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Guidance on the application of cable median barrier: tradeoffs between crash frequency, crash severity, and agency costs

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Guidance on the application of cable median barrier: Tradeoffs between crash frequency, crash severity, and agency costs

by

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ABSTRACT

Median-crossover crashes present the highest risk of fatality and severe injury among collision types on freeways. These crashes can be caused by a variety of factors, including drowsiness, driver distraction, impaired driving, and loss of control. The primary countermeasure to reduce the opportunity for such crashes is the installation of median barriers. The Michigan Department of Transportation (MDOT) began installing high-tension cable median barriers in 2008, and has installed approximately 317 miles of cable median barrier on state freeways as of January 2014. Given the capital costs required for this installation program, a comprehensive before-after evaluation was conducted in order to ascertain the efficacy of cable barrier systems installed to date, and to develop guidelines to identify candidate locations for subsequent installations.

Crash reports were reviewed to identify target median-related crashes and this manual review provided critical supplementary information not normally available from the standard fields on police crash report forms. Statistical analyses which accounted for regression-to-the-mean effects showed that fatal and incapacitating injury crashes were reduced by 33 percent after cable barrier installation. The analysis also showed the median cross-over crash rate was reduced by 86.8 percent and the rate of rollover crashes was reduced by 50.4 percent. In contrast, less severe crashes were found to increase by 155 percent after cable barrier installation. A detailed analysis of crashes involving a cable barrier strike found the barriers were 96.9 percent effective in preventing penetration through the barrier. Weather conditions, horizontal curvature, and offset of cable barrier from the roadway were also

found to play a role in the frequency and severity of crashes, as well as cable barrier performance.

In addition to cable barrier segments, comparison roadway segments with thrie-beam guardrail and concrete median barriers were also analyzed as part of this research. Statistical models were developed to analyze factors affecting crash frequency, crash severity, and barrier strike outcomes among all three median barrier types. This study provides one of the first comprehensive analyses of thrie-beam median guardrail using observed highway-crash data, as most previous studies have focused on the more common w-beam guardrail.

CHAPTER 1

INTRODUCTION

1.1 Statement of Problem

Lane departure crashes result from vehicles veering from their intended travel lane and colliding with other vehicles in an adjacent lane, striking a roadside object after running off the road, or crossing the median and striking oncoming traffic in the opposite direction. From 2009 through 2013, a total of 46,589 lane departure crashes occurred on Michigan Interstates, resulting in 257 fatalities (*1*). Nationally, roadway departure crashes resulted in approximately 18,850 fatalities and 795,000 injuries in 2010. Such crashes accounted for 57 percent of all traffic fatalities and resulted in $73 billion in economic costs (*2*). Among the most hazardous roadway departure events are median-crossover crashes, which can be caused by a variety of factors including drowsiness, driver distraction, impaired driving, and loss of control on a horizontal curve or slippery road surface. The risk of collisions in such situations is particularly high on freeways where both traffic volumes and travel speeds are higher, elevating the risk of a collision and a resultant fatality. This is clearly illustrated by the fact that 555 head-on crashes occurred on Michigan Interstates during the same five-year period (2009 to 2013), resulting in 27 fatalities and 61 incapacitating injuries; rates that are significantly higher than other crash types (*1*).

According to the AASHTO *Roadside Design Guide* (*RDG*), the primary countermeasure to reduce the opportunity for median crossover crashes is the installation of median barriers (*3*). The *Highway Safety Manual* (*HSM*) provides estimates that the installation of median barriers results in average reductions of 43 percent for fatal crashes and 30 percent for injury crashes (*4*). However, the *HSM* also indicates that median barriers increase overall crash frequency by approximately 24 percent, primarily due to higher numbers of property damage only (PDO) crashes because of the reduced recovery area for errant vehicles (*4*).

Given economic considerations, the decision to install a barrier system on a particular freeway segment requires careful examination of the expected frequency of median-crossover crashes in the absence of a barrier, as well as the expected frequency of barrier-related crashes if such a system were in place. The frequency of median-crossover crashes can be influenced by numerous factors, including traffic volumes and median widths, which are the two criteria upon which the *RDG* bases its recommended guidelines for barrier installation (*3*), as well as geometric factors including horizontal alignment, vertical alignment, and median cross-slope.

In addition to determining whether a barrier system is warranted, transportation agencies are also faced with the decision among various alternatives that include concrete barriers, thrie-beam guardrail, and high-tension cable barriers. Each of these alternatives has associated costs and benefits that must be carefully considered in selecting the most cost-effective treatment for a specific road segment. For example, the *RDG* suggests "As a rule, the initial cost of a system increases as rigidity and strength increase, but repair and maintenance costs usually decrease with increased strength" (*3*).

In recent years, high-tension cable barrier has become a preferred median barrier treatment on freeways due to advantages that include reduced installation costs, lesser impact forces on vehicles that strike the barrier, reduced sight distance issues, and greater aesthetic appeal (*5*). A 1997 survey conducted as a part of *NCHRP Synthesis 244* (*6*) reported that cable barriers were in use in four states and, as of 2010, at least 37 states had installed some type of cable barrier (*7*). While cable median barrier use has increased significantly, cable barriers do present possible disadvantages such as an increase in less severe crashes and the need for frequent maintenance.

Michigan is one of several states that have recently begun installing cable barriers as a treatment at locations exhibiting a history of cross-median crashes. The Michigan Department of Transportation (MDOT) began installing cable median barriers in 2008 and has installed approximately 317 miles of high-tension cable median barrier on state freeways as of January 2014.

Given the capital costs required for this initial cable barrier installation program, as well as the anticipated annual maintenance and repairs costs, it is imperative that a comprehensive evaluation be conducted in order to ascertain the efficacy of cable barriers in reducing the occurrence of median-crossover events and crashes. An assessment of the safety performance of Michigan cable barrier systems will allow for a determination of cost-effectiveness on both a localized and system-wide basis, in addition to allowing for the identification of locations in which subsequent cable median barrier installations may be warranted. Furthermore, recent research using crash tests and models of vehicle dynamics has examined the conditions under which barrier penetration is most likely to occur (*7*). The results of an analysis of in-service cable barrier penetration events can add further insight into such circumstances using real-world data.

1.2 Research Objectives

While various studies have reported significant benefits associated with cable barrier installations (*8-21*), high-tension cable barrier is not necessarily an appropriate alternative for all settings as certain factors, such as narrow median width, may reduce the effectiveness under certain conditions. Additionally, experiences with cable barrier in southern states may not translate well to northern states which experience different weather characteristics and driving populations. As such, a careful analysis is required in order to determine the effectiveness of high-tension cable barriers that have been installed on Michigan freeways, as well as the conditions under which these systems have been most effective. Given this overview, the following objectives were identified as a part of this study:

- Determine the effectiveness of high-tension cable barriers in reducing median crossover crashes in Michigan.
- Explore the effects of traffic volumes, median width, lateral offset, horizontal alignment, and other factors as part of a disaggregate-level analysis of median-involved crashes.
- Perform an economic analysis to gain insight into the cost-effectiveness of cable median barriers.
- Develop guidelines for installing high-tension cable barriers based upon the characteristics of specific roadway segments, as well as the performance characteristics of various cable barrier design configurations investigated as a part of this study.
- Investigate other under-researched areas of concern related to cable median barriers such as the safety effects on motorcyclists and the frequency and spacing of emergency vehicle (EV) median crossovers.
- Compare the relative safety performance among cable barrier, thrie-beam guardrail, and concrete barriers. Develop safety performance function incorporating all three barrier types.
- Investigate factors associated with barrier penetration or vehicle re-direction back onto the roadway in cases where a vehicle strikes a barrier.

1.3 Organization of Dissertation

This dissertation consists of six chapters. The first chapter describes the problem being investigated, provides a brief introduction of cable median barrier and presents the research objectives. The second chapter summarizes previous research related to cable median barriers as well as other median barrier types, and presents the results of a survey of emergency responders. The third chapter presents details of data collection methodologies and summaries of several types of data required for this study including crash data, roadway geometry and traffic data, and environmental data. The fourth chapter presents the results of the before and after crash analysis of cable median barriers including summaries of injury and crash type outcomes before and after cable barrier installation, development of safety performance functions, an Empirical Bayes before and after analysis, an economic analysis, and development of cable barrier guidelines based on the crash analysis. Chapter five presents a crash analysis of alternative median barrier treatments (concrete barrier and thrie-beam guardrail) and a comparison of these treatments with cable barrier. Additionally, statistical models are developed to investigate factors which may affect injury severity outcomes and barrier strike outcomes among all three median barrier types. Chapter six presents an overall summary of this research, conclusions, limitations, and directions for future research.

CHAPTER 2

LITERATURE REVIEW

Modern cable barrier systems have been used as a treatment for median crossover crashes on high-speed roadways since the 1960s (*19*). However, installation of cable median barriers has increased rapidly throughout the United States in recent years. National estimates show that the quantity of cable barrier installation increased from 1,048 miles in May 2006 to 2,283 miles in January 2008 (*22*). More recent estimates report that over 2,900 miles of cable median barrier was installed as of 2009, with numerous additional installations planned at that time (*20*). Given their widespread application, guidance as to the cost-effectiveness and optimal deployment of cable barrier is an important concern of transportation agencies.

A principal advantage of cable barriers, in comparison to alternative treatments, is the fact that installation costs are generally much lower than other treatments. Recently, the Washington State Department of Transportation compared costs on a per-foot basis among three types of barrier treatments, with 4-strand high-tension cable median barriers averaging $46.00 per foot with minor grading, followed by W-beam guardrail at $53.00 per foot with minor grading, and concrete median barriers at $187.00 per foot with minor grading (*16*). Further cost savings can be realized due to the fact that cable barriers can generally be installed on steeper slopes (up to 4:1 in comparison to 10:1 for other barrier types) that would require re-grading and the construction of drainage structures for other barrier treatments (*7*).

2.1 Safety Performance of Cable Median Barriers

In addition to lower installation costs, cable barriers have also proven effective in reducing the frequency of cross-median crashes, as well as related injuries and fatalities. A summary of evaluations of in-service cable barriers from various states was prepared in 2009, which reported reductions of between 43 percent and 100 percent in the number of fatal median crossover crashes (*21*) after barrier installation. Table 1 provides a summary of these evaluations. It should be noted that many of these evaluations are based on very limited data and the percent reductions may not take into consideration changes in traffic volumes or other relevant characteristics. Nonetheless, these data suggest that cable barriers are very effective in reducing fatal cross-median crashes, as well as cross-median crashes in general.

Table 1. Summary of Cross-Median Crash Reductions in Several States After Cable Median Barrier Installation (*20*)

State	Average Annual Before (number)	Average Annual After (number)	Reduction (%)
Fatal Cross-Median Crashes			
AL	47.5	27.0	43
AZ	1.7	0.7	59
MO	24.0	2.0	92
NC	2.1	0.0	100
OH	9.4	0.0	100
OK	2.0	0.2	91.5
OR	0.6	0.0	100
TX	30.0	1.0	97
UT	5.9	0.0	100
Cross-Median Crashes			
FL	N/A	N/A	70
NC	25.4	1.0	96
OH	348.3	83.0	76
UT	114.0	55.0	52
WA	16.0	3.8	76

An in-service study conducted after the installation of 189 miles of cable barrier in Missouri showed fatal cross-median crashes were reduced by 92 percent (*12*). Similarly, an evaluation of installations in South Carolina found cable barriers reduced crossover fatalities from 35 per year in the period immediately prior to cable barrier installation to 2.7 per year in the period afterward (*8*). More recently, an evaluation of 293 miles of cable median barrier in Washington found fatal collision rates were reduced by half and an estimated 53 fatal collisions were prevented after the installation of cable median barrier (*16*). Additionally, a recent evaluation of 101 miles of cable barrier in Florida found a 42.2 percent decrease in fatal median crash rates after cable installation (*17*) and an evaluation of 14.4 miles of cable barrier in Tennessee found fatal crashes were reduced by 80 percent after installation (*18*).

It is important to note that if only cross-median crashes are considered, the potential increases in property damage only (PDO) and minor injury crashes associated with cable median barrier strikes are not captured. Such increases are expected because errant vehicles will have less distance to recover if a run-off-the-road event occurs after a cable median barrier has been installed, thereby increasing the likelihood of a barrier strike. A North Carolina study found fatal and severe injury crashes were reduced 13 percent after cable barrier installation, but PDO and moderate/minor injury crashes increased by 150 percent and 68 percent, respectively (*7*). Similarly, a Washington study found decreases in fatal and serious injury median crashes after cable barrier installation, but an increase of 180 percent in total median collisions (*16*). In general, the benefit realized by the reduction in severe crashes tends to outweigh the costs of this increase in PDO crashes. However, if these increases in PDO and minor injury crashes are not accounted for, the safety effects and potential economic benefits of cable median barrier installation may be overstated.

Much of the safety benefit attributable to cable barriers is due to the fact that such systems have proven to be effective at preventing vehicles from penetrating the barrier during a crash (*8; 23*). A series of previous evaluations as of 2009 have shown that cable barriers were between 88.9 percent and 100 percent effective at preventing penetration during crashes (*21*).

Table 2 shows a summary of these previous evaluations. It should be noted that the effectiveness reported in Table 2 refers to the percent of cable barrier strikes in which a vehicle did not penetrate the barrier and enter opposing traffic lanes (i.e. the barrier prevented a cross-median crash).

Table 2. Summary of Cable Barrier Effectiveness in Preventing Penetration (*20*)

State	Collisions (number)	Penetrations (number)	Effectiveness (%)
AR	1,829	152	91.7
IA	20	0	100
NC	71	5	93
NY	99	4	96
OH	372	4	98
OK	400	1	99.8
OR	53	2	94.3
RI	20	0	100
SC	3,000	15	99.5
UT	18	2	88.9
WA	774	41	94.7

In a recent evaluation of cable median barrier failures using data from nine states, Stolle and Sicking (*23*) found an overall failure rate of 14.6 percent in cable barrier median crashes for passenger vehicles, either by vehicle penetration through the cable or rollover. It should be noted that these crash evaluations and barrier penetration evaluations included a wide range of installation locations; however, the effects of other factors such as traffic volumes and roadway geometry were not always controlled for.

2.2 Cable Median Barrier Installation Guidelines

Given their potential safety benefits, high-tension cable barriers are clearly a viable solution at locations prone to cross-median events. However, effective capital investment requires an informed approach in selecting candidate locations for cable barriers. Guidance on median barrier installation is generally dictated by traffic volumes and median width. As shown in Figure 1, AASHTO (*3*) recommends median barriers on roads with median widths less than 30 feet and an annual average daily traffic (AADT) volume greater than 20,000 vehicles while median barriers are optional on roads with an AADT volume below 20,000 vehicles or with medians wider than 50 feet.

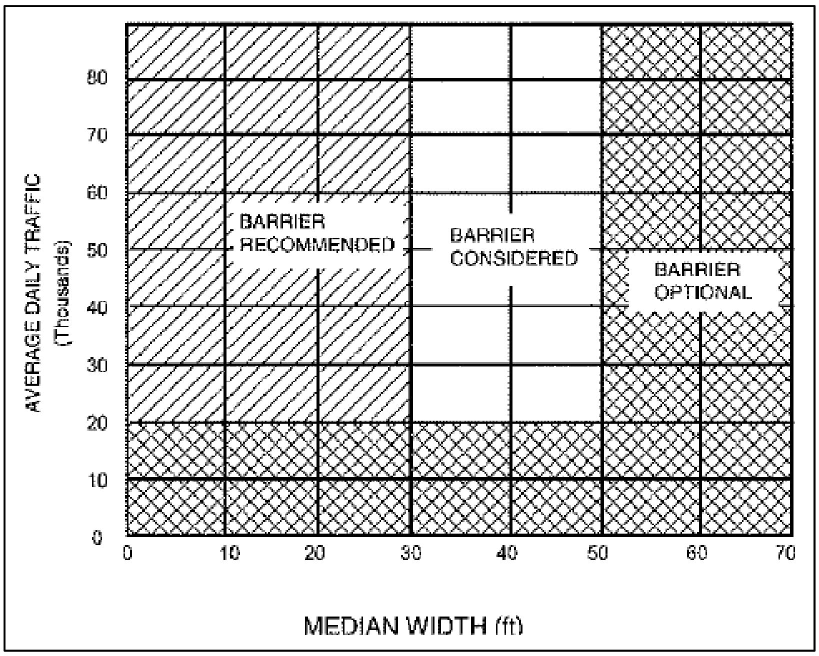

Figure 1. AASHTO Median Barrier Guidelines (*3*)

Various states have been more progressive when installing barriers as past research has shown that barriers may be warranted in a wider range of median configurations (*24*). For example, a study of 631 median-crossover crashes in Wisconsin showed that 81.5 percent of these crashes occurred at ADT and median width combinations where a median barrier was not warranted (*25*).

In addition to ADT and median width, several states like Texas, California, Connecticut, Kentucky, and Washington also use crash history to identify freeway sections for median barrier placement (*3; 19; 21; 26*). Figure 2 shows median barrier guidelines developed for Texas based on an economic analysis of median-crossover and median-related crashes (*26*). It should be noted that these guidelines were developed for general median barrier installation on relatively flat, traversable medians, and were not developed specifically for cable median barrier.

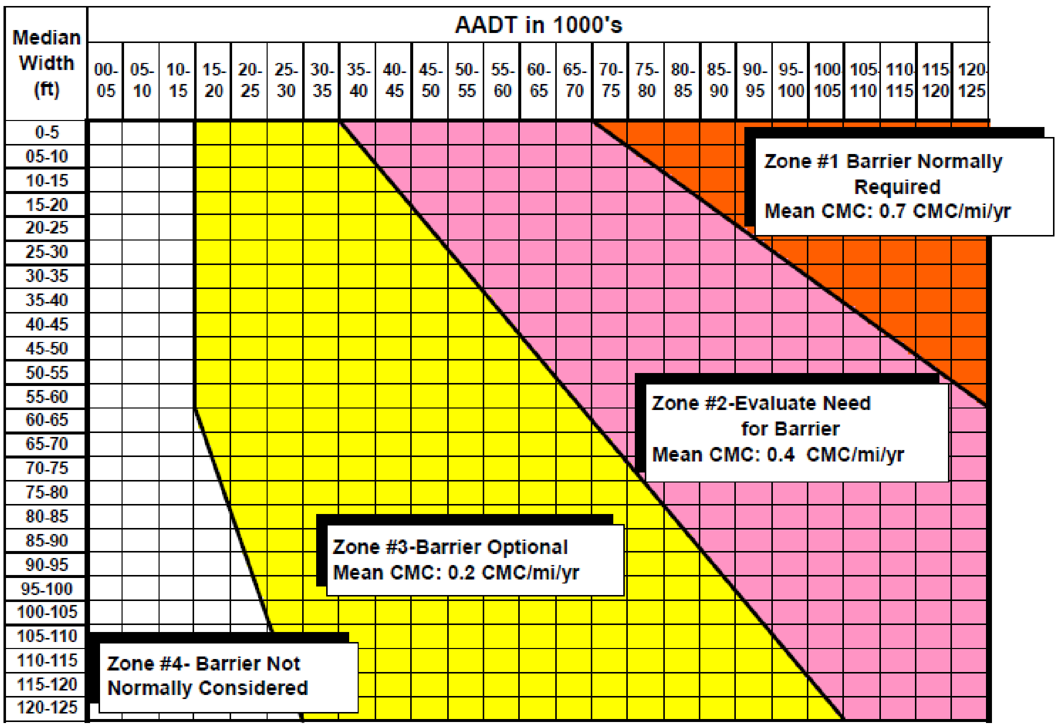

Figure 2. Guideline for Installing Median Barriers on Texas Interstates and Freeways (*26*)

With respect to cable median barrier specifically, some states such as South Carolina and North Carolina have installed cable barriers on all medians with widths of less than 60 feet and 70 feet, respectively (*8; 9*). Several other states were found to have minimum median widths as high as 50 feet and maximum median widths as low as 50 feet specifically for cable median barrier installation (*21*). Table 3 shows a summary of several states' cable median barrier installation guidelines with respect to median width, traffic volumes, and crash rates as of 2009. Given the substantial variability in policies among states, there is a need to develop guidelines suitable to the conditions present in the State of Michigan.

Table 3. Summary of Several States' Cable Median Barrier Installation Guidelines (*20*)

State	Median Width		Minimum Traffic Volume (Veh/Day)	Crash Rate
	Minimum (feet)	Maximum (feet)		
AZ	30	75	All urban	
DL	50	-		
VA	-	40		
OH	-	75	36,000	
NC	36	70		
OR	30	50		
MO	36	60	20,000	0.8 cross-median crashes /100 MVVT
NY	36	72	20,000	
KY				0.31 fatal crashes/m/yr
WA	30	50		

Besides these examples of general installation guidelines, there are widely varying state guidelines for minimum lateral offsets and maximum slopes on which cable median barriers can be installed. This include minimum offsets from the edge of the travel way ranging from 8 to 12 feet and maximum slopes ranging from 4:1 to 10:1 (*20; 23*). AASHTO (*3*) notes, "A cable barrier should be used only if adequate deflection distance exists to accommodate approximately 12 feet of movement; i.e., the median width should be at least 24 feet if the barrier is centered." While placing the barrier directly in the center of the median would minimize impacts with vehicles (and potential property damage only crashes), maintenance becomes more difficult due to the accumulation of water at the bottom of the ditch. In such areas, poor soil conditions can also affect the performance of cable barrier foundations. Furthermore, median slopes may be prohibitively steep in the center of the median. Grading medians to a flatter grade to address these issues would result in significantly higher installation costs, which negates one of the main advantages of cable barriers over other median barrier treatments.

NCHRP Report 711: Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems (*7*) examined tradeoff criteria between different cable barrier designs (e.g., cable systems utilizing 3 cables and 4 cables, various post spacings, end anchor spacings, lateral offsets, different transition treatments, cable weaving, initial level of cable tension, etc.) under a variety of roadway conditions (e.g., median width, cross-slope, soil conditions, etc.). These guidelines were developed largely upon the basis of computer simulation modeling of vehicle dynamics. As such, their usefulness can be enhanced by integrating them with real-world experiences based on data collected from Michigan's cable barrier installations.

2.3 Economic Analyses of Cable Median Barriers

The costs and benefits of any highway safety improvement must be carefully considered before a treatment is installed, and evaluated to analyze performance after installation. Cable median barriers are a particularly attractive treatment to reduce cross-median crashes on freeways due to their relatively low cost of installation compared with other barrier types. The economic benefit of cable median barriers is realized by the reduction in crash severity associated with cross-median crashes. However, the potential increase in property damage only (PDO) or minor injury crashes must be considered as part of an economic analysis, as well as repair and maintenance costs incurred after cable barrier strikes. A summary of previous economic analyses from other states is presented below:

- The most recent evaluation of cable median barriers in Washington (*16*) presented an analysis comparing cable median barrier with other barrier types (concrete median barrier and thrie-beam guardrail). While a full economic analysis of cable barrier installations was not conducted, it was found that cable barriers could produce the most cost-effective reduction in fatalities as compared to the other barrier types.

- An evaluation of freeway crash data in Texas (*27*) was used to develop benefit/cost (B/C) ratios for concrete barriers, as well as favorability ratios for installing high-tension cable barrier over concrete barrier. Although the analysis relied on several assumptions, it was found cable barriers were more cost-effective than concrete barriers for all roadways with medians 75 feet or greater regardless of AADT, and for narrower medians (25-70 feet) with lower ranges of AADT.

- An economic analysis of cable median barrier performance in Wisconsin (*28*) found B/C ratios ranging from 3.62 to 12.98 depending on cable barrier type. It should be noted that this analysis was based on crash data from approximately 45 miles of cable barrier but the economic analysis was conducted under the assumption that cable barrier was installed on all interstate highways in Wisconsin (743 miles).

- An older (2004) evaluation of 24 miles of cable median barrier in Washington (*19*) found that societal benefit of installing cable median barrier was $420,000 per mile per year. It should be noted that approximately half of the 24 miles of cable barrier only had less than 2 years of crash data available (1.54 years for one installation and 1.75 for the other).

Overall, the installation of cable median barrier has generally proven to be economically beneficial by reducing crash severity. However, there has not been a comprehensive economic analysis of a state's complete cable barrier program involving a detailed before and after crash review. The installation of several hundred miles of cable barrier in Michigan starting in 2008 presents an opportunity to conduct a full economic analysis using observed before and after crash data.

2.4 Feedback from Emergency Responders

One concern with the installation of cable median barriers is the ability to provide access to emergency vehicles and first responders who need to turn around and travel in the opposite direction on a freeway in order to respond to an incident or emergency. This can be accomplished by providing crossover locations at regular intervals to allow access for emergency vehicles. Additionally, first responders must be familiar with procedures for safely removing vehicles entangled in the cables after a cable barrier strike. In order to gain feedback on these issues, a survey of emergency personnel and first responders was conducted regarding concerns related to the installation of high-tension cable median barriers in Michigan.

The survey was conducted via mail, fax, and internet (using www.surveymonkey.com) and a total of 53 responses were received. A sample of the survey that was distributed is shown in Figure 3. The majority of the responses were received from fire departments (43 responses) while there were 9 responses from police agencies and 1 response from an emergency medical technician. The summary of responses to each question can be found in Table 4.

For those respondents who indicated that cable median barriers introduced difficulty in responding to an incident, they were asked what the primary issues of concern were from among the following list:

- Inability to locate a median cross-over or too much spacing between cross-overs
- Difficulty removing the vehicle from the barrier

- Difficulty removing the vehicle from the median as a result of the cable barrier
- Difficulty providing medical attention to victims due to the cable barrier
- Other

1. Your Name and Title: ____

   Agency : ____

   Phone: (______) ______________ E-Mail: ______________________________

2. Do you feel that cable barrier has improved safety on Michigan freeways?
   □Strongly agree □Agree □Uncertain □Disagree □Strongly disagree

3. Have you responded to an incident that occurred on a freeway where cable barrier was installed?
   □Yes □No

4. Have you responded to an incident that required cutting a high-tension cable median barrier?
   □Yes □No

5. Does your agency have any guidelines or training that specifically relates to cable median barriers?
   □Yes □No

6. Have cable median barriers added difficulty in responding to an incident on a roadway on which cable barriers were installed?
   □Yes □No

7. If you responded "Yes" to Question 6, specify the factors that contributed to this difficulty (Check all that apply):
   □ Inability to locate a median cross-over or too much spacing between cross-overs
   □ Difficulty removing the vehicle from the barrier
   □ Difficulty removing the vehicle from the median as a result of the cable barrier
   □ Difficulty providing medical attention to victims due to the cable barrier
   □ Other, please specify: ____

8. In your opinion, what is the maximum distance that should be provided between median cross-overs on roads with cable barrier?
   ______ miles

9. Please provide any other comments you may have regarding the use of cable median barriers?

   ____

   ____

   ____

Figure 3. Emergency Responder Survey

A total of 30 respondents (56.6 percent) indicated that cable barriers had introduced issues when responding to an incident on a roadway where cable barriers were installed. Table 5 summarizes the most common issues. It should be noted that respondents were instructed to mark all reasons that applied, so the total responses in Table 5 are greater than the number of respondents.

Table 4. High-Tension Cable Barrier Survey Results (N = 53)

Survey Question	Number	Percent
Responding Agency		
Police	9	17.0%
Fire	43	81.1%
EMS	1	1.9%
Do you feel cable barriers improve safety on Michigan freeways?		
Strongly Agree	12	22.6%
Agree	15	28.3%
Uncertain	20	37.7%
Disagree	3	5.7%
Strongly Disagree	3	5.7%
Have you responded to an incident that occurred on a freeway where cable barrier was installed?		
Yes	32	60.4%
No	20	37.7%
No Response	1	1.9%
Have you responded to an incident that required cutting high-tension cable median barrier?		
Yes	8	15.1%
No	45	84.9%
Does your agency have any guidelines or training that specifically relates to cable median barriers?		
Yes	32	60.4%
No	20	37.7%
No Response	1	1.9%
Have cable median barriers added difficulty in responding to an incident on a roadway on which cable barriers were		
Yes	30	56.6%
No	23	43.4%
In your opinion, what is the maximum distance that should be provided between median cross-overs on roads with cable		
<1 Mile	3	5.7%
1 Mile	30	56.6%
2 Miles	8	15.1%
3 Miles	5	9.4%
No Response	7	13.2%
TOTAL RESPONDENTS	**53**	**100%**

From the respondents who marked 'Other', additional issues that were cited included:

- Cable barrier too close to the traffic lane which necessitates shutting down lanes of traffic to clear accident scene.
- Difficulty loosening the cable when a vehicle is entangled in it.

Table 5. Reasons for Difficulty in Responding to Crashes on Roadways with Cable Barrier

Reason for Difficulty	Number of Responses
Inability to locate a median cross-over or too much spacing between cross-overs	23
Difficulty removing the vehicle from the barrier	13
Difficulty removing the vehicle from the median as a result of the cable barrier	6
Difficulty providing medical attention to victims due to the cable barrier	14
Other	7

The respondents were asked to provide any other comments related to the use of cable median barriers. The most common remarks provided by the respondents included:

- Cable barriers are located too close to the roadway.
- The median cross-overs are spaced too far apart.
- Several respondents indicated they would like their agencies to receive advanced training on responding to cable barrier crashes.

In summary, most emergency responders feel that installation of cable median barriers add some level of difficulty in responding to an incident, though most do agree that cable barriers improve overall safety on Michigan roadways. The main issues identified by emergency responders are:

- Increased response time due to large distances between crossovers.
- Difficulty removing vehicles from the barrier in the event of a crash.
- Necessity to close lanes due to cable barrier's close proximity to the edge of the roadway.

Approximately 40 percent of respondents indicated their agency does not have any guideline or training that specifically relates to cable median barriers. MDOT requires that the cable barrier manufacturer provide training to MDOT staff and local emergency first responders (EFRs) as part of every cable barrier installation. However the results of the survey indicate that some responders may not have received training. Providing additional training opportunities or increasing the publicity of such training may aid in mitigating some of the issues that were noted by survey respondents.

2.5 Comparison with Other Median Barrier Types

Before and after in-service performance evaluations of median barrier types other than cable barrier are not as commonly found in the research literature. Several studies have examined the effects of roadway median characteristics in general (including median barriers) on median and/or cross median crashes (*29-31*). Median barriers are generally found to reduce cross median crashes, and other roadway characteristics such as median and shoulder widths, median cross slope, and horizontal curvature are found to affect median or cross median crash characteristics.

Studies analyzing factors affecting injury severity between median barrier types are quite limited. A recent study (*32*) analyzed factors affecting crash severity in single-vehicle, run off the road crashes (left or right side) occurring on roadway segments with cable barriers, w-beam guardrails, and concrete barrier walls in Indiana. Binary logistic regression with mixed effects was utilized for the analysis and several person, roadway, and barrier type characteristics were found to affect injury severity outcomes. Among other findings, collisions with cable barriers were found to be least likely to result in injuries compared to collisions with fixed objects or other barrier types. Factors affecting crash frequency on roadways with each of the barrier types and factors associated with penetration through the barriers were not analyzed as a part of the study. Another study analyzed injury outcomes for motorcyclists in collisions with different barrier types and found that the odds of injury were greater in collisions with w-beam guardrail than with concrete barrier, but there was no significant difference in injury outcomes between w-beam guardrail and cable barrier (*33*).

Research has been somewhat limited on the performance of different barrier types with respect to crash outcomes in the event of a median barrier collision (e.g. vehicle containment, vehicle penetration through the barrier, or re-direction of the vehicle back onto the roadway). One recent study (*34*) analyzed median barrier strike crashes in Florida to compare the safety performance of G4 (1S) w-beam guardrail and cable median barriers. Odds ratios were computed and it was found that w-beam guardrails were more effective in preventing penetrations in the event of a collision, but cable barriers tended to result in fewer severe injury crashes.

2.6 Literature Review Summary and Areas of Research Need

The preliminary literature review shows that high-tension cable barrier use continues to increase rapidly throughout the United States, although there is substantial variability in its use among states in terms of installation guidelines and warrants. Previous evaluations of cable median barrier installations from other states have shown substantial reductions in fatal cross-median crashes (*20*), although these evaluations were not all comprehensive and some were based on small lengths of cable median barrier installation. Additionally, some of these studies may suffer from potential selectivity bias or regression-to-the-mean effects, which can lead to over-stated safety benefits based on a before-after observational analysis. To investigate this issue, an Empirical Bayes analysis will be conducted to evaluate Michigan's cable median barrier program while accounting for these potential biases.

Previous evaluations have also shown cable median barriers to be between 88.9 and 100 percent effective in preventing penetration in the event of a cable barrier strike (*20*), although some of these studies were based on very small sample sizes. The performance of cable median barrier performance in Michigan in terms of percent of crashes resulting in penetrations will be analyzed as a part of this study and compared with other states. Additionally, the performance of median thrie-beam guardrail and concrete median barrier in Michigan will be analyzed and compared with the performance of cable median barrier.

In addition to the overall safety effects of installing cable median barriers and the performance of the cable barriers themselves, there are several issues which warrant additional investigation. There has been limited research as to the effects of adverse weather conditions on the efficacy of cable barriers, which may be particularly important in northern climates. Past research has found that median related crashes and crashes with median barriers are more prevalent during adverse weather and road conditions (*14; 28; 29*), but severe crashes and cable barrier penetrations are less likely to occur under such conditions (*23; 28*). It's important to investigate this issue in Michigan as it may have significant impacts on the decision to install a cable median barrier or the placement characteristics of the barrier in geographic regions which experience a significant amount of snowfall.

Impacts of cable median barriers on motorcyclists are a potential concern that is also in need of additional research. A few studies have investigated this issue (*16; 33*) and both concluded there were no significant increases in probability of serious injuries for motorcyclists after installation of cable median barriers. Although some motorcycle advocacy groups and members of the public have expressed concern about this issue, the data have not supported these concerns thus far. Effects on motorcyclists are analyzed as a part of this study and the results will add to the literature with respect to this issue. It is important to note that Michigan repealed its Universal Helmet Law in 2012, so the results of this study may add some insight into the effects of this change in legislation.

Another issue with cable median barriers is their effect on access for emergency vehicles or maintenance vehicles which need to turn around on the freeway. As cable barriers are continuous, sections must be designed such that gaps are available for median crossing by these groups at regular intervals (*24*). This can be done either by terminating guardrail sections at specific lengths or providing staggered barrier sections on each direction of roadway (e.g., a westbound section continues at a point where an eastbound section terminates). The frequency and spacing of emergency turnarounds within cable median sections are important characteristics to consider because although they provide emergency vehicles necessary access, these locations also may be susceptible to cross-median crashes at the cable median openings, as well as crashes caused by drivers illegally using the crossovers. This issue will be investigated as part of this study in terms of emergency vehicle crossover-related crashes, as the surveys of emergency responders have shown that crossover spacing is a major concern with cable median barrier installation.

In summary, past research indicates that high-tension cable median barriers generally are an effective countermeasure to reduce cross-median crashes, and generally improve safety. However, some of these studies suffer from potential selectivity bias, which can lead to inaccurate results when regression-to-the-mean effects are not accounted for. This study will account for this effect through the use of a before-after Empirical Bayes analysis. Additionally, the effects of several under-researched variables on the safety performance of cable median barriers will be investigated such as cable barrier type (3-cable system vs. 4-cable system) lateral offset, horizontal curvature, weather and road condition characteristics, and several other variables of interest.

Collectively, the results of this study will add to the literature by providing additional guidance on the potential effects of cable median barriers and conditions where they may be most effective. Other under-researched areas of interest will also be investigated, such as effects on motorcyclists and the potential impacts of emergency crossover frequency and spacing. Additionally, insights will be gained on the performance of other median barrier types, particularly thrie-beam guardrail, which has not been extensively studied in the literature.

CHAPTER 3

DATA COLLECTION AND DESCRIPTION

3.1 Cable Median Barrier Installation Data

Segments of roadway in which cable median barrier have been installed (as of January 2014) were identified using MDOT physical reference (PR) numbers and beginning and ending mile points. The PR beginning mile point (BMP) and PR ending mile point (EMP) for each cable barrier installation were initially obtained from construction proposals and plans obtained from MDOT's bid letting website. The BMP and EMP of each cable barrier installation were then confirmed (or adjusted as necessary) based on satellite images from Google Earth (*35*) as well as the Google Street View tool. There were four cable barrier installations which were too recently constructed to be captured by Google Earth, and as such, field visits were conducted to confirm the BMP, EMP, and other installation characteristics of these installations. The cable median barriers were first installed on controlled-access freeways in Michigan in 2008, and subsequent installations continued in subsequent years. As of January 2014, there was a total of approximately 317 miles of cable median barrier installed in Michigan, all of which were analyzed as a part of this study. Figure 4 shows a map with all cable median barrier installations as of January 2014. The freeway segments in which cable median barrier was installed were chosen by MDOT from locations with a median narrower than 100 feet and historical cross-median crash occurrence.

As stated previously, the exact locations of the cable barrier installations were obtained from MDOT and confirmed using Google Earth imagery and/or field visits. MDOT also provided the cable barrier type (including number of cables in each system) and the completion date for each cable barrier installation. Additionally, the engineering and construction costs for most of the installations were obtained from MDOT's bid letting website. Cost data were not available for 9 of the installations, so costs were estimated for these installations based on an average per-mile cost obtained from the installations in which cost data were available. All cable barrier installations in Michigan were high-tension systems and were either CASS, Gibraltar, or Brifen cable barrier systems. It should be noted that MDOT installed 3-cable versions of the CASS and Gibraltar systems and 4-cable version of the Brifen system.

All high-tension cable systems installed by MDOT met the requirements of *National Cooperative Highway Research Program Report 350, Test Level 4* (NCHRP 350, TL-4) when the barrier was placed on a 1V:6H (1 vertical:6 horizontal) slope or flatter. Furthermore, high tension cable systems installed by MDOT on slopes steeper than 1V:6H, up to 1V:4H, met the requirements of NCHRP 350, TL-3. For all high tension cable systems, MDOT specified a maximum post spacing of 10.5 feet, except in areas where conflicting utilities or underground obstructions required a larger post spacing, and so long as the post spacing utilized did not exceed manufacturer's recommendations. Table 6 shows a summary of each cable barrier installation including route, MDOT Region, install year, installation length, and total cost. It should be noted that there are a total of 7 MDOT Regions consisting of counties clustered together by geographic location, and Figure 5 shows a map of these regions. In addition to installation cost data, repair data for years 2010-2012 were provided by MDOT in the form of crash reports with the cost of cable barrier repair listed on each crash report. This repair cost data was utilized in the economic analysis of cable median barriers, with details presented in Chapter 6.

Other cable barrier characteristics for each installation were obtained from Google Earth and/or site visits. This included the side of roadway in which the cable barrier was located nearest to and the lateral distance from the edge of the nearest travel lane in each direction to the cable barrier. Most of the installations had cable barrier installed near the edge on one direction of travel, while some had cable barrier installed on both sides of the median, and one had cable barrier installed approximately in the center of the median. The PR and mile points where the cable barrier switched from one side of the median to the other or where an installation switched from a single run of barrier along the median to dual runs of barrier along the median (i.e., two runs of barrier, with one on each side of the median, running parallel along the median) were recorded for use in the separating segments in later analyses. Figure 6 shows an example screen shot from Google Earth which was used to identify cable barrier location and lateral distance from edge of left travel lanes. The distance measured using Google Earth's ruler tool was found to be accurate within 1 foot when compared with known measurements of lane width.

3.2 Roadway Geometry and Traffic Volume Data

3.2.1 Cable barrier roadway and traffic volume data

In order to analyze the safety performance of cable median barrier installations, several characteristics needed to be obtained for each cable barrier roadway segment, including data related to traffic crashes (which will be discussed in detail in the following section of this report), roadway geometry, traffic volumes, and characteristics of the actual cable barrier installation. The total length for each cable barrier installation was divided into segments based primarily on the MDOT sufficiency file, which divides roadways into segments based on their characteristics. Horizontal curves were also segmented such that each curve was an individual segment. An attempt was also made to divide the segments where the cable barrier switched from one side of the road to the other; however, this was not always possible as some installations alternated sides of the median within short distances. The minimum segment length used for this study was 0.25

miles, as it was determined the location indicated on crash reports may not be accurate enough to apply to segments less than this length.

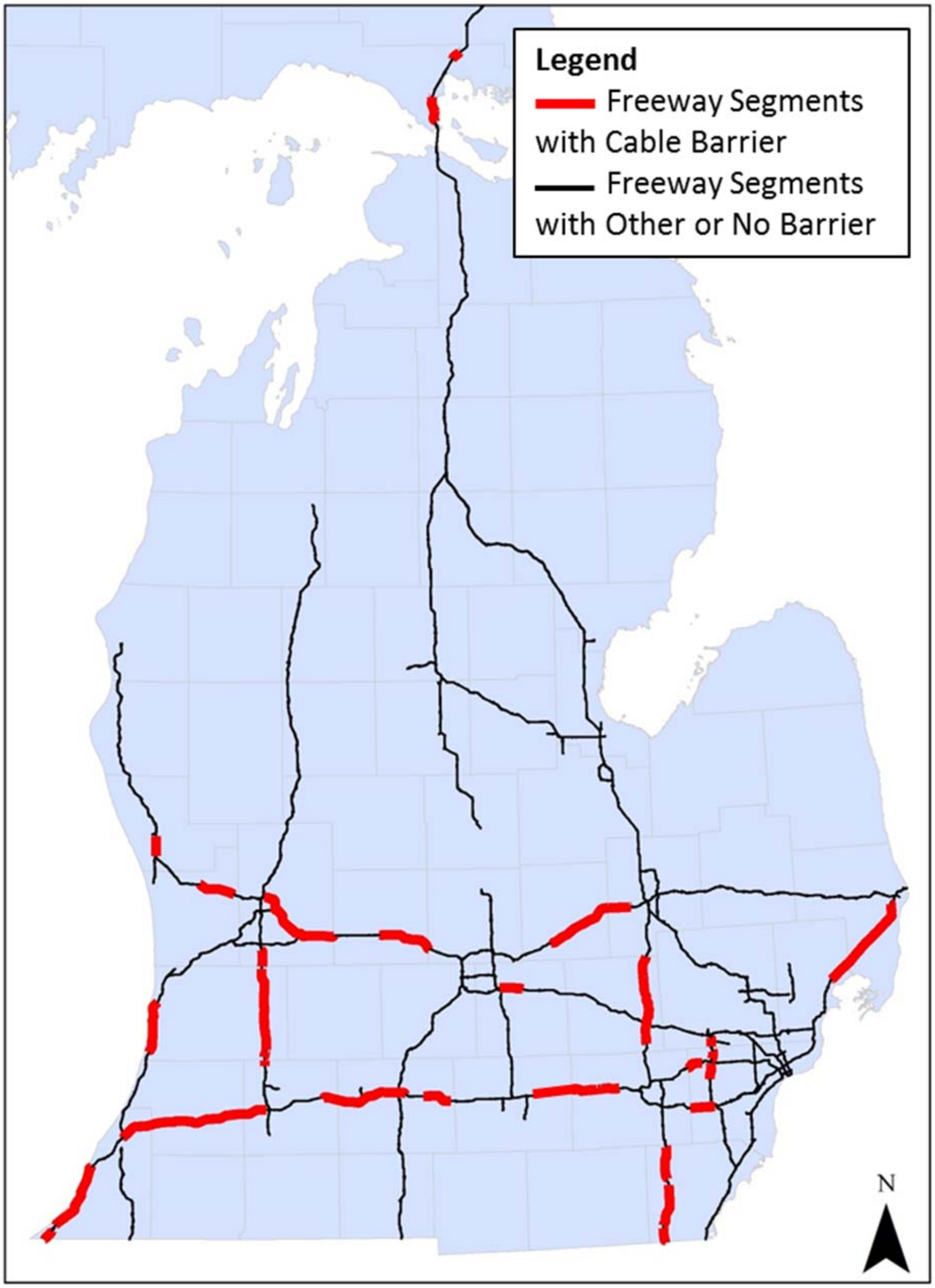

Figure 4. Map Showing Michigan Cable Barrier Installation Locations

Table 6. Summary of Cable Median Barrier Installations

Install Number	Route	MDOT Region	Install Year	Cable System	Number of Cables	Installation Length (miles)	Total Cost (Engineering and Construction)
1	I-94	Southwest	2008	CASS	3	3.8	$433,875
2	I-94	Metro	2008	CASS	3	6.2	$889,444
3	I-69	Bay	2008	Gibraltar	3	5.8	$568,907
4	I-94	Metro	2009	CASS	3	6.2	$1,064,375
5	I-94	Metro	2009	CASS	3	6.1	$898,122
6	I-94	Southwest	2009	CASS	3	28.3	$2,948,450
7	I-96	Grand	2009	Gibraltar	3	13.5	$2,245,053
8	US-131	Grand	2009	Gibraltar	3	4.1	$969,043
9	I-69	University	2009	Gibraltar	3	17.6	$2,583,941
10	US-23	University	2009	Brifen	4	14.1	$2,191,775
11	I-275	Metro	2009	CASS	3	7.4	$1,395,992
12	I-96	Grand	2010	Gibraltar	3	9.0	$2,910,988
13	I-96	Grand	2010	Gibraltar	3	19.2	$2,565,989
14	I-196	Southwest	2010	Brifen	4	6.9	$1,009,483
15	I-94	Metro	2010	Gibraltar	3	3.6	$523,543
16	I-94	Southwest	2010	Gibraltar	3	17.6	$3,374,999
17	I-75	Superior	2010	CASS	3	8.7	$1,563,721
18	I-94	Southwest	2010	Gibraltar	3	20.9	$2,734,397
19	I-94	Southwest	2010	Gibraltar	3	6.0	$615,565
20	US-131	Southwest	2010	Gibraltar	3	24.7	$3,391,285
21	I-94	Metro	2010	Gibraltar	3	3.3	$440,135
22	US-31	Grand	2010	Gibraltar	3	4.5	$806,166
23	I-94	Southwest	2010	Gibraltar	3	2.6	$433,515
24	I-94	Southwest	2011	Brifen	4	7.5	$972,220
25	I-94	University	2011	Gibraltar	3	7.6	$1,210,969
26	I-196	Southwest	2011	Gibraltar	3	6.5	$783,805
27	I-96	University	2012	Gibraltar	3	2.6	$977,672
28	US-23	University	2012	Gibraltar	3	22.6	$3,714,723
29	I-94	University	2012	Gibraltar	3	12.1	$2,128,058
30	M-14	Metro	2012	Gibraltar	3	4.0	$674,453
31	I-94	Metro	2013	Gibraltar	3	6.1	$967,618
32	US-23	University	2013	Brifen	4	8.1	$1,375,791
					Total:	**317.2**	**$49,364,071**

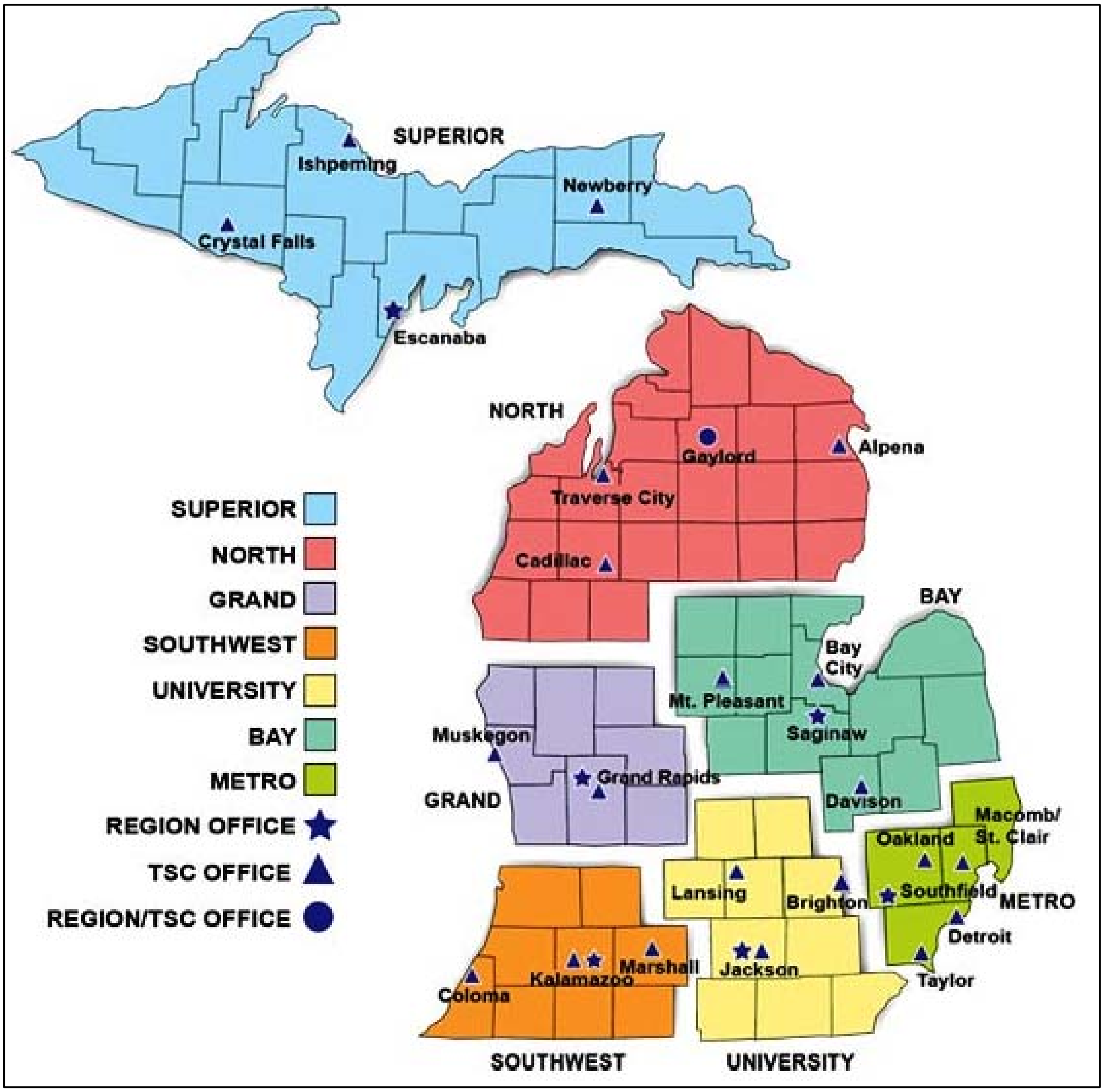

Figure 5. Map Showing MDOT Regions (Source: MDOT)

The sufficiency file is updated annually and freeway segments contain separate records for each direction of freeway (i.e. there will be one sufficiency file record for Northbound (NB) or Westbound (WB) and one for Southbound (SB) or Eastbound (EB) for each freeway segment). The relevant variables extracted from the sufficiency file for each cable barrier roadway segment include:

- Median type and median width
- Shoulder type and shoulder width
- Number of lanes and lane width
- Annual Average Daily Traffic (AADT) for each year on each segment from 2004-2013.

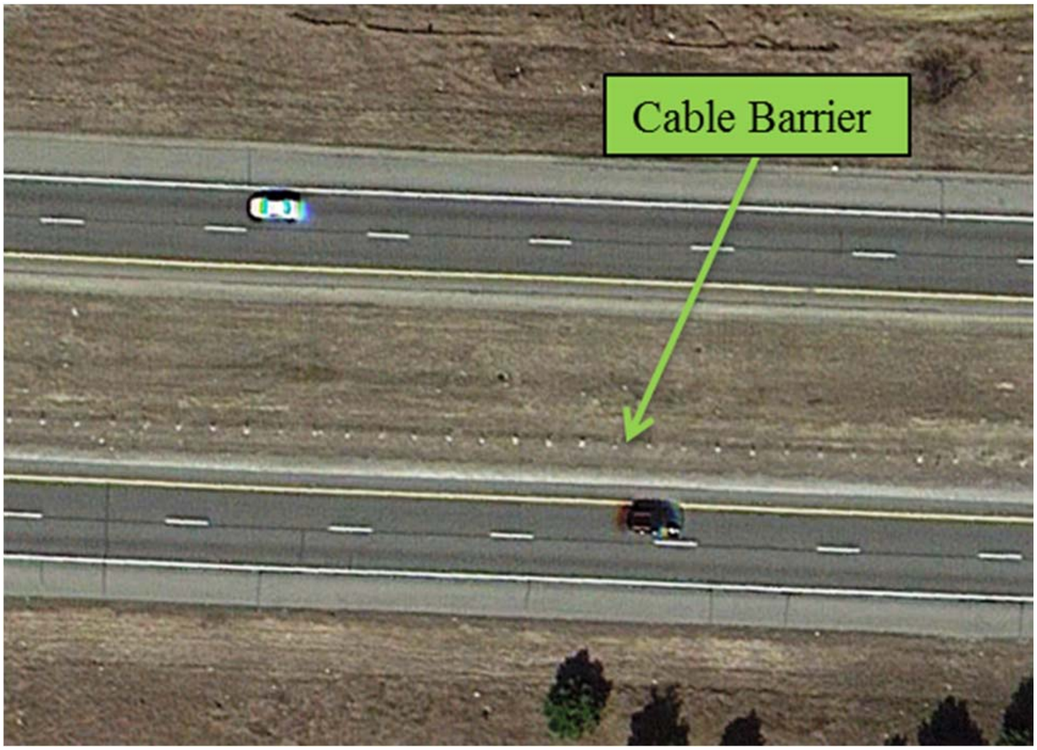

Figure 6. Screen Shot from Google Earth Showing Cable Median Barrier (*35*)

In cases where the sufficiency file segment start and end points changed slightly from year to year, a length-weighted average was used to compute the AADT for each cable barrier roadway segment. Horizontal curves and curve radii were identified and measured using GIS shapefiles. Table 7 shows a summary of the cable barrier roadway segments including average segment length, median width, horizontal curve presence, lateral offset distance, and AADT before and after cable barrier installation. It should be noted that that the segment information in Table 7 is for one-directional segments, as found in the MDOT sufficiency file

Table 7. Summary of Cable Barrier Roadway Segments

Characteristic		3-Cable Segments		4-Cable Segments		All Cable Barrier Segments	
Total Centerline Mileage		280		37		317	
Directional Segment Length (mi)	Mean	1.2		1.1		1.2	
	St.Dev.	1.0		0.8		1.0	
	Min	0.25		0.25		0.25	
	Max	6.3		3.3		6.3	
Median Width of Segments (feet)	Mean	62.8		64.1		63.0	
	St.Dev.	13.4		10.9		13.1	
	Min	26.0		36.0		26.0	
	Max	94.0		70.0		94.0	
Left Shoulder Width of Segments (feet)	Mean	8.2		7.9		8.1	
	St.Dev.	0.9		0.5		0.7	
	Min	5		6		5	
	Max	12		8		12	
Number of Horizontal Curve Segments	No Curve*	437 (95.2%)		69 (100%)		506 (95.8%)	
	Radius 2,500-3,500 ft	15 (3.3%)		0 (0.0%)		15 (2.8%)	
	Radius<2,500ft	7 (1.5%)		0 (0.0%)		7 (1.3%)	
Number of Directional Travel Lanes (number of segments)	2 Lanes	386 (84.1%)		69 (100%)		455 (86.2%)	
	3 Lanes	65 (14.2%)		0 (0.0%)		65 (12.3%)	
	4+ Lanes	8 (1.7%)		0 (0.0%)		8 (1.5%)	
Speed Limit (number of segments)	55 mph	0 (0.0%)		0 (0.0%)		0 (0.0%)	
	65 mph	0 (0.0%)		0 (0.0%)		0 (0.0%)	
	70 mph	459 (100%)		69 (100%)		528 (100%)	
Lane Widths (number of segments)	11 feet	4 (0.9%)		0 (0.0%)		4 (0.8%)	
	12 feet	455 (99.1%)		69 (100%)		524 (99.2%)	
Lateral Distance From Near Side Cable Barrier to Edge of Nearest Travel Lane (feet)	Mean	13.5		15.0		13.7	
	St.Dev.	2.5		3.4		2.7	
	Min	7.4		12.1		7.4	
	Max	24.2		23.0		24.2	
Annual Average Daily Traffic per segment (one-directional)		Before	After	Before	After	Before	After
	Mean	22,369	22,364	15,291	15,395	21,382	21,632
	St.Dev.	13,204	15,071	2,975	3,083	12,526	14,451
	Min	1,508	1,749	8,944	9,124	1,508	1,749
	Max	99,850	100,600	22,941	21,437	99,850	100,600
Average Annual Snowfall (in)		62.0	43.7	47.0	34.2	59.9	42.7

*'No curve' includes curved segments with radii greater than 3,500 ft.

Historical snowfall data were also obtained for each cable barrier segment. This data was downloaded from the National Oceanic and Atmospheric Administration's (NOAA) National Climactic Data Center (*36*). Annual snowfall amounts in inches were obtained for every weather station in Michigan, Ohio, and Canada which were within 45 miles from the midpoint of a cable barrier road segment. Annual average snowfall amounts were then calculated for each cable barrier road segment (for each year from 2004 to 2013) based on data from the weather station(s) within 45 miles of the midpoint of the segment. The average annual snowfall in inches for cable barrier segments before and after cable barrier installation can be found in Table 7.

3.2.2 Comparison segment roadway and traffic volume data

In order to compare the performance of cable median barrier with other median barrier treatments, freeway segments with the following median characteristics were identified to serve as comparison segments for this study:

- Segments with no median barrier and median widths less than 100 feet
- Segments with thrie-beam median guardrail
- Segments with concrete median barrier

The comparison segments were identified using the MDOT sufficiency file along with Google Earth and Google Maps street view imagery. The PR, BMP, and EMP of each segment were identified manually and the total lengths were divided into segments for analysis using the MDOT sufficiency file in a similar manner as the cable barrier sections described previously. After a review of Michigan's entire controlled-access freeway system, there were a total of 337 miles of segments with no median barrier and median width less than 100 feet, 104 miles of segments with thrie-beam median guardrail, and 226 miles of segments with concrete median barrier, all of which were analyzed as part of this study. Table 8 shows a summary of the no barrier, thrie-beam guardrail, and concrete barrier roadway segments.

Table 8. Summary of Comparison Roadway Segments

Characteristic		No Barrier Segments	Thrie-Beam Guardrail Segments	Concrete Barrier Segments
Total Centerline Mileage		337	104	226
Directional Segment Length (mi)	Mean	1.2	1.0	0.8
	St.Dev.	1.0	0.7	0.7
	Min	0.25	0.25	0.25
	Max	67.2	3.4	6.3
Median Width of Segments (feet)	Mean	77.3	42.3	24.6
	St.Dev.	16.2	14.3	9.3
	Min	26	12	6
	Max	94	70	70
Left Shoulder Width of Segments (feet)	Mean	8.3	8.9	8.6
	St.Dev.	0.9	1.4	2.6
	Min	8	3	1
	Max	12	11	17
Number of Horizontal Curve Segments	No Curve*	515 (91.5%)	196 (92.9%)	458 (79.0%)
	Radius 2,500-3,500 ft	29 (5.2%)	11 (5.2%)	66 (11.4%)
	Radius<2500 ft	19 (3.4%)	4 (1.9%)	56 (9.7%)
Number of Directional Travel Lanes (number of segments)	2 Lanes	464 (82.4%)	59 (30.0%)	85 (14.7%)
	3 Lanes	99 (12.3%)	143 (67.8%)	339 (58.4%)
	4+ Lanes	8 (1.5%)	9 (4.2%)	156 (26.9%)
Speed Limit (number of segments)	55 mph	5 (0.9%)	2 (0.9%)	111 (19.1%)
	65 mph	0 (0.0%)	0 (0.0%)	11 (1.9%)
	70 mph	558 (99.1%)	209 (99.1%)	458 (79.0%)
Lane Widths (number of segments)	11 feet	2 (0.4%)	0 (0.0%)	1 (0.2%)
	12 feet	561 (99.6%)	211 (100%)	579 (99.8%)
Annual Average Daily Traffic per Segment (one-directional)	Mean	16,927	34,188	45,766
	St.Dev.	10,004	15,750	18,225
	Min	2,464	2,706	2,706
	Max	57,450	99,200	97,150
Average Annual Snowfall (in)		44.7	37.0	38.1

*'No curve' includes curved segments with radii greater than 3,500 ft.

The geometric, traffic, crash, and snowfall data were obtained for each comparison segment in the same manner as the cable barrier segments described previously. However, five years (2009-2013) of data were examined for the comparison segment analysis (there are no 'before and after' periods for the comparison segments as there are for the cable barrier segments). Table 8 present several summary statistics for the comparison segments including average segment length, median width, horizontal curve presence, AADT, and average annual snowfall. Similar to table 7, the segment information in Table 8 is for one-directional segments, as found in the MDOT sufficiency file.

3.3 Traffic Crash Data

3.3.1 Cable barrier segment crash data

All crashes occurring on each cable barrier segment were obtained for years 2004 through 2013 from MDOT. The crashes were assigned to each cable barrier segment based on the PR and mile point which was coded for each crash. Since the primary purpose of this study is to analyze the safety effectiveness of cable median barriers, target crashes (which were defined as crashes that could be affected by the installation of cable median barriers) needed to be identified. These target crashes include both median-crossover crashes and all median-related crashes. There was no reliable way to identify target crashes based on the electronically coded crash data alone, therefore a manual review of every crash occurring on the cable barrier segments was conducted. Crash reviewers were trained and instructed to code each crash into one of the following eight target crash categories:

Median or Median Crossover Crashes:

1 – Median Crash - vehicle left roadway and entered median, but did not strike any barrier or cross into opposing lanes of traffic. This includes vehicles which enter the median and re-enter the roadway onto original lanes of travel.

2 – Cross-Median Event – vehicle left roadway and entered median, travelled all the way across the median and entered into opposing traffic lanes, but did not strike an opposing vehicle.

3 – Cross-Median Crash – vehicle left roadway and entered median, travelled all the way across the median and entered into opposing traffic lanes and struck an opposing vehicle.

Cable Median Barrier Strike Crashes:

4 – Cable Barrier Strike – vehicle struck cable barrier, did not penetrate the barrier, and was contained in the median.

5 – Cable Barrier Strike – vehicle struck cable barrier, penetrated all the way through the cable barrier (including vehicles that flipped over the cable barrier), but did not enter opposing travel lanes.

6 – Cable Barrier Strike – vehicle struck cable barrier, penetrated all the way through the cable barrier (including vehicles that flipped over the cable barrier), and entered opposing traffic lanes, but did not strike opposing vehicle.

7 - Cable Barrier Strike – vehicle struck cable barrier, penetrated all the way through the cable barrier (including vehicles that flipped over the cable barrier), and entered opposing traffic lanes, and struck an opposing vehicle.

8 – Cable Barrier Strike – vehicle struck cable barrier, and was re-directed back onto original lanes of travel.

In general, crash reviewers used the police narrative and crash diagrams found on each crash report to identify which, if any, target category each crash belonged to. For cases where the narrative and/or diagram did not clearly indicate which target category, if any, a crash belonged to, crash reviewers used the 'sequence of events' listed on each crash report to aid in the decision. Specifically, the following events were used to help identify target crashes:

- Cross centerline/median
- Ran off roadway left
- Guardrail face
- Guardrail end
- Median barrier

Crashes that did not fall into any of the target categories were excluded from the analysis.

In addition to the target category for each crash, crash reviewers recorded which vehicle (in the case of multi-vehicle crashes) entered the median or struck the cable barrier in order to obtain vehicle type and other information. Crash reviewers also recorded whether the crash involved an emergency vehicle median crossover. Although time consuming and labor intensive, the manual review of every crash provides a very accurate determination of each crash scenario as compared to relying solely on electronically coded crash data. It should be noted that crashes occurring on bridge decks or involving bridge abutments were not coded as target crashes as cable barriers would not be installed in these locations. Figures 7-14 show example crash narratives and diagrams of each target crash category.

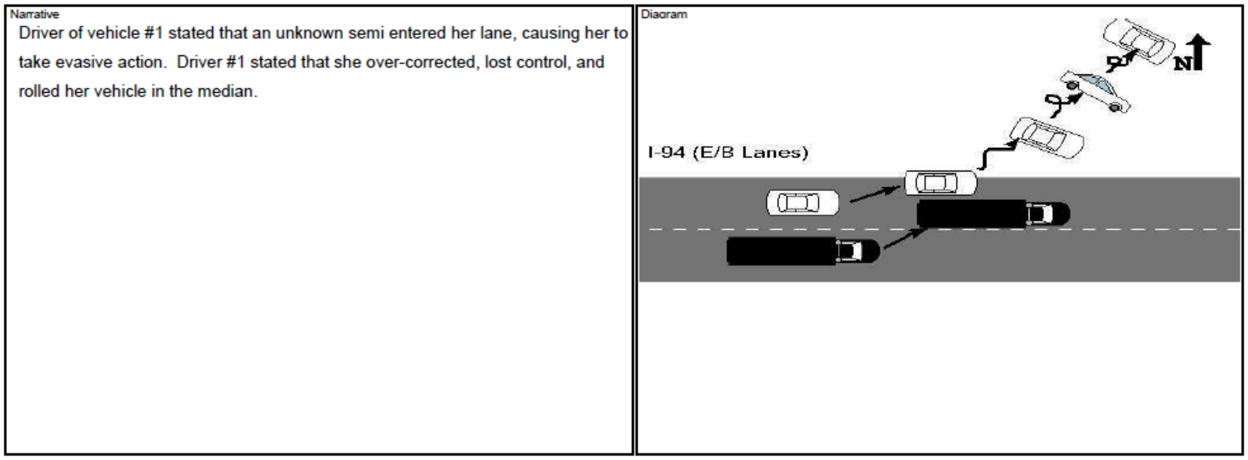

Figure 7. Target 1 Crash – Median Crash

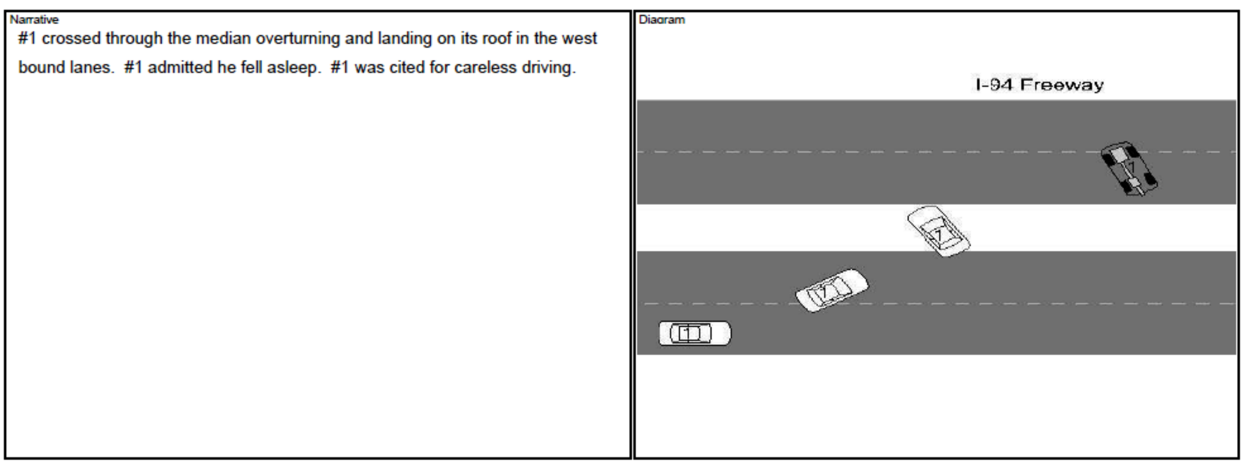

Figure 8. Target 2 Crash – Cross-Median Event

Narrative

Veh. #1 left the roadway on W/B I-196 for an unknown reason. Veh. #1 entered the median and then rolled over into the path of E/B Veh. #2. Driver #1 was deceased at the scene. Driver #2 had right foot and elbow pain, a deep laceration to the hand, left shoulder pain and numerous glass lacerations.

Diagram

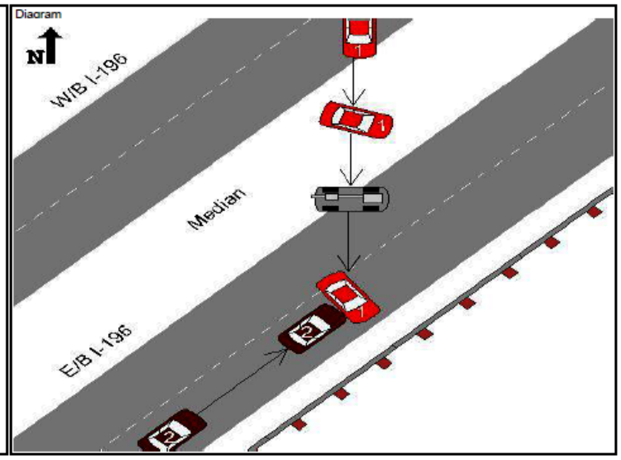

Figure 9. Target 3 Crash – Cross-Median Crash

Narrative

Vehicle 1 states that he was east on I-94 travelling in the driving lane when a Red travelling in the passing lane began passing him. He states that Jeep began to lose control and turn sideways coming into his lane. He states that to avoid hitting the jeep he hit his brakes which caused him to spin on the icy roads. He lost control and hit the cable barriers. There was not any contact between the red Jeep and Vehicle 1. The driver of vehicle one complained of minor injury. He was transported to Bronson by Pride Care. No citation was issued as the crash was clearly caused by the red Jeep coming into Vehicle 1 lane forcing him to take evasive action. There was no other information on the red Jeep.

Diagram

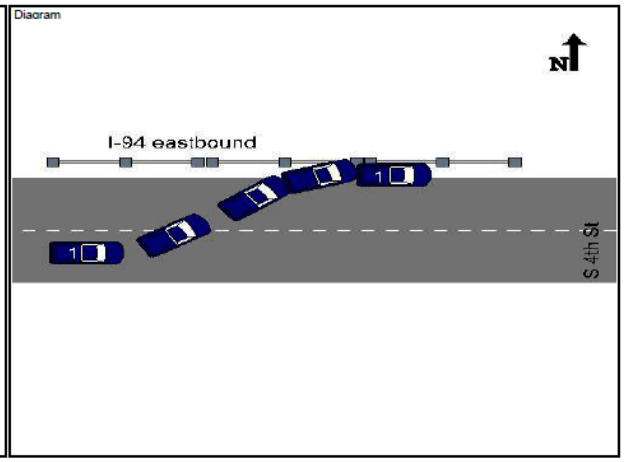

Figure 10. Target 4 Crash – Contained by Cable Barrier

Narrative

#1 advised he is unsure of what occurred. He states he drove slightly onto the right shoulder and then lost control of his vehicle. From evidence on scene, U/O determined that #1 did run off the road onto the right shoulder where he lost control of the vehicle, traveled across both lanes of travel, striking the median guard cables. At this point the vehicle, slid under the guard cables into the ditch. Impact with the cables and support pole caused heavy damage to the vehicle.

Diagram

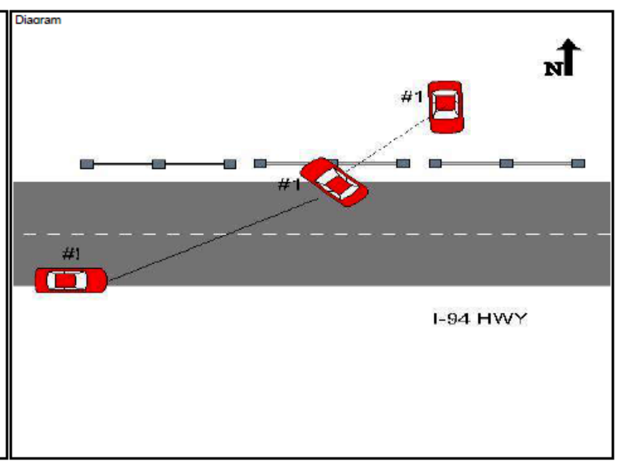

Figure 11. Target 5 Crash – Penetrated Cable Barrier but Did Not Enter Opposing Lanes

Narrative

Vehicle 1 lost control ran off roadway left hit the cable barrier. Vehicle 1 went through the cable barrier crossed over e/b lanes of traffic and into the ditch.

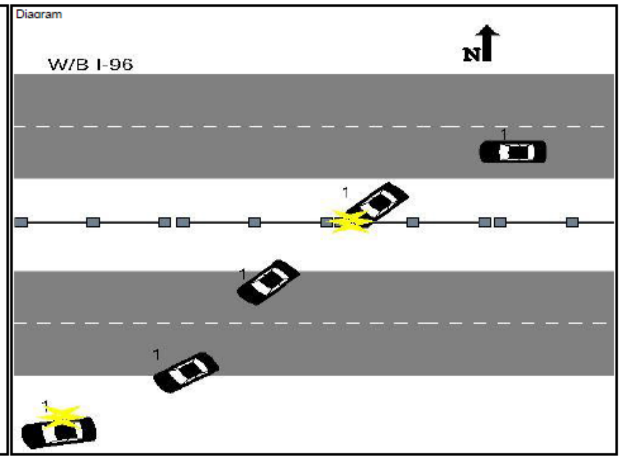

Figure 12. Target 6 Crash – Penetrated Cable Barrier and Entered Opposing Lanes, but Did Not Strike Opposing Vehicle

Narrative

Vehicle #1 was EB on I-94 when Driver #1 lost control on snow covered, icy roads. Vehicle #1 ran off the roadway to the left and drove through the median cable barrier. Driver #1 then steered left through the median and entered WB I-94 going the wrong way into the path of Vehicle #1. Vehicle #1 then struck the trailer of Vehicle #2 which was travelling WB on I-94. Driver #1 initially complained of a sore left ankle but refused treatment by EMS. Driver #1 later stated his ankle no longer hurt.

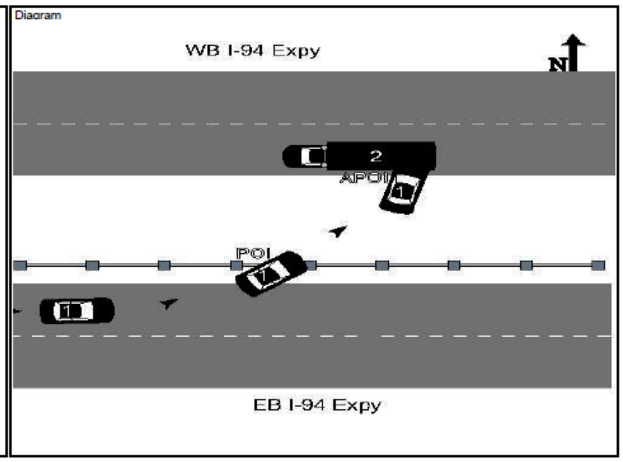

Figure 13. Target 7 Crash – Penetrated Cable Barrier and Entered Opposing Lanes, and Struck Opposing Vehicle

Narrative

#1 was e/b I-96 and lost control on standing water due to heavy rainstorm. #1 struck the cable barrier and then ran off the road striking trees.

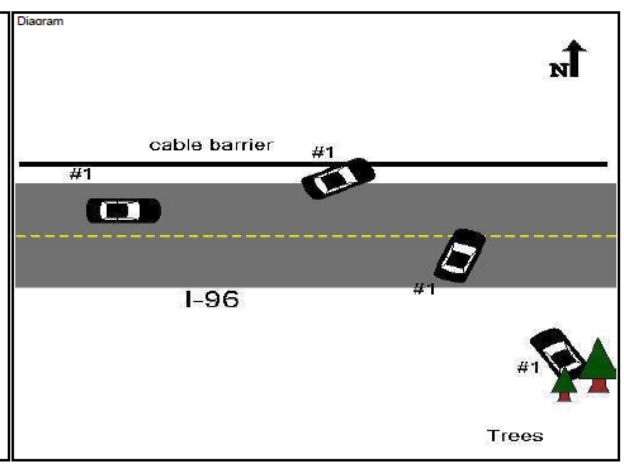

Figure 14. Target 8 Crash – Struck Cable Barrier and Re-Directed Onto Travel Lanes

Ultimately, over 45,000 crashes were manually reviewed and 7,874 target crashes were identified in the before and after periods for the for cable median barrier segments. In addition to the manually determined target crash identification, further data were extracted from the electronic crash database for each crash including:

- Most severe injury in each crash
- Number of injuries by severity per crash
- Number of vehicles involved in each crash
- Whether crash was a rollover crash
- Road, weather, and lighting conditions at the time of crash

The injury level for each crash-involved person is reported on the KACBO injury scale which classifies injuries into one of five discrete categories (*1*):

- K - Fatality (results in the death of a crash-involved person)
- A - Incapacitating injury (any injury, other than a fatal injury, that prevents an injured crash-involved person from walking, driving, or normally continuing the activities the person was capable of performing before the injury occurred.)
- B - Non-incapacitating injury (any injury not incapacitating but evident to observers at the scene of the crash in which the injury occurred.)
- C - Possible injury (any injury reported or claimed that is not a fatal injury, incapacitating injury or non-incapacitating injury.)
- O - No Injury (crash-involved person reported as not receiving bodily harm from the motor vehicle crash; also known as property damage only (PDO) crash)

Detailed description and analysis of the cable median barrier segment crash data is presented in Chapter 4 and Chapter 5 of this dissertation.

3.3.2 Comparison segment crash data

The crash data for the comparison segments were obtained and analyzed in a similar method as the cable barrier sections. All crashes occurring on each no barrier (median width < 100ft), thrie-beam barrier, and concrete barrier segment were obtained for years 2009 through 2013 from MDOT. The crashes were assigned to each segment based on the PR and mile point which was coded for each crash. Crash reviewers then reviewed the comparison segment crashes in a similar manner previously described for the cable barrier segments. The target crash coding for the comparison segments were similar to those for the cable barrier segments:

Median or Median Crossover Crashes:

1 – Median Crash - vehicle left roadway and entered median, but did not strike any barrier or cross into opposing lanes of traffic. This includes vehicles which enter the median and re-enter the roadway onto original lanes of travel.

2 – Cross-Median Event – vehicle left roadway and entered median, travelled all the way across the median and entered into opposing traffic lanes, but did not strike an opposing vehicle.

3 – Cross-Median Crash – vehicle left roadway and entered median, travelled all the way across the median and entered into opposing traffic lanes and struck an opposing vehicle.

Median Barrier Strike Crash (for thrie-beam guardrail and concrete barrier segments only):

4 – Median Barrier Strike – vehicle struck median barrier, did not penetrate the barrier, and was contained in the median.

5 – Median Barrier Strike – vehicle struck median barrier, penetrated all the way through the barrier (including vehicles that flipped over the barrier), but did not enter opposing travel lanes.

6 – Median Barrier Strike – vehicle struck median barrier, penetrated all the way through the barrier (including vehicles that flipped over the barrier), entered opposing traffic lanes, but did not strike opposing vehicle.

7 – Median Barrier Strike – vehicle struck median barrier, penetrated all the way through the barrier (including vehicles that flipped over the barrier), entered opposing traffic lanes, and struck opposing vehicle.

8 – Median Barrier Strike – vehicle struck median barrier, and was re-directed back onto original lanes of travel.

Similar to the cable median segment crash data, crashes occurring on bridge decks or with bridge abutments were not coded as target crashes. The same additional data was extracted from the crash reports as the cable barrier segment crashes including injury data, number of vehicles involved, whether the crash was a rollover crash, and road, weather and lighting conditions at the time of each crash. Ultimately, over 73,500 crashes were manually reviewed and 16,431 target crashes were identified between all three different types of comparison segments. Detailed description and analysis of the comparison segment (no barrier, thrie-beam, and concrete barrier) crash data is presented in Chapter 4 and Chapter 5 of this dissertation.

CHAPTER 4

BEFORE-AND-AFTER ANALYSIS OF CABLE BARRIER PERFORMANCE

Ultimately, the objective of this study was to evaluate the effectiveness of high-tension cable median barriers in reducing the frequency of median-crossover crashes on freeways and the resultant injuries from such crashes. However, since cable median barriers present an opportunity for collisions in cases where errant vehicles previously had room for possible recovery after they left the roadway, all median-related crashes must be considered in the analysis to evaluate the overall safety effects of installing cable median barriers.

The cable median barrier program in Michigan began in 2008 with three installations totaling approximately 16 miles. Subsequent installations continued annually through 2013 for a system total of approximately 317 miles analyzed as part of this study. For the purpose of the before-after evaluation of the cable median barrier program in Michigan, the year of construction for each installation was excluded from the analysis. Crash data for 2004 through 2013 were analyzed for this study, and, as such, each cable barrier installation had between 4 and 9 years of before data and between 0 and 5 years of after data, depending on the year of construction. It should be noted that data for the installations in 2013 is presented in subsequent summary tables in this section but these installations are not included in the before-after Empirical Bayes analysis or the economic analysis due to lack of after period data.

4.1 Comparison of Target Crashes Before and After By Crash Severity and Crash Type

As stated in the previous section, a 'target' crash is defined as any crash in which a vehicle left the roadway and entered the median. In order to examine the effects of cable median barriers being installed, the frequency and severity of target crashes occurring annually in the before and after periods for each installation was determined. Table 9 shows a summary of average annual target crashes by installation and analysis period. It should be noted that these summary statistics do not consider changes in traffic volume or other geometric features such as median width or horizontal curvature. Nonetheless, some clear trends emerge:

- Average annual PDO target crashes significantly increased in the after period, and C injury target crashes increased marginally in the after period. These results are consistent with past studies (*7; 16; 17*) and expected as errant vehicles will have less distance to recover when entering the median after cable barrier installation, increasing the likelihood of a barrier strike. Additionally, it is likely that a number of minor run-off-the-road crashes in the before period went unreported, as vehicles can potentially return to the roadway if there is minimal damage after a run-off-the-road event.
- Incapacitating and fatal injury average annual crashes both decreased by approximately 50 percent in the after period. This is consistent with past results (*7; 8; 16; 17; 19; 20*) and also suggests that cable barriers were successful in reducing severe median related crashes; particularly median crossover crashes.

Examining target crashes at an aggregate level with all installations combined, the percent of target crashes by severity in the before and after periods also indicates an increase in PDO crashes and decrease in severe injury and fatal crashes after cable barrier installation. Figure 15 shows the percent of target crashes by crash severity and analysis period.

In addition to examining the percent of crashes by severity in the before and after period, the percent of target crashes which were median-crossover crashes were examined for the before and after periods. As shown in Table 10, 17.4 percent of target crashes were cross-median in the before period while only 1.0 percent of target crashes were cross-median in the after period.

This dramatic reduction in cross-median crashes in the after period is consistent with past research (*7-9; 12; 14; 16; 19; 20; 23*). Additionally, examination of the severity distributions of median crashes (non-crossover median crashes) vs. cross-median crashes shows that cross-median crashes result in significantly higher percentages of incapacitating and fatal injuries than median crashes in both the before and after periods, particularly when the cross-median event resulted in a collision with a vehicle traveling in the opposite direction. With the installation of cable median barriers, the percentage of cross-median crashes are significantly reduced thereby reducing the opportunity for the most severe injury outcomes. However, as stated previously, the overall average annual increase in PDO and C injury crashes must be considered to determine the true safety performance of cable median barriers.

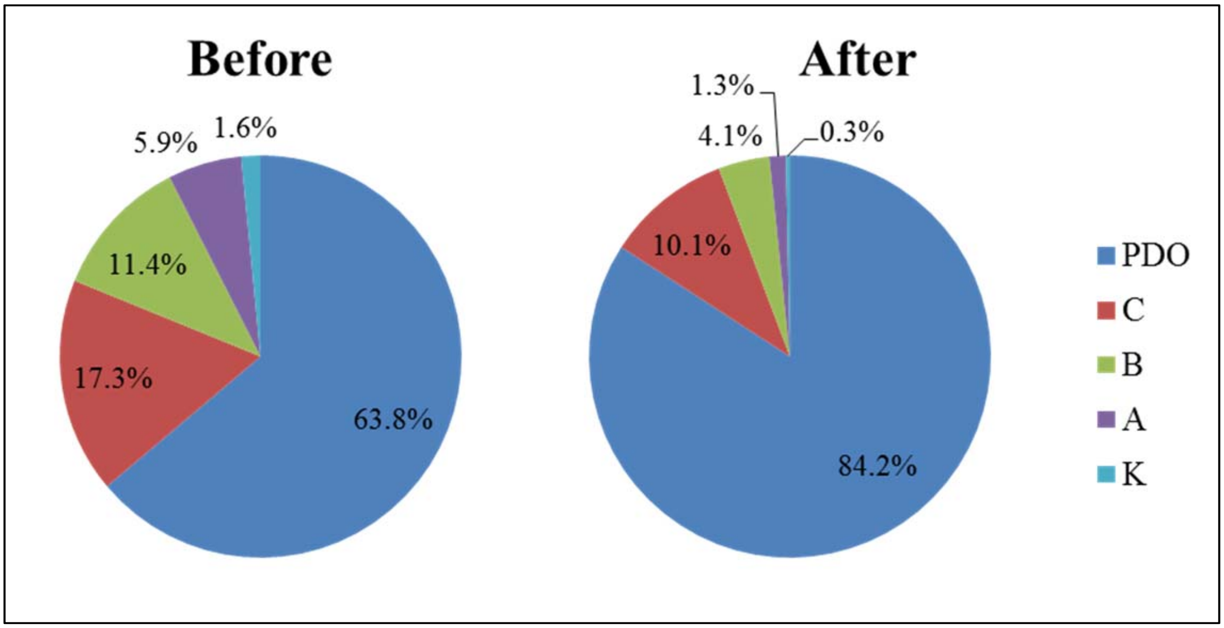

Figure 15. Percent of Target Crashes by Crash Severity and Analysis Period

TABLE 9. Summary of Average Annual Target Crashes by Installation and Analysis Period

Install Number	Route	MDOT Region	Install Year	Years Before Data	Years After Data	Installation Length (miles)	Before Period Average Annual Target Crashes by Severity					After Period Average Annual Target Crashes by Severity				
							PDO	C	B	A	K	PDO	C	B	A	K
1	I-94	Southwest	2008	4	5	3.8	2.8	3.0	2.3	0.8	0.0	20.8	1.8	0.4	0.0	0.2
2	I-94	Metro	2008	4	5	6.2	2.5	1.8	1.0	0.0	0.0	7.6	1.0	0.0	0.2	0.0
3	I-69	Bay	2008	4	5	5.8	4.0	1.5	0.8	0.0	0.0	19.0	2.4	0.2	0.2	0.0
4	I-94	Metro	2009	5	4	6.2	8.6	3.4	1.4	1.6	0.2	33.8	6.5	3.8	0.3	0.0
5	I-94	Metro	2009	5	4	6.1	3.2	1.2	1.0	0.2	0.0	10.3	1.0	0.3	0.3	0.0
6	I-94	Southwest	2009	5	4	28.3	55.4	7.8	5.8	4.0	1.4	157.5	13.8	6.3	2.3	0.8
7	I-96	Grand	2009	5	4	13.5	13.4	3.4	3.0	1.2	0.2	40.0	5.8	2.3	1.0	0.0
8	US-131	Grand	2009	5	4	4.1	10.6	2.2	1.2	1.0	0.8	45.5	6.5	3.3	0.5	0.0
9	I-69	University	2009	5	4	17.6	19.2	2.4	2.2	1.2	0.6	24.5	3.8	1.5	0.3	0.0
10	US-23	University	2009	5	4	14.1	15.6	5.2	3.2	2.6	0.2	24.5	2.0	0.8	0.0	0.0
11	I-275	Metro	2009	5	4	7.4	17.0	7.6	3.6	1.6	0.8	57.3	9.5	3.3	0.8	0.3
12	I-96	Grand	2010	6	3	9.0	25.8	5.3	4.8	1.7	0.2	52.0	7.0	3.0	0.3	0.0
13	I-96	Grand	2010	6	3	19.2	29.0	8.3	6.7	3.5	0.5	83.0	11.7	5.0	2.3	0.3
14	I-196	Southwest	2010	6	3	6.9	8.8	1.5	1.2	1.3	0.0	15.7	2.7	0.7	0.3	0.3
15	I-94	Metro	2010	6	3	3.6	2.3	0.5	0.5	0.5	0.0	6.3	0.3	0.0	0.0	0.0
16	I-94	Southwest	2010	6	3	17.6	19.5	3.7	3.7	2.3	1.0	45.7	5.7	1.7	1.7	0.3
17	I-75	Superior	2010	6	3	8.7	1.7	1.0	0.3	0.3	0.0	7.3	0.3	0.3	0.0	0.0
18	I-94	Southwest	2010	6	3	20.9	24.8	6.5	4.5	1.3	0.5	69.7	10.7	4.0	1.0	0.3
19	I-94	Southwest	2010	6	3	6.0	8.7	2.2	1.7	0.8	0.2	15.7	2.3	1.3	1.0	0.0
20	US-131	Southwest	2010	6	3	24.7	34.5	8.2	5.7	3.0	0.2	124.7	7.0	4.7	1.7	0.3
21	I-94	Metro	2010	6	3	3.3	2.5	1.0	0.7	0.2	0.0	6.0	1.0	0.0	0.0	0.0
22	US-31	Grand	2010	6	3	4.5	7.8	3.2	2.7	1.0	0.0	31.7	3.3	1.7	0.3	0.0
23	I-94	Southwest	2010	6	3	2.6	4.7	0.7	0.8	0.0	0.2	6.0	0.7	0.3	0.0	0.3
24	I-94	Southwest	2011	7	2	7.5	5.9	0.6	1.1	0.3	0.1	14.5	1.5	0.5	0.0	0.0
25	I-94	University	2011	7	2	7.6	10.3	4.1	1.7	1.1	0.3	15.0	3.5	0.0	0.0	0.0
26	I-196	Southwest	2011	7	2	6.5	6.3	2.4	1.9	0.6	0.0	14.5	2.5	1.5	0.0	0.0
27	I-96	University	2012	8	1	2.6	3.1	1.3	0.9	0.6	0.1	5.0	2.0	0.0	0.0	0.0
28	US-23	University	2012	8	1	22.6	20.3	7.1	4.3	2.4	0.8	100.0	9.0	7.0	3.0	2.0
29	I-94	University	2012	8	1	12.1	18.1	7.0	2.6	1.0	0.6	28.0	5.0	2.0	2.0	0.0
30	M-14	Metro	2012	8	1	4.0	6.6	2.0	0.4	0.8	0.3	20.0	2.0	0.0	0.0	0.0
31	I-94	Metro	2013	9	0	6.1	5.7	1.1	0.8	0.2	0.1	N/A	N/A	N/A	N/A	N/A
32	US-23	University	2013	9	0	8.1	5.6	1.4	0.3	0.4	0.4	N/A	N/A	N/A	N/A	N/A
						SUM:	**404.2**	**108.5**	**72.5**	**37.6**	**9.6**	**1,101.3**	**132.1**	**55.5**	**19.3**	**5.2**

While the summary of target crashes by type and severity in the before and after periods allow for examination of general trends, these summary statistics do not account for changes in traffic volumes over time. As such, a summary of average before and after crash rates, expressed in 100 million vehicle miles of travel (100 MVMT), were calculated. These crash rates take into account segment lengths as well as annual changes in traffic volumes between the before and after periods. Table 11 shows a summary of before and after target crash rates along with the percent change for each crash type.

As shown in Table 11, the overall target crash rate increased 123.6 percent in the after period, increasing from 15.60 per 100 MVMT to 34.88 100 MVMT. This increase is largely a result of the increase in PDO target crash rate. The PDO/C crash rate increased 154.7% after cable barrier installation, while the B-injury level crash rate decreased by 28.1%. Considering the crashes of greatest concern, the target crash rate for K and A level injury crashes combined decreased by 49.6 percent, results which are consistent with past studies (*16; 17*). Additionally, the median-crossover crash rate decreased by 86.8 percent in the after period, indicating the installation of cable barriers are successful in terms of reducing cross-median crashes. The target rollover crash rate decreased by 50.4 percent in the after period, indicating the installation of cable barriers may prevent errant vehicles from overturning in the event of a run-off-the-road crash. This reduction in rollover crashes can also be seen in Table 12 which shows the percentage of total target crashes which were rollover crashes decreased from 32.0 percent in the before period to 6.4 percent in the after period.

Table 10. Before and After Target Crashes by Type and Severity

Crash Type		PDO	C	B	A	K	TOTAL	% of Target Crashes
		Before Period Target Crashes by Type and Severity						
Median	**No.**	2,131	531	312	130	22	3,126	82.6%
	%	68.2%	17.0%	10.0%	4.2%	0.7%	100.0%	
Cross-Median (Struck Opposing Veh.)	**No.**	58	35	36	39	31	199	5.3%
	%	29.1%	17.6%	18.1%	19.6%	15.6%	100.0%	
Cross-Median (Did Not Strike Opposing Veh.)	**No.**	227	89	82	55	6	459	12.1%
	%	49.5%	19.4%	17.9%	12.0%	1.3%	100.0%	
All Target Crashes	**No.**	2,416	655	430	224	59	3,784	100.0%
	%	63.8%	17.3%	11.4%	5.9%	1.6%	100.0%	
		After Period Target Crashes by Type and Severity						
Crash Type		**PDO**	**C**	**B**	**A**	**K**	**TOTAL**	**% of Target Crashes**
Median	**No.**	3,430	401	163	50	8	4,052	99.0%
	%	84.6%	9.9%	4.0%	1.2%	0.2%	100.0%	
Cross-Median (Struck Opposing Veh.)	**No.**	0	4	0	2	1	7	0.2%
	%	0.0%	57.1%	0.0%	28.6%	14.3%	100.0%	
Cross-Median (Did Not Strike Opposing Veh.)	**No.**	12	7	6	2	4	31	0.8%
	%	38.7%	22.6%	19.4%	6.5%	12.9%	100.0%	
All Target Crashes	**No.**	3,442	412	169	54	13	4,090	100.0%
	%	84.2%	10.1%	4.1%	1.3%	0.3%	100.0%	

Table 11. Summary of Before and After Crash Rates

Crash Severity/Type	Average Annual Crash Rate (crashes per 100 MVMT)		
	Before Period	After Period	Percent Change
All Target Crashes	15.60	34.88	123.6%
Target PDO & C Crashes	12.90	32.85	154.7%
Target B Crashes	1.85	1.33	-28.1%
Target K & A Crashes	1.15	0.58	-49.6%
Median Crossover Crashes	2.66	0.35	-86.8%
Target Rollover Crashes	4.88	2.42	-50.4%

Table 12. Summary of Target Rollover Crashes by Period

Period	Target Crashes by Crash Type (Rollover vs. Non-Rollover)					
	Rollover		Non-Rollover		Total	
	Number	Percent	Number	Percent	Number	Percent
Before	1,212	32.0%	2,572	68.0%	3,784	100.0%
After	263	6.4%	3,827	93.6%	4,090	100.0%

4.2 Comparison of Before and After Target Crashes by Road Conditions

Past research has found that median-related crashes and crashes with median barriers are more prevalent during adverse weather and road conditions (*14; 28; 29*), but severe crashes and cable barrier penetrations are less likely to occur under such conditions (*23; 28*). This factor is especially important for Michigan, which generally experiences a significant amount of snowfall during winter months (*37*) which can leave roads icy and reduce friction between the road and vehicle tires. As such, target crashes were summarized by road condition, crash severity, and analysis period to investigate trends related to road conditions. For this analysis, any crash coded as occurring on roads with wet, icy, snowy, or slushy road conditions were grouped and all other crashes occurring on dry road conditions were grouped. Table 13 presents a summary of crashes by road condition and analysis period, while Table 14 shows a summary of target crashes by road condition, severity, and analysis period.

Table 13. Summary of Target Crashes by Road Condition and Analysis Period

	Target Crashes by Road Condition					
	Wet/Icy/Snowy		Dry		Total	
Period	**Number**	**Percent**	**Number**	**Percent**	**Number**	**Percent**
Before	2,261	59.8%	1,523	40.2%	3,784	100.0%
After	2,837	69.4%	1,253	30.6%	4,090	100.0%

As seen in Table 13, approximately 60 percent and 70 percent of target crashes occurred on wet/snowy/icy roads in the before and after periods, respectively. This indicates that weather conditions may be a significant factor in the frequency of run-off-the-road crashes. Additionally, as seen in Table 14, the target crashes tended to be less severe on adverse road conditions in both the before and after periods. This may be attributable to the fact that motorists may drive more cautiously at lower speeds during such conditions.

Table 14. Summary of Target Crashes by Road Condition, Severity, and Analysis Period

Period	Pavement Condition		Target Crashes by Road Condition and Severity					
			PDO	C	B	A	K	TOTAL
Before	Wet/Icy/Snowy	No.	1,605	353	201	80	22	2,261
		%	71.0%	15.6%	8.9%	3.5%	1.0%	100.0%
	Dry	No.	811	302	229	144	37	1,523
		%	53.3%	19.8%	15.0%	9.5%	2.4%	100.0%
After	Wet/Icy/Snowy	No.	2,544	210	67	13	3	2,837
		%	89.7%	7.4%	2.4%	0.5%	0.1%	100.0%
	Dry	No.	898	202	102	41	10	1,253
		%	71.7%	16.1%	8.1%	3.3%	0.8%	100.0%
Total for Before and After	Wet/Icy/Snowy	No.	4,149	563	268	93	25	5,098
		%	81.4%	11.0%	5.3%	1.8%	0.5%	100.0%
	Dry	No.	1,709	504	331	185	47	2,776
		%	61.6%	18.2%	11.9%	6.7%	1.7%	100.0%

4.3 Emergency Vehicle Crossover-Related Crashes

As part of the crash review process, reviewers identified target crashes which involved a vehicle pulling into, pulling out of, or crossing through an emergency vehicle crossover. These median crossovers are provided on freeways for use by emergency or maintenance vehicles on road segments between interchanges for use during an emergency or maintenance operation. The MDOT Road Design Manual (*38*) states these crossovers should be spaced at least 1,500 feet from interchange ramps and that the crossovers should be "spaced such that maintenance or emergency vehicles are provided crossover opportunities within 5 miles either by an interchange or a subsequent median crossover" (*38*). Other states such as Missouri have recommended spacing EV crossovers no more than 2.5 miles apart (*39*). The concern with providing crossovers too frequently on cable barrier segments is that there is an increased potential for errant vehicles to cross through them, and for unauthorized vehicles to use them illegally, increasing the likelihood of cross-median crashes. On the other hand, if these crossovers are spaced too far apart, emergency response times can be further delayed in the event of a crash or other emergency.

In the survey of emergency responders that was conducted as a part of this study, 23 out of 53 respondents indicated they had difficulty in responding to an incident on a roadway with cable barrier due to "Inability to locate a median crossover or too much spacing between crossovers". Additionally, approximately 60 percent of respondents indicated that in their opinion, median crossovers should be located with a spacing of 1 mile or less.

While data was not available for this study to analyze possible changes in emergency response time after cable median barriers were installed, the before and after trends of emergency vehicle crossover-related crashes were examined. Table 15 presents a summary of emergency vehicle (EV) crossover-related crashes by severity and analysis period.

Table 15. Summary of EV Crossover-Related Target Crashes by Severity and Analysis Period

	Number of E.V. Crossover Related Crashes by Period							
	Crash Severity					Total E.V. Crossover-Related Crashes	Total Target Crashes	% E.V. Crossover-Related Crashes
Period	PDO	C	B	A	K			
Before	49	12	6	6	2	75	3,784	1.98%
After	16	8	3	2	1	30	4,090	0.73%

From Table 15 it can be seen that the percent of target crashes involving EV crossovers was less after cable barrier installation (1.98 percent in the before period and 0.73 percent in the after period). The majority of EV crossover-related crashes in both periods were the result of drivers attempting to illegally use the crossovers. An in-depth analysis of EV crossover-related crashes in the after period which resulted in a cross-median crash revealed only 2 crashes where a driver just happened to lose control near an EV crossover and travel through the crossover into opposing lanes (between runs of cable barrier). One of these crashes was a PDO crash and one resulted in a B-level injury. This analysis indicates that EV crossovers present a safety issue mainly when motorists attempt to illegally use them, and it is quite rare for a motorist to cross all the way through one into opposing traffic just by chance after cable barrier installation.

In order to examine the average distance between EV crossovers and interchanges, a sample of 100 miles of cable barrier road segments and 100 miles of no barrier control section were analyzed. The distance between EV crossovers (or EV crossover to Interchange – since interchanges may be used by emergency vehicles to change bounds) was measured using Google Earth. It was found that the average distance between EV crossovers (or between EV crossovers and interchanges) for freeway sections with cable barrier was 1.05 miles, and the average distance for freeway sections with no barrier was 0.88 miles. The maximum distance observed for freeway sections with cable barrier was 4.2 miles, while the maximum for freeway sections with no barrier was 3.4 miles. This analysis indicates that freeway segments with cable barrier tend to have larger spacing between EV crossovers as compared to freeway segments with no barrier. The crash analysis indicates that a larger spacing between EV crossovers results in fewer EV crossover-related crashes, because many of these crashes are caused by motorists attempting to illegally use them.

4.4 Analysis of Cable Barrier Strike Crashes

The summary of crashes in the previous sections included all target crashes (i.e. median-related crashes). However, in order to analyze the effectiveness of cable barriers in containing a vehicle in the event of a cable barrier strike, a detailed analysis was conducted of all crashes in the after period in which a vehicle struck a cable barrier. Table 16 shows a summary of cable barrier crashes by severity and crash outcome scenario.

As seen in Table 16, 96.9 percent of cable barrier strikes did not result in a penetration of the cable barrier. This indicates the cable median barriers have been highly successful with regard to their intended purpose of preventing cross-median crashes. This performance is comparable, and even slightly more successful than experiences with cable barrier in several other states (*16; 17; 20; 23*). Although only 0.7 percent of cable barrier strikes resulted in a cross-median event or crash, an additional 2.3 percent resulted in a cable barrier penetration but no median crossover (i.e. the vehicle penetrated the barrier but came to rest in the median). Unfortunately, a large amount of the crash reports were not detailed enough to determine the exact manner in which each vehicle penetrated the barrier (over-ride, under-ride, or penetration through). As stated previously, the cable barriers contained 96.9% of vehicles which struck the barrier. Of all crashes that resulted in a cable barrier strike, the cable median barriers contained 89.3 percent of vehicles in the median after a strike (the most favorable result), while 7.6 percent of cable barrier strikes resulted in the vehicle being re-directed back onto travel lanes.

Table 16. Summary of Cable Barrier Strikes by Severity and Crash Outcome Scenario

Cable Barrier Crash Outcome Scenario		After Period Cable Barrier Strikes by Type and Severity						Percent of Total Cable Barrier Crashes
		PDO	C	B	A	K	TOTAL	
Contained by cable barrier in median	No.	2,861	291	101	21	6	3,280	89.3%
	%	87.2%	8.9%	3.1%	0.6%	0.2%	100.0%	
Struck cable barrier and re-directed back onto travel lanes	No.	222	36	16	4	2	280	7.6%
	%	79.3%	12.9%	5.7%	1.4%	0.7%	100.0%	
Total cable barrier strikes which did not penetrate cable barrier	No.	3,083	327	117	25	8	3,560	96.9%
	%	86.6%	9.2%	3.3%	0.7%	0.2%	100.0%	
Penetrated cable barrier but contained in median	No.	55	16	11	4	0	86	2.3%
	%	64.0%	18.6%	12.8%	4.7%	0.0%	100.0%	
Penetrated cable barrier and entered opposing lanes (struck opposing veh)	No.	0	3	0	1	1	5	0.1%
	%	0.0%	60.0%	0.0%	20.0%	20.0%	100.0%	
Penetrated cable barrier and entered opposing lanes (did not strike opposing veh)	No.	10	4	5	1	3	23	0.6%
	%	43.5%	17.4%	21.7%	4.3%	13.0%	100.0%	
Total Cable Barrier Crashes	No.	3,148	350	133	31	12	3,674	100.0%
	%	85.7%	9.5%	3.6%	0.8%	0.3%	100.0%	

In terms of severity distribution, crashes which were contained in the median by the cable barrier were by far the least severe with only 0.8 percent of these crashes resulting in a fatal or incapacitating injury. Conversely, 40.0 percent and 17.3% of cable barrier strikes resulting in cross-median crashes and cross-median events, respectively, resulted in a fatal or incapacitating injury and 4.7 percent of crashes which penetrated the barrier but remained in the median resulted in fatal or incapacitating injuries (i.e., K and A crashes, respectively). Of crashes which were re-directed back onto travel lanes, only 2.1 percent resulted in fatal or incapacitating injuries. Overall, 85.7 percent of cable barrier strikes did not result in any level of injury (property damage only) while 1.1 percent resulted in fatal or incapacitating injuries.

Table 17 shows a summary of cable barrier strike crashes by vehicle type. It should be noted that the data presented in Table 17 represents the first vehicle to strike the cable barrier as reported on the crash report in the case of multi-vehicle crashes. Overall, passenger cars accounted for 79.6 percent of cable barrier strike crashes and 0.5 percent of these resulted in penetration and a cross-median event or cross-median crash. Vans accounted for 4.2 percent of cable barrier strike crashes and 2.6 percent of these crashes resulted in a penetration and cross-median event. Pick-up trucks accounted for 11.5 percent of cable barrier strike crashes, and while 0.7 percent of these crashes resulted in a penetration or the cable barrier, none resulted in a cross-median event or crash. This may suggest that pick-up trucks are less susceptible to under-ride cable barrier systems compared with passenger cars due to their larger height and higher center-of-gravity. Small trucks weighing less than 10,000 pounds and motorcycles accounted for 1.6 percent and 0.2 percent of cable barrier strike crashes, respectively. No cable barrier crashes of these two vehicle types resulted in a penetration, cross-median event, or cross-median crash, although the sample sizes were quite small for each. Trucks and busses weighing over 10,000 pounds accounted for 0.2 percent of cable barrier strike crashes, and 6.7 percent of these crashes resulted in a penetration and a cross-median event or crash. This over-representation of penetrations by large trucks and busses is consistent with experiences in other states (*17; 23*), and is not surprising due to the increased forces associated with crashes involving such heavy vehicles.

Table 17. Summary of Cable Barrier Strikes by Vehicle Type

Vehicle Type	Contained by cable barrier in Median		Struck cable barrier and re-directed back onto travel lanes		Penetrated cable barrier but contained in median		Penetrated cable barrier and entered opposing lanes (struck opposing veh)		Penetrated cable barrier and entered opposing lanes (did not strike opposing veh)		Total Cable Barrier Crashes by Veh Type		Percent of Cable Barrier Crashes by Veh Type
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	
Passenger Car	2,608	89.2%	221	7.6%	78	2.7%	4	0.1%	13	0.4%	2,924	100%	79.6%
Van	133	86.4%	16	10.4%	1	0.6%	0	0.0%	4	2.6%	154	100%	4.2%
Pickup Truck	389	92.2%	30	7.1%	3	0.7%	0	0.0%	0	0.0%	422	100%	11.5%
Small Truck Under 10,000 lbs	50	87.7%	7	12.3%	0	0.0%	0	0.0%	0	0.0%	57	100%	1.6%
Motorcycle	6	100.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	6	100%	0.2%
Truck/ Bus Over 10,000 lbs	89	84.8%	5	4.8%	4	3.8%	1	1.0%	6	5.7%	105	100%	2.9%
Unknown Veh Type	5	83.3%	1	16.7%	0	0.0%	0	0.0%	0	0.0%	6	100%	0.2%
All Vehicle Types	3,280	89.3%	280	7.6%	86	2.3%	5	0.1%	23	0.6%	3,674	100%	100.0%

As mentioned previously, weather conditions can play a role in terms of frequency or severity of median-related or cable barrier strike crashes. Table 18 shows a summary of cable barrier strikes by road condition at the time of crash, and outcome scenario resulting from the crash. It is clear that cable barrier strikes occurring during dry road conditions result in slightly less favorable outcomes as compared to cable barrier strikes occurring during wet or icy road conditions (1.6 percent of cable strikes resulted in a penetration and cross-median event or crash during dry road conditions, as compared to 0.4 percent during wet or icy road conditions). This is consistent with past findings (*23*), and likely due to lower travel speeds associated with adverse weather or road conditions which would reduce the impact energy associated with a cable barrier strike.

Table 18. Summary of Cable Barrier Strike Crashes by Road Condition and Crash Outcome Scenario

Cable Barrier Crash Outcome Scenario	Dry Road		Wet/Icy Road	
	No.	%	No.	%
Contained by cable barrier in median	930	86.4%	2,350	90.5%
Struck cable barrier and re-directed back onto travel lanes	83	7.7%	197	7.6%
Penetrated cable barrier but contained in median	46	4.3%	40	1.5%
Penetrated cable barrier and entered opposing lanes (struck opposing veh)	3	0.3%	2	0.1%
Penetrated cable barrier and entered opposing lanes (did not strike opposing veh)	14	1.3%	9	0.3%
Total Cable Barrier Crashes	1,076	100.0%	2,598	100.0%

4.5 Analysis of Motorcycle Crashes

One concern that has been raised with the installation of high-tension cable median barriers is their potential to cause especially severe injuries in the event of a motorcycle crash. Motorcyclists have expressed concerns that a crash with a cable median barrier may result in severe lacerations or even dismemberment by the cables (*16*). To investigate this concern, all target crashes involving a motorcycle were analyzed and the summary of these crashes is shown in Table 19. While motorcycle crashes in general are known to be more severe due to the lack of protection offered by passenger vehicles (*40*), it does not appear cable barriers have contributed to a marked increase in motorcycle crash severity in Michigan. This is consistent with experiences in other states (*16; 17; 33*). As seen in Table 19, there were no fatal target motorcycle involved crashes in the before or after periods, or during years of cable barrier construction.

Of crashes where a motorcyclist made contact with the cable median barrier (in the after period or during cable barrier construction), 5 resulted in C-level injuries and 4 resulted in A-level injuries. None of the narratives on the crash reports for these crashes indicated specifically that the cables or posts caused lacerations or dismemberment. In April 2012, Michigan repealed its universal helmet law and motorcyclists are now legally allowed to ride without a helmet as long as they carry a minimum amount of insurance and are at least 21 years old (*41*). Of the 9 motorcycle cable barrier impacts, 6 motorcyclists were wearing helmets, one motorcyclist's helmet use was unknown, and 2 motorcyclists were riding unhelmeted. The two crashes in which the motorcyclists were riding unhelmeted resulted in one C-level injury crash and one A-level injury crash, and both occurred after the Michigan universal helmet law was repealed. Overall, it appears that the installation of cable barriers on Michigan freeways has not had a significant effect on motorcyclist safety. Table 19 also presents a summary of motorcycle-involved crashes for comparison segments with different median barrier treatments (no barrier, thrie-beam guardrail, and concrete barrier). Similar to cable barrier segments, the sample sizes of motorcycle-involved target crashes on comparison segments are quite low, and strong conclusions regarding the effect median treatment type on motorcycle-involved crash severity outcomes cannot be made.

Table 19. Summary of Motorcycle Involved Target Crashes

Target Crash Analysis Period for Cable Barrier		Number of Target Motorcycle Involved Crashes by Severity (including cable strikes)					
		PDO	C	B	A	K	TOTAL
Before Period		5	6	10	3	0	24
During Construction Year		1	1	1	4	0	7
After Period		0	5	1	3	0	9
Total for All Periods		6	12	12	10	0	40
Total % by Severity		15.0%	30.0%	30.0%	25.0%	0.0%	100.0%
Motorcycle Cable Barrier Strikes		Number of Motorcycle Cable Barrier Strike Crashes by Severity					
Number		0	5	0	4	0	9
Comparison Segment Median Treatment		Number of Target Motorcycle Involved Crashes For Comparison Segments by Severity					
No Barrier	No.	2	2	9	7	1	21
	%	9.5%	9.5%	42.9%	33.3%	4.8%	100.0%
Thrie-beam Median Guardrail	No.	1	2	3	1	1	8
	%	12.5%	25.0%	37.5%	12.5%	12.5%	100.0%
Concrete Median Barrier	No.	3	7	17	9	2	38
	%	7.9%	18.4%	44.7%	23.7%	5.3%	100.0%

4.6 Analysis of Cable Barrier Performance by Number of Cables

Most of the high-tension cable median barrier installed in Michigan is comprised of a CASS or Gibraltar 3-cable system (280 miles). However, a few installations consist of the Brifen 4-cable system (37 miles). In order to compare the performance of 3-cable and 4-cable systems, especially in their ability to capture or redirect impacting vehicles, cable barrier strike crashes were summarized by the number of cables in each system impacted (3 cables vs. 4 cables) and the results are shown in Table 20. It should be noted that one of the 4-cable installations was installed in 2013, and, as such, the after data for this installation is not available, leaving only 28.5 miles of 4-cable segments for comparison.

Table 20. Summary of Cable Barrier Strikes by Number of Cables

Cable Barrier Crash Type	Cable Barrier Crashes by Type and No. of Cables					
	3 Cables		4 Cables		Total	
	No.	Percent	No.	Percent	No.	Percent
Contained by cable barrier in median	3,116	89.1%	164	93.2%	3,280	89.3%
Struck cable barrier and re-directed back onto travel lanes	275	7.9%	5	2.8%	280	7.6%
Total cable barrier strikes which did not penetrate cable barrier	3,391	96.9%	169	96.0%	3,560	96.9%
Penetrated cable barrier but contained in median	82	2.3%	4	2.3%	86	2.3%
Penetrated cable barrier and entered opposing lanes (struck opposing veh)	4	0.1%	1	0.6%	5	0.1%
Penetrated cable barrier and entered opposing lanes (did not strike opposing veh)	21	0.6%	2	1.1%	23	0.6%
Total Cable Barrier Crashes	3,498	100.0%	176	100.0%	3,674	100.0%

Comparing the effectiveness of 3-cable vs. 4-cable systems in capturing or redirecting errant vehicles, 96.9% of impacting vehicles were captured or redirected by 3-cable systems, compared to 96.0% for 4-cable systems. Although a slightly higher percentage of cable barrier crashes resulted in penetration and cross-median crashes for 4-cable systems, the sample of crashes for 4-cable systems is too small to draw any meaningful conclusions regarding the relative performance of 3-cable vs. 4-cable systems.

4.7 Development of Safety Performance Functions

In order to gain an understanding of factors which affect the frequency of median-related, cross-median, and median barrier strike crashes both before and after installation, a series of safety performance functions (SPFs) were developed. The HSM defines SPFs as "models that are used to estimate the average crash frequency for a facility type with specific base conditions" (*4*). The SPFs developed as a part of this study are based on the empirical before-and-after cable median barrier installation crash data presented in the preceding sections, as well as crash data from comparison segments with other median barrier treatments (no barrier, thrie-beam guardrail, and concrete barrier). SPFs are used to predict the frequency of crashes of a certain type or severity on a specific roadway segment type (or intersection) based on a set of independent variables; usually AADT and certain geometric characteristics.

Because crash frequency is a form of count data (i.e. crash frequency for a certain segment consists only of non-negative integers), the appropriate statistical framework is that of a Poisson or negative binomial regression model (*42*). In the case of traffic crash frequency, the data are often over-dispersed, meaning the variance is greater than the mean. In this case, the negative binomial model is more appropriate because this distribution does not restrict the mean and variance to be equal as the Poisson does (*42*). As such, negative binomial regression modeling was used to develop all SPFs as a part of this study.

4.7.1 Negative binomial regression modeling

In order to identify those factors that influence the frequency of median-involved crashes, a series of negative binomial regression models were estimated. This statistical framework is appropriate for modeling crash frequency because the dependent variable (number of crashes on a given road segment) consists solely of non-negative integers. The negative binomial is a generalized form of the Poisson model. In the Poisson regression model, the probability of road segment i experiencing y_i crashes during one year is given by (*42*):

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!},$$

where $P(y_i)$ is probability of road segment i experiencing y_i crashes during a one year period and λ_i is the Poisson parameter for road segment i, which is equal to the segments expected number of crashes per year, $E[y_i]$. Poisson regression models are estimated by specifying the Poisson parameter λ_i (the expected number of crashes per period) as a function of explanatory variables, the most common functional form being, $\lambda_i = EXP(\beta X_i)$, where X_i is a vector of explanatory variables and β is a vector of estimable parameters (*42*).

The negative binomial model is derived by rewriting the Poisson parameter for each road segment i as $\lambda_i = EXP(\beta X_i + \varepsilon_i)$, where $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as $VAR[y_i] = E[y_i] + \alpha E[y_i]^2$ (*42*). The α term is also known as the over-dispersion parameter, and will be utilized during the before and after Empirical Bayes (EB) analysis in the following sections of this report. The negative binomial models developed as a part of this study utilize a logarithmic (log) link function. As such, each model is offset by the natural log of the segment length (because segments vary in length, the models are normalized to a per mile analysis length). The final model form presents the expected number of crashes per segment per year as:

$\lambda_i = X_{Li}EXP(\beta_0 + \beta_1 X_1 + \beta_i X_i)$,

where λ_i is the expected number of crashes per mile per year on road segment *i*, $X_{Li}$is the length of segment *i* in miles, β_0 is the estimated intercept term, and β_i and X_i are vectors of estimable parameters and explanatory variables, respectively.

The models were developed using SPSS statistical software (*43*). The explanatory variables included in the models were natural log of AADT and the median width in feet. Table 25 presents the results of the SPFs for cable barrier segments in terms of crashes per mile. As expected, crashes of all severities increase with increasing AADT, although PDO/C and B crashes increase at a higher rate after installation of cable barriers. Additionally, crashes of all severities decreased as median width increased (except for K/A crashes in the after period where median width was not a significant predictor). The magnitude of increase or decrease depended on the crash model and analysis period.

4.7.2 Cable median barrier segment SPFs

Safety Performance Functions (SPFs) were developed for cable barrier road segments both before and after installation. Three separate modes were developed for each period, one for PDO- and C-level severity crashes combined, one for B-level severity crashes, and one for K- and A-level severity crashes combined. Because of the small sample of 4-cable installations, the SPFs were developed for all cable median barrier installations combined. The summary statistics for the cable barrier roadway segments were presented previously in Table 7. Table 21 shows a summary of before and after annual target crashes per segment by severity.

Table 21. Before and After Average Annual Target Crashes Per Segment by Severity

Crash Type	Parameter	Average Annual Crash Frequency Per Cable Barrier Segment	
		Before	After
Target PDO/C Crashes	Mean	1.13	2.88
	St.Dev	1.53	3.47
	Min	0.00	0.00
	Max	15.00	26.00
Target B Crashes	Mean	0.16	0.13
	St.Dev	0.43	0.40
	Min	0.00	0.00
	Max	4.00	3.00
Target K/A Crashes	Mean	0.10	0.05
	St.Dev	0.33	0.23
	Min	0.00	0.00
	Max	3.00	2.00

To illustrate the effect of installing cable median barriers, predicted crashes were calculated for the before and after periods using the SPFs from Table 22 for PDO/C, B, and K/A crashes separately. The before and after predicted PDO/C crashes, B crashes, and K/A crashes are shown in Figures 16, 17, and 18, respectively. For the purpose of these examples, the median width was fixed at the averages for all cable barrier segments and directional AADT ranging from 1,000 to 80,000 is shown. From figures 16-18, it can be seen that PDO/C crashes increase significantly after cable barrier installation, B crashes are almost unchanged, and K/A crashes are decreased significantly after cable barrier installation.

Table 22. Before and After SPFs for Cable Barrier Road Segments

Dependent Variable	Parameter	Before Period β	Before Period Std. Error	Before Period P-Value	After Period β	After Period Std. Error	After Period P-Value
Target PDO/C crashes per mile per year	Intercept	-4.739	0.511	<0.001	-5.741	0.524	<0.001
	lnAADT	0.517	0.053	<0.001	0.734	0.053	<0.001
	Median Width	-0.009	0.002	<0.001	-0.011	0.002	<0.001
	Dispersion pmtr.	0.343			0.443		
	Log-Likelihood	-2,983.84			-2,687.81		
	AIC	5,975.68			5,383.61		
Target B crashes per mile per year	Intercept	-7.505	1.176	<0.001	-11.162	1.436	<0.001
	lnAADT	0.648	0.120	<0.001	0.972	0.145	<0.001
	Median Width	-0.017	0.004	<0.001	-0.013	0.006	0.019
	Dispersion pmtr.	0.464			0.094		
	Log-Likelihood	-975.58			-487.40		
	AIC	1,959.17			982.80		
Target K/A crashes per mile per year	Intercept	-8.713	1.368	<0.001	-9.360	2.329	0.000
	lnAADT	0.684	0.141	<0.001	0.608	0.238	0.011
	Median Width	-0.011	0.005	0.040	0.001	0.010	0.924
	Dispersion pmtr.	0.002			0.000		
	Log-Likelihood	-703.00			-255.96		
	AIC	1,414.01			519.92		

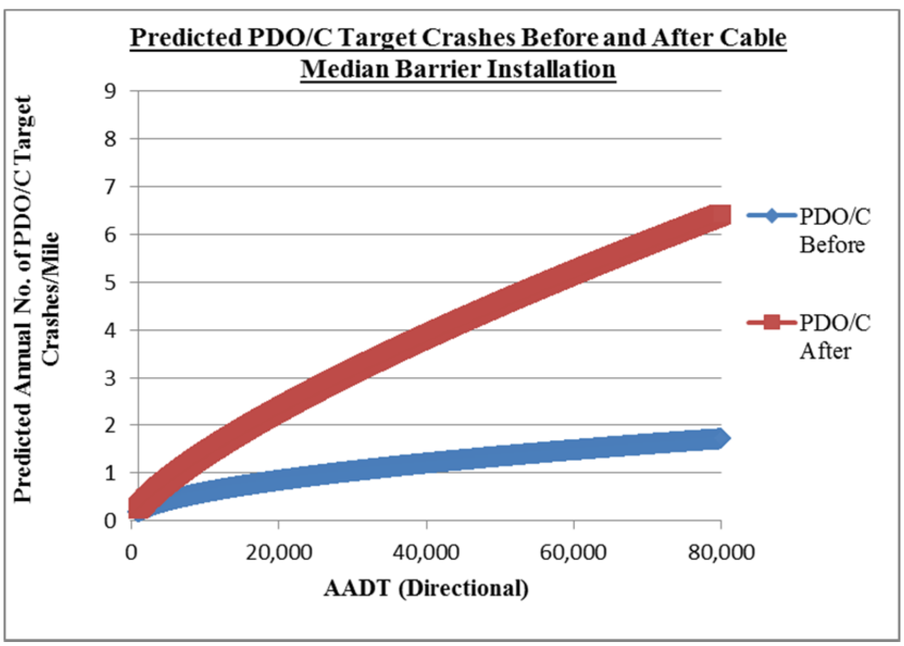

Figure 16. Before and After Cable Barrier SPF Predicted PDO/C Crashes

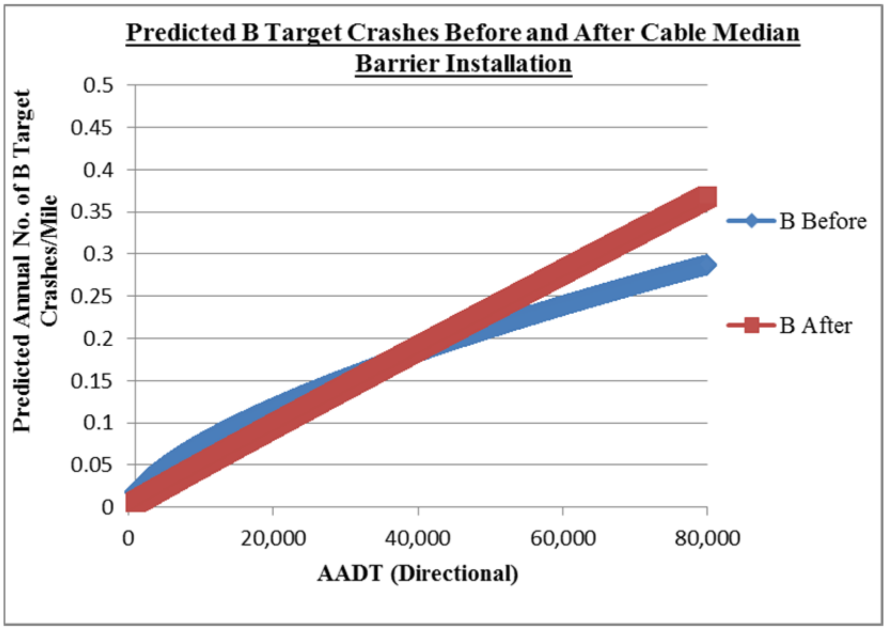

Figure 17. Before and After Cable Barrier SPF Predicted B Crashes

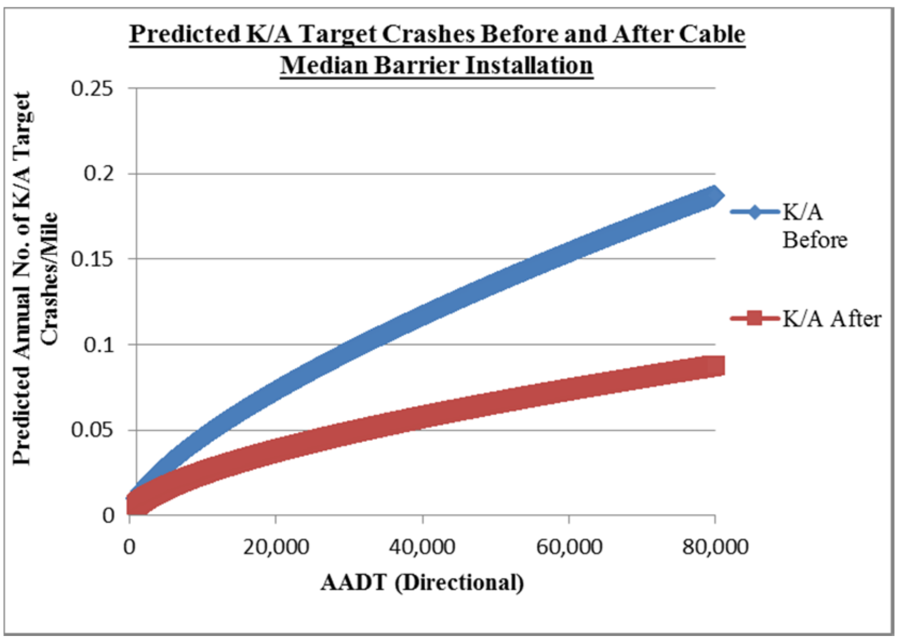

Figure 18. Before and After Cable Barrier SPF Predicted K/A Crashes

4.7.3 No median barrier segment SPFs

Crash data from the control roadway segments with no median barrier and medians less than 100 feet were used to develop SPFs for PDO/C/, B, and K/A crashes separately in a similar manner as cable barrier segment SPFs. Summary statistics for the no barrier segments were shown previously in Table 8 and a summary of average annual target crashes per no barrier segment by severity is shown in Table 23.

The parameter outputs for the no barrier SPFs are shown in Table 24. The results are quite similar to the SPFs developed from before period crash data on cable barrier segments (increased crashes with increasing AADT, and decreased crashes with greater median widths), which was expected. Ultimately, the SPFs developed for the no barrier control segments will be used in the Empirical Bayes analysis presented in subsequent sections of this report for use in predicting expected crashes on cable barrier segments had cable barriers not been installed. To compare the SPFs from no barrier segments to cable median barrier segments before cable barrier installation, predicted crashes were calculated for the before and after periods using the SPFs for PDO/C, B, and K/A crashes in a similar manner to the before and after cable barrier SPFs presented previously.

The no barrier segment and cable median barrier (before installation) predicted PDO/C, B, and K/A crashes are shown in Figures 19, 20, and 21, respectively. For the purpose of these examples, the average value for median width of cable barrier segments was again assumed (similar to the previous example) and directional AADT ranging from 1,000 to 80,000 is shown. It can be seen from Figures 19-21 that the predicted crashes on no barrier segments are slightly less than those on cable barrier segments before installation (especially at higher traffic volumes and for B and K/A crashes). This is not surprising as the segments chosen for cable barrier installation were selected based on their history of severe cross-median crashes, and were generally limited to median widths of 100 feet or less.

Table 23. No Barrier Control Segments Average Annual Target Crashes Per Segment

Crash Type	Parameter	Average Annual Crash Frequency Per
		Before
Target PDO/C Crashes	Mean	0.69
	St.Dev	1.05
	Min	0.00
	Max	13.00
Target B Crashes	Mean	0.08
	St.Dev	0.30
	Min	0.00
	Max	4.00
Target K/A Crashes	Mean	0.05
	St.Dev	0.23
	Min	0.00
	Max	2.00

Table 24. SPFs for No Barrier Control Road Segments

Crash Frequency Model	Parameter	No Barrier Segment SPFs		
		Estimate (β)	Std. Error	P-Value
PDO/C Injury Target Crashes per mile	Intercept	-4.543	0.566	<0.001
	lnAADT	0.533	0.053	<0.001
	Median Width	-0.018	0.002	<0.002
	Dispersion parameter	0.333		
	Log-Likelihood	-2,320.22		
	AIC	4,648.43		
B Injury Target Crashes per mile	Intercept	-6.273	1.461	<0.001
	lnAADT	0.401	0.136	0.003
	Median Width	-0.006	0.005	0.226
	Dispersion parameter	0.499		
	Log-Likelihood	-638.31		
	AIC	1,284.61		
K/A Injury Target Crashes per mile	Intercept	-8.883	1.980	<0.001
	lnAADT	0.667	0.183	<0.001
	Median Width	-0.012	0.006	0.049
	Dispersion parameter	1.015		
	Log-Likelihood	-416.39		
	AIC	840.78		

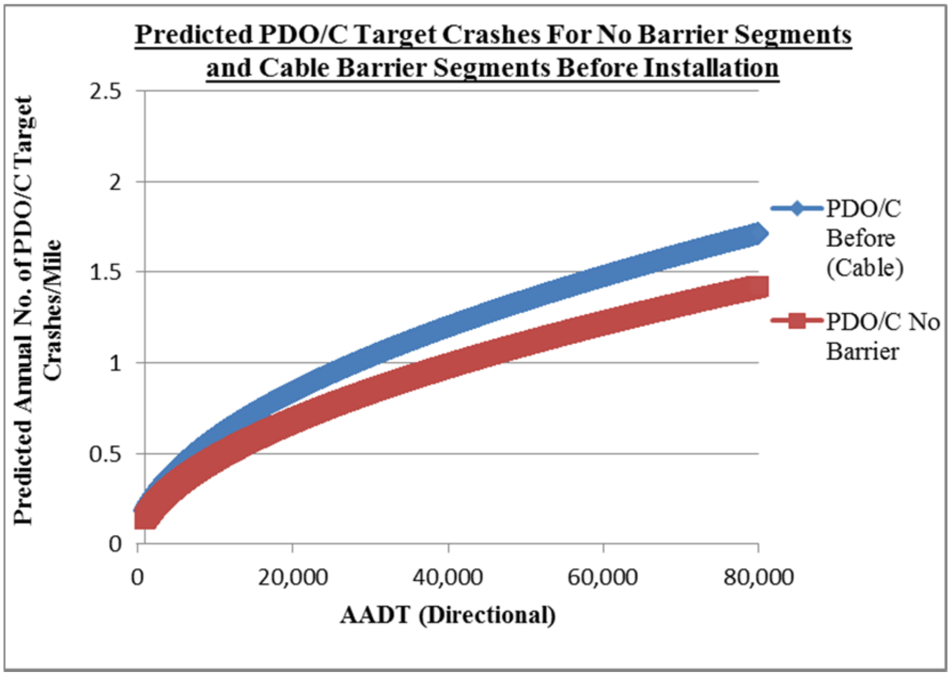

Figure 19. No Barrier and Cable Barrier (before) SPF Predicted PDO/C Crashes

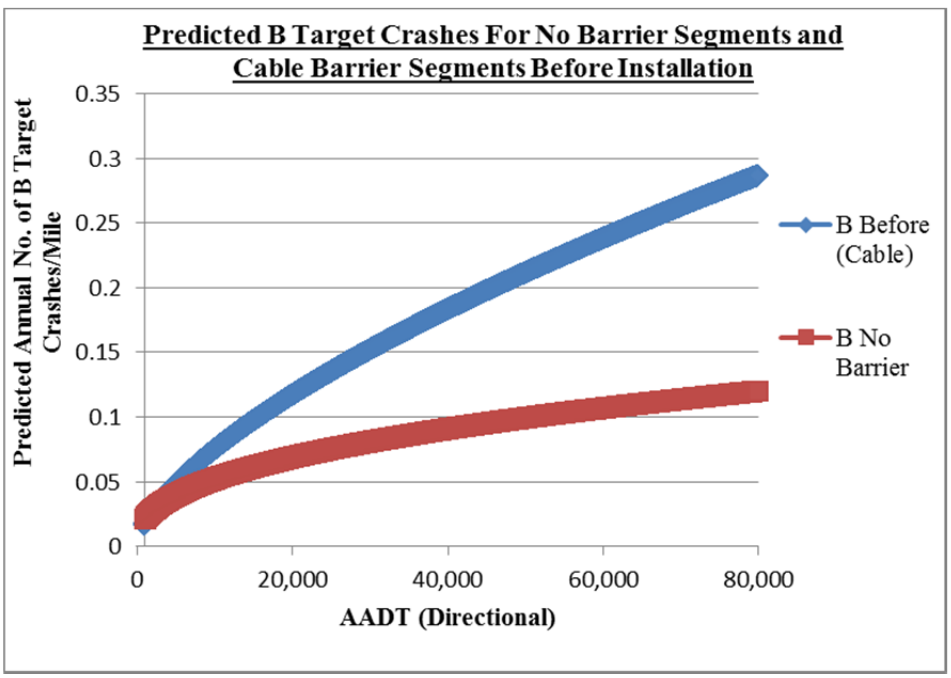

Figure 20. No Barrier and Cable Barrier (before) SPF Predicted B Crashes

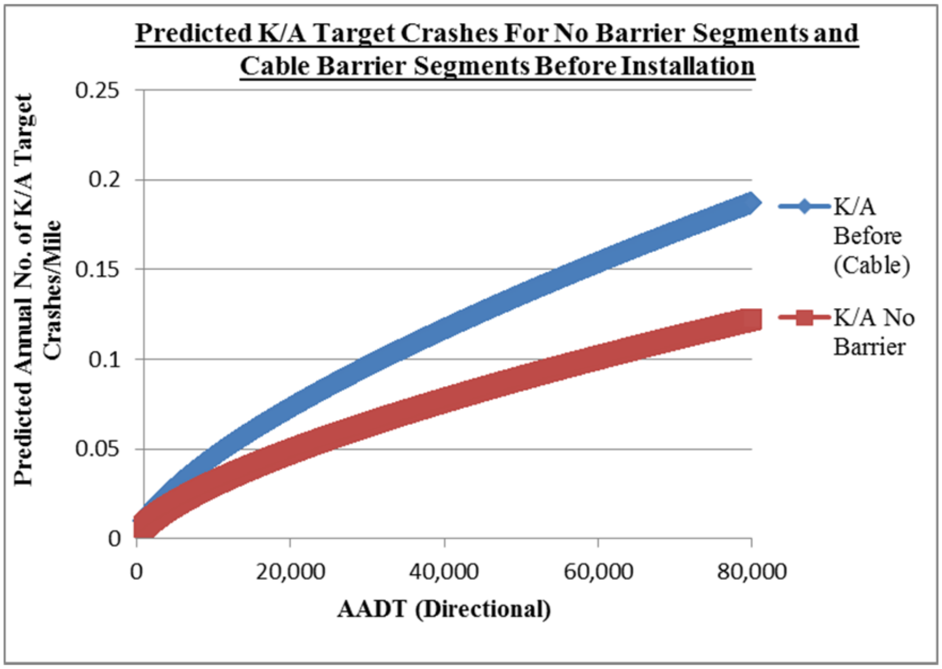

Figure 21. No Barrier and Cable Barrier (before) SPF Predicted K/A Crashes

4.8 Observational Before and After Empirical Bayes (EB) Analysis

As discussed in the literature review section, various state-level assessments have been conducted aimed at determining the effectiveness of cable median barriers in reducing cross-median crashes and improving safety. These studies have generally demonstrated significant reductions in the number of fatal and injury crashes resulting from vehicles crossing over the median (*8; 12; 14; 16; 17; 19; 20; 44; 45*). However, additional research on this issue is warranted for several reasons. First, the frequency of crashes experienced on a specific freeway segment is influenced by various factors, including traffic volumes and various geometric characteristics. If these factors are not taken into account, any changes in crash frequency may tend to be overstated or understated. Secondly, the selection of locations for cable median barrier installation in Michigan was based in part on a history of cross-median crash experience. As such, this selection process is vulnerable to a regression-to-the-mean (RTM) effect whereby the effectiveness of the barrier may be overstated if the potential selectivity bias is not accounted for (*46*).

As the determining factor for installation of cable median barriers has been the history of cross-median crashes, a simple comparison of crashes between the before and after periods may be subject to the RTM effect. Specifically, locations that experience a high number of crashes in a particular year may tend to experience a crash frequency closer to the long-term average in subsequent years as shown in the example in Figure 22. Since the median barrier treatment is generally installed at locations following a "high period", a direct comparison of crashes between the periods before and after installation may tend to overstate the reductions.

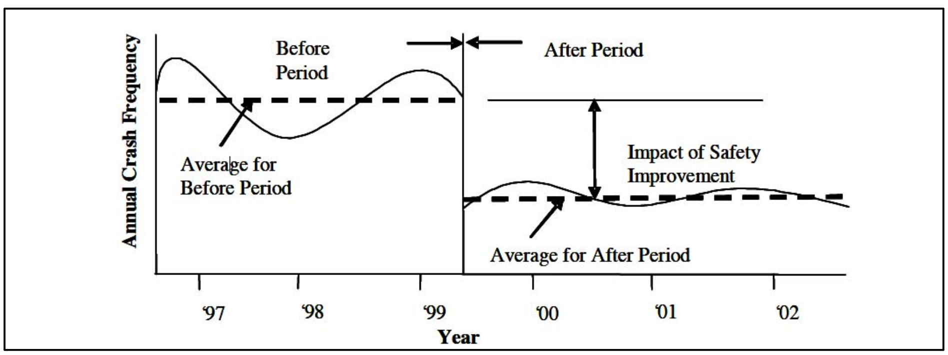

Figure 22. Example of Fluctuation in Crashes Before and After Countermeasure Implementation (*47*)

In such cases, the *Highway Safety Manual* recommends the use of either a before-and-after comparison with data from a control group or the use of the Empirical Bayes (EB) method (*4*). The purpose of either approach is to use historical (i.e., before installation) crash data from locations where the treatment has been applied (i.e., where the cable barriers are installed), as well as a control group of locations where the treatment has not been applied (i.e., the no barrier control segments with medians less than 100 feet). The mean crash rates for both sets of locations are then combined in order to determine the "best" estimate (*4*). In practical terms, the data for the specific sites where the median barrier has been installed is given greater weight as the analysis time period increases (i.e., as more years of data are available) or as the overdispersion parameter increases for the control group SPFs.

4.8.1 Empirical Bayes (EB) statistical methodology

The change in safety performance at a freeway segment or cluster of segments after installation of a cable median barrier is given by:

$$B - A$$

where B is the EB calculated expected number of crashes that would have occurred in the after period without installation of a cable median barrier and A is the observed number of crashes in the after period. The estimate of B is obtained using the EB procedure and is calculated using a combination of the SPF estimated crashes and the observed number of crashes in the before period. The safety performance functions (in the form of negative binomial regression models) which were presented in the previous sections of this dissertation were utilized for the EB analysis. The EB procedure was completed separately for PDO/C, B, and K/A crashes.

The analytical process for the cable barrier before and after EB analysis followed the procedure outlined by Persuad et al. (*48*) which is detailed by Hauer (*49*). First, P_b (the regression estimate of crashes per year during the before period) is estimated for each cable barrier segment based on the SPFs for segments without barriers, as presented in the previous section of this report. Next, the expected annual number of crashes during the before period is estimated as:

$m_b = (k + x_b)/(k/P_b + y_b)$

Where:

m_b= the expected annual number of crashes during the before period

k = SPF regression estimated overdispersion parameter

x_b= observed count of crashes during the before period

P_b= regression estimate of crashes per year during the before period

y_b = length of the before period in years

As stated previously, the EB method accounts for differences in volumes between the before and after periods. To achieve this, the ratio of the annual regression predictions must first be calculated as:

$R = P_a/P_b$

Where R is the ratio of regression predictions for the after and before periods and P_a is the regression estimate of crashes per year during the after period (calculated in the same manner as P_b). The EB estimated expected number of crashes (B) can then be calculated as:

$B = m_b \times R \times y_a$

where y_a is the number of years in the after period. The variance of B can then be calculated by:

$Var(B) = (m_b) \times (R \times y_a)^2/[(k/P) + y_b]$

where $Var(B)$ is the variance of the EB estimated expected number of crashes.

To estimate the effects installing cable median barriers, the index of effectiveness (which is equivalent to a crash modification factor (CMF)) is calculated. An approximate unbiased estimate of the index of effectiveness can be calculated as (*49; 50*):

$$\theta = (\Sigma A/\Sigma B)/\{1 + [Var(\Sigma B)/(\Sigma B)^2]\}$$

where θ is the index of effectiveness. The variance of θ is calculated as (*49; 50*):

$$Var(\theta) = \theta^2\{[Var(\Sigma A)/(\Sigma A)^2] + [Var(\Sigma B)/(\Sigma B)^2]\}/[1 + Var(\Sigma B)/(\Sigma B)^2]^2$$

where $Var(\theta)$ is the variance of the index of effectiveness. It should be noted that $\Sigma Var(A)$ is simply equal to ΣA assuming a Poisson distribution. At the end of the procedure, a value of θ greater than 1.0 indicates the installation of cable median barriers increased crash occurrence (of the type of crash being analyzed), while a value less than 1.0 indicates a reduction in crashes.

4.8.2 Results of the before-after Empirical Bayes (EB) analysis

The EB procedure was performed separately for: (1) PDO/C-injury crashes; (2) B-injury crashes; and (3) K/A-injury crashes. Crashes were aggregated into these severity levels based upon the methods employed by MDOT as part of the safety planning process. The results of the EB analysis are summarized below. For each severity level, the index of effectiveness (θ) is presented, which is the average change in crash frequency between the before and after period. If θ equals one, there is no change in crashes following barrier installation. Values of θ less than one indicate a decrease in crashes while values greater than one indicate an increase in crashes at that specific severity level:

PDO/C Crashes: θ = 2.55 (155 percent increase after cable barrier installation)

Standard deviation (θ) = 0.07

B Crashes: θ = 1.01 (1 percent increase after cable barrier installation)

Standard deviation (θ) = 0.09

K/A Crashes: θ = 0.67 (33 percent decrease after cable barrier installation)

Standard deviation (θ) = 0.09

These results are slightly different compared to the reductions observed using simple before and after crash rates presented in Table 11 of this dissertation (154.7 percent increase in PDO/C, 28.1 percent decrease in B, and 49.6 percent decrease in K/A). It appears the effectiveness of cable barriers was slightly overstated when observing only before and after rates, which indicates some level of selectivity bias and RTM effect. The use of the observational before-and-after EB method provides estimates of cable barrier effectiveness which account for these biases and provide a more accurate estimate of the true effects of installing cable median barrier.

4.9 Cable Barrier Economic Analysis

4.9.1 cable barrier installation and maintenance costs

Table 6 of this report shows the total cost per installation of cable median barrier, along with the length of each installation. These costs were obtained from MDOT's bid letting website and include both engineering and construction costs (costs for 9 of the installations were not available and were estimated based on installation length). The total cost for the 317.2 miles of cable median barrier installed in Michigan was $49,364,071. Average costs were calculated based on the number of cables in each system (i.e., 3 cables vs. 4 cables), as well as a statewide average of all cable barrier systems installed:

- 3-Cable Systems: $156,174.66 per mile ($29.58 per linear foot)
- 4-Cable System: $151,387.76 per mile ($28.67 per linear foot)
- All Cable Barrier Systems: $155,621.49 per mile ($29.47 per linear foot)

The cost of each cable barrier installation can vary based on manufacturer, total installation length and region. For the purpose of this economic analysis, the average cost of all installations in Michigan was utilized ($49,364,071 total; $155,621 per mile). These installation costs are lower than recent analyses from Washington State where the average installation cost for high tension cable barrier with 4 cables was estimated at $46.00 per linear foot ($242,880 per mile) with minor grading, and $71.00 per linear foot ($374,880 per mile) with major grading (*16*). A 2009 Texas evaluation of cable median barrier found the total average cost per mile was $110,000 (*14*). The evaluation also provided a summary of high tension cable barrier costs from several states which is shown in Table 25. It should be noted that comparison of installation costs from other states or from cable barriers installed several years ago are not directly comparable because they do not account for regional differences in construction practices or changes in costs of materials over time.

Table 25. High-Tension Cable Barrier Cost per Mile in Several States (*14*)

State	Cost Per Mile
Alabama	$123,000
Colorado	$66,000
Florida	$80,000
Georgia	$227,000
Illinois	$100,000
Indiana	$80,000
Iowa	$170,000
Minnesota	$100,000
Missouri	$80,000
North Carolina	$230,000
Ohio	$72,000
Oklahoma	$84,000
Utah	$65,000
Washington	$65,000

Cable barrier repair data for the years 2010-2012 were provided by MDOT in the form of crash reports with the cost of cable barrier repair listed on each crash report. There were a total of 1,050 cable barrier repair records obtained and the average repair cost by crash severity was:

- All Crashes: $848.58 per repair
- Injury Crashes: $1,379.80 per repair
- Fatal Crashes: $1,563.89 per repair

Due to the low sample of injury and fatal crash repairs, the average cost for all crashes ($848.58 per crash) was selected for use in the economic analysis as a part of this study. This value is slightly lower but comparable to average cable barrier repair costs recently experienced in Washington State ($922 per repair for high tension cable barrier with 3 cables) (*16*).

4.9.2 Cost of crashes by severity

The economic benefit of installing cable barriers is realized by the reduction in fatal and severe injury crashes. In order to estimate the benefits associated with this reduction, crash costs must be applied at each crash severity level. The National Safety Council (NSC) provides estimates for the pure economic costs of motor vehicle injuries which include wage and productivity losses, medical expenses, administrative expenses, motor vehicle damage, and employers' uninsured costs (*51*). The NSC cautions that these costs "should not be used, however, in computing the dollar value of future benefits due to traffic safety measures because they do not include the value of a person's natural desire to live longer or to protect the quality of one's life". Instead, the NSC advises the use of comprehensive crash costs, which "also include a measure of the value of lost quality of life which was obtained through empirical studies of what people actually pay to reduce their safety and health risks"(*51*). Table 26 shows the average economic and average comprehensive costs of motor vehicle crashes by injury level. For the first four categories, these costs are on a per-injury basis while the PDO crash costs refer to the total costs resulting from a crash with no resultant injury. It should be noted that the estimate of economic costs for PDO crashes is $8,900 (as compared to $2,500 for comprehensive costs) because this cost includes the costs of non-disabling injuries. It is important to note that benefit of installing cable median barriers will be slightly offset by the cost of increased PDO and C-level crashes.

Table 26. Average Crash Costs by Injury Severity (*51*)

Injury Severity	Average Economic Costs ($)	Average Comprehensive Costs ($)
Fatality (K)	1,410,000	4,538,000
Incapacitating Injury (A)	72,700	230,000
Non-incapacitating Injury (B)	23,400	58,700
Possible Injury (C)	13,200	28,000
Property Damage Only (PDO)	8,900	2,500

4.9.3 Benefit/cost analysis

In order to determine the economic impacts of Michigan's cable median barrier program, a benefit/cost (B/C) economic analysis was conducted. The B/C ratio is calculated by dividing the annual benefits (from crash severity reduction) by the annualized costs to install and maintain cable median barriers. It should be noted that the analysis does not include 2013 cable barrier installations because no after crash data was available for such installations, and, as such, the total mileage included in the analysis is 302.9 miles. The benefits were calculated using the expected average annual target crashes (and sum of injuries) for the before period obtained from the EB analysis and the average annual target crashes (and sum of injuries) observed in the after period. The benefits are calculated by multiplying the reduction (or increase) by the cost for each injury level, and the benefits were calculated for both economic and comprehensive costs (as shown in Table 26). It should be noted that the costs for PDO/C crashes and K/A injuries were blended using weighted averages. This is consistent with the methodology used by MDOT for economic analyses of safety initiatives. These blended costs, along with the results of the benefit/cost analysis are shown in Table 27. It should be noted that the total average annual number of crashes does not match the total average annual number of injuries because it is possible to have multiple injuries in one crash.

Table 27. Summary of Benefit/Cost Analysis

Injury Severity	**Expected Annual Crashes/ Injuries After Installation (from EB estimate)**	**Observed Annual Crashes/ Injuries After Installation**	**Blended Economic Costs of Crashes/ Injuries ($)**	**Blended Comprehensive Costs of Crashes/ Injuries ($)**
PDO/C	496.8	1233.4	8,900	6,548
B	77.4	79.4	23,400	58,700
K/A	49.7	30.5	278,878	894,186

Economic Factors	**Annualized Amounts**
Installation Costs	$3,159,789
Maintenance Costs	$1,115,034
Economic Crash Cost Savings (Benefit)	-$1,248,025
Comprehensive Crash Cost Savings (Benefit)	$12,227,714
Benefit/Cost Ratio (Economic Costs)	**-0.29**
Benefit/Cost Ratio (Comprehensive Costs)	**2.86**

In order to annualize the total installation costs, an appropriate discount rate and analysis period must be determined. MDOT recently used a discount rate of 2.7 percent for an economic analysis of their highway program (*52*), however the Federal Highway Administration (FHWA) recommends using discount rates ranging from 3 percent to 7 percent (*53*). Accordingly, a discount rate of 3 percent was adopted for the B/C economic analysis of cable median barriers in Michigan which is close to the 2.7 percent recently used by MDOT but also falls within the FHWA recommended range. A discount rate of 3 percent was also used in a past B/C economic analysis of cable median barriers in Wisconsin (*54*). An analysis period of 20 years was chosen, which is conservative as this is less than the typical service life of a roadway (25-30 years). A 20-year analysis period was also used in the economic analysis of cable median barriers in Wisconsin (*54*).

With a discount rate of 3 percent and an analysis period of 20 years, the capital recovery factor (CRF) which is applied in order annualize the initial costs of installing the cable median barriers was found to be:

CRF (i=3%, n=20 yrs) = 0.0672

Therefore, the annualized cost of installation was ($47,020,662.95 x 0.0672) = $3,159,788.60

The annual maintenance costs were determined by multiplying the total average annual number of crashes in the after period by the average cost per cable barrier repair after a crash:

Annual Maintenance/Repair Costs: 1,314 crashes x $848.58 per repair = $1,115,034.12

The total annual cost for the cable barriers was then found by summing the annualized installation costs and the annual maintenance/repair costs:

Total Annual Cost: $3,159,788.60 + $1,115,034.12 = $4,274,822.60 per year

The B/C Ratios were then calculated:

B/C (Economic Crash Costs) = -$1,248,025/$4,274,821 = **-0.29**

B/C (Comprehensive Crash Costs) = $12,227,714/$4,274,821 = **2.86**

When considering economic crash costs, the B/C ratio was less than 1.0, indicating the reduction in severe injuries did not outweigh the costs of installation, maintenance, and increase in PDO and minor injury crashes. However, when the B/C ratio was calculated assuming comprehensive crash costs as recommended by the NSC for the purposes of a cost-benefit analysis (*51*), the resulting B/C ratio was 2.86-to-1. Ultimately, these results indicate that the installation of cable median barriers has proven cost-effective through the substantial reductions in fatal and incapacitating injuries when comprehensive crash costs are considered (as recommended by the NSC).

4.10 Cable Median Barrier Installation Guidelines

One of the primary emphases of this study was to develop guidelines to assist the Michigan Department of Transportation (MDOT) in the prioritization of candidate locations for the installation of cable median barrier. State agencies generally install median barrier on the bases of: (a) historical data for median-involved crashes; or, (b) segment-specific data for traffic volume and median width. In the latter case, guidelines have been developed such as those presented in the AASHTO Roadside Design Guide (*3*). AASHTO recommends barrier installation on roads with median widths less than 30 feet and an annual average daily traffic (AADT) volume greater than 20,000 vehicles (*3*). AAHSTO also suggests that barrier installation be considered on roads with medians of up to 50 feet and similar traffic volumes. Barrier installation is considered optional on roadways with AADT of less than 20,000 vehicles or with median widths beyond 50 feet.

Recent research suggests that barrier installation may be warranted across a wider range of median configurations (*24*). The results of these studies, coupled with state-specific concerns such as high levels of annual snowfall, motivated the development of guidelines for barrier installation in the state of Michigan. For the purposes of this project, six primary factors were considered as screening criteria for assessing the suitability of high-tension cable as a median barrier alternative:

- Average daily traffic (ADT);
- Median width;
- Number of lanes;
- Lateral offset of the barrier from the travel lane;
- Annual snowfall; and
- Horizontal curvature

Using these criteria, guidelines were developed such that a stepwise procedure can be utilized to:

1. Estimate the expected annual number of target (i.e., median-involved) crashes for a given freeway segment where no barrier currently exists;
2. Estimate the expected annual number of target crashes following cable barrier installation; and
3. Adjust these estimates on the basis of site-specific factors.

4.10.1 Predictive models for segments before cable barrier installation

The initial step in guideline development was to estimate a series of simple regression equations (i.e., safety performance functions, or SPFs) that can be used to predict the expected number of target (i.e., median-related) crashes for a given freeway segment using ADT and median width as predictor variables. Other variables such as snowfall and number of lanes did not have significant or consistent effects on target crash frequency for segments with no barrier; consequently, these variables are not included in the SPFs. The SPFs were developed using negative binomial regression modeling, details of which can be found in Appendix A of this report.

The safety analyses presented previously showed fatal (K-level) and incapacitating (A-level) injury crashes to decrease after cable barrier installation, property damage only (PDO) and possible (C-level) injury crashes to increase, and non-incapacitating (B-level) injuries to be relatively unaffected. Consequently, separate predictive models were developed for estimating K/A-level injury crashes and PDO/C-level injury crashes before cable barrier installation. The models were developed utilizing data from all freeway segments with no median barrier and median width less than 100 feet throughout the state, and therefore could be applied to similar locations statewide. The models are presented here:

$$Crashes_{K/A\ BEFORE} = ADT^{0.667} exp(-8.883 - 0.012 \times WIDTH)$$

$$Crashes_{PDO/C\ BEFORE} = ADT^{0.533} exp(-4.543 - 0.018 \times WIDTH)$$

where:

$Crashes_{PDO/C\ BEFORE}$ = annual number of PDO and C-injury crashes per mile per year before cable barrier installation;

$Crashes_{K/A\ BEFORE}$ = annual number of K/A-injury crashes per mile per year before cable barrier installation;

ADT = directional average daily traffic; and

WIDTH = median width (feet).

Using these models, the expected number of crashes for a given freeway segment where no barrier is currently installed can be estimated. Figure 23 provides plots illustrating how the number of crashes (per mile per year) changes with respect to ADT and median width. The model output, which will be in terms of crashes per mile per year, can be multiplied by segment length to arrive at the expected annual number of crashes for a segment of any length. This estimate provides a baseline comparison that can be used to assess the suitability of cable median barrier for installation on a specific road segment.

4.10.2 Predictive models for segments after cable barrier installation

Similar analyses were conducted in order to estimate the expected number of crashes that would occur if cable barrier were installed at a given location. For the case of K/A-level injury crashes, ADT was found to significantly influence the rate of serious or fatal injuries, but median width was not. This finding is supported intuitively as cable barriers tend to reduce the opportunity for cross-median collisions with vehicles traveling in the opposite direction. The cable barrier systems were 96.9 percent effective in preventing penetrations thereby drastically reducing the opportunity for cross-median crashes, and this effectiveness was not shown to vary across segments with different median widths. Consequently, the expected number of K/A-injury

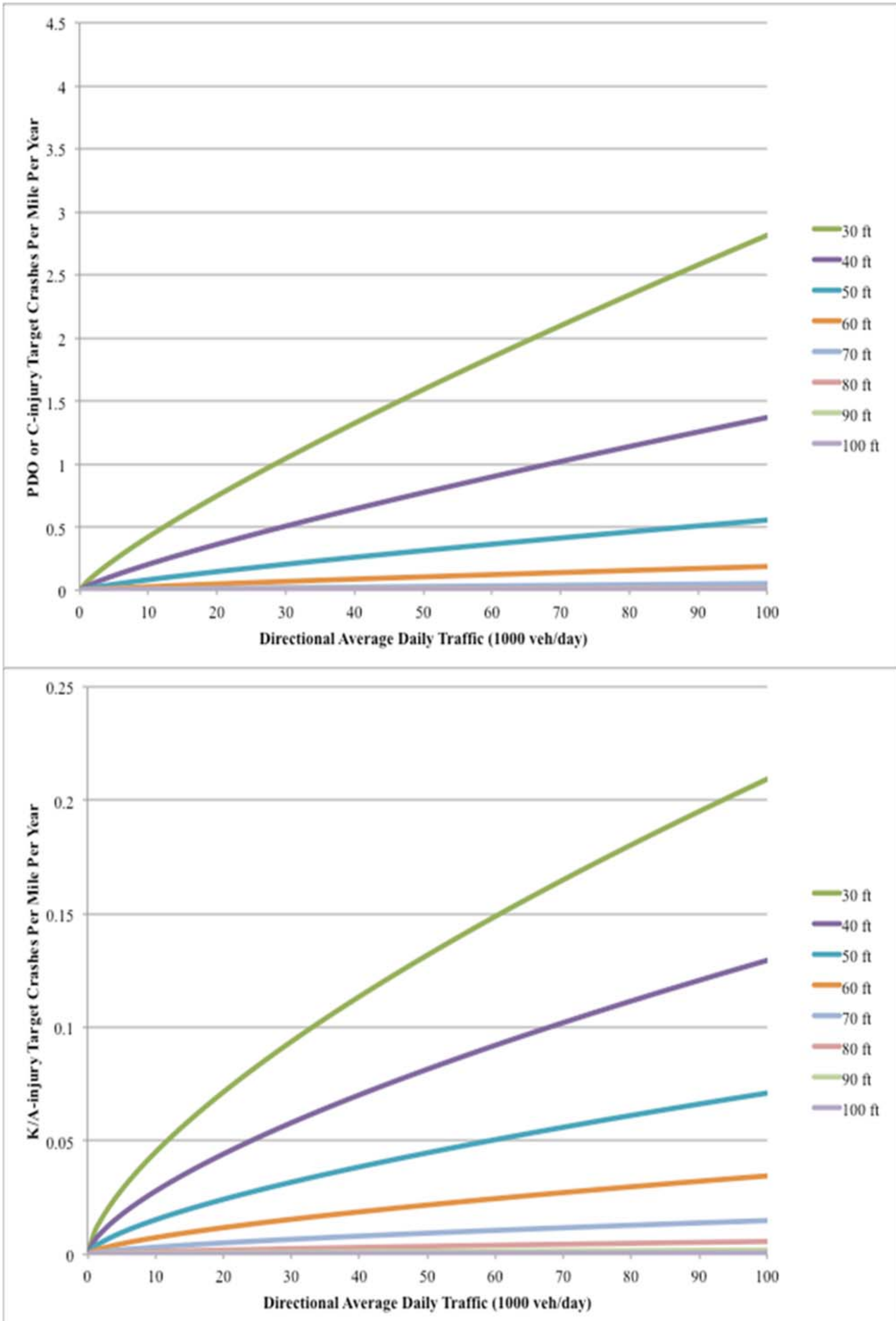

Figure 23. Predicted Number of Target Crashes by Severity Level Based upon Directional Average Daily Traffic and Median Width

crashes per mile per year can be estimated using the following equation, where all variables are as previously defined:

$$Crashes_{K/A\ AFTER} = ADT^{0.613} exp(-9.343).$$

Where:

$Crashes_{K/A\ AFTER}$ = annual number of K/A-injury crashes per mile per year after cable barrier installation;

ADT = directional average daily traffic.

For PDO- and C-level injuries, cable barrier installation was found to increase crashes as detailed previously. However, the rate of this increase was found to vary based upon various site-specific factors. Consequently, the following two-step approach is recommended to estimate the expected number of crashes for the post-installation period:

1. Estimate the expected number of crashes for baseline conditions using ADT and median width as predictors; and
2. Adjust these baseline conditions to account for the effects of number of lanes, lateral clearance to the barrier, annual snowfall, and horizontal curvature.

The baseline SPF for PDO/C-injury crashes at locations where cable barrier has been installed is as follows:

$$Crashes_{PDO/C\ AFTER} = ADT^{0.734} exp(-5.741 - 0.011 \times WIDTH)$$

where:

$Crashes_{PDO/C\ AFTER}$ = annual number of PDO and C-injury crashes per mile per year after cable barrier installation;

ADT = directional average daily traffic; and

$WIDTH$ = median width (feet).

Entering ADT and median width into this equation will result in the baseline prediction of crashes per mile per year. These baseline conditions are as follows:

- Number of lanes = 2;
- Lateral clearance = more than 20 ft; and
- Annual snowfall = less than 40 inches.
- Horizontal curvature = No curve (or curve with radius greater than 3,500 feet)

If any of these conditions are not met, the values in Table 28 should be used to adjust the baseline prediction for these characteristics. These values were derived from safety performance functions (SPFs) that were estimated in a similar manner to those presented previously in this report.

Table 28. PDO/C-injury SPF Results for Cable Barrier Segments Based on Site Characteristics.

Criterion	Values	Adjustment (i.e., Percent Change in PDO/C Crashes)
Number of lanes	2 lanes	Baseline
	3 or more lanes	39.7% decrease
Lateral clearance	More than 20.0 ft	Baseline
	10.0 to 20.0 ft	58.2% increase
	Less than 10.0 ft	144.2% increase
Snowfall	0.0 to 39.9 inches	Baseline
	40.0 to 49.9 inches	27.3% increase
	50.0 to 69.9 inches	70.2% increase
	70.0 inches or above	122.3% increase
Horizontal Curvature	Tangent Section or Curve w/ Radius >	Baseline
	Curve w/ radius 2,500-3500 feet	70.2% increase
	Curve w/ radius <2,500 feet	104.2% increase

4.10.3 Effects of number of lanes

The number of lanes on a roadway segment was found to be a significant predictor of PDO/C crash frequency after cable barrier installation. Roads with 3 or more lanes were estimated to experience 40.7 percent fewer PDO/C crashes after installation as compared with 2-lane road segments. This may be attributable to the extra space that is available for vehicles to avoid a potential secondary collision if a vehicle is directed back into or near the travel lane after striking the cable barrier.

4.10.4 Effects of Cable Barrier Lateral Offset

The placement of the cable barrier with respect to the edge of the travel lane was also found to significantly impact the frequency of target crashes experienced after installation. This is expected as the nearer a barrier is to the travel lanes, the more likely a vehicle is to strike the barrier, increasing both single-vehicle crashes and multi-vehicle crashes involving vehicles redirected back onto the roadway. As part of the safety analysis, the effects of offset distances were examined in one-foot increments to identify any trends in safety performance. The results, illustrated in Figure 24 show that target crash frequency plateaued at offset distances of more than 20 feet from the leftmost travel lane.

At offset distances of 10 to 20 feet, PDO/C crashes increased by 59.5 percent on average, while offsets of less than 10 feet increased crashes by 144.5 percent relative to the baseline case (more than 20 feet). It is important to note that barrier installation costs can be significantly affected by site conditions. While some of the less severe crashes could be avoided by placing the barrier in the center of the median, this may be impractical due to soil conditions, slope grade, drainage characteristics, or the increased installation and maintenance costs. Consequently, there are a variety of competing factors that should be considered when determining the optimal barrier placement location.

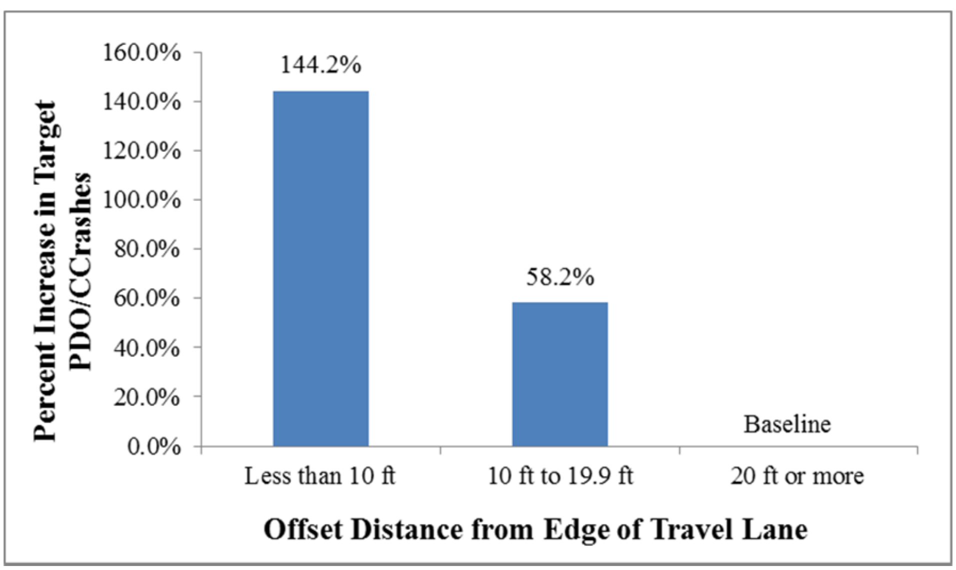

Figure 24. Effects of Offset Distance on Target PDO/C Crash Frequency

4.10.5 Snowfall impacts

In addition to the site-specific factors noted previously, regional weather patterns are a unique concern in Michigan as the state experiences intense snowfall in several areas of the state. Similar to the procedure that was utilized to assess offset distance, target crash trends were examined with respect to annual snowfall totals in 10-inch increments. Those increments that exhibited similar trends were then combined. Figure 25 shows that target PDO/C crashes increased by greater amounts in those areas of the state that experienced higher levels of snowfall. Compared to low snow regions (defined as those areas experiencing less than 40 inches per year), PDO/C crashes were 27.6 percent greater in areas with 40 to 49.9 inches per year, 69.4 percent greater in areas with 50 to 69.9 inches per year, and 114.3 percent greater in areas experiencing 70 inches or more of snowfall per year.

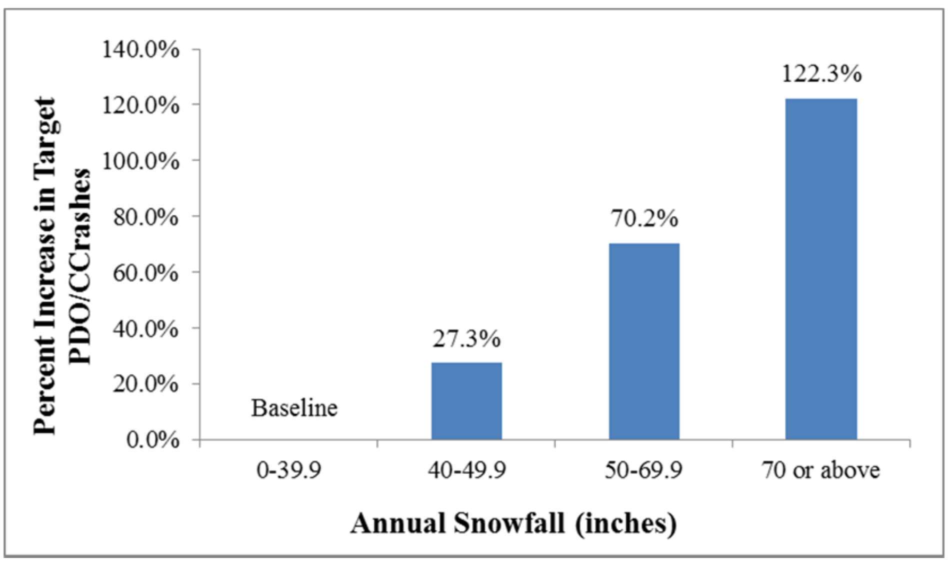

Figure 25. Effects of Snowfall on Target PDO/C Crash Frequency

4.10.6 Effects of horizontal curvature

The presence of a horizontal curve with a radius less than 3,500 feet was found to significantly impact the frequency of target PDO/C crashes experienced after installation. This is expected as vehicles have a higher propensity to lose control when traversing horizontal curves. As part of the analysis, the effects of horizontal curve radius were examined in 500 foot increments. Ultimately, it was determined that curves with radii of less than 2,500 feet significantly increase the frequency of PDO/C crashes. Curves with radii between 2,500 and 3,500 feet also increase PDO/C crashes, but with a lesser magnitude than sharper curves with radii less than 2,500 feet. Curves with radii greater than 3,500 feet did not exhibit significant differences in crash patterns than tangent sections of roadway. Figure 26 shows the increase in PDO/C crashes with decreasing horizontal curve radius. These results are similar to those from *NCHRP Report 790: Factors Contributing to Median-Encroachments and Cross-Median Crashes* (*31*) which found increased median-related crash rates on horizontal curves with radii less than 3000 feet.

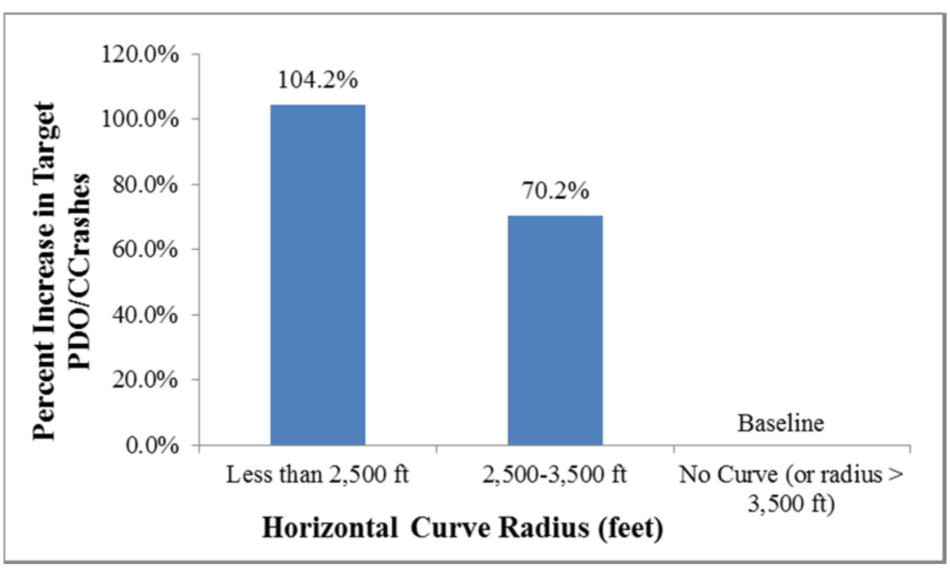

Figure 26. Effects of Horizontal Curvature on Target PDO/C Crash Frequency

4.10.7 Guideline use

Collectively, the information presented in this chapter provides general guidance as to the relationships between traffic crashes and average daily traffic, median width, number of lanes, offset distance, and snowfall at locations where cable median barrier may be installed. These analytical tools can be used to estimate the annual number of crashes at candidate locations for barrier installation, as well as to estimate the percent reduction in K/A crashes (and increase in PDO/C crashes) that would occur if cable barrier were installed.

It is important to note that safety impacts are merely one factor that should be considered when installing cable barrier. These guidelines and supporting information should be combined with the results of a detailed economic analysis and site assessment that considers additional factors including terrain and soil conditions, median slope, horizontal and vertical alignment, drainage characteristics, and other factors.

CHAPTER 5

COMPARISON WITH OTHER BARRIER TYPES

5.1 Comparison of Crash Outcomes between Different Median Barrier Types

In order to compare the relative effectiveness of cable median barriers with other median barrier treatments, an in-depth crash analysis was conducted for both thrie-beam median guardrail and concrete median barriers to serve as comparison segments. Figure 27 shows an image of all three median barrier treatment types. The details of the identification and crash review for the thrie-beam guardrail and concrete barrier segments were described in Chapter 3 of this dissertation. All target crashes for both comparison barrier types were analyzed in a similar manner as the cable barrier segments. Crashes which involved a vehicle striking either the thrie-beam guardrail or concrete barrier were also identified. These crashes were summarized by crash severity and crash outcome scenario (contained/penetrated/re-directed). Table 29 presents a summary of thrie-beam median guardrail crashes and Table 30 presents a summary of concrete median barrier crashes.

Figure 27. Median Barrier Treatment Options Used on Michigan Freeways

Thrie-beam guardrail performance is similar to that of cable barrier in terms of containing vehicles. Cable barriers prevented penetration in 96.9 percent of crashes involving a barrier strike while thrie-beam guardrail prevented penetration in 99.2 percent of crashes involving a barrier strike. The main difference in performance is that more vehicles were re-directed back onto the roadway after striking thrie-mean guardrail as compared to cable barrier (15.8 percent for thrie-beam vs. 7.6 percent for cable barrier). Overall, 0.5 percent of vehicles which struck thrie-beam median guardrail penetrated the barrier and entered opposing travel lanes compared with 0.7 percent for cable median barriers. A study of w-beam median guardrail in Florida found 1.7 percent of vehicles which struck w-beam median guardrail penetrated the barrier and entered opposing travel lanes (*55*), indicating both thrie-beam guardrail and cable barrier in Michigan outperform the w-beam guardrail analyzed in Florida.

Overall, concrete barriers were most successful in terms of preventing penetrations; only 0.1 percent of vehicles that struck a concrete barrier penetrated the barrier. However, a large percentage of concrete barrier crashes resulted in vehicles being re-directed back onto the travel lanes (31.0 percent), compared with cable barrier or thrie-beam guardrail. The higher percentage of re-directions back onto travel lanes for thrie-beam and concrete barrier as compared to cable barrier inherently raises the possibility of secondary collisions with other vehicles. This trend can be seen in Table 31 which shows the percentage of single- vs. multi-vehicle crashes for cable barrier strike, thrie-beam strike, and concrete barrier strike crashes. The percentage of multi-vehicle crashes was 14.7 percent for cable barrier segments as compared to 21.1 percent and 22.6 percent for thrie-beam guardrail segments and concrete barrier segments, respectively.

Table 29. Summary of Thrie-Beam Strikes by Severity and Crash Outcome Scenario

Thrie-Beam Guardrail Crash Outcome Scenario		Thrie-Beam Median Guardrail Strikes by Type and Severity						Percent of Total Thrie-Beam Crashes
		PDO	C	B	A	K	TOTAL	
Contained by thrie-beam in median	No.	1,481	319	109	45	6	1,959	83.4%
	%	75.6%	16.3%	5.6%	2.2%	0.3%	75.6%	
Struck thrie-beam and re-directed back onto travel lanes	No.	221	92	33	20	4	370	15.8%
	%	59.7%	24.9%	8.9%	5.4%	1.1%	100.0%	
Total thrie-beam strikes which did not penetrate thrie-beam	No.	1,702	411	142	64	10	2,329	99.2%
	%	73.1%	17.6%	6.1%	2.7%	0.4%	100.0%	
Penetrated thrie-beam but contained in median	No.	4	2	0	0	0	6	0.3%
	%	66.7%	33.3%	0.0%	0.0%	0.0%	100.0%	
Penetrated thrie-beam and entered opposing lanes	No.	4	0	4	5	0	13	0.5%
	%	30.8%	0.0%	30.8%	38.5%	0.0%	100.0%	
Total thrie-beam crashes	No.	1,710	413	146	69	10	2,348	100.0%
	%	72.9%	17.6%	6.2%	2.9%	0.4%	100.0%	

In terms of injury severity distributions among barrier strike crashes, cable barrier crashes exhibited the lowest combined percentages of fatal and incapacitating injuries (1.1 percent), followed by concrete barriers (1.9 percent), and thrie-beam guardrail (3.3 percent). Figure 28 shows a comparison of the injury distributions for cable barrier, thrie-beam guardrail, and concrete median barrier. It should be noted that thrie-beam guardrail and concrete median barrier are generally installed in locations with different traffic characteristics and different roadway geometries than locations best suited for cable barrier. For example, cable barrier is not installed on very narrow medians because there needs to be enough space to accommodate the larger deflections associated with cable barrier strikes. Overall, cable median barriers installed in Michigan have been quite effective and are comparable to thrie-beam guardrail and concrete barrier in preventing cross-median crashes; and outperform thrie-beam guardrail and concrete barrier in terms of preventing re-direction of vehicles back onto travel lanes.

Table 30. Summary of Concrete Barrier Strikes by Severity and Crash Outcome Scenario

Concrete Barrier Crash Outcome Scenario		Concrete Median Barrier Strikes by Type and Severity						Percent of Total Concrete Barrier Crashes
		PDO	C	B	A	K	TOTAL	
Contained by concrete barrier in median	No.	5,892	1,656	546	105	13	8,212	68.9%
	%	71.7%	20.2%	6.6%	1.3%	0.2%	100.0%	
Struck concrete barrier and re-directed back onto travel lanes	No.	2,288	940	356	102	16	3,702	31.0%
	%	61.8%	25.4%	9.6%	2.8%	0.4%	100.0%	
Total concrete barrier strikes which did not penetrate concrete barrier	No.	8,180	2,596	902	207	29	11,914	99.9%
	%	68.7%	21.8%	7.6%	1.7%	0.2%	100.0%	
Penetrated concrete barrier but contained in median	No.	0	1	1	0	0	2	0.0%
	%	0.0%	50.0%	50.0%	0.0%	0.0%	100.0%	
Penetrated concrete barrier and entered opposing lanes	No.	6	1	2	0	0	9	0.1%
	%	66.7%	11.1%	22.2%	0.0%	0.0%	100.0%	
Total concrete barrier crashes	No.	8,186	2,598	905	207	29	11,925	100.0%
	%	68.6%	21.8%	7.6%	1.7%	0.2%	100.0%	

Table 31. Percent of Single- vs. Multi-Vehicle Target Crashes by Barrier Type Segment

Crash Type	Cable Barrier Segments		Thrie-Beam Guardrail Segments		Concrete Barrier Segments	
	No.	%	No.	%	No.	%
Single-Vehicle	3,487	85.3%	2,115	78.9%	9,259	77.4%
Multi-Vehicle	603	14.7%	565	21.1%	2,698	22.6%
Total	4,090	100.0%	2,680	100.0%	11,957	100.0%

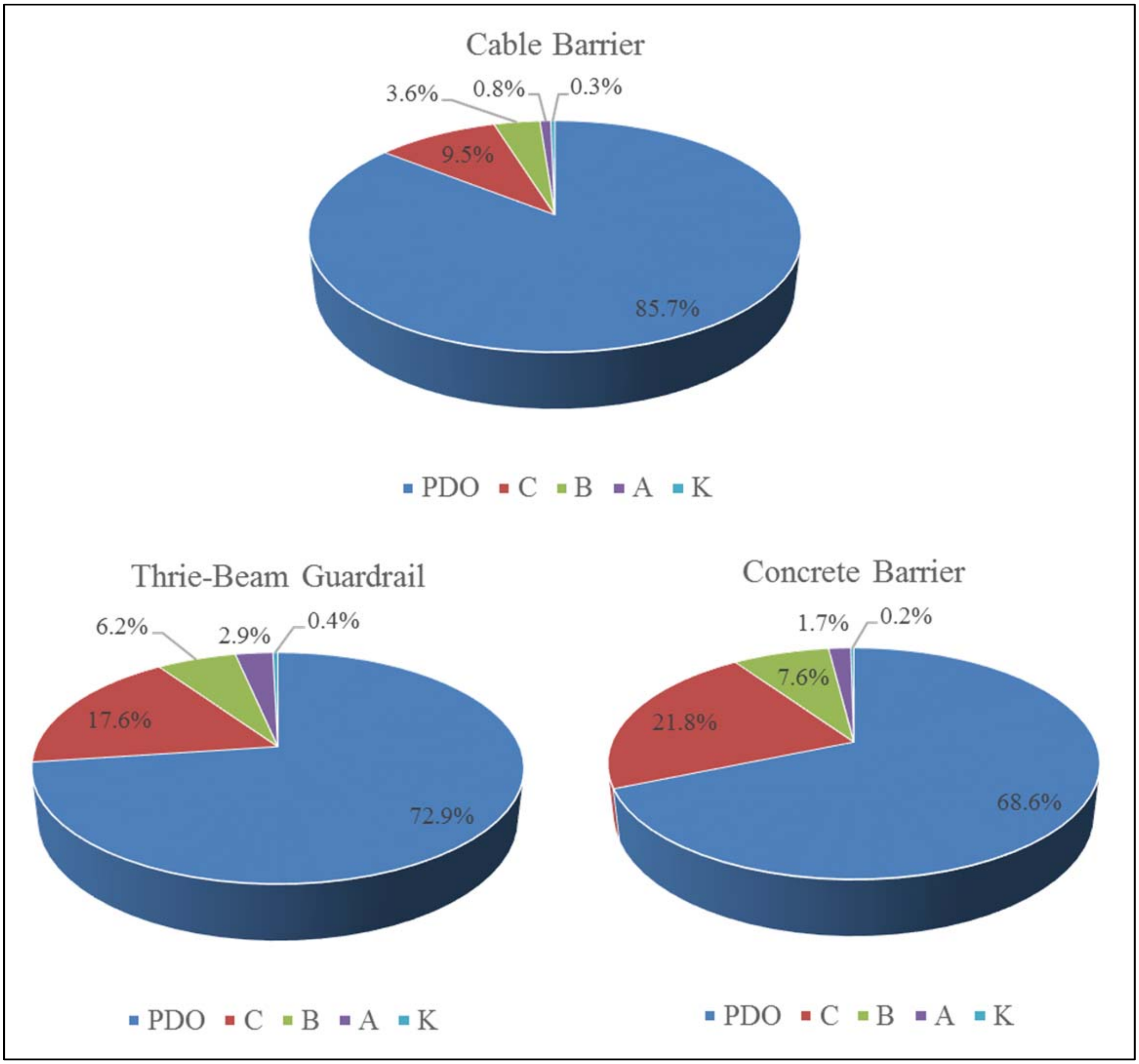

Figure 28. Comparison of Severity Distributions by Median Barrier Type

The next three sections of this dissertation present statistical analyses of crash frequency, crash severity, and barrier strike outcomes between all three barrier types (cable barrier, thrie-beam guardrail, and concrete barrier). Table 32 presents a summary of crash data for all three barrier types which are utilized for the subsequent statistical analyses.

Table 32. Summary of Target Crash Characteristics for All Barrier Types

Crash Characteristic		Cable Barrier Segments (after installation)		Thrie-Beam Guardrail Segments		Concrete Barrier Segments	
		No.	%	No.	%	No.	%
Crash Severity	K	13	0.3%	11	0.4%	30	0.3%
	A	54	1.3%	84	3.1%	208	1.7%
	B	169	4.1%	178	6.6%	909	7.6%
	C	412	10.1%	474	17.7%	2,600	21.7%
	PDO	3,442	84.2%	1,933	72.1%	8,210	68.7%
Median Crash Outcome	Did not strike barrier	417	10.2%	332	12.4%	32	0.3%
	Struck barrier, contained in median	3,277	80.1%	1,959	73.1%	8,212	68.7%
	Struck and penetrated barrier	116	2.8%	19	0.7%	11	0.1%
	Struck barrier and re-directed onto roadway	280	6.8%	370	13.8%	3,702	31.0%
Rollover Crash	Rollover Crash	263	6.4%	170	6.3%	513	4.3%
	Non-Rollover Crash	3,827	93.6%	2,510	93.7%	11,444	95.7%
Vehicle Type (first to strike barrier or enter median)	Passenger Veh.	3,235	79.1%	2,142	79.9%	10,048	84.0%
	Van	184	4.5%	80	3.0%	340	2.8%
	Pickup Truck	466	11.4%	331	12.4%	1,071	9.0%
	Motorcycle	9	0.2%	7	0.3%	34	0.3%
	Small Truck (<10,000 lbs)	60	1.5%	68	2.5%	277	2.3%
	Large Truck (>10,000 lbs)	129	3.2%	45	1.7%	143	1.2%
	Other (large equipment)	1	0.0%	2	0.1%	6	0.1%
	Unknown	6	0.1%	5	0.2%	38	0.3%
Pavement Condition	Dry	1,243	30.4%	962	35.9%	3,854	32.2%
	Wet/Icy	2,837	69.4%	1,694	63.2%	8,004	66.9%
	Unknown	10	0.2%	24	0.9%	99	0.8%
Lighting Condition	Daylight	2,169	53.0%	1,476	55.1%	6,438	53.8%
	Dark/Dawn/Dusk	1,915	46.8%	1,192	44.5%	5,439	45.5%
	Unknown	6	0.1%	12	0.4%	80	0.7%
Day of Week	Weekday (Mon-Fri)	2,837	69.4%	1,818	67.8%	8,076	67.5%
	Weekend (Sat-Sun)	1,253	30.6%	862	32.2%	3,881	32.5%
Single vs. Multi-veh	Single Veh. Crashes	3,487	85.3%	2,115	78.9%	9,259	77.4%
	Multi-Veh. Crashes	603	14.7%	565	21.1%	2,698	22.6%
Total Target Crashes		4,090	100.0%	2,680	100.0%	11,957	100.0%

5.2 Development of SPF for All Barrier Types

In order to analyze factors affecting median crash frequency, an SPF (in the form of a negative binomial regression model) was estimated which incorporated all three median barrier types (cable barrier, thrie-beam guardrail and concrete barrier) and the results of the model are shown in Table 33. SPFs developed specifically for cable barrier segments and details of the negative binomial regression methodology were previously presented in Chapter 4 of this dissertation. Similar to the cable-specific SPFs, traffic exposure is accounted for by including the natural log of the AADT, and the model was offset by the natural log of the segment length so the results of the crash prediction model are in terms of annual crashes per mile. During model development, total target crashes (median crashes) served as the dependent variable (as opposed to the separate injury-level SPFs developed specifically for cable barriers in Chapter 4). Several independent variables were found not to significantly affect median crash frequency such as lane widths and pavement condition, and these variables are not included in the final model. When interpreting the model results, a positive coefficient indicates that parameter tends to increase median crashes, while a negative coefficient indicates that parameter is associated with fewer median crashes.

In order to account for possible interactions between different barrier types and other independent variables, a series of interaction terms were developed (e.g. snowfall on cable barrier segments) and assessed. In cases where there were significant differences in the effects of independent variables on segments with different barrier types, the interaction variables were retained in the final model. In cases where the effects of a certain variable did not significantly differ between barrier types, that variable was retained in the final model and the effects are assumed to be constant across all three barrier types. It should be noted that the barrier type indicator variables are separated into five discrete categories (cable barrier with lateral clearance <10 ft., cable barrier with lateral clearance 10-20 ft., cable barrier with lateral clearance >20 ft., thrie beam guardrail, and concrete barrier), and cable barrier with lateral clearance >20 ft. is excluded as the reference barrier type variable. Additionally, the horizontal curve variables have been converted from radius in feet to degree of curvature (using the standard conversion formula: degree of curvature = 5729.6/radius in feet (*56*)) and these variables are included in continuous form in the final model as they were shown to provide an improved model fit as compared to the categorical curve radius variables.

Table 33. Results of Crash Frequency Model (SPF) for All Barrier Types

Parameter	**β**	**S.E.**	**p-value**
Intercept	-10.239	0.360	<0.001
Cable barrier w/ lateral offset < 10 ft.	0.896	0.143	<0.001
Cable barrier w/ lateral offset 10-20 ft.	0.443	0.051	<0.001
Concrete median barrier	1.059	0.122	<0.001
Thrie beam median guardrail	0.553	0.147	<0.001
LnAADT	1.001	0.031	<0.001
Annual snow-cable barrier (in.)	0.019	0.002	<0.001
Annual snow-concrete barrier (in.)	0.007	0.001	<0.001
Annual snow-thrie beam guardrail (in.)	0.014	0.003	<0.001
Degree of curvature-cable barrier	0.198	0.044	<0.001
Degree of curvature-concrete barrier	0.234	0.011	<0.001
Degree of curvature-thrie beam guardrail	0.201	0.040	<0.001
Two lanes-cable barrier	0.452	0.074	<0.001
Two lanes-concrete barrier	0.208	0.046	<0.001
Two lanes-thrie beam guardrail	0.260	0.068	<0.001
Speed Limit 55 mph	0.201	0.040	<0.001
Median width (ft.)	-0.004	0.001	0.004
Left shoulder width (ft.)	-0.021	0.007	0.001
Overdispersion	0.304	0.012	<0.001
Restricted Log Likelihood	-12,165.45		
Log Likelihood at Convergence	-11,388.19		

With respect to median barrier type, concrete barrier segments tend to experience the highest frequency of target crashes, followed by cable barrier segments with lateral clearance of less than 10 ft.., while cable barrier segments with lateral clearance of greater than 20 ft. experienced the lowest frequency of target crashes, all other factors being equal. Roadway segments with higher average annual snowfalls were found to experience a higher frequency of median crashes among segments with all three median barrier types. This is expected as motorists are more likely lose control and run off the road during adverse (snowy and icy) road conditions. It should be noted that the effect of snowfall is most pronounced on cable barrier segments, and Figure 29 shows a graphical representation of the expected change in crashes (i.e. percent increase in target crashes) associated with different levels of snowfall among all three barrier types.

Roadway segments with higher degrees of horizontal curvature (i.e. sharper curves) tended to experience higher frequencies of median crashes than tangent segments. Again, this is an expected result as drivers may be more likely to lose control while navigating horizontal curves. Figure 30 shows a graphical representation of crash of the expected change in crashes associated with different degrees of horizontal curvature on among segments with all three barrier types On roadway segments with all barrier types, segments with two directional travel lanes (as opposed to three or more) were associated with higher frequencies of median crashes. This may be attributable to the extra width of roadway associated with more lanes that is available for possible recovery in the event a motorist losses control. Based on the model results, the presence of two lanes (as opposed to three or more) was found to be associated with 57.1%, 23.1%, and 29.7% increases in total target crashes on cable barrier, concrete, and thrie beam segments, respectively.

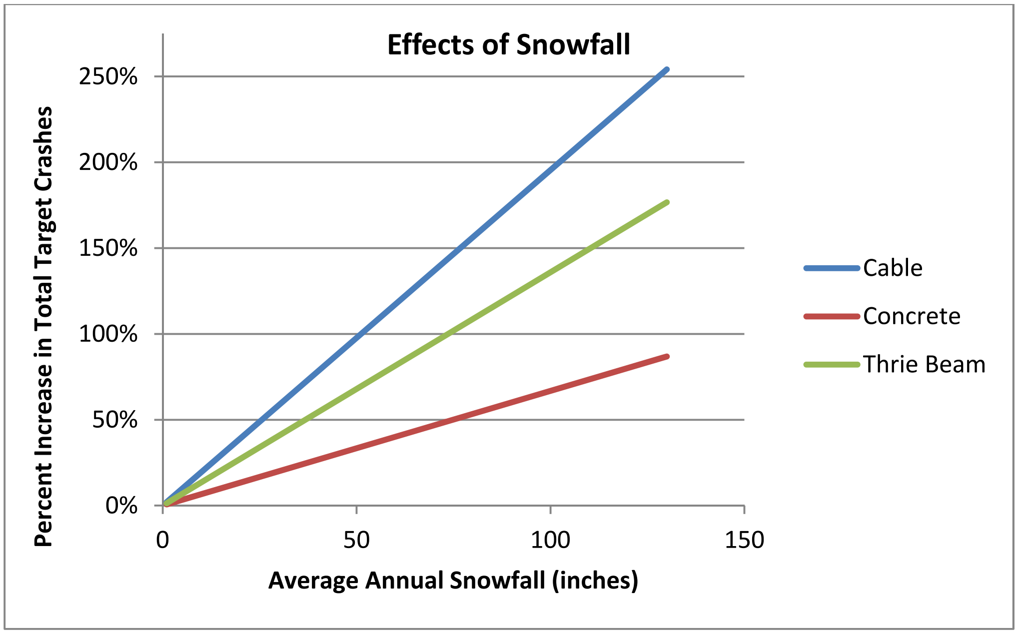

Figure 29. Effects of Snowfall on Total Target Crash Frequency among All Barrier Types

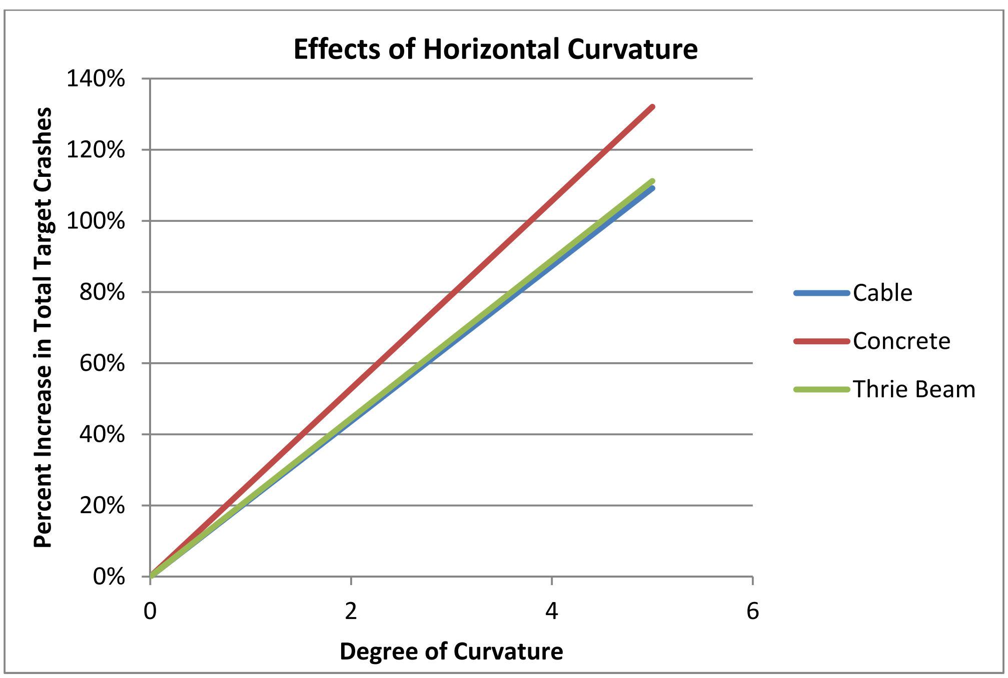

Figure 30. Effects of Horizontal Curvature on Total Target Crash Frequency among All Barrier Types

Segments with lower speed limits (55 mph) were associated with a higher frequency of median crashes (22.2% higher frequency than segments with 65 or 70 mph speed limits). This result is most likely capturing the effects of urban segment characteristics (as opposed to rural), as freeway speed limits are generally decreased in urban environments. Target crashes tended to decrease on segments with wider median widths and wider left shoulder widths, an expected result as vehicles have greater chance for recovery when medians and/or shoulders are wider. Based on the model results, crashes tended to decrease by 0.4% for every foot of median width and 2.1% for every foot of left shoulder widths. Ultimately, these models can help predict expected crash frequencies on roadways with different median barrier treatments.

5.3 Median Crash Severity Analysis

5.3.1 Ordered logit regression modeling

In order to examine the effects of various factors on the most severe degree of injury sustained as a result of a median crash, an ordered logit model was estimated. The ordered logit is appropriate in this setting because the dependent variable (most severe level of injury sustained by a crash involved person) can be classified into one of 4 discrete categories (K- and A-level crashes were combined due the small sample size of fatal crashes) with an inherent ordering structure (1 = PDO, 2 = C-Injury, 3 = B-Injury, 4 = K- or A-Injury). Since this analysis is completed at the crash-level (as opposed to person-level), only single-vehicle crashes occurring on cable barrier, thrie-beam guardrail, and concrete barrier segments are included. This ensures that the crash injury severity and vehicle type are in fact associated with the vehicle which entered the median.

The ordered logit is derived by specifying a latent variable, *z*, which is used as a basis for modeling the ordinal ranking of data (*42*). This unobserved variable is most often specified as a linear function for each crash observation, such that (*42*):

$$Z = \beta X + \varepsilon$$

where:

X : vector of variables determining the discrete ordering for each crash observation

β : vector of estimable parameters

ε : disturbance term

With this specification, observed ordinal-injury data, *y*, for each observed crash is defined as,

$y = 1$ if $z \le \mu_0$

$y = 2$ if $\mu_0 < z \le \mu_1$

$y = 3$ if $\mu_1 < z \le \mu_2$

$y = 4$ if $z > \mu_2$,

where:

μ : estimable threshold parameters that define *y*, which corresponds to integer ordering

The μ are parameters that are estimated jointly with the model parameters β and, without loss of generality, μ_0 can be set to 0. If the error term, *ε*, is assumed to be logistically distributed across observations, the ordered logit model results. Setting the lower threshold, μ_0, equal to zero results in the outcome probabilities, $P(y = i) = \nabla(u_i - \beta X) - \nabla(u_{i-1} - \beta X)$ where μ_i and μ_{i-1} represent the upper and lower thresholds for injury severity *i* (*42*).

One methodological concern related to the development of injury-severity models is that the effects of certain parameters may vary across observations due to unobserved heterogeneity

(*57*). This may be due to differences in the driving population such as such as risk-taking behavior or physiological factors (*57*), and constraining the model parameters to be constant across observations may lead to inconsistent and biased parameter estimates (*42; 57; 58*). To address this issue, random parameters can be estimated, allowing for the effects of parameters to vary across observations. This technique has been utilized successfully in recent traffic safety research (*59-63*). Random parameters (RP) can be incorporated into the ordered logit model by allowing parameters to vary as follows (*64*):

$$\beta_i = \beta + \mu_i$$

where:

β_i : vector of estimable parameters

μ_i : randomly distributed term (i.e. normally distributed with mean zero and variance σ^2)

To improve the efficiency of estimation, 200 Halton draws were utilized during model development as recommended through other research in the field (*58; 65; 66*), and the model was developed using NLOGIT 5 statistical software (*67*).

5.3.2 Results of the median crash severity analysis

Table 34 shows the results of the RP ordered logit regression model analyzing crash injury severity. In contrast to the crash frequency analysis, one joint model was developed for all study segments and indicator variables were included for each barrier type. The model was first developed with all parameters specified as random, however the vehicle type indicators (motorcycle and pickup truck) were found not to exhibit significant variability, so they were maintained as fixed parameters. The remaining parameters in the model do exhibit significant variability (as evidenced by their significant standard deviations in Table 34), indicating the effects of these parameters vary across the driving population. After estimation of the RP ordered logit model, the signs of the parameter estimates are of particular interest. A positive sign indicates an increase in the probability of the most severe outcome (fatal/ incapacitating injury crash) and a decrease in the probability of the least severe outcome (property damage only crash), and the converse is true for negative parameter estimates.

Table 34. Results of the RP Ordered Logit Crash Severity Model

Variable	β	S.E.	p-value	Std. Dev.	S.E.	p-value
Constant	-1.100	0.354	0.002	0.075	0.021	<0.001
Concrete Barrier	0.912	0.081	<0.001	0.089	0.025	<0.001
Thrie Beam Guardrail	0.632	0.093	<0.001	1.056	0.062	<0.001
Dry Road	0.727	0.047	<0.001	1.239	0.040	<0.001
Re-Direct	0.479	0.049	<0.001	0.313	0.040	<0.001
Penetrate	0.874	0.242	<0.001	1.706	0.244	<0.001
Overturn	1.912	0.082	<0.001	1.368	0.082	<0.001
Motorcycle	3.374	0.326	<0.001	-	-	-
Pickup Truck	-0.186	0.076	0.014	-	-	-
Two Lane Indicator	-0.391	0.074	<0.001	0.225	0.046	<0.001
Three Lane Indicator	-0.159	0.054	0.003	0.502	0.031	<0.001
Speed Limit 55 mph	0.220	0.063	<0.001	0.175	0.053	0.001
Lane Width 12 ft.	-1.292	0.343	<0.001	0.421	0.022	<0.001
Curve Indicator	0.101	0.058	0.078	0.580	0.052	<0.001
Threshold 1	1.797	0.035	<0.001	-	-	-
Threshold 2	3.866	0.079	<0.001	-	-	-
Restricted Log Likelihood (LL)	-10,840.21					
LL at Convergence	-9,973.81					

Examining the binary indicator parameter estimates for median barrier type, it was found that median crashes tended to be least severe on cable barrier segments as compared to thrie-beam or concrete barrier segments (concrete barrier segments were excluded from the model to serve as the reference category). This is attributable to the fact that cable barriers are the least rigid median barrier treatments, and can deflect laterally to absorb collision forces. This indicates that the rigidity of the barrier plays a major role in injury severity outcomes, as expected.

With respect to environmental factors, crashes occurring on dry roadways (as opposed to wet or icy roadways) had a higher probability of resulting in severe injuries. This result is consistent with past findings (*32*) and may be attributable to the fact that drivers tend to drive slower and more cautiously during adverse weather and road conditions. Crashes which involved barrier penetration or barrier strike and re-direction of a vehicle back onto the roadway also resulted in more severe injuries, an expected result as these crashes would tend to involve more severe collision forces as compared to median crashes which did not involve a barrier strike or barrier strikes in which the vehicle is contained in the median. Median crashes in which a vehicle overturned were also more likely to result in severe injuries. This result is expected as occupants are subjected to more severe forces during a rollover crashes.

Crashes involving motorcycles were more likely to result in severe injury outcomes than any other vehicle type. These results are consistent with past findings (*32*) and also expected due to the increased mass and collision forces associated with large trucks and the lack of protection associated with motorcycle occupants. Compared with all other vehicle types, crashes involving pickup trucks were least likely to result in severe injuries or fatalities. Median crashes occurring on freeways with four or more lanes in each travel direction (as opposed to two or three lanes) were associated with more severe injury outcomes, as were crashes occurring on roadways with 55 mph speed limits. Both of these characteristics (four or more lanes and 55 mph speed limits) are associated with urban areas, which may be a factor associated with this result. The finding that lower freeway speed limits result in more severe crashes is somewhat counterintuitive, but may be picking up on the risk for severe crashes when the speed standard deviation of the traffic stream is high (*68*), which is sometimes the case on lower speed limit freeways.

Crashes occurring on roadway segments with narrow lane widths (11 ft. as opposed to 12 ft.) were found to be associated with more severe injury outcomes, as were crashes occurring on curved roadway segments (with radius less than 3,500 ft.). Overall, one of the most interesting findings from the ordered logit severity model was that median crashes occurring on cable barrier segments tended to result in less severe injury outcomes while crashes occurring on concrete barrier segments were associated with more severe injury outcomes, all else being equal.

5.4 Barrier Strike Outcome Analysis

5.4.1 Multinomial logit modeling

In addition to analyzing factors affecting median crash frequency and severity, an analysis was conducted to investigate factors associated with barrier penetration and re-direction of vehicles back onto travel lanes. Only single-vehicle barrier strike crashes were included in this analysis since penetration or re-direction are not possible outcomes in non-barrier strike median crashes. Since the dependent variable (barrier strike outcome) is discrete and unordered in nature (contained by barrier, penetrated barrier, or re-directed onto roadway), multinomial logit regression modeling was chosen as an appropriate framework for the analysis. The multinomial logit model is specified by first defining a linear function that determines vehicle *n's* barrier strike outcome *i* as (*69*):

$$S_{in} = \beta_i X_{in} + \varepsilon_{in}$$

where:

β_i : vector of estimable parameters

X_{in} : vector of measurable characteristics (vehicle and roadway characteristics) that determines the barrier strike outcome for vehicle *n*

ε_i : error term accounting for unobserved effects influencing barrier strike outcome

If the ε_i are assumed to be generalized extreme value distributed, the standard multinomial logit model results with the following form (*69; 70*):

$$P_n(i) = \frac{\mathrm{EXP}[\beta_i X_{in}]}{\sum_{\forall I} EXP(\beta_i X_{in})}$$

where:

$P_n(i)$: probability that crash *n* will result in barrier strike outcome *i*

I : set of possible barrier strike outcomes

The multinomial logit model for this study was developed using NLOGIT 5 statistical software (*67*). During the modeling process, the 'contained by barrier' outcome was excluded to serve as the reference category, and the parameter outputs for 'penetrated barrier' and 're-directed onto roadway' correspond to that parameters effect on the outcome as compared with the reference category. A positive parameter output indicates an increase in the probability of that barrier strike outcome, and the converse is true for negative parameter estimates

5.4.2 Results of the barrier strike outcome analysis

The results of the multinomial logit barrier strike outcome model are presented in Table 35. As stated previously, only single-vehicle barrier strike crashes were included in this analysis since penetration or re-direction are not possible outcomes in non-barrier strike median crashes. It should be noted that a multinomial logit model with random parameters was also developed, but the parameter estimates were found not to exhibit significant variability and the RP model did not result in a significantly better model fit. Therefore, the fixed parameters multinomial logit model was retained as the final model presented in Table 35.

Table 35. Results of the Multinomial Logit Barrier Strike Outcome Analysis

Barrier Strike Outcome*	Parameter	β	S.E.	p-value
Penetrated Barrier	Constant	-5.051	0.445	<0.001
	Cable Barrier	3.894	0.376	<0.001
	Thrie Beam	1.861	0.436	<0.001
	Dry Road	0.877	0.187	<0.001
	Passenger Car	-1.781	0.310	<0.001
	Van	-1.599	0.542	0.003
	Pickup Truck	-3.653	0.767	<0.001
	Small Truck	-2.434	1.051	0.021
	Two Lanes	-0.974	0.215	<0.001
Re-Directed onto Roadway	Constant	-1.509	0.199	<0.001
	Cable Barrier	-1.653	0.074	<0.001
	Thrie Beam	-0.989	0.073	<0.001
	Dry Road	0.254	0.045	<0.001
	Passenger Car	0.442	0.194	0.022
	Van	0.426	0.227	0.060
	Pickup Truck	0.341	0.204	0.095
	Small Truck	0.658	0.234	0.005
	Curve Indicator	0.290	0.052	<0.001
	Speed Limit 70 mph	0.119	0.056	0.033
Restricted Log Likelihood		-8,311.21		
Log Likelihood at Convergence		-7,675.72		
***Note: Vehicle contained by barrier is excluded as reference category**				

With respect to barrier penetration, collisions with cable barriers were most likely to result in vehicle penetration, while concrete barriers were least likely to result in penetration.

This result is expected and is a function of the rigidity of each median barrier type. In contrast to thrie-beam or concrete barriers, cable median barriers may be prone to lower height vehicles under-riding the cable or larger vehicles penetrating through the cables. Crashes occurring on dry roadways (as opposed to wet or icy roadways) had a higher probability of resulting in barrier penetration. Similar to the severity model, this may be attributable to the fact that drivers tend to drive slower during adverse weather and road conditions and the greater impact forces from faster vehicle speeds may lead to higher likelihoods of penetration. With respect to vehicle type, crashes in which a large truck struck the barrier were most likely to result in penetration, likely attributable to the higher impact forces associated with their large mass. Interestingly, passenger vehicles and vans were more likely to penetrate barriers than pickup trucks or small trucks (which were the vehicle types least likely to penetrate). This may be attributable to the height of passenger cars and vans and their tendency to either penetrate under or through cable barriers, or flip over any of the barrier types. Crashes occurring on freeways with two lanes in each direction (as opposed to three or more lanes) were less likely to result in barrier penetration, though the reasons for this finding aren't clear and warrant further investigation.

Turning to the analysis of vehicle re-direction, collisions with cable barriers were least likely to result in vehicle re-direction back onto the roadway, while concrete barriers were most likely to result in re-direction. Similar to the barrier penetration analysis, this result is a function of the rigidity of each median barrier type. In contrast to thrie-beam or concrete barriers, cable median barriers can deflect laterally up to 12 feet which helps absorb some of the collision force, making re-direction of the vehicle back onto the roadway less probable. Crashes occurring on dry roadways (as opposed to wet or icy roadways) had a higher probability of resulting in Re-direction back onto the roadway. Similar to the severity and penetration models, this may be attributable to the fact that greater impact forces from faster vehicle speeds may lead to higher likelihoods of re-direction all the way back onto the roadway, especially with the more rigid barrier types. With respect to vehicle type, large trucks and motorcycles were least likely to be re-directed back onto the roadway likely due to the large mass of the trucks and loss of control of the motorcycle in the event of a barrier strike. Small trucks, passenger cars, and vans were most likely to be re-directed back onto the roadway, likely a result of their smaller mass as compared to other vehicle types.

Crashes occurring on curved segments were more likely to result in re-direction, likely a result of impact angles and vehicle trajectory while navigating curves. Crashes occurring on roadway segments with higher speed limits (70 mph as compared with 50-65 mph) were more likely to result in re-direction onto the roadway, likely a function of vehicle speed as the time of barrier impact. Collectively, these results provide new insights into the factors which are associate with barrier penetration and re-direction onto the roadway as compared with containment by a median barrier; which is the most desirable result.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary and Conclusions

High-tension cable barrier has become a preferred median barrier treatment on freeways due to advantages that include reduced installation costs, lesser impact forces on vehicles that strike the barrier, reduced sight distance issues, and greater aesthetic appeal. While cable median barrier use has increased significantly across the United States, cable barriers do present potential drawbacks, such as an increase in less severe crashes and the need for frequent maintenance. The Michigan Department of Transportation began installing cable median barriers in 2008 and has installed approximately 317 miles of high-tension cable median barrier on state freeways as of January 2014. Ultimately, the objectives of this study were to ascertain the safety and economic impacts of Michigan's cable median barrier program. To accomplish these objectives, the research study involved:

- A comprehensive, state-of-the-art review of research examining the impacts of cable median barrier installation. This included a survey of emergency responders to obtain feedback on several issues including the frequency and spacing of emergency vehicle crossovers and difficulty in responding to crashes involving cable median barriers.
- A manual review and analysis of crash reports to determine the effectiveness of high-tension cable barriers in reducing median-crossover crashes in Michigan, as well as to determine the overall safety impacts considering all median-related crashes. Additionally, the relative safety performance of cable barrier, thrie-beam guardrail, and concrete barrier was analyzed, and a comparison of the three barrier types was conducted.

- A comprehensive before-and-after evaluation of cross-median and median-related crashes. Safety performance functions (SPFs) were estimated for cable barrier segments before and after installation, as well as for control segments with no barriers present. The SPFs were utilized in performing an Empirical Bayes before-after evaluation to examine the effectiveness of cable barriers while accounting for potential selectivity bias and the regression-to-the-mean effect.
- Exploring the effects of traffic volumes, median width, lateral offset, horizontal alignment, cable barrier type, and other factors as part of a disaggregate-level analysis of median-involved crashes after cable barrier installation.
- Investigating under-researched areas of concern related to cable median barriers such as the frequency and spacing of emergency crossovers, safety effects on motorcyclists, and effects of weather and road conditions using the observed crash data.
- Performing an economic analysis to consider agency costs, as well as safety benefits. The economic analysis included a benefit-cost analysis, which considered cable barrier installation and maintenance costs, as well as associated crash costs savings due to cable barrier installation.
- Developing guidelines to assist in screening freeway locations as candidates for cable barrier installation. These guidelines consider a number of factors such as AADT, median width, lateral clearance of the cable barrier to edge of left travel lane, and annual snowfall.
- Comparison of cable median performance with thrie-beam guardrail and concrete median barrier. This analysis included development of an SPF for all median barrier types and development of statistical models which analyze both injury severity outcomes and

barrier strike crash outcomes (i.e. vehicle contained in median, vehicle penetrated median barrier, or vehicle re-directed back onto roadway).

Based on the collection and detailed review of police crash reports before and after cable barrier installation, it was found fatal and severe injury crashes decreased significantly after barrier installation, while less severe injury and property damage only (PDO) crashes increased. To estimate the precise safety impacts of the cable barrier system, separate safety performance functions (SPFs) were developed for cable barrier road segments before and after installation, as well as for control segments where no barrier was installed and where median widths were less than 100 feet. These SPFs allowed for consideration of changes in traffic volumes while controlling for other potential confounding factors such as median width. The SPFs for the control segments were used in performing an Empirical Bayes (EB) analysis, which allowed for consideration of potential selectivity bias or a regression-to-the-mean effect since barrier installation was determined on the basis of prior crash history. The results of the statistical analysis showed that low severity (i.e., PDO/C) crashes increased 155 percent after cable barrier installation, B level severity crashes increased marginally (1 percent), while severe and fatal (K/A) injury crashes decreased 33 percent after cable barrier installation.

The analysis also showed a significant reduction in cross-median crashes after cable barrier installation. When considering changes in traffic volumes, the median-crossover crash rate was reduced by 86.8 percent. Another significant finding was that the target rollover crash rate was reduced by 50.4 percent. This is a safety benefit that has not been well documented, and is most likely a result of vehicles being contained by the cable barrier instead of traveling into the median and overturning.

In addition to the overall before-after crash evaluation, a more detailed analysis of crashes involving a vehicle striking the cable barrier was conducted. The results showed that cable barriers were 96.9 percent effective in preventing penetration in the event of a cable barrier strike. Overall, 89.3 percent of cable barrier strikes resulted in the vehicle being contained by the barrier in the median, 2.3 percent resulted in the vehicle penetrating the barrier but remaining in the median, 7.6 percent resulted in vehicles being re-directed back onto the roadway, and only 0.7 percent resulted in vehicles penetrating the cable barrier and entering opposing traffic lanes (cross-median event or crash). Vehicle type was also examined in terms of cable barrier performance in the event of a barrier strike, and, unsurprisingly, large trucks/buses were over-represented with respect to cable barrier penetration.

The relative performance of cable barrier systems with 3 cables and 4 cables was also examined. While the results were quite similar, the sample size of cable barrier segments with 4 cables was too small to draw any meaningful conclusions. The performance of cable median barriers in the event of a strike was also compared with thrie-beam median guardrail and concrete median barrier. Overall, thrie-beam median guardrail was 99.2 percent effective in preventing penetration of the guardrail in the event of a barrier strike; however 15.8 percent of vehicles were re-directed back onto the roadway, increasing the probability of a secondary crash event. Similarly, concrete median barrier was 99.9 percent effective in preventing cross-median crashes in the event of a barrier strike, but 31.1 percent of vehicles were re-directed back onto the roadway in the event of a barrier strike. These results suggest the relationship between barrier rigidity and the likelihood of a vehicle being redirected back onto the roadway after a barrier strike is directly proportional. Overall, cable median barriers are slightly more prone to penetration than thrie-beam guardrail or concrete barrier, but they are more effective in preventing re-direction back into travel lanes.

The success in cable barriers preventing re-direction back onto the roadway is further demonstrated by the fact that only 12.5 percent of cable barrier strikes resulted in a multi-vehicle crash, while 19.2 percent and 22.5 percent of thrie-beam guardrail and concrete barrier strikes resulted in multi-vehicle crashes, respectively. In terms of injury outcomes, only 14.3 percent of cable barrier strikes resulted in an injury as compared to 27.1 percent and 31.4 percent for thrie-beam guardrail and concrete barrier strikes, respectively.

The safety impact of cable barrier installation on motorcyclists was also examined as a part of this study. It was found that there were no fatal target motorcycle crashes in the before or after period. A total of 9 crashes were identified in which a motorcyclist struck the cable median barrier; 4 of these crashes resulted in A-level injuries while 5 resulted in C-level injuries. Of the 9 motorcycle cable barrier strikes, two of the motorcyclists were riding un-helmeted (one resulted in an A-level injury and one resulted in a C-level injury), and both crashes occurred after Michigan's universal helmet law was repealed. Overall, installation of cable barriers was not found to have a significant effect on motorcyclist crash trends.

The effects of frequency and spacing of EV-crossovers were examined through a survey of emergency responders and the analysis of crash data, which was manually reviewed to identify target crashes involving an EV-crossover. Emergency responders indicated that the greatest difficulty introduced by cable barrier was an inability to locate a median-crossover due to the relative infrequency of crossover/turnaround locations. Interestingly, the crash analysis indicated that 1.98 percent of target crashes in the before period involved the use of a crossover location, compared with only 0.73 percent after installation. It was found that an overwhelming majority of these crashes were caused by motorists attempting to illegally use the crossovers. Consequently, it appears the installation of cable barrier has significantly reduced the frequency of such events.

Weather and road conditions were also found to play a role in the frequency or severity of crashes, as well as cable barrier performance. An analysis of crashes that occurred on dry roads vs. wet/icy/snowy roads was conducted for the before and after periods. The results indicate the majority of target crashes occurred on wet/snowy/icy roadways both before and after cable barrier installation (59.8 percent before and 69.4 percent after). However, the crashes that occur on wet/icy/snowy roads tend to be less severe than crashes occurring on dry roads. In terms of cable barrier performance, crashes that occurred on dry roads were more likely to penetrate the cable barrier or be re-directed back onto the roadway. Overall, 86.4 percent of cable barrier strikes occurring during dry road conditions resulted in the vehicle being contained by the barrier in the median compared to 90.5 percent when crashes occurred during wet/icy/snowy road conditions. These results indicate that while the frequency of crashes may increase during periods of adverse weather and road conditions, causing increased repair/maintenance requirements, the cable barriers still perform their intended purpose during these periods.

While the results of the safety analysis provided important insight into the in-service performance of cable median barriers, an economic analysis was conducted to determine the cost-effectiveness of the cable barrier system. A benefit-cost analysis was performed using a discount rate of 3 percent and an analysis period of 20 years. This analysis considered agency costs including the initial construction cost of the cable barrier system, as well as annual maintenance for repair of the system required after collisions occur. These costs were compared with the crash cost savings that resulted from the reductions in fatal and incapacitating injuries.

While these savings were offset to a degree by the concurrent increase in PDO and minor injury crashes, the B/C ratio was found to be 2.86 when comprehensive costs of crashes were considered. These results suggest that cable median barrier has been a cost-effective solution to reduce cross-median crashes on freeways. It should be noted, however, that the economic benefit associated with cable median barriers is highly sensitive to the value assigned to the cost of traffic crash fatality.

One of the key goals of this research was to develop guidelines to assist in the prioritization of candidate locations for the installation of cable median barrier. These guidelines considered a number of factors as screening criteria, including average daily traffic, median width, number of lanes, lateral clearance of the cable barrier from edge of travel lanes, and annual snowfall. Predictive models were developed to allow for the prediction of target crashes before and after cable median barrier installation for a specific freeway segment. Separate predictive models were developed for PDO/C target crashes and K/A target crashes, as different factors affect the frequency of each type differently. For PDO/C crashes, base conditions were identified and adjustment factors for number of lanes, lateral clearance, snowfall ranges, and horizontal curvature were developed in order to more accurately estimate the effects of installing cable median barrier. Ultimately, these predictive models can help to identify locations where installation of cable median barrier would be most effective.

It is important to note that while cable barrier is cost-effective, it may not be appropriate for installation at all locations. As stated in the AASHTO Roadside Design Guide (*3*), "A cable barrier should be used only if adequate deflection distance exists to accommodate approximately 12 feet of movement; i.e., the median width should be at least 24 feet if the barrier is centered." While the study results show that placing the barrier toward the center of the median (i.e., further from the traveled way) would minimize the frequency of crashes (particularly property damage only collisions), maintenance becomes more difficult due to water accumulation at the bottom of the ditch. In such areas, poor soil conditions could also affect the performance of cable barrier foundations. Furthermore, median slopes may be prohibitively steep in the center of the median for proper cable barrier installation and optimal barrier performance.

As such, this research also analyzed the performance of thrie-beam guardrail and concrete median barrier in addition to cable median barrier. Each of these barrier types has associated costs and benefits that must be carefully considered in selecting the most effective treatment for a specific road segment. This research presented an analysis of factors which affect median crash frequency, severity, and barrier collision outcomes on freeway segments in Michigan which can provide transportation agencies with valuable guidance as to the performance and selection of various types of median barrier treatments. Additionally, this study provides one of the first comprehensive analyses of thrie-beam median guardrail using observed highway-crash data, as most previous analyses have focused on the more common w-beam guardrail.

Ultimately, several roadway, traffic, environmental, and vehicle related factors were found to affect median crash frequency, crash severity, and barrier strike outcome in terms of barrier penetration and vehicle re-direction back onto the roadway. Among the most important findings, crashes occurring on segments with cable median barrier were least likely to result in fatal or incapacitating injuries, but were also most likely to result in a barrier penetration, which introduces the possibility of a cross-median crash. Furthermore, crashes on cable median barrier segments were least likely to result in vehicle re-direction back onto the roadway, which introduces the possibility of a secondary crash. It's important to note again, however, that not all barrier types are suitable for all median conditions.

6.2 Limitations and Directions for Future Research

Throughout the course of this research, there were a few limitations with respect to the data which were available. First, the location of crashes in some instances was found to be imprecise through the manual review of the crash report forms; an issue faced frequently when working with observed highway crash data (*71*). This issue should be diminished in the future as GPS technology is incorporated into highway crash reporting. To mitigate the issue in this research, roadway segments were restricted to a minimum length of one quarter mile to reduce the chance of assigning a crash to the wrong roadway segment.

Another issue faced was related to the necessity of the manual review of the crash report forms. While crash report reviewers were able to extract the necessary information in most cases, there were instances where a police officer's diagram or crash narrative were not exactly clear. In such cases, crash report reviewers relied on other fields in the crash report to make their best estimate as to the nature of the crash. Moving forward, it is recommended that crash reports incorporate more detailed event outcomes for each vehicle, particularly in cases where a barrier, guardrail, or fixed object is struck.

With respect to data availability, there were a few roadway geometry elements which were not available for this study because they were not included in MDOT's roadway database. Ultimately, two variables of potential interest, median cross-slope and lateral distance from the edge of the roadway to barrier, were not available (lateral distance from edge of roadway for cable barriers was collected manually for this study through an exhaustive review using Google

Earth). If these fields of interest are included in future versions of roadway inventory databases, they can be incorporated into research to better understand the effects of roadway geometric characteristics on traffic safety.

With respect to the before-after crash analysis methodology, this study utilized the Emprical Bayes (EB) before-after method (in addition to a simple comparison of before and after crash rates). The EB method has been shown to be very promising in the context of traffic safety studies due to the ability to account for potential regression-to-the-mean bias which can occur when treatment sites are selected on the basis of high short-term crash counts (*46*). Nonetheless, there are other alternative methods which can be used to estimate the effectiveness of countermeasures on road safety.

Cross-sectional analyses, which utilize data from control locations (as opposed to before-after data from treatment locations) have been used in traffic safety evaluations, however this method can still suffer from selectivity bias (*72; 73*). Recently, 'propensity score' methods, which also use control location data, have been utilized in road safety countermeasure evaluations (*74; 75*), and these methods have been shown to potentially reduce treatment selectivity bias (*75*). A potential topic for future research, which would be a natural extension of the research presented in this dissertation, would be to evaluate the effectiveness of cable barriers using these alternative methods (cross-sectional and propensity scores) and to compare the results with the EB analysis.

While this study focused on cable barriers as median treatments on freeways, some states, such as Iowa, also use cable barriers on the right side of the roadway to prevent run-off the road crashes (*76*). An analysis of these installations could provide further insights into cable barrier's efficacy and cost-effectiveness in other scenarios, as these treatments are not focused on preventing cross-median crashes, but preventing collisions with fixed objects on the right side of the roadway. Additionally, cable median barriers installed on non-freeway medians should be evaluated as the crash characteristics on these lower speed facilities will differ from the higher speed freeway segments evaluated in this study.

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