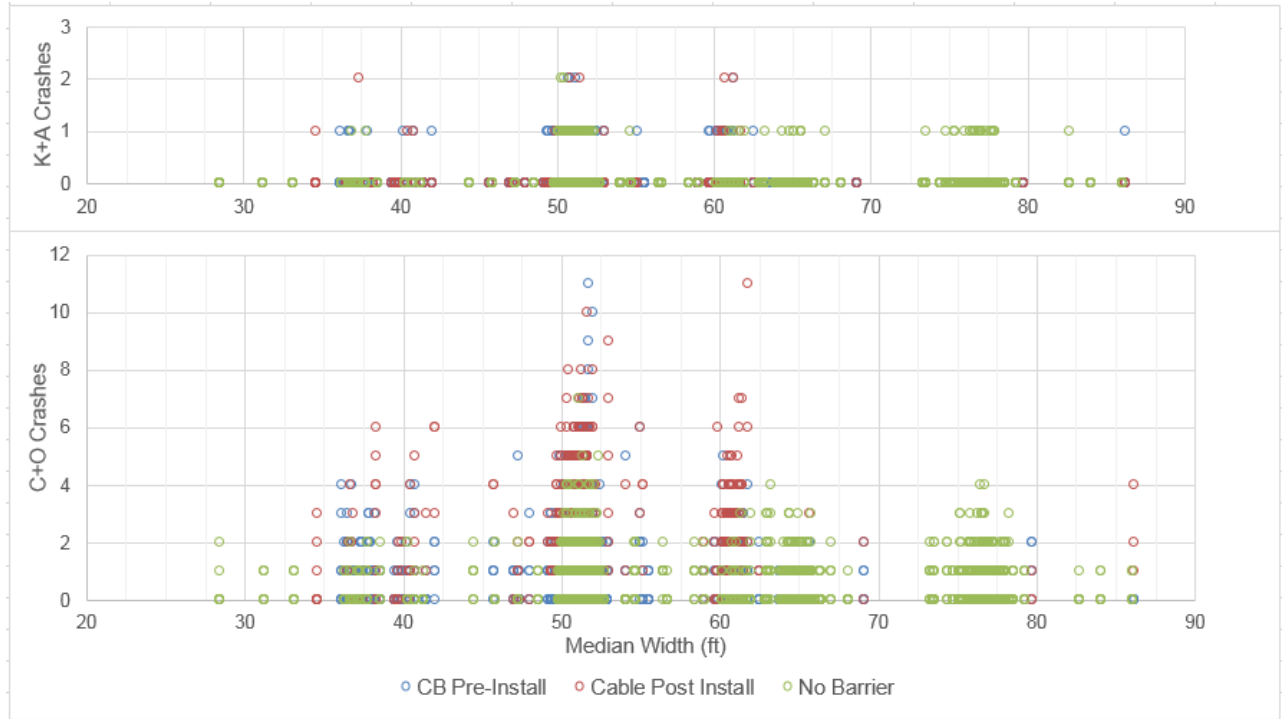


Figure 11: Distribution of Crashes to Median Width

Also, compared to existing literature describing the impact of snowfall (Russo 2014), Iowa's median cable barrier is generally centrally located in the state near I-80. As seen in Figure 12, the most northern installation of median barrier is the top part of Hamilton County on I-35 and the most southerly portion is I-35 in Clark County. The effects of snowfall are relatively minor.

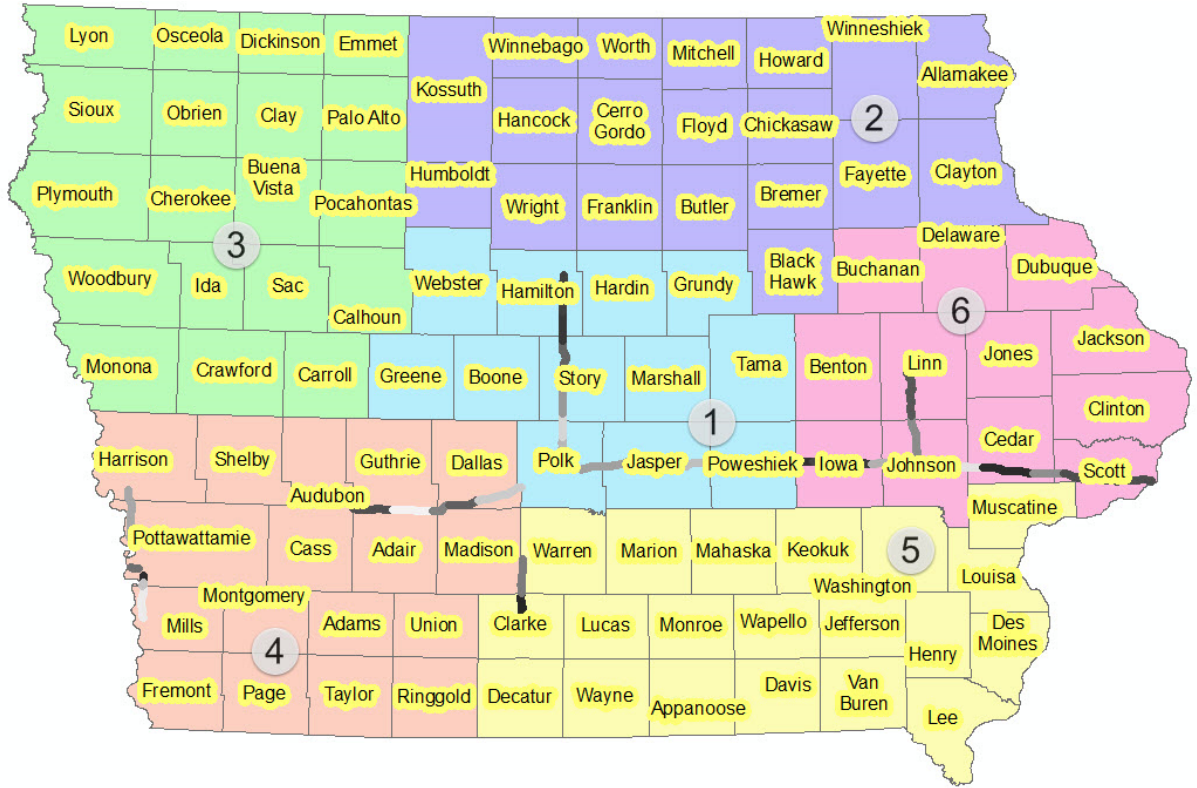


Figure 12: Map of Median Cable Barrier Installation by District and County

4.3 Maintenance Cost Breakdown

As stated in the data section, installation and repair information had been provided by both the Iowa DOT and the various maintenance districts around Iowa. Currently, four of the six districts have median cable barrier installed in their district including District 1, 4, 5, and 6. No repair information was available from District 4. A summary of the maintenance information can be found in Table 6. In general, the greatest indicator of approximate repair is the post replacement count. The cost of repair per crash for District 6 in 2011 is notably high for two reasons. First, there are very few reported target crashes for that year. Since the cost rate presented in the table is cost per reported crashes, having more unreported crashes will increase the average cost per reported crash. The cost uses these units as reported crashes

is a unit that can be quantified and projected for future maintenance budgets. Secondly, the contract stated both repairs and replacements were bid at a unit cost of \$106 per each. The unit price was subsequently changed to differential between a repair (adjusting or unbending a post) or furnishing and installing a new post. In 2015, District 6 unit price for repair was \$36 each and \$72 per replacement. Districts 1 and 5 have similar unit prices across the same years.

Table 6: Maintenance Repair Summary

Year_ District	# Actual Post Count	# Anchor Replaced	\$ Mobilization	Total Cost	% Mobilization	Count Repairs	Average Cost Per Repair	Average Cost Per Mileage of Barrier	Average Cost Per Crash
2011_1	130	1	\$ 23,666.66	\$ 45,215.66	52%	25	\$ 1,808.63	\$ 1,974.48	\$ 1,130.39
2011_6	277	1	\$ 15,000.00	\$ 48,962.00	31%	40	\$ 1,224.05	\$ 1,654.12	\$ 6,120.25
2012_1	1534	9	\$ 107,006.86	\$ 289,286.56	37%	338	\$ 855.88	\$ 3,447.99	\$ 3,045.12
2012_6	2031	7	\$ 95,951.61	\$ 356,450.61	27%	406	\$ 877.96	\$ 3,014.38	\$ 1,866.23
2013_1	2027	24	\$ 92,701.30	\$ 342,902.90	27%	331	\$ 1,832.99	\$ 4,087.04	\$ 1,344.72
2013_6	3530	39	\$ 44,985.29	\$ 541,673.29	8%	597	\$ 907.33	\$ 4,580.75	\$ 1,907.30
2014_5	53	1	\$ 6,000.00	\$ 25,053.00	24%	11	\$ 2,277.55	\$ 2,596.17	\$ 1,565.81
2014_6	2444	45	\$ 108,534.54	\$ 640,792.54	17%	660	\$ 970.90	\$ 5,418.96	\$ 1,918.54
2015_1	2537	33	\$ 106,681.25	\$ 432,493.25	25%	274	\$ 1,578.44	\$ 5,154.87	N/A
Total	14563	160	\$ 600,527.51	\$ 2,722,829.81	22%	2682	\$ 1,015.22	\$ 4,072.43	\$ 1,872.72

The mobilization cost from the repair data is also notable as there is a trade-off between mobilization costs and repair frequency. Almost a quarter of the total amount spent to repair the barrier is spent on the cost associated with mobilization of a crew. In District 6, their contract specifies that the barrier must be fixed within two weeks of the hit before the contractor incurs a penalty. The cost per mobilization is \$3,000 for Districts 1, 5, and 6. (The price had changed starting in 2014. In prior contracts for District 6, mobilization cost was \$1,000 to \$1,500.) The mobilization cost is divided over the number of locations repaired during the deployment of the contractor's labor which can span from a day to little over a week of working days. The more repairs done within a mobilization, the lower the cost per repair. Over time, a trend of a smaller percentage of cost associated with mobilization can be seen. The jump found in the District 6's 2014 mobilization percentage can be attributed to the doubling of the contract price for mobilization. Requiring less frequent repairs can be a significant cost savings for the districts, and already seems to be a trend occurring. No study to date has quantified the amount of hits a median cable barrier can take before it is no longer effective, but past literature has supported that a gain from this barrier system is that it can remain effective even after being hit (Ray 2010). Overall, a careful balance between the frequency of repairs needs to be considered with safety. If a barrier is not repaired in a timely manner in an effort to save money, and a vehicle departing the roadway crosses over the broken barrier system resulting in a fatal crash, then no cost is saved. A non-functioning barrier adds no value to the system or safety benefit, and the benefit from the benefit-cost analysis could be overstated if a trend towards more non-functioning barrier arises. Further investigation is recommended in this area.

One concern here relates to the rising annual repair costs. As seen in Table 6, the cost per mileage of barrier greatly increases each year. While it is true that both the installed mileage of barrier and many of the unit costs have increased over the years, a more prominent change that is causing increasing repair cost is the increase in crashes. In the next section, a benefit-cost analysis of the median cable barrier program is presented.

4.4 Benefit-Cost Analysis

In order to assess the effectiveness of the current median cable barrier program and make judgements on future expansions, a comprehensive analysis considering all costs and benefits attributed to the median cable barrier was conducted. The crashes from pre- to post-installation for the median cable barrier, the cost of each crash, and the cost of the repairs, were used in this analysis.

Table 7 shows the rate of crashes in the before period per mile of roadway. The after crashes utilize the crash rates from the cross-sectional analysis in section 4.1 applied to the before rates. The difference between these rates multiplied by the cost per person affected in the crash will be used to find the cost and benefit associated with changes in frequency and severity of crashes. The economic and comprehensive costs in Table 7 are in 2015 values from the National Safety Council (2017), and the Iowa costs are from the assigned values in the Iowa-specific benefit-cost analysis worksheet (Iowa DOT 2016).

The differences between the economic cost, comprehensive costs, and Iowa costs should be noted, particularly the differences found in the fatal injuries and the property-damage-only/no injury crashes. The economic cost compared with the comprehensive cost is an increases about six-and-a-half times from the economic costs to the comprehensive, while the property-damage-only/no injury increases about four times from economic costs to

comprehensive. Wage and productivity losses, medical expenses, administrative expenses, motor vehicle damage, and employers' uninsured costs are included in the economic costs while the comprehensive costs include the same things with the additional "value of a person's natural desire to live longer or to protect the quality of one's life." The National Safety Council prescribes that a benefit-cost analysis should be done with the comprehensive costs because these costs reflect what people are willing to pay to avoid the quality of life lost (National Safety Council, 2017). The Iowa benefit-cost numbers fall about in the middle of the economic cost and the comprehensive costs, with the only exception the cost of property-damage-only/no injury instances. For people involved in property damage only crashes, the Iowa cost are \$3,000 less than the economic costs. Since the most frequent type of crash and the greatest increased in crashes are seen in the property-damage-only crashes, this difference in value will significantly impact the benefit-cost ratio.

It should be noted that the numbers below reflect the cost per person affected rather than the number of crashes. In the crash database, the crashes were coded with the KABCO scale (as defined in Section 2.2 in this thesis) at both the crash level and the person level. While the before-and-after analysis was conducted looking at the crash level, this benefit analysis uses the person level. In the target crash dataset, an average of 1.42 vehicles were involved in each crash, and within the units was on average of 1.49 people, excluding the crashes with an unknown number of people in the vehicle.

Table 7: Observed Before-and-After Crashes with Crash Costs

	Before	After	Difference	NSC Economic Costs	NSC Comprehensive Cost	Iowa Cost
	(Crashes/Mile/Year)			(\$/person affected)		
Total	1.495	2.696	1.202	-	-	-
K	0.033	0.015	-0.018	\$1,542,000	\$10,082,000	\$4,500,000
A	0.065	0.049	-0.015	\$90,000	\$1,103,000	\$325,000
B	0.172	-0.638	-0.810	\$26,000	\$304,000	\$65,000
C	0.213	0.272	0.060	\$21,400	\$141,000	\$35,000
O	1.012	2.207	1.195	\$11,400	\$46,600	\$7,400

For the installation cost, the average cost of the median cable barrier-related unit items multiplied by the total mileage of barrier was used instead of the sum of the actual project cost. In this benefit cost, 229.5 miles of median cable barrier is included. This method was used in order to exclude extra costs from non-related pay items such as a pavement reconstruction in the total comparison. The installation costs for the 229.5 miles of barrier in this section was found to be \$11,381,728 using the average install cost of \$49,594. It should be noted in comparison to other states' installation costs, most prior research present the average cost of cable instead of a cost that includes the anchor and turnbuckle installation in addition to the cable. The average cost of just cable and posts per mile for Iowa is \$45,071 which is similar to Washington at \$44,000 (Blincoe et al. 2010). In this benefit-cost, a discount rate of 4% was used when factoring the installation cost in as an annual rate.

For maintenance costs, the total number of report crashes in the after period in Districts 1, 5, 6 were used along with the total cost of all the repairs. Repairs that took place on segments of roadway without the cable barrier placed in the median were removed from the total number as it was likely these were repairs on cable barrier on the left side of the

roadway (non-median cable barrier), and repairs happening in 2015 were also removed from this total as the target crashes were not identified for 2015. The average cost per reported target crash was \$1,872.72. An effort was made to break down the cost of maintenance per severity and per vehicle type to more accurately quantify the increased costs. Overall two trends emerged from this effort. The first showed that trucks on average cause more damage than vans or sport utility vehicles, which cause more damage on average than sedan-style vehicles. The second trend showed fatal crashes causing less damage to the median cable barrier system than the property damage only crashes on average. This is likely due to the nature of a fatal crash post-installation, which typically involves a penetration of the barrier system (Marzougui 2012). If the system is penetrated, then the posts may not break away like intended, in which case the overall repair cost is less. In the benefit-cost analysis, additional cost to society, the department of transportation, and the driver is included to look beyond simply the cost of repair, particularly for the more severe crashes.

The greatest problem that arises when looking at the cost of a specific crash is the known nature that not all hits to the median cable barrier are reported. The average stated above is in units of per reported crash, therefore it represents the costs in repairing the unreported crashes and general maintenance. An attempt was made to match the repairs with the crashes, however, less than 20% of the number of repairs could be matched with individual crashes. Other states, including Indiana, have begun to implement systems to identify damage to infrastructure at the time of the police report to link repairs to crashes (Li et al. 2011). Iowa has begun developing a similar procedure to the Indiana tagging method and will be implemented in the future.

The costs included installation costs, maintenance costs, and cost from crashes. The benefits included the reduced cost from crashes with the barrier installed. From the results seen in Table 8, the current median cable barrier program is cost-effective in Iowa by both national safety estimates and Iowa-specific associated crash costs. The design lives were estimated to be 15, 20, 30, and 50 years in an effort to illustrate the sensitivity of the design life.

Table 8: Benefit-Cost for Median Cable Barrier System

Design Life	Economic Costs		Comprehensive Costs		Iowa Costs	
	Benefit-Cost	B/C	Benefit-Cost	B/C	Benefit-Cost	B/C
15 Year	\$221,844,000	2.57	\$1,901,507,000	2.44	\$890,043,000	8.93
20 Year	\$299,516,000	2.62	\$2,539,066,000	2.45	\$1,190,448,000	9.15
30 Year	\$454,652,000	2.68	\$3,813,977,000	2.45	\$1,791,051,000	9.38
50 Year	\$764,173,000	2.71	\$6,363,048,000	2.45	\$2,991,504,000	9.56

Since there are limited median cable barrier systems in the United States that have reached the end of their design life, this number ranges between different state DOTs. Gibraltar, a manufacturer of median cable barrier, recommends using an industry-developed method of estimating the life of in-field steel based primarily how long the zinc coating will protect the cable and end equipment from corroding to the point of replacement (Bjerke 2017). The major factor in these calculations is the atmospheric salinity and sulfur dioxide levels, both of which can increase corrosion. The Institute for Transportation, Iowa-specific data was collected and considering these factors mentioned, the recommended design life was 20 years for the cable and 30 years for the anchor and posts. In the NRCHP Report 711, it is also recommended that the system be inspected after a severe weather event such as a flood to make sure the system is performing correctly. The report also mentions that while

each of the various types of barrier systems are approved, they can potentially differ in cost and benefit. This analysis was not broken down by manufacturer, however the data is available.

CHAPTER 5. CONCLUSIONS

5.1 Conclusion

While median cable barrier can be an effective method of reducing fatal and serious injuries caused by multi-vehicle cross median crashes, this benefit does not come without cost. The presence of the barrier will generally increase the overall frequency of crashes, particularly the less severe property-damage-only crashes. From the results, an overall increase of 80.4% in total crashes, an increase of 118.1% in PDO crashes, and a reduction of 51.3% in fatal crashes was observed.

While the median cable barrier has the lowest installation cost compared to concrete and steel beam, additional considerations need to be made for the yearly maintenance. As seen, the increased number of crashes need to be factored into the estimated maintenance repair cost. It was found that on average, the repair cost for reported number of crashes is \$1,872.72. This repair cost includes repairs of reported and unreported crashes. In the effort to pair crashes one-to-one with repairs, a lower repair cost per crash was found. In order to use repair cost calculated at the individual repair level, a rate of unreported crashes would need to be applied to the anticipated crashes to estimate repair costs. By taking the total aggregated repair cost over the total number of report crashes, the unreported crashes are already factored into the average cost rate and an additional unknown rate of non-reporting does not need to be added.

This repair cost has been calculated based on Iowa repair history. If another state has or assumes a higher rate of unreported crashes, the average repair cost should be increased. Factors like roadway geometrics or barrier manufacturer may have an impact on repair costs, but were not considered in this study.

Through the discovery of effect on crashes, installation cost, and maintenance costs, the benefit-cost was calculated. As seen from the three different sets of crash cost assumed, the cost-effectiveness of the barrier can be significantly different. For recommendations for Iowa, the Iowa costs are to be used which show a markedly benefit over cost for the state of Iowa with a benefit-cost ratio of 9.153 with a 20-year design life.

When interrupting the results, two consideration about the inherent bias could be noted. Consistent with general transportation engineering practice, the barrier was first installed on locations that demonstrated the greatest need based upon pre-existing crash history. As the barrier continues to be installed, it is generally placed on lower-priority segments of roadway with fewer historical fatal and major injury multi-vehicle cross-median crashes. A selection bias is potentially present in that the highest risk roadway segments, in terms of multi-vehicle cross-median crashes, are treated first.

These models were created based on the effects of the barrier installed before 2013, so median cable barriers installed 2014 or later were not included in this study. The benefits at later installations may be less than those shown in the analysis results. Consequently, it is possible that increases in property-damage only crashes may outweigh the reduction in fatal and serious injury crashes, which are likely to be less frequent on lower priority segments.

The second consideration is the life span of the barrier. In only a few repair cases was a strand of cable itself replaced due to the vehicle burning during the hit, compromising the integrity of the steel cable. It is unknown how long a median cable barrier system will last before it would need extensive repair. Currently, the oldest barrier in place for this study was installed in 2003. As time goes on, increased maintenance due to age will be necessary in addition to the crash experience rising with annual average daily traffic. Overall, it was

recommended the Iowa DOT use a design life between 20 to 30 years based on Iowa atmospheric characteristics and the properties of the steel components of the barrier.

The largest cost in the benefit-cost analysis was the cost of increased crashes in the 15, 30, and 50 year estimates. Since crashes have the largest impact on the benefit-cost, choosing the costs associated with the crashes influences the ratio greatly. The National Safety Council recommends that the comprehensive costs be used in cost analyses, however the Iowa costs have been prescribed for all safety improvements in Iowa and it is recommended to use those results on this project.

5.2 Study Limitations

While most data was possible to be collected, some information was not able to be added to this study. Slope information is available in the dataset, but could not reliably be used. Repair information was provided by three of the four Maintenance Districts. Though this data contained repair dates, crash information was not related to each of these repairs. In an effort to manually pair repairs with crashes, it was found that some repairs likely included an unknown number of crashes, both reported and unreported. Due to the known, yet underquantified phenomenon of drive-offs after a barrier is hit, repair data was not able to match one-to-one extensively for the gathered data.

The scope of this project was limited to the Interstate system. In Iowa, there are limited-access divided freeways with similar characteristics as the Interstate system. These locations could be considered for future installations. The exclusion of these segments do not imply that they are not suitable for median cable barrier placement. It is recommended in future studies to include non-Interstate segments with similar characteristics as Interstate segments warrant median cable barrier.

5.3 Future Studies

Throughout this thesis, future studies were mentioned. The first continued investigation recommended is the connection between the effectiveness between the roadway characteristics and the effectiveness of the median cable barrier. As mentioned prior, the existing literature has found relationships between barrier effectiveness, crash rates, and roadway geometric characteristics such as median width, shoulder width, slope, and barrier offset. While no relationship has been identified in this study, continued effort in this area is recommended to discover why Iowa's median cable barrier installations would be unique in this regard.

Another future study recommended is to observe the difference in effectiveness in median cable barrier installations over time in each district. The potential selection bias was discussed in this thesis. With nearly 100 miles of current median cable barrier not included in the post-installation period of this study, concern related to such a bias should be considered. Seeing also how much crashes impact the B/C ratio, a decreasing reduction in K/A crashes and greater increases in C/O crashes may warrant some later installations of median cable barrier less cost effective than represented here in the study.

Other future studies include the effectiveness of the median cable barrier on specific vehicle types and crash situations. Large trucks and motorcycles have both been a concern in relation to median cable barrier. Trucks with their great momentum raise the concern that the barrier will not be able to contain the vehicle within the median. For motorcyclists, the concerns are raised that these vulnerable road users have an increased likelihood of a severe injury or death with the barrier in place as opposed to no barrier in the median. The majority of the vehicles in this study were sedan-style passenger vehicles. For these two unique road

users, an in-depth investigation is warranted. Specific crash situations like barrier penetrations and secondary crashes were not flagged in the manual target review and therefore not contained in this thesis. These specific cases in previous literature have been studied and factored into the overall safety effectiveness of the median cable barrier, and could be investigated in Iowa with the available data.

A future study unique to Iowa is the use of median cable barrier to protect fixed objects. As stated in the literature review, not only is this a rare use unique to Iowa, but it is not recommended due to the deflection width required by the barrier (Marzougui, 2012). From the beginning of the study, these small segments were not included in the scope. A separate investigation to change or reinforce existing literature is recommended.

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