Analysis of High-Tension Cable Median Barrier Crashes and Associated Severities

By

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ABSTRACT

Often severe, cross median crashes (CMCs) are crashes in which a vehicle enters the roadway median, fully traverses it, and enters the opposing traveled way. Their severe nature stems from the fact that they often result in fatal head-on collisions. In an effort to prevent CMCs, many transportation agencies have installed high-tension cable median barriers along their highways. At this point in time, the literature has shown that cable median barriers do in fact help prevent CMCs, although often at the expense of an increase in the frequency of lower-severity crashes. Currently, however, little is known about factors influencing cable median barrier crash severity and crash outcome.

This thesis investigates these issues through a variety of statistical analyses. Logistic regression analyses of barrier containment showed factors such as AADT, number of cables in the barrier cross-section, and occurrence of another crash prior to and/or after the barrier hit to significantly affect the likelihood of stopping an errant vehicle upon impact. Analysis of barrier breach crashes showed that in general, they result in higher severity than non-breach crashes and that the majority of vehicles breaching cable barriers were not heavy vehicles. Regression analyses of crash severity associated with cable median barrier crashes showed that pavement condition at the time of the crash can influence crash severity. Further, when examining models for all injury crashes regardless of severity, crash outcome and occurrence of another collision prior to the barrier hit were shown to influence the odds of a barrier crash resulting in injury.

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EXECUTIVE SUMMARY

Statistics published by the National Highway Traffic Safety Administration (NHTSA) showed that in 2011, 51 percent of the total fatal crashes resulted from roadway departure (*1*). A further breakdown found that 17 percent of those fatal roadway departure crashes involved crossing the median in the case of divided roadways or the centerline for undivided roadways (*2*). Crashes in which a vehicle enters the median, fully traverses the median, and enters the opposing-direction traveled way are known as cross median crashes (CMCs). CMCs are often among the roadway departure crashes which result in the highest severity in comparison to other types (*3*). The high fatal crash rate for CMCs has prompted much research to identify causes of the problem. In an effort to prevent CMCs, many transportation agencies have installed high-tension cable median barriers along their highways. At this point in time, the literature has shown that cable median barriers do in fact help prevent CMCs, although often at the expense of an increase in lower-severity crash frequency.

The study of cable median barrier crashes has far from been exhausted. Issues such as factors affecting crash outcome, barrier containment and influencing factors, barrier breach propensity, and aspects influencing cable median barrier crash severity provide tremendous opportunity for investigation. As the result of a study performed by the author on behalf of the Wisconsin Department of Transportation and further data collection following that project, a wealth of data is now available to use as the basis of this thesis.

In total, data collected from 16 study sites in Wisconsin, with a total of 82.06 miles of high-tension cable median barrier, were used in the analyses. Each study site featured cable barrier systems with either three- or four-cables in their cross-sections. Data were collected

from a variety of sources such as police crash reports and construction plan sets. A final set of 753 cable median barrier crashes was extracted following review of 3,274 police crash reports.

Once data were collected and organized, preliminary investigations were performed to look for any trends. It was observed that the majority of crashes (69.7 percent) were low-severity property damage only crashes that occurred during winter months (November through March). Additionally, it was observed that crashes were split rather evenly between three- and four-cable barriers in terms of count and severity.

Following the preliminary analyses, more rigorous statistical techniques were used to analyze the data. The first main component of the statistical analyses involved a logistic regression analysis of barrier containment. Said analysis sought to find what if any factors influenced a cable median barrier stopping an errant vehicle upon impact, as opposed to redirecting it back into the traveled way. A variety of variables including geometric characteristics of the median, traffic volume, characteristics of the crash, and characteristics of the barriers themselves were investigated. Overall, it was observed that the presence of a collision occurring prior to the barrier hit, traffic volumes, number of cables in the barrier cross-section were found to increase the odds of an errant vehicle being stopped/contained by the barrier. On the other hand, the occurrence of a collision involving the errant vehicle after the barrier hit was shown to be associated with a decrease in the likelihood of the barrier stopping the vehicle.

Barrier breach crashes (i.e., crossing over the barrier via underride, override, or penetration of the cables) were the next target of investigation. It was observed that the vast majority (85.7 percent) of barrier breach crashes did not involve heavy vehicles. A chi-squared analysis of barrier breaches versus non-breach crashes showed an association between breach crashes and said crashes resulting in injuries (i.e., not simply property damage). Further analysis showed that when considering injury crashes only, breach crashes are more severe than non-breach crashes. This result, however, depends on the system used to rank/weight crash severities. A logistic regression analysis of breach crashes showed the presence of a collision involving the errant vehicle prior to the barrier hit was associated with an increase in the odds of an errant vehicle breaching the barrier upon impact. Additionally, an association between decreasing odds of a crash resulting in barrier breach and increasing median width was found. An interesting result, though not as surprising considering the distribution of vehicle types involved in barrier breach crashes, was that heavy vehicles were not found to have a statistically significant effect on increasing the odds of a barrier breach.

The final component of the analyses involved a search for factors influencing a barrier crash to result in a severe (fatal or incapacitating) injury or any injury at all (i.e., the result of the crash was not property damage only). As in aforementioned cases, logistic regression was used as the analysis tool. In the case of severe injuries, dry pavement condition at the time of the crash was found to be the only statistically significant variable shown to have an effect in terms of increasing the odds of a cable barrier crash resulting in a severe injury. When considering all injury crashes, factors including dry pavement condition at the time of the crash, the errant vehicle being involved in a collision prior to the barrier hit, and crash outcome with the barrier (i.e., stop, redirect, or breach) were found to be associated with an increase in the odds of a given cable median barrier crash resulting in an injury.

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1 INTRODUCTION

1.1 Background

Statistics published by the National Highway Traffic Safety Administration (NHTSA) showed that in 2011, 51 percent of the total fatal crashes resulted from roadway departure (*1*). A further breakdown found that 17 percent of those fatal roadway departure crashes involved crossing the median, in the case of divided roadways, or the centerline for undivided roadways (*2*). Crashes in which a vehicle enters the median, fully traverses the median, and enters the opposing-direction traveled way are known as cross median crashes (CMCs). CMCs are often among the roadway departure crashes which result in the highest severity in comparison to other types (*3*). The high fatal crash rate for CMCs has prompted much research to identify causes of the problem. As a result, a variety of countermeasures to prevent CMCs have been proposed.

One typical countermeasure is the use of longitudinal barriers (*4*). Among a variety of alternative longitudinal barriers, high-tension cable median barriers have become increasingly popular throughout the last decade because of lower cost compared to other barrier types and their potential safety benefits. The high-tension cable barriers are designed to stop and/or redirect vehicles, which have departed the roadway and entered the median, thus allowing CMCs to be prevented. When a vehicle impacts the cable barrier, increased tension is experienced in the cables as they deflect laterally, reducing the deceleration rate and bringing the vehicle to a stop. At the same time, the cable barrier decreases the impact forces imparted on the occupants and vehicle (*5*). Although cable barriers can help prevent CMCs, their installation can lead to increases in crash frequency due to the presence of the barrier in the formerly open median clear zone; hence, errant vehicles entering the median may have less chance of recovery as they may come into contact with the barrier.

1.2 Problem Statement

High-tension cable median barriers have been used by transportation agencies in the United States (U.S.) and abroad for more than the past decade. At this point in time, benefits of high-tension cable barriers including the prevention of high-severity CMCs, are generally accepted. However, this benefit does come at a price. First and foremost, installation of cable median barriers has been shown to lead to an increase in lower-severity (typically property damage) crashes; the logic being that errant vehicles entering a median protected by a cable barrier now have a piece of roadside hardware with which to collide. Additionally, unlike rigid barrier types such as concrete longitudinal barriers, cable barriers typically take on damage when struck. This damage most commonly comes in the form of broken posts which need to be replaced following crashes by highway maintenance staff.

With significant research already having been done on the “proof-of-concept” of cable median barriers, much is known on the fundamental benefits of roadside systems. However, a number of specific questions still remain. First, high-tension cable median barriers used in the U.S. are currently produced by one of five predominant manufacturers. A research project recently completed by the Wisconsin Traffic Operations and Safety (TOPS) Laboratory sought to evaluate barriers produced by each manufacturer and compare/contrast their performance under a variety of conditions (*6*). Additionally, safety performance functions dealing with median-related crashes do not currently exist in the present incarnation of the *Highway Safety Manual* (HSM) (*7*). This issue, however, is currently being addressed as a part of a National Cooperative Highway Research Program (NCHRP) study

22-21 “Median Cross-Section Design for Rural Divided Highways” (*8*). Detailed analyses of crashes with cable median barriers, however, are less numerous and thus a potential research topic arises. Specifically, the issues of factors affecting crash severity and crash outcome (i.e., manner of interaction between the vehicle and cable barrier) are less well understood. Additionally, the interaction of heavy vehicles (HVs) and cable median barriers is an issue that needs to be addressed. Currently, cable median barriers are not designed to protect against crashes with heavy vehicles (*3*, *9*). There is, however, a possibility that they still can mitigate crashes with heavy vehicles and that guidance based on crash tests may be overly conservative. Therefore, research is needed to examine the aforementioned issues and factors in order to more fully understand the nature of cable median barrier crashes.

1.3 Research Objectives

The objectives of this thesis research were as follows:

- Examine characteristics of crashes with high-tension cable median barriers to look for preliminary trends;
- Compare performance between barriers with different numbers of cables in their cross-sections;
- Study factors affecting crash outcome for cable median barrier crashes;
- Examine barrier containment behavior and the factors that influence it;
- Analyze the issue of cable barrier breaches including factors affecting propensity to be breached and overall breach severity; and
- Study factors affecting crash severity for cable median barrier crashes.

In the aforementioned investigations of crash severity, severities of cable barrier crashes were reported according to the following scale that is used in this thesis:

- K – fatality;
- A – incapacitating injury;
- B – non-incapacitating injury;
- C – possible injury; and
- PD – property damage only.

1.4 Research Scope

Crash data collected in the State of Wisconsin from January 1st, 2009 through December 31st, 2013 serve as the primary data source for this study. All data collected involve crashes that took place on the Wisconsin State Trunk Network (STN) Highway System. For this thesis, a total of 16 study sites with high-tension cable median barrier installations were investigated. All study sites were on interstate (IH) or U.S. Highways (USH). A state map showing the study sites as well as a table showing the type(s) of barrier in use at each study site are presented in Figure 1 and Table 1, respectively. In Table 1, the notations "TL" is used to denote Test Level according to the American Association of State and Highway Transportation Officials' (AASHTO) *Manual for Assessing Safety Hardware* (MASH) (*9*). Additionally, the notation "str" is used to abbreviate "strand," or the number of cables used in the barrier cross-section. Table 1 shows that barriers examined in this study had either three or four cables (strands) in their cross-sections. At least one study site was selected from each of the Wisconsin Department of Transportation's (WisDOT) five regions.

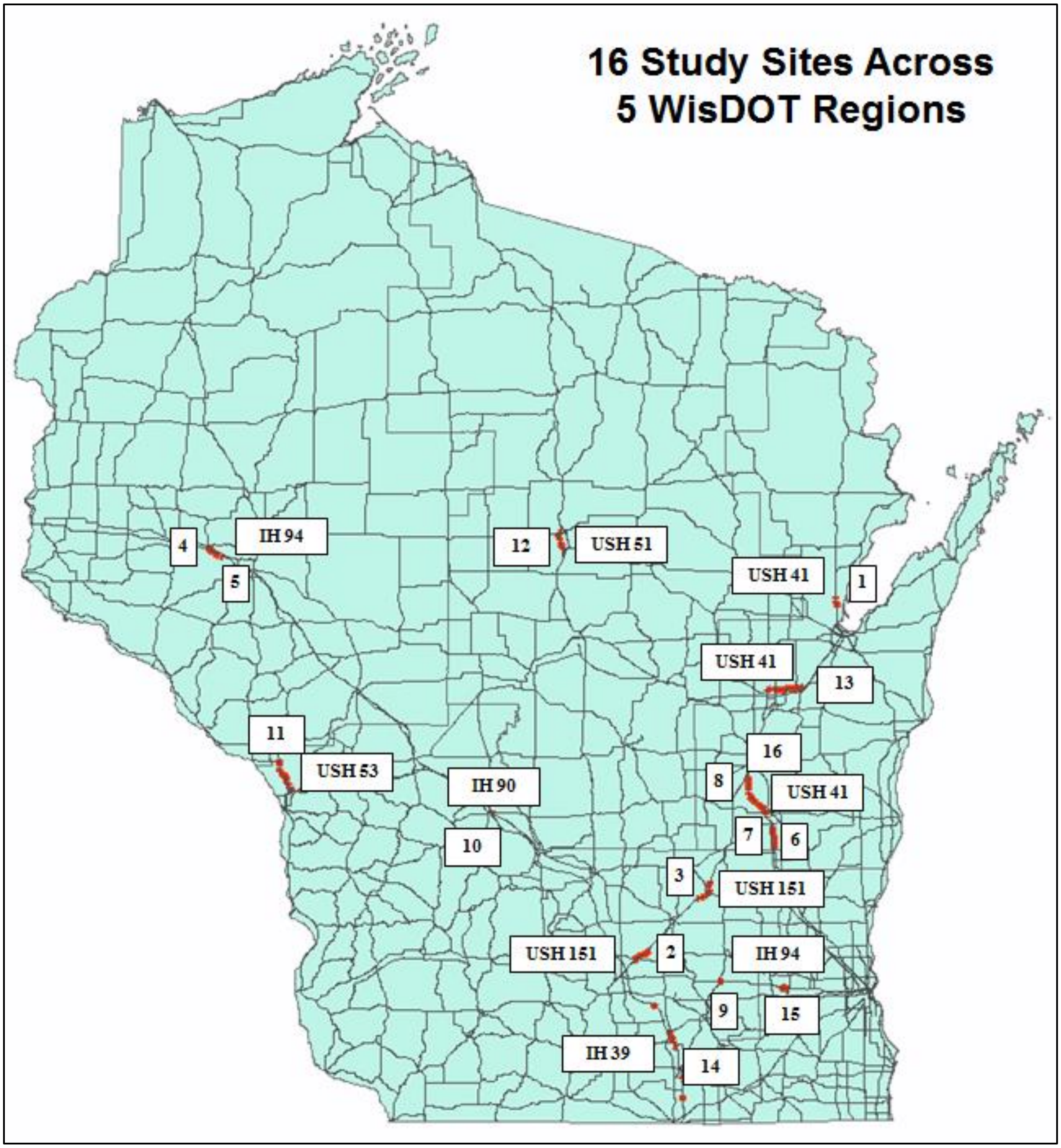

Figure 1 Map of Study Sites

Table 1 Study Sites and High-Tension Cable Median Barrier Systems Used

Study Site	County	Barrier Manufacturer	Barrier Type
1	Brown/Oconto	CASS	TL-3, 4-str, 15" low cable
2	Dane	CASS	TL-3, 3-str, S4-post
3	Dodge	Brifen	TL-4 as TL-3, 4-str
4	Dunn	Gibraltar	TL-4 as TL-3, 3-str
5	Eau Claire	Gibraltar	TL-4 as TL-3, 3-str
6	Fond du Lac	Brifen	TL-3, 4-str
		CASS	TL-3, 3-str, C-post
7	Fond du Lac	Brifen	TL-3, 4-str
		CASS	TL-3, 3-str, C-post
8	Fond du Lac	Brifen	TL-3, 4-str
		CASS	TL-3, 3-str, C-post
9	Jefferson	Gibraltar	TL-3, 3-str
10	Juneau	Safence	TL-3, 4-str
11	La Crosse	CASS	TL-3, 3-str, S4-post
		NUCOR	TL-3, 3-str
12	Marathon	Brifen	TL-3, 4-str
		Safence	TL-3, 4-str
13	Outagamie	NUCOR	TL-4, 4-str, 15" low cable
14	Rock/Dane	Gibraltar	TL-3, 3-str
		Safence	TL-3, 4-str
15	Waukesha	Gibraltar	TL-3, 3-str
16	Winnebago	CASS	TL-3, 3-str, C-post

1.5 Thesis Organization

The research topic and overall thesis are broken down into five main chapters. The motivation for the research and issues to be addressed are covered in the introduction in Chapter One. Chapter Two presents a comprehensive literature review of cable median barriers, their usage, and cable median barrier safety issues. Analysis methodologies used in later sections are also presented in Chapter Two. Chapter Three lays out the study design including the research tasks and data collection and processing methods. Chapter Four presents the core analysis of the thesis and addresses each of the aforementioned research objectives. Finally, conclusions based upon results of the analysis are drawn in Chapter Five.

2 LITERATURE REVIEW

2.1 Background

2.1.1 Cross Median Crashes and Cable Barriers

Typically, CMCs are quite severe due to the nature of the crash creating the possibility of a head-on collision (*3*). Chitturi et al. (2011) identified a total of 291 such crashes to have occurred in Wisconsin between 2001 and 2007. Of these crashes, 22 percent were fatal, 59 percent involved injuries to participants, and 19 percent involved property damage only (PDO). On average, 4.22 participants were found to be involved in a typical fatal CMC in Wisconsin, 1.32 of whom were killed. The average total cost of a fatal CMC in Wisconsin (in 2009 dollars) was found to be $4,303,057 through the use of data from the Crash Outcomes Data Evaluation System (CODES) (*10*).

The CMC issue was evaluated on a national level by the Federal Highway Administration (FHWA) via a survey of more than 25 states in 2004. The survey found a high proportion of fatal CMCs resulted from vehicles fully traversing medians wider than 30 feet (9.1 meters). Nearly two thirds of the CMCs took place over medians that were less than 50 feet (15.2 meters) wide. Nationally, guidance on the usage of safety treatments to help prevent CMCs, including high-tension cable median barriers, can be found in the *Roadside Design Guide* (RDG) published by AASHTO (*4*).

2.1.2 Guidance for Installation of Cable Barrier

In order to provide guidance on the design and implementation of roadside safety hardware, including cable barriers, AASHTO began publishing the *Roadside Design Guide* in 1989. The most recent edition was published in 2011 and has an entire chapter (i.e., Chapter Six) covering various types of median barriers including cable median barrier and W-beam barrier. According to the RDG, 80 percent of motorists departing the traveled way to the left (i.e., toward the median) could recover at or before a distance of 30 feet (9.1 meters) from where they departed. Thus, many designers felt installing median barriers in medians that were wider than this maximum recovery distance of 30 feet (9.1 meters) was unnecessary. However, increasing numbers of CMCs experienced by states in the 1990s changed this belief. As a result, policies were put in place by some states under which median barriers could be installed in medians up to 75 feet (22.9 meters) in width (*4*).

Chapter Six of the RDG provides guidance on when to install a barrier. Information presented in the RDG give guidance on whether a median barrier is recommended for installation, considered for installation, or could be optionally installed according to median width and average daily traffic (ADT). Specifically, median barriers are recommended when the median is less than 30 feet (10 meters) wide and ADT is greater than 20,000 vehicles per day (vpd). Barriers may be considered when median width is between 30 and 50 feet (10 to 15 meters) and ADT is greater than 20,000 vpd. Barriers are optional under the following criteria (*4*):

- Median width is less than 50 feet (15 meters) and ADT is less than 20,000 vpd; and
- Median width is between 50 and 70 feet (15 to 21.3 meters); ADT is not considered an influencing factor in this instance.

In the State of Wisconsin, Chapter 11 of the *Facilities Development Manual* (FDM) includes discussion of warranting criteria for median barrier installation which is primarily based on preventing CMCs. Figure 2 (FDM Attachment 2.10) shows the pairings of design ADT values and median width that warrant a median barrier to be installed on new freeway construction projects. The FDM states that, "Attachment 2.10 is a warrant for installing median barrier on new freeway. It may not be appropriate to use this warrant to install barrier on new expressways. The need to have access for cross roads is not taken into account with this warrant (e.g. intersection spacing, sight distances…). For situations other than new freeway construction, evaluate the need for median barrier on a case-by-case basis" (*11*).

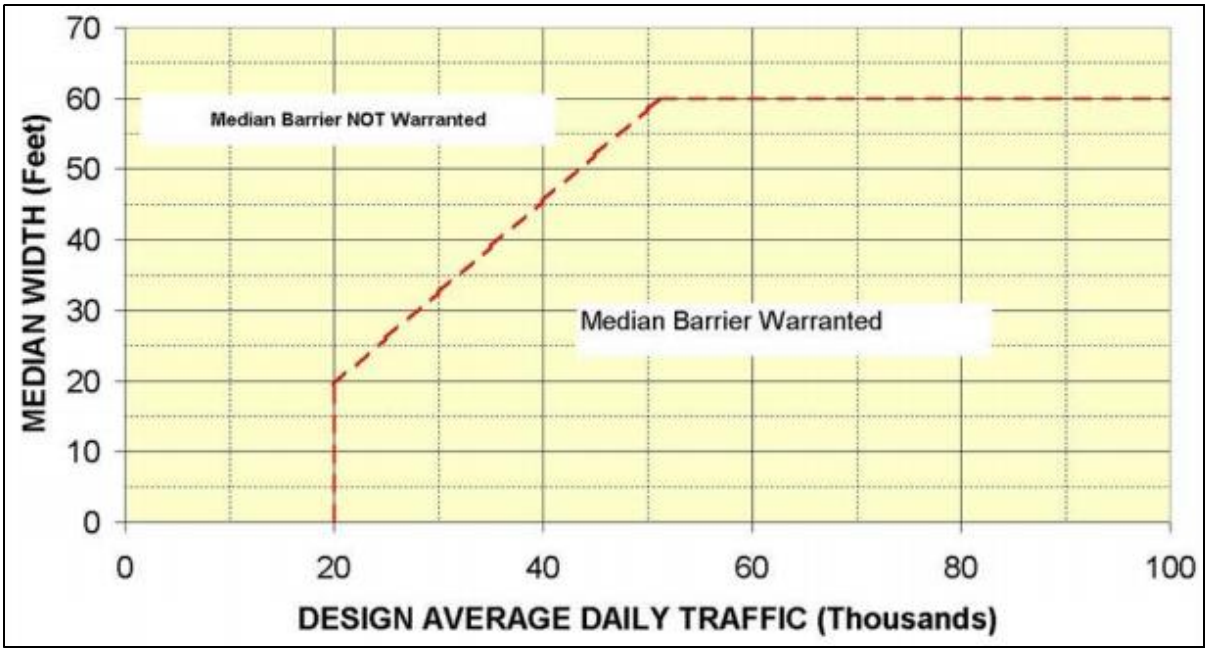

Figure 2 Median Barrier Warranting Criteria for New Freeway Construction (*11*)

2.1.3 Types of Cable Barrier

Currently, there are two main types of cable barrier systems in use: high-tension systems and low-tension systems. The following sections briefly explain key characteristics of each.

<u>2.1.2.1 Low-Tension Cable Barriers</u>

Low-tension cable barriers have been in existence since the 1960s when they were introduced by the New York Department of Transportation (*12*). The low tension maintained in the cables is transmitted to the cables via springs at the anchors on both ends of the run. The tension is sufficient to keep the cables elevated above the ground and prevent excessive sagging (*13*). Under the "National Cooperative Highway Research Program (NCHRP)

Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features" test scenarios, the low-tension cable can deflect up to 11.2 feet (3.4 meters) laterally upon vehicle impact. Therefore, state agencies often allow for up to 12 feet (3.7 meters) of deflection for low-tension cable barriers. The lateral space needed for deflection necessitates a median width of no less than 24 feet (7.3 meters) to minimize the chances of vehicle striking the barrier reaching the opposing traveled way following barrier deflection (*4*).

2.1.2.2 High-Tension Cable Barriers

High-tension cable barriers, as shown in Figure 3, can experience lower deflections upon impact than their low-tension counterparts. Typical deflections for high-tension cable barrier systems can range from 6.6 feet (2 meters) to 9.2 feet (2.8 meters) which allows for them to be used in narrower medians compared with low-tension barriers (*4*).

Average tension maintained in high-tension cables can vary between two and nine kips (approximately nine to 40 kilonewtons). Tension in the cables is set based upon ambient temperature at the site (*13*). The increased tension in high-tension cable barrier systems also makes the barrier sustain less damage than low-tension barriers when being struck. In some cases, the cables are able to be maintained at their correct heights following a crash that causes damage to the weak posts in the system (*4*). The increased tension allows the barrier systems to span longer distances than low-tension systems (*13*).

Figure 3 High-Tension Cable Median Barrier System (*14*)

2.1.3 Sideslope Requirement for High-Tension Cable Barrier

Maximum grades of sideslopes on which cable median barriers can be used are outlined in NCHRP Report 350 and MASH (*9, 15)*. High-tension cable median barrier systems in use today meet NCHRP Report 350 Test Level 3 (TL-3) or Test Level 4 (TL-4) criteria. Sideslopes are commonly presented in the form of a ratio XH:YV, where "XH" represents the number of horizontal units of distance change per "YH" units of vertical distance change. Depending on the Test Level, the cable barrier system can be installed on a median sideslope of 6H:1V or flatter. In certain instances, the systems can be installed on slopes as steep as 4H:1V. In these cases, a TL-4 system may be regarded to only meet the TL-3 criteria due to changed vehicle behavior on steeper grades. When installed on the 4H:1V slopes, the barrier must be installed at most 4 feet (1.2 meters) down the slope and at least 9 feet (2.7 meters) from the ditch centerline. Further discussion and guidance for barrier placement on slopes with respect to barrier performance is presented in the *Roadside Design Guide*, NCHRP Report 711, and a 2007 Memorandum from FHWA (*4, 5, 16*).

2.1.4 Placement of High-Tension Cable Barrier to Prevent Override and Underride

The location in the median where the barrier is installed is crucial and should be determined to reduce the likelihood of vehicle override and underride when vehicles hit the barrier. When determining the location, consideration must be given to the vehicle dynamics associated with each scenario. A vehicle can override the barrier system by leaving the traveled way, traveling over the hinge point in a depressed median, becoming airborne, and traveling over the uppermost cable in the barrier system. Underriding the system happens when the vehicle leaves the traveled way, enters the median, traverses the hinge point and ditch centerline, and lands on the opposing sideslope. In the underriding scenario, the vehicle's compressed suspension leads the vehicle to have a lower effective height than normal, allowing the vehicle to travel under the lowest cable in the system. In the overriding and underriding scenarios, the vehicle may not become fully airborne upon traversing the hinge point, but rather experience a reduced compressive loading on the suspension system (*5*). The RDG notes that on 6H:1V slopes, reduced chances of override or underride were observed when the barrier was not installed in the range of 1 (0.3 meters) to 8 (2.4 meters) feet from the centerline of the ditch (*4*).

2.1.5 Crash Testing Standard for Cable Barriers

In order to evaluate the performance of roadside hardware, such as cable median barriers and determine if these devices are cost-effective, full-scale crash testing is one of the most effective methods. Since the early 1960s, guidelines for crash tests have been in existence. These guidelines have evolved over time due to changes in technology and types of vehicles on the roadway (*15*). In 2009 AASHTO's MASH was published as the new standard for procedures for full-scale crash testing of safety hardware. MASH was developed to replace NCHRP Report 350, which had been the standard reference document for the aforementioned tasks since 1993 (*9*). Procedures outlined in MASH are used to determine what Test Level safety hardware including cable barriers adheres to. A few main points of the crash testing process are:

1) Devices tested are evaluated based on three main criteria: "structural adequacy," "occupant risk," and "after-collision vehicle trajectory." Structural adequacy defines how well the device performs the intended job of interacting with the vehicle (i.e., stopping, redirecting etc.). Occupant risk is based upon measurements of velocity that a crash participant who is not wearing a seatbelt will impact specific parts inside the vehicle. Higher velocities indicate a greater risk to the occupant's well-being. After-collision vehicle trajectory considers the path of the vehicle following a collision and involves consideration of how likely the vehicle is to crash into other vehicles (*15*).

2) A tested device can be assigned to one of six Test Levels, i.e., one through six. Each Test Level considers factors during the collision such as speed and angle, as well as type of vehicle involved in the collision. Many types of devices which have different applications and purposes can fall under the same Test Level. In cases when a device meeting TL-3 criteria is to be used, selection of what type of device to deploy often depends on the vehicle type(s) the device is intended to shield from the hazard. Additionally, choice of devices from TL-1 to TL-3 categories can be based on speed, although TL-1 devices are rarely used (*15*).
3) Changes in crash test guidelines often arise as a result of changes in vehicle designs and sizes over time. For example, FHWA has noted that increases in the heights of bumpers on light trucks and overall increases in vehicle size have necessitated the updates of NCHRP Report 350 seen in MASH (*9*). Similar to NCHRP Report 350, guidelines in MASH do not take precedence over any provisions of the AASHTO *Roadside Design Guide*. Any devices being developed prior to the publication date of MASH were still allowed to be tested following the provisions outlined in NCHRP Report 350. Any requests sent to FHWA for approval of new or updated devices tested under NCHRP Report 350 were no longer heard as of January 1, 2011. Any devices conforming to criteria in NCHRP Report 350 can, however, still be used, produced, and installed (*9*).

A sample of the changes to provisions in NCHRP Report 350 appearing in MASH is as follows (*9*, *17*):

- The weight of the small car test vehicle was increased from 1,800 pounds to 2,420 pounds;

- The small car impact angle was increased from 20 to 25 degrees;
- The weight of the light truck test vehicle was increased from 4,400 pounds to 5,000 pounds;
- Windshield damage criteria is now objective and quantifiable; and
- Rebound of vehicles is mandated in crash cushion tests.

2.2 National Practice of Cable Median Barrier Systems

2.2.1 Cable Barrier Usage in the United States

In 2008, a survey was sent out to state agencies to gather information on the level of cable barrier usage across the country. In addition, another purpose of the survey was to learn about different states' guidelines that govern the design and construction of cable barrier systems as part of "NCHRP Report 711: Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems." By 2010, 40 states had responded to the survey. Review of the responses showed that three of the 40 states did not have any cable barrier systems in place, while 15 states had more than 100 miles of cable barrier in place. According to the report, 58 percent of the cable barrier systems in place were high-tension, while 35 percent were of the non-proprietary low-tension variety; the seven percent not encompassed in either of these categories was classified as "other." The majority (79 percent) of cable barriers were three-cable systems, while the other 21 percent were four-cable systems. Survey results also showed that 70 percent of the barriers installed met the requirements for TL-3, while the other 30 percent met the requirements for TL-4 (*5*).

Another part of the survey focused on gathering information on the geometry of the medians in which the cable barrier systems were used. The most common slope conditions, found at 55 percent of installations, were 6H:1V side slopes. The steepest sideslope conditions reported were 4H:1V for 11 percent of the installations. The most gradual sideslope conditions reported were 10H:1V for eight percent of installations. The shape(s) of medians in which the cable barrier systems were installed included V-shaped, flat-bottom, rounded-bottom, non-symmetric, and “other.” The most popular shape was the V-shaped median. Approximately half of the responding states (21 out of 40) noted that they install cable median barriers in V-shaped medians with 6H:1V sideslopes. The minimum reported median width in which a cable barrier was installed was 12 feet (3.7 meters), while the maximum width was 104 feet (31.7 meters). A few states reported installations in medians having a width less than 10 feet (3 meters). However, these responses were regarded as outliers. The average median width for 6H:1V sideslopes was 46 feet (14 meters) (*5*).

Warranting conditions for the installation of cable barriers were also investigated in the survey. Based on the survey results, the two most popular warranting factors for cable barrier installation in a median were identified to be (*5*):

1) Width of the median; and
2) Crash history.

The choice to use a cable barrier system over a rigid or semi-rigid system was primarily due to the width of the median (57.5 percent of the states) and the cost of the system (52.5 percent of the states). Approximately half of the respondent states noted that agencies did have design standards for cable barriers such as requiring testing of median soil to ensure the soil and other materials meet certain criteria. The presence of construction guidelines for cable barrier systems was noted by 75 percent of states. Maintenance guidelines for tasks such as adjusting cable tension and inspecting anchors, however, were only seen in 45 percent of states (*5*).

2.2.2 Evaluations of Cable Median Barrier by State

Cable barrier systems have been studied with respect to safety performance throughout the United States. A summary of key national studies are presented in the following sections.

2.2.2.1 Wisconsin

In 2010, the Wisconsin TOPS Laboratory published the Phase I report on the evaluation of high-tension cable barriers in Wisconsin. A total of four types of cable median barrier systems were evaluated between 2003 and 2008, three of which were of the high-tension variety and the fourth of which was of the low-tension variety. The high-tension barrier types included the Brifen TL-3, 4-str barrier, the CASS TL-3, 3-str C-post barrier, and the Gibraltar TL-3, 3-str barrier. The low-tension system evaluated was of the generic variety. Cable barrier systems were evaluated in terms of their safety and maintenance performance. For the safety evaluation, the simple before-after methodology was used. The primary goal of the report was to determine if cable barriers were effective; hence, less emphasis was placed on comparing different types (*3*).

Upon examining the after period crash data, Qin et al. found that the frequency of lower-severity crashes (typically property damage (PD) crashes) increased following the installation of cable barrier. Further, crash severity decreased following cable barrier installation. Zero fatalities and only one incapacitating injury were observed across all study sites in the after analysis period. In terms of containment performance, the three high-tension cable barrier systems were observed to have successfully stopped between approximately 70 and 80 percent of the vehicles that struck the barriers (*3*).

The maintenance evaluation compared cable barrier systems in terms of repair costs, number of posts destroyed per crash, and number of man-hours needed per repair. In terms of these three metrics, there was no large difference in performance between the three high-tension systems (*3*).

2.2.2.2 National Studies

Ray et al. studied safety performance and state policies on cable barrier usage and installation for a total of 23 states (*18*). The study analyzed composite data on the number of CMCs prior to and after installation, as well as the percent reduction observed. Analysis on the number of cable barrier crashes and the number of penetrations experienced showed that all examined states experienced a decrease in the number of CMCs by 40 to 100 percent following cable median barrier installation. Ray et al. also discussed how to examine safety and crash data carefully and realize the sources of possible error and associated variation between states. In summary, sources of potential inaccuracy, which can make comparisons difficult include (*18*):

- The source of the data and the method through which the data were collected;
- The format of the crash reports examined;
- The amount and accuracy of the information on the crash reports examined;
- Failure of some jurisdictions to record incidents in which the median is traversed by the errant vehicle, but the vehicle is ultimately not involved in a crash with another vehicle;
- Failure of some jurisdictions to record crashes where the barrier is penetrated, but the vehicle does not come to rest in the opposing direction traveled way; and
- The methods used to summarize crash data.

Stolle et al. (2012) investigated cable median barrier failures with crash data obtained from 12 states including Illinois, North Carolina, Ohio, Oklahoma, and Wisconsin among others. The data spanned various periods between 1996 and 2010. One part of the analysis involved comparing several proprietary high-tension cable barrier systems and reporting on penetration, rollover, and fatal/severe crash statistics for each system. Data were combined from multiple states and values were only computed if there were at least 200 crashes for the given barrier type/crash type pair. Penetration rates were fund to be similar for the two barrier types for which they were computed and ranged from 8.9 to 9.1 percent. Rollover rates for cable median barrier crashes ranged from 3.2 to 4.9 percent (*19*).

2.2.2.3 Florida

Alluri et al. (2012) analyzed cable median barrier performance in Florida. At the time of study, the Florida Department of Transportation (FDOT) had five different types of high-tension cable median barrier installed including Brifen WRSF, Safence 350 Wire Rope Barrier, Nucor High Tension Cable Barrier, Trinity Industries Cable Safety System, and Gibraltar Cable Barrier System. The study focused on installations of all of the aforementioned types with the exception of Nucor and consisted of two main components: a crossover analysis and a simple before-after study. The crossover analysis took into account 23 study sites with a total of approximately 100 miles of high-tension cable barrier installed and examined crash data between (and including) the years of 2003 and 2010. For the before-after study, all reports for crashes occurring in the study period were reviewed manually in order to extract only the median-related crashes. A median-related crash was defined as one in which the vehicle departs the traveled way in the direction of the median (*20*).

Manual review of crash reports found 549 crashes in which a vehicle hit a cable median barrier during the study period across all study sites. Overall, 83.6 percent of these crashes involved vehicles being stopped or redirected by the barrier while 16.4 percent of crashes involved breaching the barrier. Of the 16.4 percent of total barrier crossover crashes, 2.2 percent involved the vehicle traveling under the cables (underriding), 37.8 percent involved the vehicle traveling over the cables (overriding), and 32.2 percent involved vehicles breaking through the cables (penetration). A total of 2.6 percent of all crashes were classified as median crossover crashes in which the vehicle crossed over the median and entered the opposing direction traveled way. Barrier collisions resulted in property damage only in 58.7 percent of crashes, yet 5.8 percent of the crashes did result in a fatality or incapacitating injury (*20*).

For the before-and-after study, three of the original 23 sites were selected for analysis, all of which had cable barriers installed between 2005 and 2007. The "before" and "after" periods were between 28 and 36 months in length. A total of 744 valid median-related crashes were identified. Examination of after period crash data showed that following the installation of cable median barrier, a 42.2 percent reduction in fatal crash rate at the study sites was observed. Incapacitating injury and non-incapacitating injury crash rates were also shown to decrease by 20.1 percent and 11.6 percent, respectively. The crash rate for property damage only crashes was found to increase by 88.1 percent, while the crash rate for possible injury crashes also increased by 53.1 percent (*20*).

2.2.2.4 Missouri

The Missouri Department of Transportation (MoDOT) has been installing cable median barriers along Missouri highways since 1980. The impetus for increasing the scale of installation was a project initiated by MoDOT that involved researching ways to help decrease the occurrence of CMCs. As a result of this project, MoDOT went forward with installing cable median barrier systems on portions of Interstate 70 and other Interstate highways that had experienced high numbers of CMCs. Following the initial installations, MoDOT began to implement cable median barrier systems on a larger scale on sections of Interstate highways that carried the highest volumes in the state in addition to having extensive CMC histories. This increased use began in the mid 1990's (*13, 21*). One example of the broader implementation, reported by Chandler, began in 2002, a year in which there were 24 fatalities on Interstate 70 resulting from crashes in which a vehicle crossed over the median. In 2002, there were a total of 18 miles of cable median barrier installed on I-70 in Missouri. By the end of 2006, MoDOT had a total of 179 miles of cable median barrier installed on this Interstate highway, which experienced two cross-median related fatalities that year. Thus, there was a 92 percent reduction in accidents involving a vehicle crossing the median that resulted in a fatality between 2002 and 2006. In 2007, MoDOT noted that the State of Missouri would have almost 500 miles of cable median barrier installed on the state's highways prior to the start of 2009. The type of barrier (i.e., high- or low-tension and specific manufacturer), however, was not specified in the aforementioned report by Chandler (*21*).

2.2.2.5 North Carolina

The North Carolina Department of Transportation began installing cable median barriers in 1994 as a response to an identified cross-median crash problem on a portion of Interstate 40. In 1999, Hunter et al. published a comprehensive study evaluating the installation of a three-strand generic low-tension cable median barrier system at several locations across the state (*22*). More recently, however, the North Carolina Department of Transportation (NCDOT) has presented the findings of a long term evaluation of median barriers in North Carolina.

Starting in 1998, NCDOT initiated a project to decrease both the number and severity of CMCs occurring in North Carolina. The project consisted of three main phases (*23*):

- Phase I: Install median barriers on freeway sections with a history of CMCs;
- Phase II: Install median barriers on freeways with median widths of less than or equal to 70 feet in an orderly manner; and
- Phase III: Modify existing design standards to ensure median barriers are implemented on planned freeways with medians that are less than or equal to 70 feet in width.

Prior to defining the phases, the scope of CMCs and their effects across the state was analyzed by examining more than 10,000 individual crashes that took place on North Carolina freeways between 1994 and 1997. Of these crashes, more than 1,000 "across median crashes" were discovered to have occurred. By the spring of 2004, 58 median barrier projects outlined in the 2000-2006 NCDOT Transportation Improvement Program (TIP) had been constructed or let for bid (*23*).

The project to prevent CMCs and reduce their severity involved installation of not only cable median barrier, but also other types of median barrier such as W-beam barrier. One goal of the long-term evaluation was to conduct a before-after crash study focusing on each median barrier type and including at least three years of crash data in the period after the barrier system was installed. In the evaluation, crash data from a total of 175 miles of freeway with cable median barrier installations (the type of which was not specified) was analyzed. The before period for the cable barrier evaluation was 6.69 years in length and the after period was 3.61 years in length. In the before period, approximately 54 CMCs occurred per year, with approximately three per year resulting in a fatality. In the after period, approximately 21 CMCs were observed per year, one of which was fatal. Additionally, 32.6 percent of the total number of observed crashes in the after period involved a vehicle colliding with a cable barrier. In approximately 4.5 percent of these crashes, the vehicle passed through the barrier, often via underride. As was the case observed in many other studies, the number of property damage crashes increased after barrier installation, in this case by approximately 126 percent. Finally, the study reported that the average crash severity for a median barrier crash was 1.31 on a scale of one to five where one represented a property damage only crash and five represented a fatal crash. As a basis for comparison, the average crash severity for W-beam barriers was found to be 1.63 (*23*).

2.2.2.6 Ohio

Safety performance of the Brifen WRSF TL-3, four-cable system was evaluated by the Ohio Department of Transportation (ODOT) for a three year period between July 2003 and June 2006. In 2003, installation of a Brifen cable median barrier system was completed a 14.5 mile segment of Interstate 75 near Cincinnati. After the barrier’s installation, the total number of crashes on the segment per year increased by at most 10 percent beyond the total number of observed crashes in each of the three years prior to installation of the barrier; these comparisons did not include any hit-and-run crashes in which a vehicle struck a cable barrier. In each of the three years in the after period, between 22 and 23 percent of the yearly total number of crashes occurring on the 14.5 mile segment with the cable barrier installed were crashes in which a vehicle struck the cable barrier (*24*).

In total, the cable barrier system was struck a total of 354 times during the three year study period. Although the barrier was penetrated 13 times in total, none of these crashes were fatal CMCs nor did they all even result in a CMC. A total of 11 percent of the cable barrier crashes were determined to have resulted in injuries, 64 percent of which were classified as resulting in a non-incapacitating injury. The other 46 percent were either classified as possible injury or unknown injury. Of the 354 recorded cable barrier collisions in the three year after study period, a subset of 256 crashes, for which pavement condition at the time of the accident was known were also examined to study the influence of weather on cable barrier crashes. Of these 256 crashes, 56 percent were observed to have taken place when the pavement was wet, snow-covered, or ice-covered (*24*).

The effects of barrier placement location in V-ditches with a range of sideslopes (less than 10H:1V to greater than 6H:1V) was investigated with the crash data from Ohio by Stolle et al. (2013). The percentage of median barrier crashes that penetrated the cable median barrier was observed to be greatest when the barrier was installed in the center of the median (14.8 percent), as opposed to either side of the median centerline, regardless of sideslope. The percentage of vehicles penetrating the barrier was smallest (8.5 percent) when the vehicles hit a barrier placed on the far side of the median (i.e., the side of the median opposite from the traveled way departed by the errant vehicle). The total percentage of rollover crashes was also observed to be the smallest when the barrier was installed in the center of the median (2.3 percent) and greatest (3.8 percent) when vehicles hit a barrier on either side (i.e., near or far) of a median (*19*).

2.2.2.7 Tennessee

Median cable barrier installations (the exact type of which is not noted) in Tennessee were evaluated in terms of safety by Chimba et al. in 2012. The study focused on a total of 27 segments with cable barrier installations along Interstates 24, 26, and 40 that comprised a total of 14.41 miles in length. The number of median-related crashes in a three year before period (2003-2006) and a three year after period (2006-2009) were evaluated to find any changes in crash severity following cable barrier installation. Median-related crashes were defined to include fixed-object collisions in the median, cable barrier crashes, roll-over crashes in the median, and median crossover crashes. For this simple before-and-after component of the study, a total of 507 crashes were found to have occurred across all of the study sites in the before period, while a total of 639 crashes were found to have occurred in the after period. These sets were filtered via manual review of the crash reports to select only median-related crashes that involved a fatality or injury and resulted in only 24 percent of the initial set of crashes being selected. Property damage only crashes were not examined in the filtering process. An Empirical Bayes (EB) analysis to determine the safety effectiveness of cable barrier installations before and following their installation was also performed (*25*).

Results of the simple before and after study are detailed in the following. After cable median barrier installation the number of fatal crashes experienced across all study sites had decreased by four (80 percent) and the number of fatalities had decreased by seven (87.5 percent). Additionally, the combined number of crashes involving fatalities and injuries decreased following the installation of the cable median barriers by nearly 21 percent. Observation of the study segments individually found that one out of the 27 segments showed an increase in fatal crashes, while eight of the 27 segments were observed to have experienced an increase in the total number of injuries. Finally, the number of PDO crashes was found to have increased by 39 percent in the after period. However, the numbers of PDO crashes given refers to all PDO crashes occurring in the study site areas and not those that are exclusively median-related (*25*).

For the EB analysis, Chimba et al. computed safety effectiveness for the cable barrier installations. Safety performance functions (SPFs) developed using coefficients from the HSM that were calibrated on national data, as well as coefficients calibrated specifically to Tennessee study site data were used. When examining the data across all study sites and using coefficients in the safety performance function based upon the study site data, installation of the cable barriers led to a 93 percent reduction in the frequency of median-related crashes resulting in a fatality when compared to what was expected had the barriers not been installed at all. Similarly, the frequency of crashes resulting in a fatality or injury was found to be 51 percent lower in the after period than expected. Results of the EB analysis performed with both HSM and study-site-specific coefficients can be seen in Table 2, where each value corresponds to the percent reduction in crash frequency observed in the after period compared to what was expected had cable median barriers not been installed. Six out of the 27 did exhibit a negative percentage for crash frequency reduction between the before and after periods compared to what was expected if the barriers were not installed. This negative percentage corresponds to an increase in crash frequency between the before and after periods (*25*).

Table 2 TN Cable Median Barrier Effectiveness

Crash Type(s)	**HSM Coefficients**	**TN Data Coefficients**
K Crashes Only	98%	93%
K & A Crashes Only	83%	85%
K, A, & B Crashes	55%	51%

2.2.2.8 Washington State

The Washington State Department of Transportation (WSDOT) has been installing cable barrier since 1995. They have, however, stopped installing generic low-tension barrier as of 2005. Between 2007 and 2009, WSDOT released three reports on the cable median barrier program as a whole that included information on barrier performance as well as discussion of cable barrier policy recommendations. According to the 2009 report, WSDOT had 181 miles of cable median barrier in place prior to 2009, 140 of which were high-tension installations. For this and the two previous reports, WSDOT examined barrier performance via a before-after comparison of crashes. The 2009 report examined a period five years prior to cable barrier installation as the basis for comparison against the period after the barrier was installed (i.e., through the end of 2008). The focus of the study was defined to be “median collision experience” and crash reports filled out by police were manually reviewed in order to gather relevant, median-related crashes for the study. According to the report, this review process was only used to examine crash reports involving a fatality or serious injury since 2000. Finally, WSDOT noted that the number of median-related crashes reported in the before period is likely an underrepresentation of the actual number. This is due to difficulty in identifying certain types of median-related crashes as a consequence of the way in which crash data is gathered and maintained (*26*).

WSDOT noted that between 2000 and 2008 there was a 58 percent decrease in the number of collisions resulting in a fatality or serious injury that took place in the median, or as a result of a vehicle crossing the median. A decrease in the number of cross median crashes of approximately 61 percent was observed following cable median barrier installation. As aforementioned, performance of cable barrier was compared to that of other barrier types. In terms of injury severity, approximately 20 percent of the collisions with a cable median barrier led to a fatality or injury. Crashes in which a vehicle struck beam guard or a concrete median barrier were found to lead to an injury or fatality in approximately 37 and 39 percent of the observed cases, respectively. Although cable median barrier was observed to perform better than concrete barrier with respect to injury severity, cable barrier was found to perform slightly worse than concrete barrier with respect to the percentage of vehicles prevented from crossing the median. High-tension cable barriers were found to stop or redirect vehicles 96.3 percent of the time, while concrete barrier was found to stop or redirect vehicles 97.8 percent of the time. Observation of crash data showed, however, that upon impact concrete barrier led to vehicles being stopped within the median 34 percent of the time, while impacts with cable barrier resulted in the impacting vehicle remaining in the median approximately 79 percent of the time. Although the percentage of vehicles redirected by concrete barrier is much higher than for cable median barrier, concrete barriers are typically used in narrower medians than where cable barrier is installed. Hence, vehicles that strike the barrier have less median area in which to come to a stop and less distance to travel upon rebounding off the barrier to return to the travel lanes (*26*). Key findings of the Washington State study as well as key findings from other aforementioned states are summarized in Tables 3 and 4. Table 3 contains summary information on crash severity, frequencies, and rates by different states. Table 4 contains information on barrier containment performance and breaches by different states. Not all studies covered barrier containment; hence, only those that did are listed in in Table 4.

Table 3 Summary of Key Crash Severity, Frequency, and Rate Findings by State

State	**Years**	**Key Findings**
Florida (*20*)	2003-2010	42.2% reduction in fatal crash rate was observed. Incapacitating injury and non-incapacitating injury crash rates also decreased by 20.1% and 11.6%, respectively. 88.1% increase in PDO crash rate.
Missouri (*21*)	2002-2006	A 92% reduction fatal CMCs was observed between 2002 and 2006.
North Carolina (*23*)	2000-2006	In the before period, an approximately 54 CMCs occurred per year (~3/year fatal). In the after period, approximately 21 CMCs were observed per year (1 fatal).
Ohio (*24*)	2003-2006	11% of crashes with the barrier resulted in an injury (64% of these were classified as non-incapacitating).
Tennessee (*25*)	2003-2009	An 80% decrease in fatal crashes was observed following barrier installation. The frequency of crashes resulting in a fatality or injury was found to be 51% lower in the after period than expected.
Washington (*26*)	2000-2008	58% decrease in the crashes resulting in a fatality or serious in the median, or as a result of crossing the median. 61% decrease in CMCs was observed following barrier installation.
Wisconsin (*3*)	2003-2008	Frequency of PDO crashes increased and crash severity decreased following the installation of cable barrier. Zero fatalities and one type A injury were observed in the after analysis period.

Table 4 Summary of Key Barrier Containment and Breach Findings by State

State	Years	Key Findings
Florida (*20*)	2003-2010	Both CASS and Gibraltar systems stopped or redirected more than 80% of crashes from entering the opposing traveled way.
North Carolina (*23*)	2000-2006	A barrier breach rate of less than 5% was observed during a 3.61 year after period.
Ohio (*24*)	2003-2006	The barrier was penetrated in less than 4% of observed hits.
Washington (*26*)	2000-2008	Of the vehicles that hit barriers, 96.3% were observed to be stopped or redirected.
Wisconsin (*3*)	2003-2008	All barrier systems examined stopped between 70% and 80% of the vehicles that struck the barriers.

2.3 Cable Barrier Crash Severity

Nearly all of the aforementioned cable barrier studies in Section 2.2 discuss crash severity associated with cable median barrier crashes. Fewer studies, however, have examined factors influencing crash severity associated with cable barrier crashes. Hu and Donnell (2005) used nested logit models to investigate median barrier crash severity in North Carolina. As their study was not specific to cable barriers (and generalized median barriers to cable, concrete, and metal guardrail), they determined that crashes with cable median barriers typically have less severe outcomes than crashes with concrete median barrier or metal guardrail. Another key finding was that cable barriers installed in medians with slopes between 6H:1V and 10H:1V were correlated with more severe crash severities than crash severities for crashes occurring in medians with slopes less than 10H:1V (*27*). Other studies have investigated the crash severity associated with median barrier crashes, such as Miaou et al. (2005), Bligh et al. (2006), and Tarko et al., (2008), yet these studies have either not been specific to cable barrier such as in Bligh et al. (2006), or have focused entirely on alternate barrier types such as concrete as in the case of Tarko et al. (2008) (*28, 29, 30*). Thus, it appears much work remains in determining what factors, if any, influence and affect crash severity specifically for cable median barrier crashes.

2.4 Cable Barrier Breach Propensity

Many studies, such as Alluri et al. (2012), make mention of cable barrier breaches/penetrations, but fail to further investigate influencing factors (*20*). Two studies by Stolle et al. investigated cable median barrier penetrations for data from several states with the goal of trying to determine factors influencing cable median barrier failure in the form of penetration. Crash reports, site characteristics (i.e., median geometry etc.), and computer simulations were all used in the analyses. Ultimately, it was determined that dry pavement and clear weather conditions were most common to and associated with cable barrier penetrations and other breaches by methods such as rolling over the barrier (*19, 31*). Marzougui et al. (2012) used vehicle dynamics analyses to study cable barrier placement within a median cross-section and overall cross-section configuration. Their goal was to determine ideal placement for cable median barriers within medians to prevent barrier breach (*5*). Overall, however, studies examining factors affecting cable barrier breach propensity and issues surrounding cable barrier breach crashes are lacking.

3 STUDY DESIGN

3.1 Research Tasks

After the research objectives were identified, a list of clearly defined tasks was created in order to guide the research process. The first task involved reviewing the literature to determine the state-of-the practice in regards to cable median barrier research, as well as to determine gaps in the existing research. Once this task was done, the data collection and reduction process began. This process is thoroughly outlined in Section 3.2. Once the raw data were analyzed and put in a more usable/analysis-ready form, methods of analysis to accomplish the research objectives were investigated and selected. The first part of the analysis involved a simple look at the data sorted by a variety of factors such as crash severity and weather conditions at the time of the crash. Once a high-level view of the data was completed, statistical analysis methods suitable to accomplish the aforementioned objectives were researched and selected. The data were then analyzed and comments on the analysis were made prior to drawing conclusions.

3.2 Data Collection and Processing

3.2.1 Study Locations

In total, 16 study sites in 14 Wisconsin counties were included in the analysis. Overall, the sites when combined have a total of 82.06 miles of high-tension cable median barrier. At least one study site is present in each of the five WisDOT regions. Several counties, such as Dane and Fond du Lac, had more than one study site. The full list of study sites by county, along with information including the highway of installation, median width, and median sideslope is summarized in Table 5. Such data were either provided directly by WisDOT, collected from construction plan sets, or measured via aerial photos of study sites. Additionally, values of minimum deflection distance, defined as the minimum distance from the edge of the inside travel lane to the cable barrier, are provided in Table 5. A map of the state showing the study sites is shown in Figure 1 of Section 1.4 of this report. For all study sites, cable barrier was installed between 2006 and 2010. At the majority of study sites, the high-tension cable median barrier was installed in response to a historical cross-median crash problem at the given location. In such cases, the locations were deemed “CMC hotspots.” Not all study sites analyzed in this report, however, were CMC hotspots. The cable barrier installed at the Marathon County study site was installed in order to meet requirements for obtaining a design exception in regards to median width; hence, the segments in Marathon County are not CMC hotspots.

Table 5 Study Sites

Site #	County	Highway	Median Width (ft)	Maximum Median Sideslope	Minimum Deflection Distance (ft)
1	Brown/Oconto	USH 41	60	6H:1V	12
2	Dane	USH 151	50	6H:1V	16
3	Dodge	USH 151	50	4H:1V	10
4	Dunn	IH 94	50	4H:1V	9.5
5	Eau Claire	IH 94	50-60	4H:1V	9.5
6	Fond du Lac	USH 41	50	6H:1V	12
7	Fond du Lac	USH 41	48-50	6H:1V	14
8	Fond du Lac	USH 41	48	6H:1V	14
9	Jefferson	IH 94	60	10H:1V	13
10	Juneau	IH 90	50	6H:1V	19
11	La Crosse	USH 53	50	6H:1V	12
12	Marathon	USH 51	54	6H:1V	14.5
13	Outagamie	USH 41	60	6H:1V	14
14	Rock/Dane	IH 39	60	6H:1V	20
15	Waukesha	IH 94	50	6H:1V	20
16	Winnebago	USH 41	48	6H:1V	12

3.2.2 Crash Data Collection and Reduction

The primary component of the safety analysis was an evaluation of crash data in periods after the cable barriers were installed at each study site. The following sections describe in detail the procedures used for crash data collection and preparation. Additionally, key definitions of cable median barrier crash types are provided.

3.2.3 Study Periods

Study periods were defined for each study site based upon construction dates and project open dates (i.e., end of construction and full removal of any temporary traffic control). For all study sites, only full years of crash data were used to avoid unfair comparisons due to inclusion or exclusion of winter months in the study periods. The study periods varied in length from three to five years depending on the date of barrier installation. In all cases, a maximum of the five most recent years following the project open date were used to form the study periods. For example, if the project open date occurred in September of 2010, the study period would be defined as January 2011 through December 2013. The study periods were chosen to begin at the start of the year following completion of construction to allow for a driver adjustment period. The adjustment period was intended to allow drivers to grow accustomed to any geometric changes that may have occurred at or near the same time as the barrier installation. For all study sites, the last year from which data were gathered was 2013.

3.2.4 Crashes Included in the Analysis

This section defines the types of crashes that were included in the datasets for analysis. In the analysis, crashes corresponding to Bligh et al.'s "Type 2" crashes were examined and were referred to as median barrier (MB) crashes (*29*). That is to say, the only crashes of interest were those that involved a vehicle hitting a cable median barrier. Crashes in which any vehicles breached the barrier, but remained in the median were classified as MB/ME crashes.

Crashes in which any vehicles breached the barrier and then continued all the way through the median were classified in one of two ways. If the vehicle came to rest after the breach and did not come into contact with another vehicle during the crash sequence, the crash was classified as a MB/CME crash, where “CME” denotes “cross median event.” If the vehicle struck another vehicle on the opposing traveled way at some point in the crash sequence following the barrier breach, the crash was classified as an MB/CMCC crash, where “CMCC” denotes “cross median crash with vehicular collision on the opposing traveled way.”

Figure 4 includes sample crash scenarios for the analysis periods. Crash type “a” represents a scenario in which a vehicle entered the median on the side of the median where the cable barrier was installed; such a crash was classified as an MB crash. Crash type “b” was excluded from the dataset since the vehicle ultimately crashed into metal beam guard installed in front of cable barrier. Crash type “c” would be included in the dataset and would be classified as an MB crash. The only difference between the scenarios represented by crash types “a” and “c” is that in crash type ”c,” the vehicle entered the median on the opposite side of the median from which the cable barrier was installed. Depending on the offset of the barrier from the traveled way, a vehicle entering the median on the side of the median on which the barrier is installed may not hit the barrier. In such cases, the crash would be excluded from the dataset.

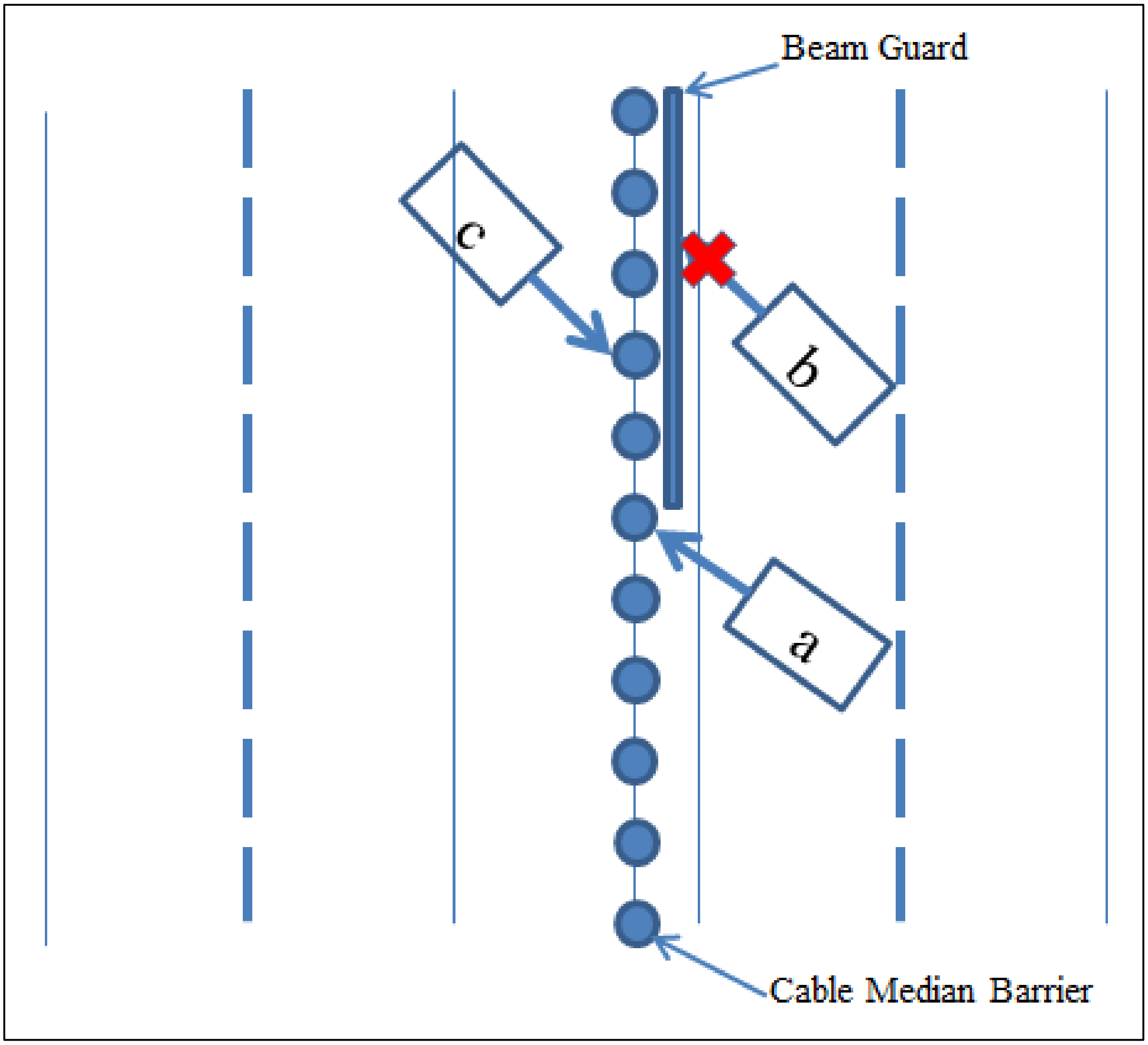

Figure 4 Crash Scenarios Included in Dataset

3.2.5 Breach Types

Following the definitions in Alluri et al. (2012), three types of barrier breaches were examined in this report, namely, (1) overriding, (2) underriding, and (3) penetrating the barrier. An override was defined as a crash in which the vehicle traveled over the uppermost cable in the barrier, while an underride was defined as a crash in which the vehicle passed under the lowest cable in the barrier. A penetration was defined as a crash in which the vehicle traveled through the cables in the barrier (*20*).

3.2.6 Barrier Containment: Stop and Redirect Crashes

Median barrier crashes were also broken down into further refined crash types. Specifically, they were classified according to whether or not the vehicle that crashed into the barrier was stopped or redirected. A "Stop" was defined as a crash in which the vehicle that hit the barrier was fully contained within the median following collision with the barrier, with the added condition that the vehicle did not breach the barrier. Possible resting places for the vehicle in a "Stop" crash included locations upon or within the barrier or anywhere else in the median such that no portion of the vehicle was at rest in the travel lanes (with one exception). Crashes in which the vehicle hit the barrier but remained partially in the travel lane were classified as "Stop" crashes as long as the vehicle did not change direction upon hitting the barrier. A "Redirect" crash was defined as an MB crash in which the vehicle, upon hitting the cable barrier, was redirected back into the travel lanes, again with the added condition that the vehicle did not breach the barrier. If any portion of the vehicle was in the travel lane(s), following redirection of the vehicle, at any time following the barrier hit, the crash was classified as a "redirect." Thus, a crash in which the vehicle ultimately came to rest in the median was classified as a "Redirect" crash if a portion of the vehicle entered the travel lane(s) at some period during the sequence of events in the crash.

Some crashes were neither classified as "Stop" nor "Redirect" crashes. Such crashes included the aforementioned breach types, as well as hit-and-runs. No assumption was made on whether a hit-and-run crash was a "Stop" or "Redirect" as the ultimate crash outcome was unknown. A final crash type that was not classified as a "Stop" nor a "Redirect" was a crash in which the driver steered the vehicle out of the median upon hitting the barrier. This outcome was quite rare, but was noted on a couple of crash reports. In such cases, how the vehicle interacted with the barrier as the driver took corrective action could not be determined. Figure 5 shows the hierarchy of median barrier crash classification based on the aforementioned descriptions.

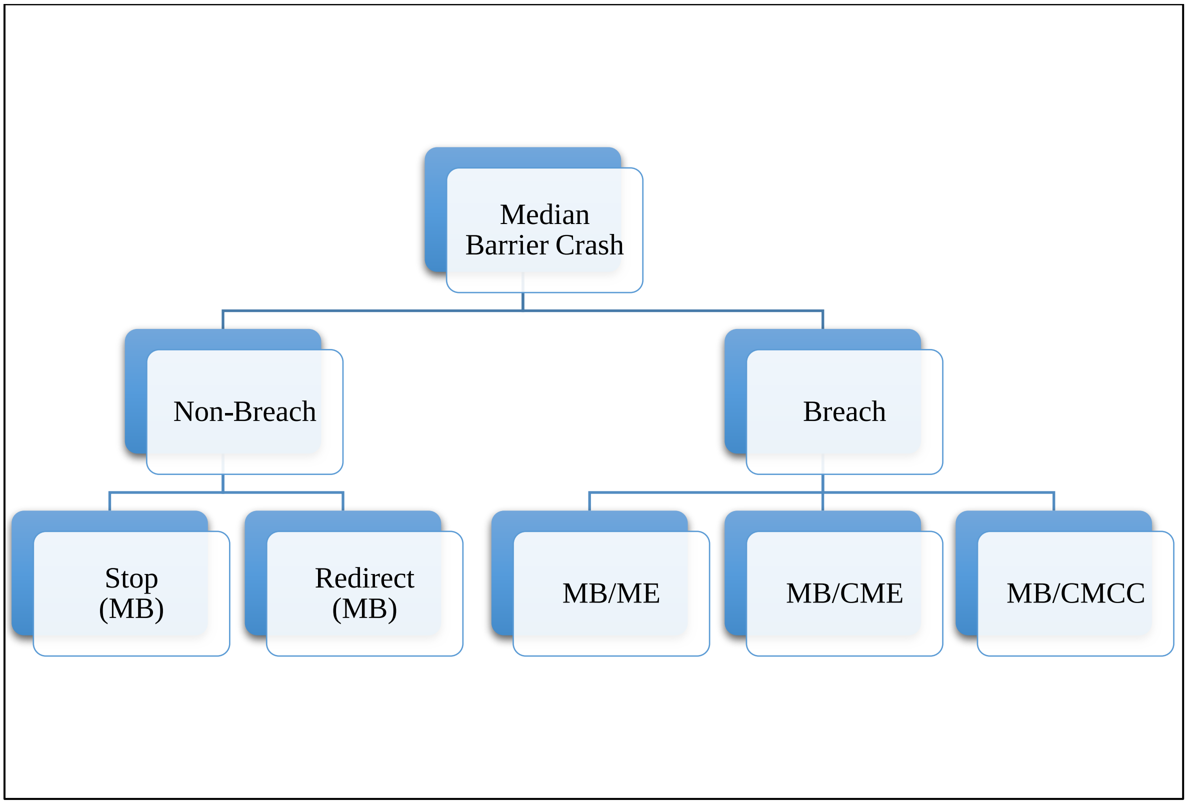

Figure 5 Median Barrier Crash Classification Hierarchy

3.2.7 Crash Data Collection and Mapping

Crash data for the specified time periods at the selected study sites were downloaded from the WisTransPortal database (*32*). The data downloaded were only filtered by county, time period, and highway as these minimum criteria would ensure all possible crashes at the sites were accounted for. The downloaded data were then imported into geographic information systems (GIS) software and in turn joined to layer of crash data containing records of all crashes that occurred along the state trunk network between the study years. Hence, crashes that occurred at each of the study sites, along the segments on which cable barrier was installed, were identified. For each segment, a 200 foot buffer zone was used on each side of the segment to ensure crashes that occurred on the segment, but were inaccurately mapped were not be excluded from the analysis. Once all crashes that occurred on the segments for a given study site during the specified time period were identified, a spreadsheet containing these records was exported from the GIS software. These spreadsheets contained a complete list of all candidate crashes for each study site in the given time period.

The final step of the data preparation for the safety analysis involved the search for and identification of median barrier crashes from the list of candidate crashes. The list of candidate crashes had to be filtered since by containing all crashes that occurred at a study site in a given time frame, the list inherently contained numerous crashes that were not relevant to the cable median barrier analysis (i.e., non-MB crashes) such as run-off-the-road to the right crashes. Prior to the filtering process, police crash reports for all candidate crashes were downloaded from the WisTransPortal crash report database. Each crash report was then manually reviewed in order to identify relevant crashes and their characteristics (*3*).

Manual review of the reports was necessary due to the nature of the current version of the crash report used in Wisconsin (i.e., the MV-4000) and the manner in which it is filled out following a crash. Although in many cases the MB crashes are easily discovered via the text “MEDIAN BARRIER” being found in the “First Harmful Event” field, many other issues arise that necessitate the manual review. In some cases, MB crashes occurred where the first harmful event did not involve collision with a barrier, but rather something else such as a rear end collision in which a vehicle was ultimately pushed into the barrier. Secondly, the text “MEDIAN BARRIER” does not guarantee that the collision was with a cable median barrier. Collisions with other types of barrier such as concrete and metal W-beam barriers occurred at many of these study sites, thus locations of crashes based upon information given in the reports were checked to confirm the type of barrier with which the collision took place. Finally, although cable median barriers are often referred to in the narratives of the crashes on the reports, officers often refer to the barriers by a variety of other names such as “fence,” “guardrail,” and “impact attenuator” that require further examination of the location of the crash as all of these are other non-cable barrier elements common in highway cross-sections. In total, 3,274 crash reports from between 2009 and 2013 were manually reviewed for this study, 753 of which were found to be median barrier crashes.

3.3 Statistical Analysis

Once the crash data were properly sorted and categorized, initial observations were made based on any noted patterns or trends in the data. Such patterns identified and conclusions reached were purely observational and were not associated with any measure of statistical significance. Later, statistical analysis methods were sought to analyze the data in a more robust and statistically rigorous manner. Core statistical analyses in the thesis fell under one of two categories: logistic regression analysis or non-parametric analysis.

3.3.1 Logistic Regression Analysis Method

Logistic regression was used to investigate the issues of barrier containment, barrier breach propensity, and crash severity associated with cable barrier crashes. In the context of barrier containment behavior, binary logistic regression which was used to model barrier containment outcome as a function of several covariates defined in this section. In general, a binary logistic regression equation with n covariates takes the form of Equation 1 (*33*).

$$\log\left(\frac{\pi(x)}{1-\pi(x)}\right) = logit\,[\pi(x)] = \alpha + \beta_1 * x_1 + \cdots + \beta_n * x_n \tag{1}$$

Where,

logit $[\pi(x)]$ = log odds of response variable (in this case the response variable is barrier containment);

α = constant in regression equation; and

β_i = regression coefficient on covariate x_i.

For the barrier containment regression analysis, the response variable chosen to be a binary variable representing barrier containment with two possible outcomes, “Stop” (1) and “Redirect” (0). Response variables for other analyses are detailed in future sections.

The dataset from which this and all forthcoming regression models in this thesis were developed off of consist of a set of points, each point representing a median barrier crash that occurred during the study period. Only samples (i.e., crashes) falling into “Stop” or “Redirect” categories were included in the barrier containment regression analysis as regression analyses of barrier breaches are covered in a later section. Also, the other possible crash outcomes corresponding to neither “stops” nor “redirects” besides breaches do not contain certain information about how the vehicle interacted with the barrier and were hence excluded from the barrier containment regression analysis. The final sample size for the barrier containment analysis was 673 crashes, 455 of which corresponded to stops and the other 218 of which were redirects. As a result of this reduced sample size, the probability considered here (i.e., the probability of a stop), is in effect a conditional probability. That is, the probability is the probability of a stop, given the crash did not result in the outcome of “Breach” or another of the aforementioned non-stop/non-redirect outcomes.

Covariates included in this and future regression analyses were grouped into two main sets. The first set described characteristics of the barrier or crash outcome. In this case, a characteristic of interest of the barrier was the number of cables in the barrier cross-section (i.e., three or four). This characteristic of each barrier was represented as a simple binary value that took the value of "1" when a three-cable system was considered and took the value of "0" when a four-cable system was considered. For simplicity, this variable will be referred to as "Three-Cable Barrier" henceforth. In each regression run, the following set of 10 additional descriptive covariates was also used in the model building process:

- Horizontal Curve (Categorical: 1~Yes, 0~No);
- Median Slope (Categorical: 1~4H:1V slope, 0~Less than 4H:1V slope);
- Heavy vehicle (Categorical: 1~Yes, 0~No);
- Pavement Condition (Categorical: 1~Dry, 0~Not Dry);
- Collision before barrier hit (Abbreviated "Collision Before," Categorical: 1~Yes, 0~No);
- Collision after barrier hit (Abbreviated "Collision After," Categorical: 1~Yes, 0~No);
- Log (AADT) (Continuous);
- Weather Condition (Categorical: 1~Clear, 0~Not Clear);
- Minimum Deflection Distance [ft] (Categorical: 2~>15, 1~10<x≤15, and 0~x≤10); and
- Median Width [ft] (Categorical: 2~≥60, 1~50≤x<60, and 0~<50).

These characteristics described the site of the crash, external factors in the environment, and characteristics of the crash sequence. The "Collision Before" variable takes the value of "1" (i.e., "yes") when the vehicle that ultimately hits the barrier is involved in another incident prior to the barrier hit. This incident could involve hitting or being hit by another vehicle, hitting or being hit by a fixed object, hitting or being hit by a piece of debris, or any combination of the aforementioned. The "Collision After" variable takes the value of "1" (i.e., "yes") when the vehicle that ultimately hits the barrier is involved in another incident after the barrier hit. This incident could take place in the form of any of the aforementioned incident types as defined for the "Collision Before" variable. For all regression scenarios in the report, AADT values used were from the year 2011. In the case of "Minimum Deflection Distance," the factor level coded to "0" was used as the base case for all comparisons. Thus, if "Minimum Deflection Distance" were to appear in a final model, the variable would actually be represented by two coefficients (β_i's). One coefficient would signify the effect on the response variable by the "1" category when compared to the base case ("0" category). That is to say, it would represent the effect on the response variable from a crash that took place under a minimum deflection distance of greater than 10 feet and less than 15 feet when compared to a crash that took place where minimum deflection distance was less than 10 feet. Similarly, the second coefficient would represent a comparison between the "2" level/category of the variable and the base case. The same logic in terms of a "0"-leveled base case and two categories (one for each additional level) applied to the "Median Width" variable.

In the regression analysis runs, a combination of backward elimination and forward selection stepwise regression algorithms were used to determine what covariates would be in the final models. In all cases, the cutoff p-value criteria for covariate entry or removal was 0.05. The overall procedure involved three main steps, as well as additional diagnostics described in the following. The first step in the model building procedure (Step 1) involved a backward elimination process. In this process, an initial model was fit in which the response variable (in this case barrier containment) was modeled as a function of all of the following ten covariates:

- Horizontal Curve;
- Median Slope;
- Heavy Vehicle;
- Pavement Condition;
- Collision Before;
- Collision After;
- Log (AADT);
- Weather Condition;
- Minimum Deflection distance and;
- Median width.

Covariates were removed from the model by examining the p-values corresponding to scaled deviance values associated with a model in which the given parameter was removed from the current model. The scaled deviance is a likelihood ratio test (LRT) statistic, following a chi-squared distribution, that helps describe model fit and is defined as follows in Equation (2) (*33*):

$$Scaled\ Deviance = 2 * \left(l_{max} - l\left(\theta\left(\hat{\beta}\right)\right)\right) \tag{2}$$

Where,

l_{max} = the log likelihood of the saturated model; and

$l(\theta(\hat{\beta}))$ = the log likelihood of the model with a given set of parameters.

In general, smaller values of the LRT statistic with p-values greater than 0.05 denote that a given parameter can be removed from the current model to improve fit. Thus, in each step the covariate with the greatest p-value was removed until all covariates left in the model had p-values less than 0.05 associated with their LRT statistics. At this point, model summary statistics were examined to confirm that all covariates currently in the model had p-values less than to 0.05. In some cases, LRT statistics showed that removal of a variable would lead to improved model fit (i.e., the LRT statistic's p-value was less than 0.05), but examination of the p-value associated with the Wald test statistic corresponding to the parameter in the model indicated a lack of significance. In this case, said parameters were removed from the models. When the backward selection process was done, the response variable would be modeled as a function of one or more of the ten aforementioned covariates, assuming proper model fit.

The next part of the process (Step 2) involved trying to re-add covariates from the list of the ten aforementioned covariates to the model. In some cases, a covariate may not appear to be significant on its own in a model, but may gain significance when paired with another covariate in the model, hence the motivation for this portion of the model building procedure. In each case, covariates with p-values for their Wald test statistics less than 0.05 were added one by one to the overall model until addition of another covariate would cause p-value(s) for term(s) in the model to increase beyond 0.05. In some cases no additional covariates were added in this step.

The third main step of the model building procedure (Step 3) involved trying to add the variable for number of cables in the barrier (i.e., "Three-Cable Barrier"). As in the other forward selection process in the model-building procedure, this covariate was only added if the p-value associated with the Wald test statistic was found to be less than 0.05. Once this process was completed, a final model was attained.

The overall regression process also had two other steps that involved examination of model fit. The first step involved the use of a quasi-likelihood regression approach to fit the binary logistic regression models. Failure to use such method assumes a distribution for the response variable that may not hold for the observed data. For example, binary logistic regression assumes the response variable (in this case containment) follows a binomial distribution, which further assumes a certain relation between the mean and variance of the data. For response data (Y) following a binomial distribution, the mean and variance are shown in Equations 3 and 4, respectively (*33*).

$$Mean = E(Y) = n * p \tag{3}$$

Where,

p = success probability; and

n = number of observations in the dataset.

$$Variance = Var(Y) = n * p * (1 - p) \tag{4}$$

Where,

All variables are as previously described.

If this relation between the mean and variance for the data does not hold, the model will not accurately fit nor represent the data; it is further possible that an overfit model could be obtained.

In order to prevent these issues, quasi-binomial regression was used to develop the binary logistic regression models. Quasi-binomial regression does not assume that the relation between the mean and variance as shown in Equations 3 and 4 holds, but rather that the variance is some multiple (φ) of the mean; φ is referred to as the dispersion parameter. If φ<1, the data are referred to as underdispersed and if φ>1, the data are referred to as overdispersed. If φ=1, the assumed relation between the mean and variance for the binomial distribution holds for the data (*33*). Hence, during the model building process, the value of the dispersion parameter (φ) was monitored to make sure that it was as close to one as possible. At the end the three step model-building procedure discussed previously, assuming the value of the dispersion parameter was very close to one, a final model was obtained using the typical binary logistic regression procedure. That is to say, once it was observed that the response data adequately followed a binomial distribution, a model that assumed this relation (i.e., one that had φ=1) was used. In some cases, it would be possible that no binary logistic regression model could be fit as the data were highly under- or overdispersed suggesting the possibility that a model attained would be overfit to the data and inaccurate. However, in all cases where a model was fit to data and presented in this report, dispersion parameter (φ) values were less than 0.04 away from 1.00. A final note on the use of quasi-binomial regression is that models developed under this scheme do not have fully specified likelihoods, thus common measures of goodness of fit such as Akaike's Information Criterion (AIC) (shown in Equation 5) cannot be defined in the traditional sense (*33*, *34*). Thus, AIC values showing model fit could not be obtained, and were not presented until a final logistic regression model was developed using traditional, maximum-likelihood and non-quasilikelihood procedures.

$$AIC = -2 * (log\ likeilhood\ of\ model - \#\ of\ parameters\ in\ model) \qquad (5)$$

Additional diagnostic tests were performed to examine model fit during the regression process. During variable selection steps for the model, plots of Cook's Distance

(CD) versus Leverage were examined for the current model. Examination of Cook's Distance can be used to see the effect of removing data points from the dataset on which a model was developed. Points with high values of Cook's Distance, in comparison to the Cook's Distance values for other data points in the set, often warrant further analysis to determine whether they may be outliers that have undue influence on a model. For example, if one data point out of 1,000 had a high CD value in comparison to the other data points, one may want to examine its effect on the model. Hence, the model could be re-fit to a dataset that would be the same as the original, except it would exclude the point with the high CD value. If parameter estimates in the new model changed in terms of sign (i.e., positive to negative or vice versa), experienced large changes in magnitude, lost significance in terms of their p-values, and/or the dispersion parameter of the model drastically changed it is likely that the observation removed was an outlier that had a large residual value. Hence, the model would be unduly influenced by the single observation and would not fit adequately. At this point, the analyst would have two options, see if another model fits better (i.e., add and/or remove covariates) or conclude a model cannot be fit. When using Cook's Distance as an analysis tool, it is important to note that data points with high CD values are not permanently removed from the dataset on which a model is based; they are only temporarily removed to search for outliers. If minimal or no changes to a given model occur upon removing the suspect observations from the dataset, it is likely such observations are not outliers and the model based upon the dataset with their inclusion fits well. If large changes in the aforementioned values occur when the suspect values are removed from the dataset, it is likely the model in its current state does not fit the data well due to the influence of outliers (*35*).

Leverage values also indicate possible undue influence on model fit of given observations. Data points with high leverage values in comparison to other data points could be possible outliers that when removed from a data set may lead to changes in model fit and indicate a lack of or improper fit (*33*). In all regression scenarios in this report, plots of Cook's Distance versus Leverage were examined for each model to determine if any outliers had undue influence on models. Points warranting further investigation as possible outliers (i.e., those with the highest values of CD and leverage) were examined by temporarily removing them from the datasets to see their effects on model fit, prior to deciding upon any possible final model. If outliers were detected, other models (possibly obtained through addition or deletion of covariates) in which such points would not have undue influence on model fit were investigated to find one with adequate fit, if possible.

In terms of final notes on the regression procedure, there two more issues that must be addressed. First, as all regression models were developed off of sets of point-based crash data, the models are independent of barrier length. Second, in some cases, final models sometimes include categorical predictors with more than one category in which one category does not appear as a significant predictor. If one category proves to be significant and other(s) do not, the analyst cannot simply remove the insignificant category from the model. This leaves the analyst with two choices: remove the variable (i.e., all categories) entirely, or leave it in and note that certain categories are not significant. In this report, the latter approach was chosen as significance of parameter estimates is not always the only criteria that should be used to build a model. Leaving in variables of this nature can further be beneficial as it can help decrease bias when estimating other coefficients and can help provide a basis for comparison with similar studies (*33*).

3.3.2 Non-Parametric Analysis Methods

A variety of non-parametric tests were performed to further study breach crashes and associated trends. The first set of tests involved a series of chi-squared tests. In particular, Yates' Chi-Squared Test was used to analyze crash data which took the form of 2X2 contingency tables. In Yates' test, the null hypothesis (H_0) is that the row and column variable in the contingency table are independent. In order to perform Yates' chi-squared test, the chi-squared test statistic must be calculated. The formula for the chi-squared test statistic is shown in Equation 6 (*33*).

$$\chi^2_{df} = \sum_{i,j} \frac{\left(|n_{ij} - \widehat{\mu_{ij}}| - 0.5\right)^2}{\widehat{\mu_{ij}}} \tag{6}$$

Where,

χ^2_{df} = Yates' chi-squared test statistic with df as discussed in the following;

n_{ij} = Observed number of crashes in cell i, j (Here, i=1, 2 and j=1, 2); and

$\widehat{\mu_{ij}}$ = Expected number of crashes for cell i, j.

In the aforementioned formula, the expected numbers of crashes are calculated as shown in Equation 7. Additionally, the 0.5 is a factor used for continuity correction (*33*).

$$\widehat{\mu_{ij}} = \frac{n_{i+} n_{+j}}{n} \tag{7}$$

Where,

$\widehat{\mu_{ij}}$ = expected number of crashes for cell i, j as defined previously;

n_{i+} = total number of crashes for row i;

n_{+j} = total number of crashes for column j; and

n = total number of crashes for the entire contingency table (i.e., the sum of all four cells).

For Yates' Chi-Squared Test, the test statistic value is first computed, which then allows computation of p-value based upon the corresponding degrees of freedom (df) for the test statistic. In this case, and for all 2X2 contingency tables, the df value corresponding with the test statistic is one.

To further investigate severity associated with breach crashes, two additional tests were used: Welch's t-test and the Mann-Whitney-Wilcoxon (MWW) test (also known as the Wilcoxon rank-sum test). Welch's t-test is used to compare the difference in means between two samples (in this case mean severity), while the MWW test is used to compare the median difference in values between two populations (in this case median severity level) (*35*).

Both Welch's t-test and the MWW test involve computing the value of test statistics and then determining the p-value corresponding to the particular test statistic value via reference tables or computer software. As noted previously, Welch's t-test involves comparing the means between two samples. For the test, the null hypothesis states that the difference between the means of the two samples is zero. In terms of the data for this project, the null hypothesis states that the mean severity level for injury crashes is the same for breach and non-breach crashes. The t-statistic for the Welch test is defined as follows in Equation 8 (*35*).

$$t_{df} = \frac{\widehat{\mu_1} - \widehat{\mu_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{8}$$

Where,

t = Welch's t-statistic with df as computed in software;

$\widehat{\mu_1}$ = mean severity of sample one;

$\widehat{\mu_2}$ = mean severity of sample two;

s_1^2 = sample variance of sample one;

s_2^2 = sample variance of sample two;

n_1 = sample size of sample one; and

n_2 = sample size of sample two.

The MWW test involves computation of the U statistic under the null hypothesis that the median difference in severity levels between two samples (i.e., breach and non-breach crashes) is zero; stated alternately, the true location shift is zero. In order to compute the test statistic, the two samples must be combined and then ranked in ascending order. In the case of a tie (or more than two observations having the same value), the rank for such observations is defined as the average rank between the observations. For example, if three observations had the same value, which was also the lowest value among all observations for both samples, all three observations would be assigned the rank of two (i.e., the average of one, two, and three). Since only four possible values were used for coding the severity levels (i.e., one for K, A, B, and C, respectively), only four ranks were possible. Further, since the ranks are not in any way weighted, the ranks are the same regardless of coding scheme used for the crash severities. The U statistic is then computed as shown in Equation 9 (*35*):

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \tag{9}$$

Where,

U = MWW test statistic;

n_1 = sample size of sample one;

n_2 = sample size of sample two; and

R_1 = sum of the ranks from sample one.

4 ANALYSIS

4.1 Crash Patterns and Trends

The first component of the crash analysis consisted of analyzing the distribution of crashes by month, road (i.e., pavement) condition, and weather condition. Tables 6, 7, 8, and 9 summarize the crash data by crash severity, time of year during which the crash occurred, pavement condition at the time of the crash, and weather at the time of the crash. Note that these tables do not take into account measures of exposure such as ADT, nor do they account for the length of installation of cable barrier; they simply present the absolute crash counts. Results from this section are purely observational and do not have a measure of statistical significance attached to them. Rather, the goal was to first investigate the data from a high (general) level prior to performing more robust statistical analyses.

Specifically, Table 6 shows the distribution of crash data by month and severity. Months with grey highlighting correspond to winter months (i.e., November through March). A quick scan of the table shows that the majority of crashes that occurred are low-severity (i.e., involving only property damage) and also occurred during the winter months. The month of December was the month during which the most crashes (153) occurred, when compared to other months. Additionally, only one fatality was found to occur for a median barrier crash. From a purely observational standpoint, the overall low number of high-severity crashes (i.e., crashes of severity K and A) suggests that cable median barriers in Wisconsin are in fact preventing high-severity crashes at the expense of an increase in the frequency of lower-severity crashes.

Table 6 Crash Data by Month and Severity

Month	Severity					Total Crashes
	K	A	B	C	PD	
January	0	1	7	5	121	134
February	1	1	9	7	119	137
March	0	1	5	4	64	74
April	0	1	0	6	30	37
May	0	0	3	4	34	41
June	0	0	1	3	24	28
July	0	4	5	4	32	45
August	0	1	1	0	17	19
September	0	1	1	2	24	28
October	0	1	4	4	21	30
November	0	1	4	1	21	27
December	0	1	5	9	138	153
Total	1	13	45	49	645	753

Table 7 shows the total numbers of crashes occurring in winter and non-winter months (i.e., April through October), as well as the proportion of the total number of crashes (753) each category makes up. Observation of the table shows that the number of crashes occurring in the winter months is generally greater than the number occurring in the non-winter months. This trend holds for all crash severities, except for incapacitating injury (A) crashes. For this severity level, the majority of crashes occurred during the non-winter months. In total, 69.7 percent of observed median barrier crashes occurred during winter months.

Table 7 Crash Counts and Percentages by Severity and Winter/Non-Winter Season

	K	A	B	C	PD	Total Crashes/ Percentage
Nov. ~ Mar. (5 months)	1 (0.1%)	5 (0.7%)	30 (4.0%)	26 (3.5%)	463 (61.5%)	525 (69.7%)
Apr. ~ Oct. (7 months)	0 (0.0%)	8 (1.1%)	15 (2.0%)	23 (3.1%)	182 (24.2%)	228 (30.3%)

Table 8 shows crash counts by pavement condition and severity. The majority of crashes occurred when the pavement was either dry or snow-covered, with the highest percentage of crashes (approximately 37.0 percent) occurring on snow-covered roadways. Although snow-covered roadways were shown to experience the most cable median barrier crashes, the majority of these crashes involved property damage only. In fact the highest proportion of severe (K and/or A) crashes occurred when the pavement was dry.

Table 8 Crash Counts by Pavement Condition and Severity

Pavement Condition	**Severity**					**Total Crashes**
	K	**A**	**B**	**C**	**PD**	
Dry	0	9	29	28	188	254
Ice	0	0	1	6	121	128
Snow	1	3	12	13	249	278
Wet	0	1	3	2	85	91
Unknown	0	0	0	0	2	2
Total	1	13	45	49	645	753

Table 9 shows crash counts by weather condition and severity. Throughout the analysis periods, the majority of the crashes (i.e., 74.9 percent) occurred under non-clear weather conditions. The sole fatality occurred during a period of snow, however, the majority of incapacitating injury (A) crashes occurred during clear weather conditions.

Table 9 Crash Counts by Weather Condition and Severity

Weather Condition	K	A	B	C	PD	Total Crashes
Clear	0	7	21	18	143	189
Cloudy	0	3	9	12	121	145
Fog	0	0	2	0	5	7
Rain	0	1	0	1	60	62
Sleet	0	0	0	2	45	47
Snow	1	2	13	15	253	284
Wind	0	0	0	1	16	17
Unknown	0	0	0	0	2	2
Total	1	13	45	49	645	753

Figure 6 shows the numbers of median barrier crashes, and proportions of total crashes, as sorted by three categories of median width (measured in feet). From Figure 6, it can be seen that slightly more than half of the observed crashes (52.6 percent) occurred in a median at least 50 feet, but less than 60 feet wide. Cable barrier crashes that occurred at sites with medians less than 50 feet in width comprised the smallest proportion of the total number of crashes and only represented 14.2 percent of the total number of median barrier crashes.

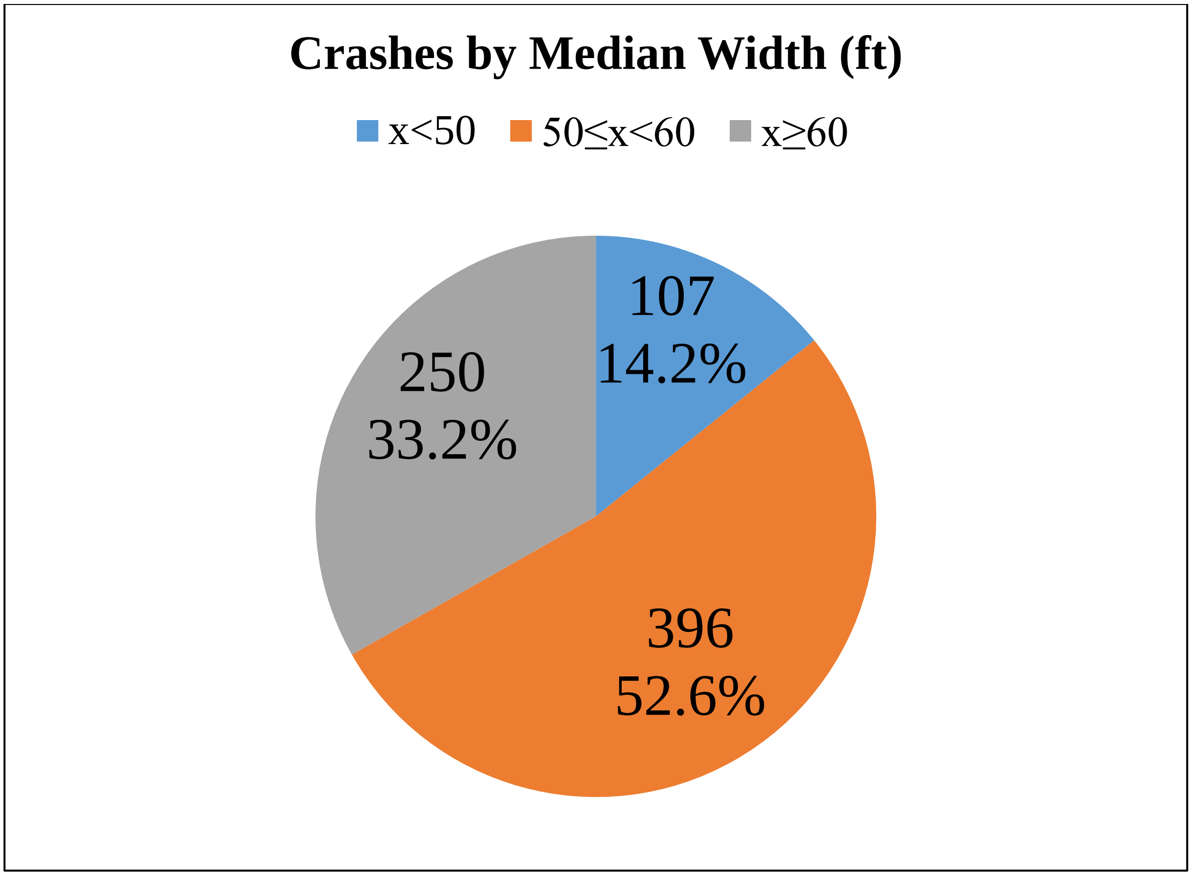

Figure 6 Numbers and Proportions of Crashes by Median Width (ft)

Table 10 further examines crash severity by median width category. In each row, the number of cable barrier crashes occurring at each severity level for a given median width category are presented. Additionally, below each crash count the proportion of total crashes for a given median width category that each crash severity level accounts for is shown. For example, 0.9 percent of cable barrier crashes occurring at sites with medians less than 50 feet wide resulted in severity A (i.e., incapacitating injury). From Table 10, it can be seen that for all median widths, more than 80 percent of crashes that occurred resulted in property damage only. Overall, sites with median widths of at least 50 feet, but less than 60 feet experienced the highest proportion of high-severity (K and A) crashes with 2.6 percent of said crashes resulting in a fatality or incapacitating injury.

Table 10 Crash Counts by Median Width and Severity

Median Width (ft)	K	A	B	C	PD	Total Crashes
x<50	0 (0.0%)	1 (0.9%)	8 (7.5%)	10 (9.3%)	88 (82.6%)	107 (100.0%)
50≤x<60	1 (0.3%)	9 (2.3%)	24 (6.1%)	26 (6.6%)	336 (84.8%)	396 (100.0%)
x≥60	0 (0.0%)	3 (1.2%)	13 (5.2%)	13 (5.2%)	221 (88.4%)	250 (100.0%)

Minimum deflection distance (i.e., the minimum distance from the edge of the travel lane to the cable barrier) was also examined in the context of crash severity. Table 11 shows crash counts as sorted by crash severity and categories of minimum deflection distance. Beneath each crash count is the percentage it comprises of total crashes for a given deflection distance category and severity level pairing. Similar to the aforementioned results for crash severity as sorted by median width, more than 80 percent of all crashes occurring under each deflection distance category resulted in property damage only. The highest percentage of severe (i.e., K and A) crashes was found to have occurred at sites with a minimum deflection distance of less than or equal to 10 feet. At such sites, 9.6 percent of observed cable barrier crashes resulted in a fatality or incapacitating injury.

Table 11 Crash Counts by Minimum Deflection Distance and Severity

Minimum Deflection Distance (ft)	K	A	B	C	PD	Total Crashes
x≤10	1 (1.1%)	3 (3.2%)	5 (5.3%)	8 (8.4%)	78 (82.1%)	95 (100.0%)
10<x≤15	0 (0.0%)	6 (1.3%)	31 (6.5%)	34 (7.1%)	408 (85.2%)	479 (100.0%)
x>15	0 (0.0%)	4 (2.2%)	9 (5.0%)	7 (3.9%)	159 (88.8%)	179 (100.0%)

As aforementioned, another goal of this study was to compare performance between barrier types with different numbers of cables running longitudinally in their cross-sections. Typical to installations across the United States, all cable barrier systems investigated in this study had either three or four high-tension cables in their cross-sections. The breakdown of the number of crashes occurring per severity level for each type of barrier based on the number of cables it has can be seen in Table 12. Overall, the total number of crashes occurring at each barrier type as well as the proportion of crashes at each severity level are quite similar regardless of the number of cables in the cross-section.

Table 12 Crash Counts by Number of Cables in Barrier and Severity

Number of Cables	K	A	B	C	PD	Total Crashes
Three	1	6	27	22	325	381
Four	0	7	18	27	320	372
Total	1	13	45	49	645	753

Further data on crash counts, crash frequencies, and crash rates per 100 million vehicle miles traveled (100 MVMT) can be found in Appendix A, Tables A-1, A-2, and A-3, respectively. Additional sections in this chapter and the core of the thesis focus on specific issues surrounding cable barrier crashes including:

- Containment behavior of cable median barrier systems;
- Cable barrier breach propensity; and
- Crash severity associated with cable median barrier crashes.

4.2 Barrier Containment Behavior

An analysis of barrier containment behavior was conducted and the results are summarized in this section. All crash reports were manually reviewed and the crashes were classified into one of three outcome categories: "Stop," "Redirect," or "Neither." The definitions for the "Stop" and "Redirect" crash outcomes can be found in Section 3.2.6 and "Neither" corresponds to crashes such as breaches, hit-and-runs, and other crashes that were neither stopped nor redirected by a barrier. An important definition for this and future sections of the study is that of heavy vehicle (HV). In the context of this document and following guidance from Qin et al. (2010) and Ash et al. (2014), a heavy vehicle is defined as a vehicle larger in size than a pickup truck or sport utility vehicle for which a cable median barrier is not crash tested against (*3, 6*). Based upon vehicle types provided in crash reports, any vehicles not classified as "CAR" or "TRK UT" (pickup truck or sport utility vehicle (SUV)) on a crash report were declared heavy vehicles. Examples include straight trucks, tractors with semi-trailers, and cars or SUVs pulling some sort of trailer.

In many cases, analyses were performed on two datasets: "All Vehicles" and "Without Heavy Vehicles." As the names suggest, the former dataset consists of all crashes regardless of vehicle type, while the later excludes all heavy vehicle crashes.

4.2.1 Barrier Containment Percentages and Crash Severities

Prior to performing any statistical tests with the data, barrier containment was simply investigated through examination of the number of crashes falling into the three pre-defined containment categories (i.e., “Stop,” “Redirect,” and “Neither”) based upon the vehicle’s interaction with the cable barrier. Breach crashes, which fall under the “Neither” category, are not a focus of this section as they are covered in depth in Section 4.3 of this document.

Tables 13 and 14 show the breakdown of barrier containment for the “All Vehicles” and “Without Heavy Vehicles” datasets when considering containment behavior by the number of cables in the barrier cross-section. When considering the “All Vehicles” dataset, it can be seen that the majority of crashes (60.4 percent in total) involved a vehicle being stopped by the cable barrier upon impact and in turn, contained within the median. Three-cable barriers were shown to have stopped 61.9 percent of vehicles, while four-cable barriers stopped 58.9 percent of vehicles. Less than one third of vehicles were redirected back into the travel lane following barrier impact for both three- and four-cable barriers (26.5 and 31.5 percent, respectively). Similar trends were found to hold when considering the “Without Heavy Vehicles” dataset.

Table 13 Barrier Containment Counts for All Vehicles Dataset

Number of Cables	Stop	Redirect	Neither	Total Crashes
Three	236	101	44	381
Four	219	117	36	372
Total	455	218	80	753

Table 14 Barrier Containment Counts for Without Heavy Vehicles Datasets

Number of Cables	Stop	Redirect	Neither	Total Crashes
Three	227	99	40	366
Four	205	116	32	353
Total	432	215	72	719

Tables 15 and 16 present the severities of "Stop" crashes for both the "All Vehicles" and "Without Heavy Vehicles" datasets. Regardless of dataset, "Stop" crashes accounted for slightly more of the high-severity (KA) crashes than "Redirect" crashes. However, "Stop" crashes also accounted for a higher proportion of PD crashes when compared to "Redirect" crashes (shown by severity in Tables 17 and 18), though the absolute difference was only around three percent regardless of dataset considered. Although "Stop" crashes accounted for a higher proportion of high-severity crashes when compared to "Redirect" crashes, "Redirect" crashes accounted for a higher proportion of injury crashes (severities K, A, B, and C) overall for both datasets. This was due to the fact that the number of crashes of severity level C was at least two times higher for "Redirect" crashes than was observed for "Stop" crashes.

Table 15 Severity of Stop Crashes for All Vehicles Dataset

	K	**A**	**B**	**C**	**PD**	**Total**
# of Crashes	1	5	24	24	401	455
% of Stops	0.2%	1.1%	5.3%	5.3%	88.1%	100.0%

Table 16 Severity of Stop Crashes for Without Vehicles Dataset

	K	**A**	**B**	**C**	**PD**	**Total**
# of Crashes	1	5	24	23	379	432
% of Stops	0.2%	1.2%	5.6%	5.3%	87.7%	100.0%

Table 17 Severity of Redirect Crashes for All Vehicles Dataset

	K	**A**	**B**	**C**	**PD**	**Total**
# of Crashes	0	2	9	23	184	218
% of Redirects	0.0%	0.9%	4.1%	10.6%	84.4%	100.0%

Table 18 Severity of Redirect Crashes for Without Vehicles Dataset

	K	A	B	C	PD	Total
# of Crashes	0	2	9	23	181	215
% of Redirects	0.0%	0.9%	4.2%	10.7%	84.2%	100.0%

4.2.2 Results of Regression Analysis of Barrier Containment

The first model built examined the logit of barrier containment (i.e., the log odds of a "Stop") as a function the aforementioned covariates, paying specific attention to the number of cables in the barrier. The idea was to see if either three- or four-cable barriers had an association with increasing the odds of stopping an errant vehicle upon impact. The final model is represented by Equation 10. Additional details of the model including:

- Parameter estimates for the coefficients (β);
- Associated standard errors (S.E.);
- Wald test statistic (Z) values;
- Degrees of freedom (df) associated with each parameter;
- p-values associated with parameter estimates;
- Odds ratios between the response variable and given covariate (Exp(β)); and
- Profiled 95% confidence intervals (CI) for the odds ratios

are presented in Table 19. Additionally, the AIC value for the final model and value of the dispersion parameter prior to switching away from non-quasi-likelihood methods to obtain a final model are presented in Table 19. Finally, Table 20 shows the covariates not included in the final model as well as the AIC value that would be obtained for the model given one and only one of those terms was added. The LRT statistic and corresponding p-value indicating whether or not addition of a given parameter (currently excluded from the final mode) to the final model would improve fit (i.e., decrease AIC) are also shown. In some cases, p-values are less than 0.05. However, although addition of such parameter(s) may lead to a lower AIC for the final model, there is no guarantee that the parameter would be statistically significant in the final model. Also, addition of said parameter(s) may lead to over- or underdispersion.

$$logit[\pi(x)] = -9.965 + 1.216 * Collision\ Before - 1.286 * Collision\ After + 0.989 * \log(AADT) + 0.443 * Three - Cable\ Barrier \quad (10)$$

Table 19 Final Model for logit (Barrier Containment) versus Number of Cables in Barrier

Final Model								
							Profiled 95% CI for Exp(β)	
Variable	**β**	**S.E.**	**Z Value**	**df**	**p-val**	**Exp(β)**	**Lower**	**Upper**
Collision Before	1.216	0.324	3.757	1	1.720E-04	3.372	1.849	6.629
Collision After	-1.286	0.432	-2.979	1	0.003	0.276	0.116	0.638
Log (AADT)	0.989	0.214	4.618	1	3.880E-06	2.687	1.775	4.114
Three-Cable Barrier	0.443	0.180	2.466	1	0.014	1.558	1.098	2.223
Constant	-9.965	2.276	-4.379	1	1.190E-05	0.000	0.000	0.004
AIC = 805.85								
φ = 1.012								

Table 20 Variables NOT Included in Final Model for logit (Barrier Containment) versus Number of Cables in Barrier

Variables NOT Included	AIC	LRT	df	p-val
Horizontal Curve	806.680	1.166	1	0.280
Median Slope - 4:1	807.030	0.818	1	0.366
Heavy Vehicle	803.520	4.332	1	0.037
Pavement Condition - Dry	806.370	1.479	1	0.224
Weather Condition - Clear	807.820	0.028	1	0.868
Minimum Deflection Distance	808.590	1.260	2	0.533
Median Width	807.370	2.483	2	0.289

From the final model, four covariates arose as significant predictors at the α=0.05 level. The first significant variable found was "Collision Before," which had a positive coefficient indicating that when the variable takes its positive value (i.e., “1”), the log odds of a “Stop” increase. Hence, the odds of vehicle being stopped by the barrier and contained within the median increase when the vehicle is involved in another collision prior to hitting the barrier. The next significant predictor in the final model was found to be “Collision After,” which had a negative coefficient. This negative association is rather logical as vehicles that are not stopped, but rather are redirected are often susceptible to secondary crashes from oncoming vehicles in the travel lanes. Log (AADT) was found to be a significant predictor with a positive coefficient, indicating that the log odds of a “Stop” increase as AADT increases. In fact, the confidence interval for the “Stop”-“Log (AADT)” odds ratio indicates that the odds of a “Stop” increase by at least 77.5 percent times for each unit increase in Log (AADT). The final significant predictor was “Three-Cable Barrier,” which had a positive coefficient. Hence, when this variable takes the value of “1” (i.e., the barrier has three cables), the odds of an errant vehicle being stopped upon barrier impact increase.

4.3 Breach Analysis

An analysis of breach crashes (i.e., crashes in which a vehicle overrode, underrode, or penetrated the barrier upon collision) was conducted based upon multiple criteria including vehicle type, crash severity, and study site characteristics. Breach crashes were identified via the crash reports, particularly through the narrative sections. In total, 35 crashes out of the 753 median barrier crashes (i.e., 4.6 percent) were breaches. Of these 35 crashes, 15 were classified as MB/CME; that is to say they involved the errant vehicle reaching the opposing traveled way following breach. None of these crashes, however, involved the breaching vehicle being struck by a vehicle traveling in the opposite direction on the opposing traveled way.

4.3.1 Characteristic of Breach Crashes

Among the 35 breach crashes, five vehicle types were involved. The distribution of breach crashes by vehicle type is shown in the histogram illustrated by Figure 7. The vehicle type definitions for the histogram, based upon the vehicle types provided in the crash reports, are as follows:

- CAR = passenger car;
- CAR W/ TRAILER = passenger car pulling trailer (classified as HV);
- TRK UT = pickup truck or sport utility vehicle (SUV);
- TRK SA = truck tractor (semi-attached); and
- TRK ST = straight truck (insert truck).

According to Figure 7, 30 of the breach crashes (85.7 percent) involved cars, pick-up trucks, or sport utility vehicles, i.e. vehicles classified as “CAR” or “TRK UT” on the crash report. Hence, the majority of breach crashes did not involve heavy vehicles. Additionally, three tractors with semi-trailers and one straight truck did breach barriers upon impact.

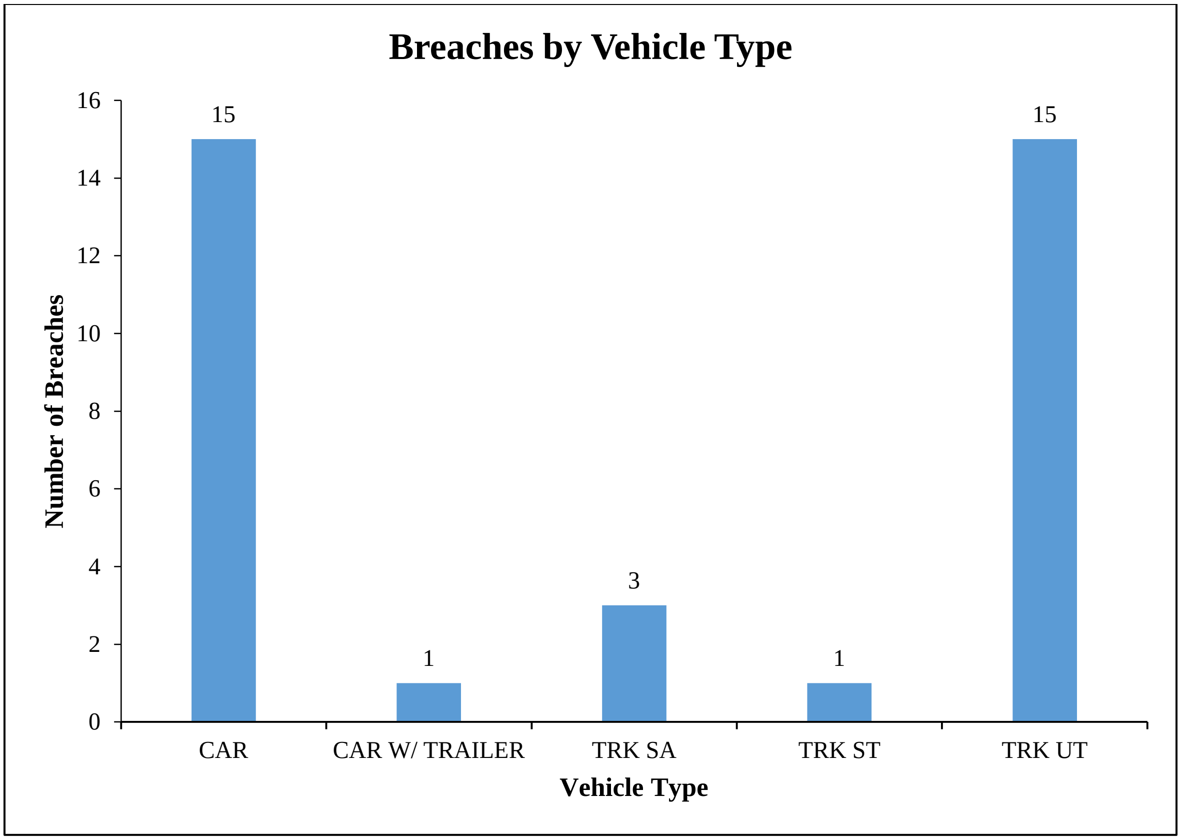

Figure 7 Breaches by Vehicle Type

Figure 8 shows the distribution of breach crashes by month of year. Of the total of 35 breach crashes, 23 (i.e., 65.7 percent) took place during the winter months of November through March. The distribution of the severity of the 35 breach crashes is shown in Figure 9. The highest proportion of breach crashes, 62.9 percent, resulted in property damage only. The injury severity category with the second highest proportion of breach crashes was the non-incapacitating (B) injury, with 20.0 percent of the breach crashes. None of the 35 breach crashes resulted in a fatality.

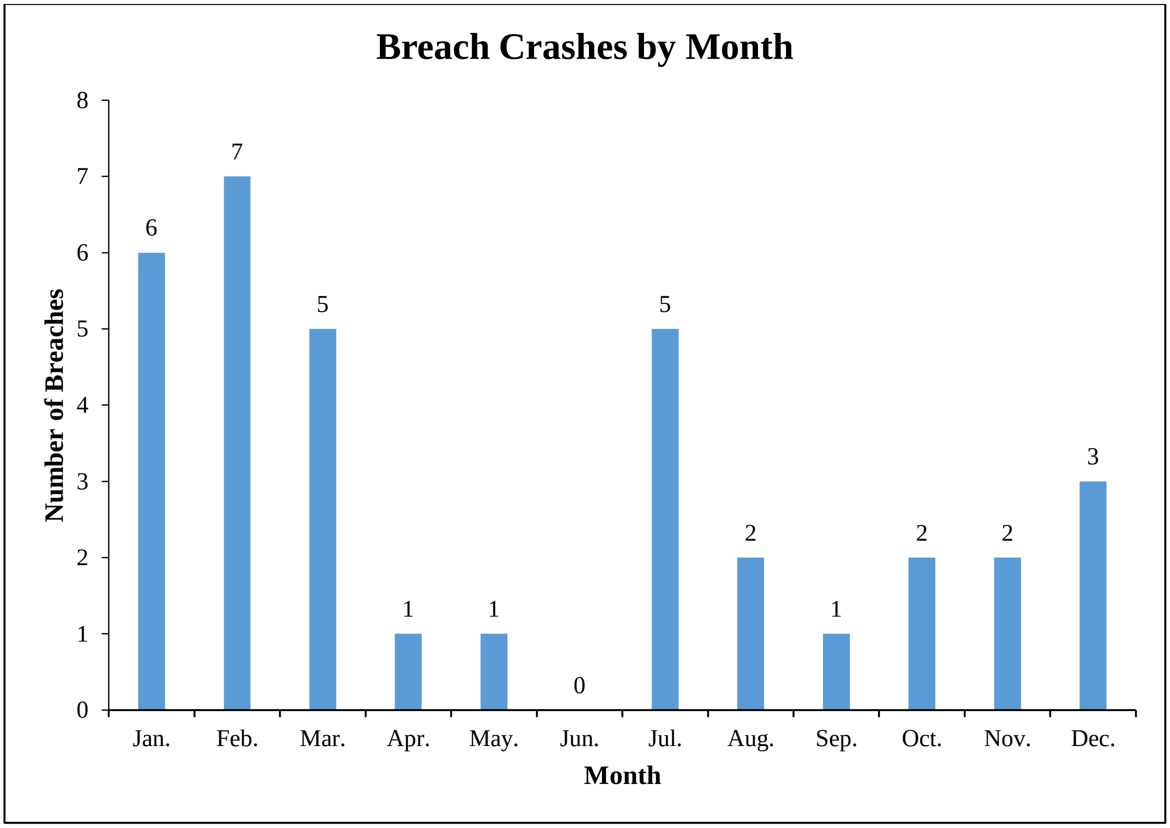

Figure 8 Histogram of Breaches by Month

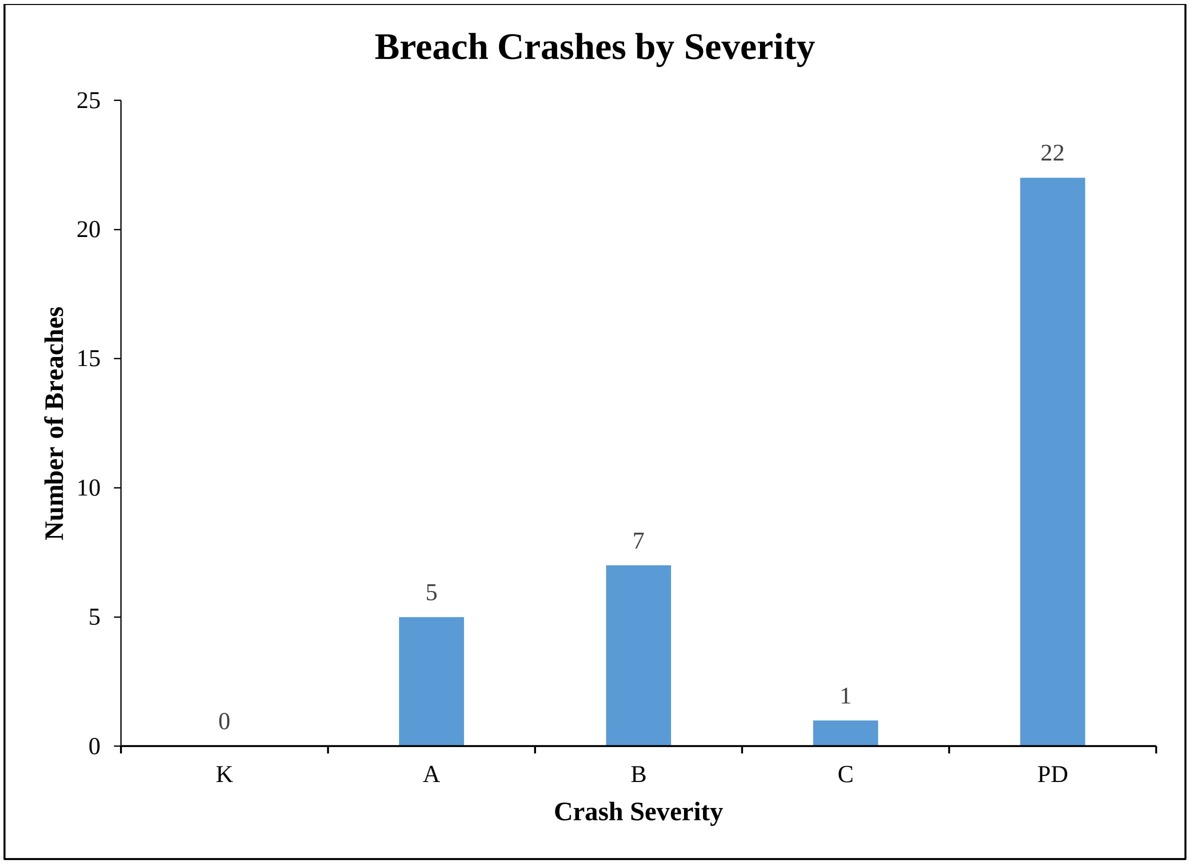

Figure 9 Histogram of Breaches by Severity

Table 21 shows the number of breach crashes for each crash severity splitting the data into two groups: non-heavy vehicles and heavy vehicles. From the table it can be seen that a slightly higher proportion of breaches involving heavy vehicles resulted in injury (severity K, A, B, or C) compared to breaches involving non-heavy vehicles (40.0 percent versus 36.7 percent). Table 22 shows the number of breaches by crash severity for three- and four-cable barrier systems. From Table 22, it can be seen that nearly two times as many breaches occurred on three-cable systems. However, the proportion of injury crashes was slightly higher for four-cable systems than three-cable systems (41.7 percent versus 39.1 percent).

Table 21 Breach Crash Severity by Vehicle Type

	Crash Severity					Totals	
Vehicle Type	**K**	**A**	**B**	**C**	**PD**	**Sub-Total**	**% of Total**
Non-HV	0	4	6	1	19	30	85.7%
HV	0	1	1	0	3	5	14.3%
Total	0	5	7	1	22	35	100.0%

Table 22 Breach Crash Severity by Number of Cables in Barrier

	Crash Severity					Totals	
Number of Cables	**K**	**A**	**B**	**C**	**PD**	**Sub-Total**	**% of Total**
Three	0	3	6	0	14	23	65.7%
Four	0	2	1	1	8	12	34.3%
Total	0	5	7	1	22	35	100.0%

4.3.2 Non-Parametric Analyses of Breach Crashes

4.3.2.1 Analysis of Breach Crashes of All Severities

For this analysis, the primary goal was to investigate if there was a statistically significant difference in the crash severities associated with breach and non-breach crashes. To make the determination, 2X2 contingency tables were created based upon the data and Yates' chi-squared test was used. In this instance of Yates' test, the null hypothesis (H_0) stated breach status and injury severity for a crash are independent of one another (*33*). The contingency tables for the "All Vehicles" and "Without Heavy Vehicles" datasets are shown in Tables 23 and 24.

Table 23 Contingency Table for All Vehicles Dataset

Crash Outcome	Injury Severity	
	PD	**KABC**
Non-Breach	623	95
Breach	22	13

Table 24 Contingency Table for Without Heavy Vehicles Dataset

Crash Outcome	Injury Severity	
	PD	KABC
Non-Breach	595	94
Breach	19	11

For the "All Vehicles" dataset, the test statistic was found to be χ^2 = 13.647 and the corresponding p-value was 2.207E-4. For the "Without Heavy Vehicles" dataset, the test statistic was found to be χ^2 = 10.443 and the corresponding p-value was 0.001. Hence, regardless of dataset, the null hypothesis was rejected as both p-values were well below typical cutoff values such as α=0.05. The interpretation of independence between breach status and injury severity implies that there is an increased probability of a crash resulting in an injury, given a crash results in barrier breach.

4.3.2.2 Analysis of Breach Crashes Resulting in Injury Only

This section further investigated how severe injuries resulted from breach crashes can be via Welch's t-test and the MWW test. For both tests, the two samples used were the sets of breach crashes that resulted in injuries and the set of non-breach crashes that resulted in injuries. Hence, all PD crashes were filtered out of both of the original breach and non-breach datasets since only injury crashes were of concern. Ultimately, both tests were performed on the "All Vehicles" and "Without Heavy Vehicles" datasets, with the added caveat that PD crashes were removed from each set prior to testing for reasons aforementioned.

In order to perform either of the tests, the severity level of each crash was coded and represented by a number. Two different coding methods were used for the severity levels, namely non-weighted coding and weighted coding.

- The non-weighted coding assigned sequential integer values to each of the severity levels as follows: C was assigned to "1," B was assigned to "2," A was assigned to "3," and K was assigned to "4." In such a scheme, the difference between severities C and B is equivalent to that between B and A, which is further equivalent to that between A and K; that is, the steps between severities are equal.
- The weighted coding used the crash cost as the weight and assigned the crash cost WisDOT uses to each severity level. The severity levels were hence coded as follows (all values in 2013 dollars): C was assigned to $27,849, B was assigned to $58,559, A was assigned to $229,504, and K was assigned to $4,513,039. This method avoided weighting different severity levels equally. Note that the weights are fixed and are based on WisDOT and national data rather than based on the actual crash costs as such data were not available (*36*, *37*).

The following tests were performed to investigate the breach severity:

- Test 1: Welch's t-test using the "All Vehicles" dataset (injury crashes only) and the non-weighted coding;
- Test 2: Welch's t-test using the "All Vehicles" dataset (injury crashes only) and the weighted coding;
- Test 3: Welch's t-test using the "Without Heavy Vehicles" dataset (injury crashes only) and the non-weighted coding;
- Test 4: Welch's t-test using the "Without Heavy Vehicles" dataset (injury crashes only) and the weighted coding;
- Test 5: MWW test using "All Vehicles" dataset (injury crashes only); and
- Test 6: MWW test using "Without heavy Vehicles" dataset (injury crashes only).

Note that it was unnecessary to perform the MWW test under both coding schemes as computation of the test statistic relies solely on the ranks of individual observations, which would be the same regardless of whether the weighted or non-weighted coding scheme was used.

The computed t-statistics for each of the previously mentioned testing scenarios, their corresponding p-values, and whether or not H_0 was rejected for the given test are shown in Table 25. In the cases involving the non-weighted severity scheme, the null hypothesis was rejected well below the α=0.05 confidence level since the individual p-values are all less than 0.05. Thus, the result of these t-tests implies that the mean severity associated with a non-breach crash will be lower than that associated with a breach crash. Again, it is important to consider that these results assume all crash severities carry the same weight and the difference between any two severity levels has the same meaning regardless of the two levels chosen. When considering the results of the t-tests under the weighted severity coding scheme, the results are quite different. In both cases, the null hypothesis could not be rejected and the conclusion was that there is no difference in the mean severity levels associated with breach and non-breach crashes. This result stems from the extremely high weight placed on fatal crashes, which is an order of magnitude larger than that for the next highest severity level. In the dataset, there was only one fatal crash and it was the result of a non-breach crash. Hence, the "pull" of this crash was enough to offset the fact overall, breach crashes may tend to result in higher severity from a proportionality viewpoint. Thus, the final conclusion on whether or not there is a difference in the mean severity between breach and non-breach crashes is open to interpretation depending on how one feels crash severities should be weighted.

Table 25 Results of Welch's t-test

Dataset	Test No.	Severity Coding Scheme	t-statistic	df	p-value	Reject H_0 at α=0.05?
All Vehicles	1	Non-Weighted	-3.751	16.206	0.002	Yes
	2	Weighted	-0.331	96.238	0.742	No
Without Heavy Vehicles	3	Non-Weighted	-3.210	12.828	0.007	Yes
	4	Weighted	-0.234	83.578	0.816	No

The computed U-statistics for each of the testing scenarios under the MWW test, their corresponding p-values, and whether or not H_0 was rejected for the given test are shown in Table 26. As in the cases of the t-tests using the non-weighted severity scheme, the null hypotheses were rejected for the MWW tests well below the α=0.05 confidence level. Hence, it can be concluded that the true location shift between the distribution of breach and non-breach crashes is not zero. In other words, the median crash severity associated with breach crashes is higher than that associated with non-breach crashes.

Table 26 Results of MWW Test

Dataset	U-statistic	p-value	Reject H_0 at α=0.05?
All Vehicles	292.00	7.714E-4	Yes
Without Heavy Vehicles	258.50	0.003	Yes

Figure 10 shows the hierarchical relationship of the datasets used in the aforementioned analyses. Finally, Figures 11 and 12 present an alternate way to view the breach versus non-breach severity data for injury crashes. In the figures, it can be seen that there is a decreasing trend in the severity bars for the non-breach crashes (i.e., the blue bars), while the trend in the bars for the breach crashes (i.e., the orange bars) is increasing. It is important to note that these histograms do not have any time scale nor weighting associated with them, but rather only show the overall proportions of injury crashes associated with each injury severity level for breach and non-beach crashes. Simply put, the trends they show simply illustrate the results of the Welch's t-tests under the non-weighted coding scheme and MWW tests.

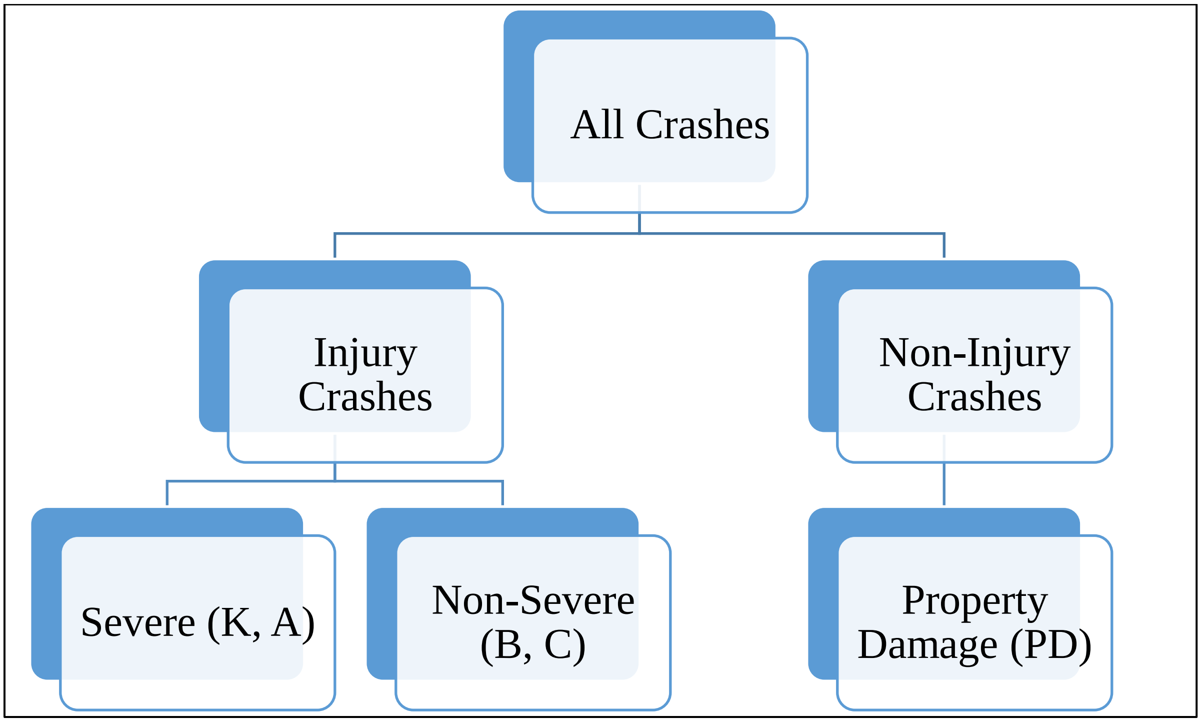

Figure 10 Hierarchy of Data for Breach vs. Non-Breach Severity Analysis

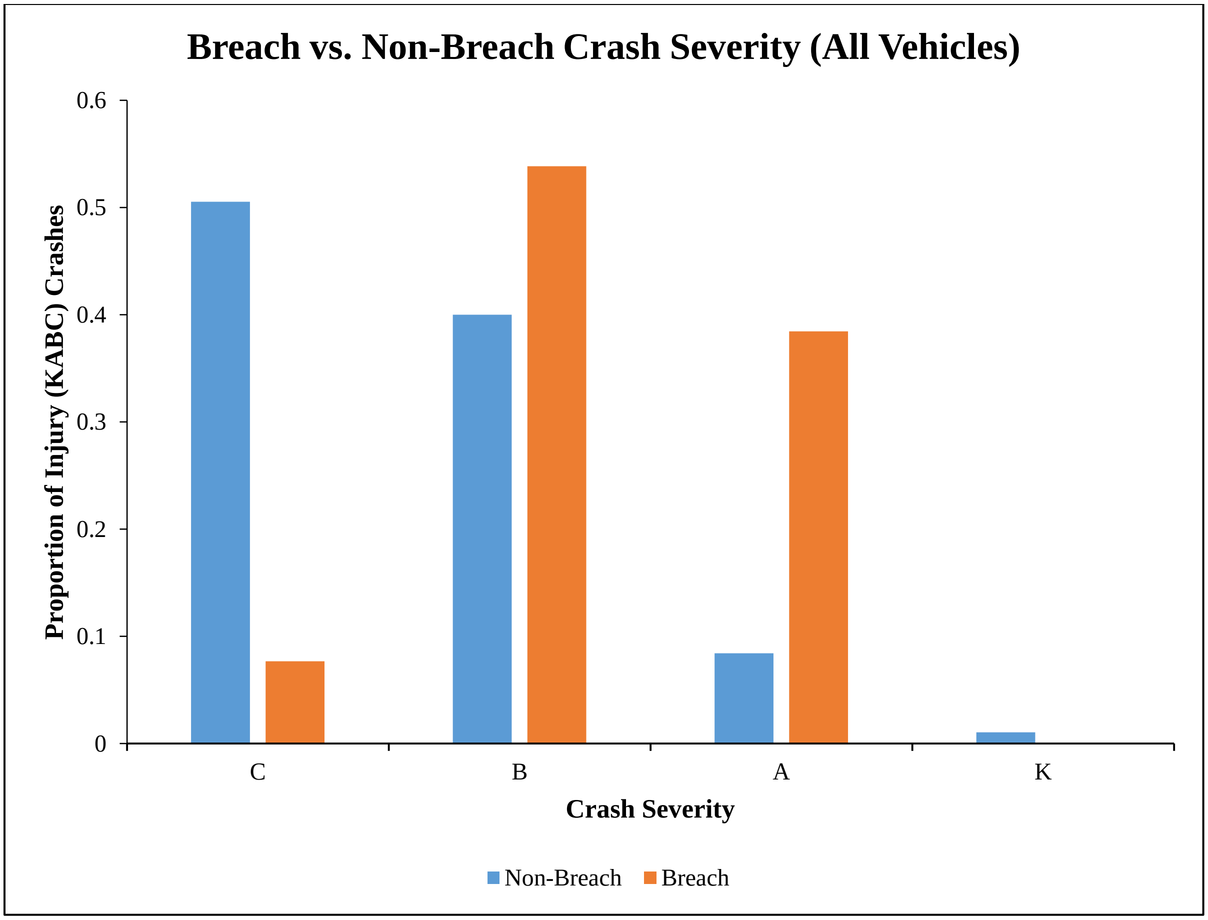

Figure 11 Breach vs. Non-Breach Crash Severity Proportions (All Vehicles Dataset)

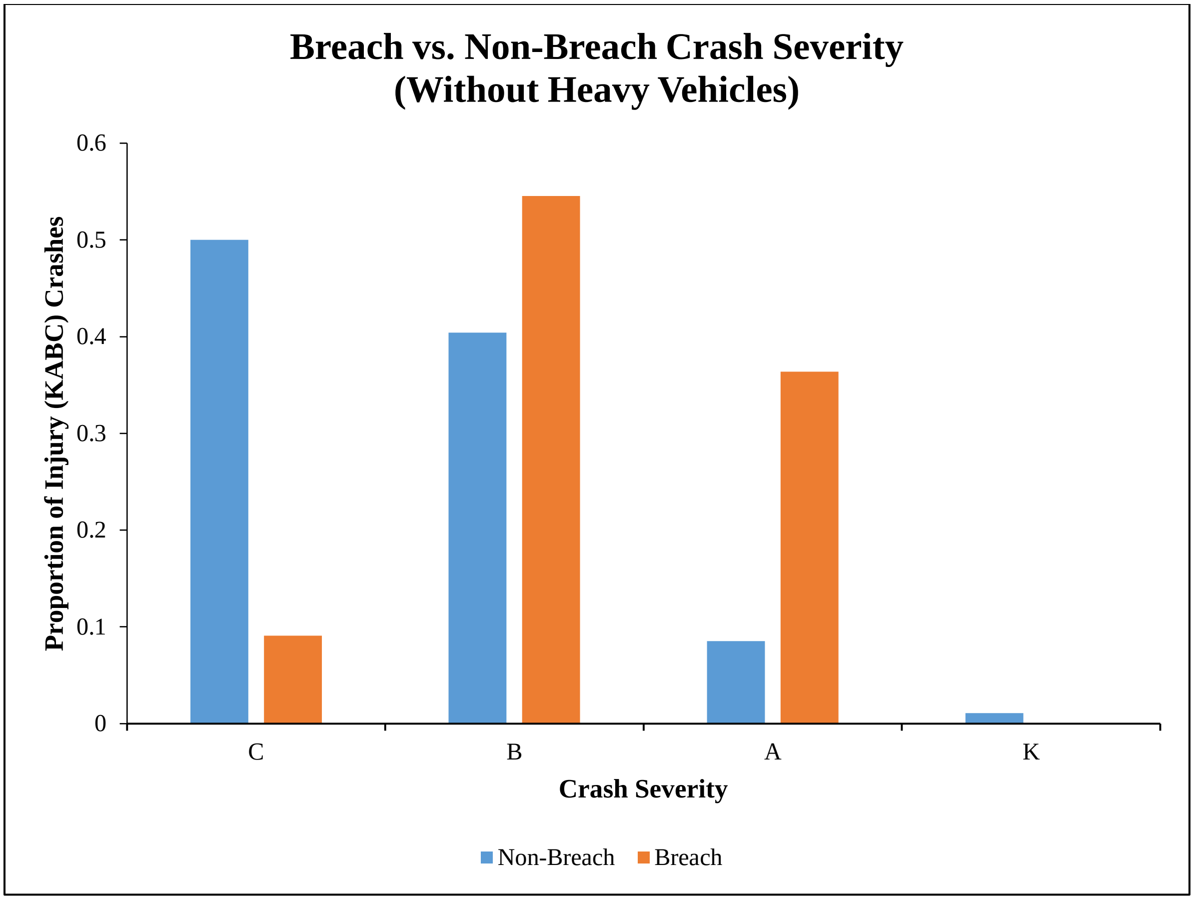

Figure 12 Breach vs. Non-Breach Crash Severity Proportions (Without Heavy Vehicles Dataset)

4.3.3 Breach Regression Analysis

A logistic regression analysis was conducted to see what factors, if any, affect the likelihood of barrier breach. For this analysis, the dependent variable was the binary variable “Breach,” which took the value of “1” when the crash of interest resulted in barrier breach and “0” otherwise. The sample used for the analysis was the entire set of 753 median barrier crashes. Equation 11 presents the final model developed from the analysis, while Table 27 presents additional information on the parameters in the model. Table 28 shows the covariates not included in the final model. It is important to note that a significant p-value in Table 28 does not necessarily mean that said term will be significant if included in the final model nor will it have a large effect on the dispersion parameter.

$$logit[\pi(x)] = -2.482 + 0.965 * Collision\ Before - 1.227 * Median\ Width\ (50 \leq x < 60) - 0.616 * Median\ Width\ (x \geq 60) \qquad (11)$$

Table 27 Final Model for logit (Breach) versus Number of Cables in Barrier

Final Model								
							Profiled 95% CI for Exp(β)	
Variable	**β**	**S.E.**	**Z Value**	**df**	**p-val**	**Exp(β)**	**Lower**	**Upper**
Collision Before	0.965	0.386	2.498	1	0.013	2.625	1.188	5.482
Median Width (50≤x<60)	-1.227	0.455	-2.700	1	0.007	0.293	0.120	0.727
Median Width (x≥60)	-0.616	0.436	-1.413	1	0.158	0.540	0.231	1.302
Constant	-2.482	0.352	-7.048	1	1.810E-12	0.084	0.039	0.158
AIC = 277.31								
φ = 1.028								

Table 28 Variables NOT Included in Final Model for logit (Breach) versus Number of Cables in Barrier

Variables NOT Included	AIC	LRT	df	p-val
Horizontal Curve	279.160	0.148	1	0.701
Median Slope - 4:1	276.800	2.509	1	0.113
Heavy Vehicle	276.170	3.136	1	0.077
Pavement Condition - Dry	279.040	0.266	1	0.606
Collision After	277.520	1.788	1	0.181
Log (AADT)	279.190	0.119	1	0.730
Three-Cable Barrier	271.730	7.579	1	0.006
Weather Condition - Clear	277.980	1.334	1	0.248
Minimum Deflection Distance	278.320	2.992	2	0.224

In the final model three predictors were selected, two of which are the categories of the “Median Width” variable. The first significant predictor chosen was “Collision Before.”

The positive sign on this variable indicates that the odds of a breach increase when this variable takes the value of “1,” corresponding to scenarios in which the errant vehicle was involved in another collision prior to hitting the cable barrier. The CI for the “Breach”-“Collision Before” odds ratio suggests that when an additional collision occurs prior to a barrier hit, the odds of the vehicle breaching the barrier increase by at least 18.8 percent.

The next covariate selected for inclusion in the model was the “Median Width” variable. This variable with three levels is represented by comparing the following two levels: “$50 \leq x < 60$” and “$x \geq 60$” to the base case “$50 > x$,” where x denotes median width in feet in all cases. The negative coefficient for the “$50 \leq x < 60$” category implies that the likelihood of barrier breach decreases when the errant vehicle strikes a barrier on a median at least 50 feet, but less than 60 feet wide, when compared to a median less than 50 feet in width. The CI for the associated odds ratio indicates that this decrease is at least 12.0 percent. Similarly, the negative coefficient on the “$x \geq 60$” category has a similar interpretation, however, one must note that the p-value associated with the Wald statistic for the coefficient is not significant at the 0.05 level. Nonetheless, the “Median Width” variable (i.e., a variable with more than two levels) was chosen to be in the final model due to the significance of the “$50 \leq x < 60$” coefficient. Additionally, the insignificant “$x \geq 60$” coefficient cannot be simply removed as doing so would necessitate changing the interpretation of the base case.

4.4 Analysis of Crash Severity

4.4.1 Regression Analyses of Crash Severity (Severe Crashes)

Two regression analyses were performed to determine what, if any, factors had a significant effect on the likelihood of crash with a cable median barrier resulting in a severe (fatal-K or incapacitating-A) injury. In the first analysis, the set of 10 descriptive covariates was considered in addition to the “Three-Cable Barrier” variable. For this analysis, the sample size was 753 and included all of the median barrier crash data points. The second analysis considered the set of 10 descriptive covariates in addition to the “Crash Outcome” variable. The “Crash Outcome” variable described the interaction between the errant vehicle and the cable median barrier and was assigned to three categories as follows:

- Stop (0, base case) – Denotes a crash in which the errant vehicle was stopped by the cable barrier per definition in Section 3.2.6.
- Redirect (1) – Denotes a crash in which the errant vehicle was redirected by the cable barrier per definition in Section 3.2.6; and
- Breach (2) – Denotes a crash in which the errant vehicle breached the cable barrier per definition in Section 3.2.6.

Crashes whose outcomes fell under the “Neither” category (per Section 4.2) that were not breaches were excluded from this analysis as assumptions were not made on how the vehicle interacted with the barrier. Thus, the sample used in the analysis considering “Crash Outcome” involved the 708 crashes whose outcome fell into one of the three aforementioned categories.

4.4.1.1 Severe Crash (KA) Analysis by Number of Cables in Barrier

As previously noted, the first model-building procedure involved trying to fit a model involving the set of 10 descriptive covariates was considered in addition to the “Three-Cable Barrier” variable. For this model, the dependent variable was severe (KA) crash, which took the value of “1” when the cable barrier crash resulted in a K or A injury and took the value of “0” otherwise.

The final model is presented in Equation 12, and additional information on the model such as Wald statistic values associated with the model parameters and the AIC value can be seen in Table 29. Table 30 shows parameters not included in the final model as well AIC values that would result if one and only one of the variables was added to the final model.

$$logit[\pi(x)] = -4.593 + 1.289 * Pavement\ Condition - Dry \quad (12)$$

Table 29 Final Model for logit (KA) versus Number of Cables in Barrier

Final Model								
							Profiled 95% CI for Exp(β)	
Variable	**β**	**S.E.**	**Z Value**	**df**	**p-val**	**Exp(β)**	**Lower**	**Upper**
Pavement Condition - Dry	1.289	0.563	2.289	1	0.022	3.630	1.240	11.920
Constant	-4.593	0.450	-10.219	1	<2.000E-16	0.010	0.004	0.022
AIC = 137.780								
φ = 1.003								

Table 30 Variables NOT Included in Final Model for logit (KA) versus Number of Cables in Barrier

Variables NOT Included	AIC	LRT	df	p-val
Horizontal Curve	137.750	2.033	1	0.154
Median Slope - 4:1	137.260	2.524	1	0.112
Heavy Vehicle	139.740	0.039	1	0.843
Collision Before	139.670	0.110	1	0.741
Collision After	137.740	2.039	1	0.153
Log (AADT)	139.730	0.050	1	0.823
Three-Cable Barrier	139.780	0.004	1	0.948
Weather Condition - Clear	139.370	0.407	1	0.524
Minimum Deflection Distance	138.530	3.256	2	0.196
Median Width	138.830	2.955	2	0.228

Ultimately, only one significant predictor was found for inclusion in the final model, that being the “Pavement Condition” variable. The positive coefficient on the variable indicates that when the variable takes the value of “1,” meaning the pavement is dry, the odds of the cable median barrier crash resulting in a severe injury increase. The CI for "KA"-"Pavement Condition" odds ratio suggests that dry pavements can cause the odds of a barrier crash resulting in a severe injury to increase by at least 24.0%. The lack of the inclusion of the "Three-Cable Barrier" in the final model indicates that the number of cables does not appear to have an effect on a barrier crash resulting in a severe injury.

4.4.1.2 Severe Crash Analysis by Crash Outcome

The second severe crash regression analysis involved attempting to fit a model to the data considering "Crash Outcome" as a possible predictor. Ultimately, however, the model developed (Equation (13)) was nearly the same as that shown in Equation (12). Additional information on the model is shown in Table 31, and parameters excluded from the final model are shown in Table 32.

$$logit[\pi(x)] = -4.556 + 1.246 * Pavement\ Condition - Dry \tag{13}$$

Table 31 Final Model for logit (KA) versus Crash Outcome

Final Model								
							Profiled 95% CI for Exp(β)	
Variable	**β**	**S.E.**	**Z Value**	**df**	**p-val**	**Exp(β)**	**Lower**	**Upper**
Pavement Condition - Dry	1.246	0.576	2.164	1	0.034	3.477	1.147	11.622
Constant	-4.556	0.450	-10.134	1	<2.000E-16	0.011	0.004	0.023
AIC = 128.85								
φ = 1.003								

Table 32 Variables NOT Included in Final Model for logit (KA) versus Crash Outcome

Variables NOT Included	AIC	LRT	df	p-val
Horizontal Curve	128.940	1.9105	1	0.167
Median Slope - 4:1	127.980	2.8728	1	0.090
Heavy Vehicle	130.770	0.0881	1	0.767
Collision Before	130.660	0.1941	1	0.660
Collision After	128.560	2.2982	1	0.130
Log (AADT)	130.780	0.0704	1	0.791
Outcome	119.480	13.3743	2	0.001
Weather Condition - Clear	129.710	1.1473	1	0.284
Minimum Deflection Distance	128.910	3.9471	2	0.139
Median Width	130.590	2.2679	2	0.321758

The positive coefficient on the sole significant predictor, “Pavement Condition-Dry,” has the same interpretation as that for Equation (12) from Section 4.4.1.1. Additionally, the magnitude of both effects are quite similar as their coefficient values are nearly identical. Hence, it can be concluded that there is no association between crash outcome and severe crashes. That is, crashes in which the vehicle is redirected or breaches the barrier are no more likely to result in a severe (KA) injury than when compared to a crash in which the vehicle is stopped by the barrier.

4.4.2 Regression Analyses of Crash Severity (All Injury Crashes)

As was the case for the severe crash analysis, two regression analyses were performed to determine what, if any, factors had a significant effect on the likelihood of crash with a cable median barrier resulting in an injury (i.e., severity K, A, B, or C). In the first analysis, the set of 10 descriptive covariates was considered in addition to the “Three-Cable Barrier” variable as was the case in Section 4.4.2.1 for KA crashes. Again, the sample size was the entire set of 753 median barrier crashes. The second analysis considered the set of 10 descriptive covariates in addition to the “Crash Outcome” variable as was done in Section 4.4.2.2 for KA crashes. Similarly, crashes whose outcomes fell under the “Neither” category (per Section 3.2.6) that were not breaches were excluded from this analysis, leading to a sample size of 708 data points.

4.4.2.1 Injury Crash (KABC) Analysis by Number of Cables in Barrier

The final model for the logit of an injury (i.e., KABC) crash is presented in Equation 14, with additional model information provided in Table 33. The list of variables not included in the final model as well as the AIC values that would arise for the model if one and only one of said parameters was added to the final model are presented in Table 34. Again, it is important to note that a significant p-value in Table 34 does not necessarily mean that said term will be significant if included in the final model nor will it have a large effect on the dispersion parameter.

$$logit[\pi(x)] = -2.489 + 1.262 * Pavement\ Condition - Dry + 0.724 * Collision\ Before \quad (14)$$

Table 33 Final Model for logit (KABC) versus Number of Cables in Barrier

Final Model								
							Profiled 95% CI for Exp(β)	
Variable	**β**	**S.E.**	**Z Value**	**df**	**p-val**	**Exp(β)**	**Lower**	**Upper**
Pavement Condition - Dry	1.262	0.218	5.779	1	7.510E-09	3.532	2.311	5.449
Collision Before	0.724	0.257	2.813	1	0.005	2.063	1.232	3.389
Constant	-2.489	0.168	-14.817	1	<2.000E-16	0.083	0.059	0.114
AIC = 577.850								
φ = 1.009								

Table 34 Variables NOT Included in Final Model for logit (KABC) versus Number of Cables in Barrier

Variables NOT Included	AIC	LRT	df	p-val
Horizontal Curve	579.850	0.000	1	0.990
Median Slope - 4:1	578.430	1.419	1	0.234
Heavy Vehicle	576.150	3.704	1	0.054
Collision After	578.590	1.260	1	0.262
Log (AADT)	576.860	2.997	1	0.083
Three-Cable Barrier	579.700	0.150	1	0.698
Weather Condition - Clear	579.810	0.045	1	0.832
Minimum Deflection Distance	578.750	0.045	2	0.212
Median Width	575.760	6.092	2	0.048

Ultimately, two significant predictors were found in the model building process. First, the "Pavement Condition" variable was found to be significant, and the positive value of the coefficient indicates that if the pavement at the time of the cable barrier crash was dry (i.e., the variable takes value "1"), the odds of the crash resulting in an injury (severity level K, A, B, or C) increase. Additionally, lower bound of the "KABC"-"Pavement Condition" odds ratio suggests that the odds of a crash resulting in an injury increase more than twofold when the pavement at the time of the crash is dry. The "Collision Before" variable was also found to be significant and hence included in the final model. The positive coefficient indicates that when the variable takes the value of "1," corresponding to the crash sequence involving the errant vehicle being involved in another collision prior to striking the cable barrier, the odds of the crash resulting in injury increase. The "Three-Cable Barrier" variable was ultimately not found to be significant, hence there does not appear to be an association between the number of cables in the barrier and a cable barrier crash resulting in injury. Stated alternately, crashes with three-cable barriers are no more likely to result in an injury for the participants than are crashes with four-cable barriers.

4.4.2.2 Injury Crash (KABC) Analysis by Crash Outcome

The final regression model developed sought to model the logit of a cable barrier crash resulting in an injury as a function of the 10 descriptive covariates and the “Crash Outcome” variable. The “Crash Outcome” variable had three categories and used “Stop” as the base case. Hence, the “Crash Outcome” variable ultimately compared “Redirect” crashes to “Stop” crashes and “Breach” crashes to “Stop” crashes. The final model developed is shown in Equation 15, and additional model information is provided in Table 35. The variables not included in the final model and associated information as discussed in previous sections is presented in Table 36.

$$logit[\pi(x)] = -2.675 + 1.263 * Pavement\ Condition - Dry + 0.597 * Collision\ Before + 0.397 * Outcome - Redirect + 1.356 * Outcome - Breach \quad (15)$$

Table 35 Final Model for logit (KABC) versus Crash Outcome

Final Model								
							Profiled 95% CI for Exp(β)	
Variable	**β**	**S.E.**	**Z Value**	**df**	**p-val**	**Exp(β)**	**Lower**	**Upper**
Pavement Condition - Dry	1.263	0.228	5.546	1	2.920E-8	3.537	2.270	5.555
Collision Before	0.597	0.281	2.127	1	0.033	1.817	1.035	3.122
Outcome - Redirect	0.397	0.248	1.599	1	0.110	1.488	0.909	2.414
Outcome - Breach	1.356	0.403	3.366	1	0.001	3.881	1.727	8.467
Constant	-2.675	0.202	-13.260	1	<2.000E-16	0.069	0.046	0.101
AIC = 536.250								
φ = 0.970								

Table 36 Variables NOT Included in Final Model for logit (KABC) versus Crash Outcome

Variables NOT Included	AIC	LRT	df	p-val
Horizontal Curve	538.230	0.020	1	0.888
Median Slope - 4:1	536.580	1.663	1	0.197
Heavy Vehicle	534.460	3.785	1	0.052
Collision After	538.040	0.212	1	0.645
Log (AADT)	536.160	2.086	1	0.149
Weather Condition - Clear	538.190	0.058	1	0.811
Minimum Deflection Distance	537.350	2.898	2	0.235
Median Width	534.850	5.393	2	0.067

Ultimately, three predictors were included in the final model, one of which was the three-level “Crash Outcome” variable. The coefficients for the “Pavement Condition” and “Collision Before” variables have the same signs as those in Equation 14 and thus have similar interpretations. That is, when either or both of these variables take the value of “1” (corresponding to dry pavement at the time of the crash and the errant vehicle being involved in an additional collision prior to the barrier hit, respectively), the odds of the cable barrier crash resulting in an injury increase. The positive coefficient on the “Outcome-Redirect” coefficient indicates that when the vehicle striking the cable barrier is redirected as opposed to stopped, the odds of the crash resulting in injury increase. However, the p-value associated with the Wald test statistic for this variable was not found to be less than 0.05. Further, the inclusion of 1.00 in the “KABC”-“Outcome-Redirect” odds ratio suggests the possibility of independence between redirect crashes and injury. Nonetheless, “Crash Outcome” was left in the final model due to the significance of the “Outcome-Breach” predictor. Again, the positive coefficient on this variable indicates that the odds of a crash resulting in injury increase when the errant vehicle breaches the barrier, as opposed to being stopped by the barrier. This increase could be at least 72.7 percent as seen from the lower bound of the

“KABC”-“Outcome-Breach” odds ratio. Finally, the inclusion of the “Outcome-Breach” predictor in the final model reinforces several of the conclusions drawn in Section 4.3.2, in which several tests found that breach crashes are typically more severe (and would hence result in injury) than non-breach crashes (a category in which “Stop” crashes would fall).

5 Conclusions and Future Work

5.1 Conclusions

To date, the majority of cable barrier studies have either examined performance via before-and-after studies or investigated issues such as crash frequency. Studies addressing cable median barrier crashes themselves in terms of severity and crash outcomes, although existing, are few in number. This thesis sought to fill the gap in the literature on these issues.

Overall, a dataset of 753 crashes occurring with high-tension cable median barriers in the State of Wisconsin between 2009 and 2013 was established. This dataset was developed through the use of crash mapping tools and the manual review of more than 3,200 police crash reports. With the crash data in hand, initial trends were sought to guide future analysis. For example, it was observed that the majority of crashes (69.72 percent) occurred during winter months. Additionally, it was observed that three-cable barriers and four-cable barriers experienced nearly the same number of crashes during the study period making them appear to be a sound choice for a comparison pair.

Barrier containment behavior (i.e., barrier stoppage and redirection behavior) was examined next. Overall, “Stop” crashes accounted for slightly more of the high-severity (KA) crashes than “Redirect” crashes. That being said, “Redirect” crashes accounted for a higher proportion of injury crashes (severities K, A, B, and C) overall. A logistic regression model for the logit of barrier containment (i.e., log odds of a “Stop”) was built to further investigate the issue. Results of the model showed that increasing AADT, a the errant vehicle being involved in a collision prior to the barrier hit, and the barrier being struck having three cables were all characteristics which led to an increase in the likelihood a barrier crash would result in a “Stop” as opposed to a “Redirect.” The “Collision After” variable was associated with a decrease in the odds of cable barrier crash resulting in a “Stop.” This is quite reasonable as vehicles that are redirected by a cable barrier are sometimes subject to collisions with vehicles back on the traveled way. Heavy vehicles were not found to influence the likelihood of a “Stop” in a positive or negative way.

An analysis of cable median barrier crashes resulting in barrier breach via override, underride, or penetration was completed next. Overall, it was found that the majority of vehicles that breached the cable barriers were not heavy vehicles. Although the majority of breach crashes did result in only property damage, a variety of non-parametric tests showed that in general, breach crashes are more severe than non-breach crashes. A logistic regression analysis showed that the odds of cable barrier crash resulting in breach are increased when the errant vehicle is involved in another collision prior to striking the barrier. Additionally, the model showed that the likelihood of a breach decreased as median width increased.

The final portion of the thesis focused on investigating factors affecting crash severity associated with cable barrier crashes. Both severe (KA) and injury (KABC) crashes were targeted and investigated through logistic regression analyses. In terms of severe crashes, dry pavement was found to be the only significant influencing factor and it led to an increase in the odds of a barrier crash resulting in a fatality or incapacitating injury. Dry pavement condition was also shown to be a significant factor in predicting injury (KABC) crashes as well, and it was found to have a similar effect in such models. The “Collision Before” variable was also found to be a significant predictor in the injury crash regression analyses and was shown to increase the odds of a crash resulting in an injury when the variable took the value “1,” indicating the errant vehicle was involved in a collision prior to the barrier hit.

Additionally, crash outcome was shown to have some effect on a cable barrier crash resulting in injury. Crashes involving breaching of the barrier as opposed to stoppage were shown to significantly increase the odds of the crash resulting in an injury. "Redirect" crashes showed a similar effect though significance for the "Outcome-Redirect" variable at the 0.05 level was lacking. Finally, one will note that none of the models for crash severity include the "Three-Cable Barrier" or "Heavy Vehicle" variables. Hence, it can be concluded that number of cables in the barrier cross-section nor vehicle type (i.e., HV or non-HV) are associated with crash severity.

5.2 Future Work

Future work on these topics could build upon this study by adding to the crash data used. A larger dataset, particularly one with more breach crashes could help strengthen results and lead to new insights. Additionally, more factors could be added to the regression analyses such as ones involving driver behavior at the time of the crash, demographics etc. to gain new perspectives in the regression analyses. Finally, cable median barrier crash severity and its influencing factors could be compared against data from other barrier types such as concrete barrier and metal beam guard.

REFERENCES

1. National Highway Traffic Safety Administration. (2012). “FARS Encyclopedia: Query.” *National Center for Statistics and Analysis Data Resource Website*, <http://www-fars.nhtsa.dot.gov/QueryTool/QuerySection/Report.aspx> (Apr. 27, 2013).
2. Federal Highway Administration (FHWA). (2012). Roadway Departure Safety. *FHWA Safety Program*, <http://safety.fhwa.dot.gov/roadway_dept/> (Apr. 27, 2013).
3. Qin, X., Wang, F., Bill, A., and Noyce, D. A. (2009). *Evaluation of High-tension Cable Barriers in Wisconsin*, Wisconsin Department of Transportation (WisDOT), Madison, WI.
4. American Association of State Highway and Transportation Officials (AASHTO). (2011). *Roadside Design Guide: 4th Edition*, AASHTO, Washington, DC.
5. Marzougui, D., Mahadevaiah, U., Tahan, F., Kan, C., McGinnis, R., and Powers, R. (2012). *National Cooperative Highway Research Program (NCHRP) Report 711: Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems*, Transportation Research Board, Washington, D.C.
6. Ash, J., Li, Z., Bill, A., and Noyce, D. (2014). *Evaluation of Wisconsin Cable Median Barrier Systems: Phase 2*, WisDOT, Madison, WI.
7. AASHTO. (2010). *Highway Safety Manual - 1st Edition: Volume 1*, AASHTO, Washington, D.C.
8. Graham, J. (2011). “NCHRP 22-21 [Completed]: Median Cross-Section Design for Rural Divided Highways.” *Transportation Research Board*, < http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=694> (Jul. 6, 2013).
9. AASHTO. (2009). *Manual for Assessing Safety Hardware*, AASHTO, Washington, D.C.
10. Chitturi, M. V., Ooms, A. W., Bill, A. R., and Noyce, D. A. (2011). “Injury outsomes and costs for cross-median and median barrier crashes.” *Journal of Safety Research*, 42(2), 87-92.
11. WisDOT. (2011). "Chapter 11 - Design, Section 45 - Other Elements Affecting Geometric Design." *Facilities Development Manual*, WisDOT, WI, 1-75.
12. Graham, M. D., Burnett, W. C., Gibson, J. L., and Freer, R. H. (1967). “New Highway Barriers: Practical Application of Theoretical Design.” *Transportation Research Record: Journal of the Transportation Research Board*, 174, 88-183.
13. Jones, J. G., Bramon, M. M., Kampeter, J. N., Chandler, B. E., Foster, G. E., Glaser, R. S., et al. (2007). *A comprehensive analysis of and direction for MoDOT's Cable Median Barrier Program*, Missouri Department of Transportation, Jefferson City, MO.
14. AASHTO Technology Implementation Group. (2007). “AASHTO TIG CMB Presentation 07-11-07.” *AASHTO Technology Implementation Group*, <http://tig.transportation.org/Documents/AASHTOTIGCMBPresentation07-11-07.pdf> (Apr. 12, 2013).

15. Ross, H. E., Sicking, D. L., Zimmer, R. A., and Michie, J. D. (1993). *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Academy Press, Washington, D.C.
16. Lindley, J.A. (2007). "Memorandum - INFORMATION: Cable Barrier Considerations." *FHWA Safety Program*, <http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/policy_memo/memo072007/> (Apr. 27, 2013).
17. FHWA. (2009). "Manual for Assessing Safety Hardware (MASH)." *FHWA Safety Program*, <http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/ctrmeasures/mash/> (Apr. 27, 2013).
18. Ray, M. H., Silvestri, C., Conron, C. E., and Mongiardini, M. (2009). "Experience with Cable Median Barriers in the United States: Design Standards, Policies, and Performance." *Journal of Transportation Engineering*, 135, 711-720.
19. Stolle, C. S., and Sicking, D. L. (2013). *Impact Conditions Associated with Cable Median Barrier Failures*, Transportation Research Board, Washington, D.C.
20. Alluri, P., Haleem, K., and Gan, A. (2012). *In-Service Performance Evaluation (ISPE) for G4 (1S) Type of Strong-Post W-Beam Guardrail System and Cable Median Barrier: Volume II*, Florida International University, Miami, FL.
21. Chandler, B. (2007). "Eliminating Cross-Median Fatalities." *TR News*, 248, 29-31.
22. Hunter, W. W., Stewart, J. R., Krull, K. A., Huang, H. F., Council, F. M., and Harkey, D. L. (1999). *In-Service Crash Evaluation of Three-Strand Cable Median Barrier in North Carolina*, University of North Carolina Highway Safety Research Center, Chapel Hill, NC.
23. North Carolina Department of Transportation. (2006). "Median Barriers in North Carolina - Long Term Evaluation." *AASHTO Technology Implementation Group*, <http://tig.transportation.org/Documents/NorthCarolinaMediamBarrierEvaluation.pdf> (Mar. 20, 2013).
24. Focke, D. (2006). *Brifen WRSF In-Service Performance Evaluation: Year 3 Report - For the period from July 2005 to June 2006*, Ohio Department of Transportation, Columbus, OH.
25. Chimba, D., Emaasit, D., Allen, S., Hurst, B., and Nelson, M. (2012). *Safety Effectiveness of the Cable Rail Systems in Tennessee*, Tennessee State University, Nashville, TN.
26. Washington State Department of Transportation (WSDOT). (2009). *Cable Median Barrier: Reassessment and Recommendations Update (October 2009)*, WSDOT, Olympia, WA.
27. Hu, W., and Donnell, E. T. (2010). "Median barrier crash severity: Some new insights." *Accident Analysis and Prevention*, 42(6), 1697-1704.
28. Miaou, S. P., Bligh, R., and Lord, D. (2005). "Developing median barrier installation guidelines: a benefit/cost analysis using Texas data." *Transportation Research Record: Journal of the Transportation Research Board*, 1904.
29. Bligh, R., Miaou, S.-P., Lord, D., and Cooner, S. (2006). *Median Barrier Guidelines for Texas*, Texas Department of Transportation, Austin, TX.

30. Tarko, A. P., Villwock, N. M., and Blond N., (2008). “Effect of median design on rural freeway safety: flush medians with concrete barriers and depressed medians.” *Transportation Research Record: Journal of the Transportation Research Board*, 2060, 29-37.
31. Stolle, C. S. (2013). “Contributing Factors to Cable Median Barrier Penetrations.” *Proc, Transportation Research Board Annual Meeting 2014*, TRB, Washington, D.C.
32. Wisconsin Traffic Operations and Safety (TOPS) Laboratory. (2013). The WisTransPortal Data Hub [information system], <http://transportal.cee.wisc.edu/> (Mar. 20, 2013).
33. Agresti, A. (2007). *An Introduction to Categorical Data Analysis: Second Edition*. Wiley, John & Sons, Incorporated, Hoboken, NJ.
34. Khan, G., Bill, A. R., Chitturi, A. R., and Noyce, D. A. (2013). “Safety Evaluation of Horizontal Curves on Rural Undivided Roads.” *Transportation Research Record: Journal of the Transportation Research Board*, 2386, 147-157.
35. Washington, S. P., Karlaftis, M. G., and Mannering, F. L. (2003). *Statistical and Econometric Methods for Transportation Data Analysis*. Chapman & Hall/CRC, Boca Raton, FL.
36. National Safety Council. (2013). “Estimating the Costs of Unintentional Injuries.” from *National Safety Council*, <http://www.nsc.org/news_resources/injury_and_death_statistics/Pages/EstimatingtheCostsofUnintentionalInjuries.aspx> (May 6, 2013).
37. U.S. Department of Commerce: Bureau of Economic Analysis. (2013).”Gross Domestic Product: Implicit Price Deflator.” *Economic Research - St. Louis Fed.*, <http://research.stlouisfed.org/fred2/data/GDPDEF.txt> (May 6, 2013).

APPENDIX A

Table A-1 Median Barrier Crash Counts by Study Site

Crash Counts								
Site #	**County**	**Study Period**	**Years**	**K**	**A**	**B**	**C**	**PD**
1	Brown/Oconto	2011-2013	3	0	0	0	0	13
2	Dane	2009-2013	5	0	0	2	4	40
3	Dodge	2009-2013	5	0	1	3	3	33
4	Dunn	2009-2013	5	0	2	2	5	34
5	Eau Claire	2009-2013	5	1	0	0	0	11
6	Fond du Lac	2009-2013	5	0	2	2	3	44
7	Fond du Lac	2010-2013	4	0	0	2	5	25
8	Fond du Lac	2009-2013	5	0	1	3	2	52
9	Jefferson	2010-2013	4	0	0	1	1	16
10	Juneau	2009-2013	5	0	1	0	0	4
11	La Crosse	2009-2013	5	0	1	9	7	84
12	Marathon	2011-2013	3	0	0	2	3	49
13	Outagamie	2010-2013	4	0	2	9	10	113
14	Rock/Dane	2010-2013	4	0	1	3	2	78
15	Waukesha	2009-2013	5	0	2	4	1	37
16	Winnebago	2009-2013	5	0	0	3	3	12

Table A-2 Median Barrier Crash Frequencies by Study Site

Crash Frequencies								
Site #	**County**	**Study Period**	**Years**	**K**	**A**	**B**	**C**	**PD**
1	Brown/Oconto	2011-2013	3	0.00	0.00	0.00	0.00	4.33
2	Dane	2009-2013	5	0.00	0.00	0.40	0.80	8.00
3	Dodge	2009-2013	5	0.00	0.20	0.60	0.60	6.60
4	Dunn	2009-2013	5	0.00	0.40	0.40	1.00	6.80
5	Eau Claire	2009-2013	5	0.20	0.00	0.00	0.00	2.20
6	Fond du Lac	2009-2013	5	0.00	0.40	0.40	0.60	8.80
7	Fond du Lac	2010-2013	4	0.00	0.00	0.50	1.25	6.25
8	Fond du Lac	2009-2013	5	0.00	0.20	0.60	0.40	10.40
9	Jefferson	2010-2013	4	0.00	0.00	0.25	0.25	4.00
10	Juneau	2009-2013	5	0.00	0.20	0.00	0.00	0.80
11	La Crosse	2009-2013	5	0.00	0.20	1.80	1.40	16.80
12	Marathon	2011-2013	3	0.00	0.00	0.67	1.00	16.33
13	Outagamie	2010-2013	4	0.00	0.50	2.25	2.50	28.25
14	Rock/Dane	2010-2013	4	0.00	0.25	0.75	0.50	19.50
15	Waukesha	2009-2013	5	0.00	0.40	0.80	0.20	7.40
16	Winnebago	2009-2013	5	0.00	0.00	0.60	0.60	2.40

Table A-3 Median Barrier Crash Rates by Study Site

Crash Rates (per 100 MVMT)								
Site #	**County**	**Study Period**	**Years**	**K**	**A**	**B**	**C**	**PD**
1	Brown/Oconto	2011-2013	3	0.00	0.00	0.00	0.00	10.85
2	Dane	2009-2013	5	0.00	0.00	1.45	2.90	29.02
3	Dodge	2009-2013	5	0.00	1.02	3.07	3.07	33.75
4	Dunn	2009-2013	5	0.00	1.22	1.22	3.04	20.69
5	Eau Claire	2009-2013	5	0.61	0.00	0.00	0.00	6.69
6	Fond du Lac	2009-2013	5	0.00	1.10	1.10	1.66	24.31
7	Fond du Lac	2010-2013	4	0.00	0.00	1.31	3.27	16.37
8	Fond du Lac	2009-2013	5	0.00	0.53	1.58	1.06	27.47
9	Jefferson	2010-2013	4	0.00	0.00	0.58	0.58	9.33
10	Juneau	2009-2013	5	0.00	0.54	0.00	0.00	2.15
11	La Crosse	2009-2013	5	0.00	0.97	8.70	6.76	81.16
12	Marathon	2011-2013	3	0.00	0.00	1.48	2.21	36.18
13	Outagamie	2010-2013	4	0.00	0.83	3.74	4.15	46.90
14	Rock/Dane	2010-2013	4	0.00	0.44	1.31	0.87	33.96
15	Waukesha	2009-2013	5	0.00	0.51	1.01	0.25	9.36
16	Winnebago	2009-2013	5	0.00	0.00	1.59	1.59	6.36