Study of High-Tension Cable Barriers on Michigan Roadways

MDOT ORBP Project Number: OR10-036

FINAL REPORT

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October 24, 2014

1. Report No. RC-1612	2. Government Accession No. N/A	3. MDOT Project Manager Carlos Torres
4. Title and Subtitle Study of High-Tension Cable Barriers on Michigan Roadways		5. Report Date October 24, 2014
		6. Performing Organization Code N/A
7. Author(s) Peter T. Savolainen, Timothy J. Gates, Brendan J. Russo, and Jonathan J. Kay		8. Performing Org. Report No. N/A
9. Performing Organization Name and Address Wayne State University 5057 Woodward, Suite 13202 Detroit, Michigan 48202		10. Work Unit No. (TRAIS) N/A
		11. Contract No. 2010-0298
		11(a). Authorization No. Z#3
12. Sponsoring Agency Name and Address Michigan Department of Transportation Research Administration 8885 Ricks Rd. P.O. Box 30049 Lansing MI 48909		13. Type of Report & Period Covered Final Report 10/1/2011 – 10/31/2014
		14. Sponsoring Agency Code N/A
15. Supplementary Notes None		

16. Abstract

Median-crossover crashes present the highest risk of fatality and severe injury among all collision types on freeways. These crashes are 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 high-tension cable median barrier on state freeways as of September 2013. Given the capital costs required for this installation program, as well as the anticipated annual maintenance and repairs costs, a comprehensive evaluation was conducted in order to ascertain the efficacy of cable barrier systems that have been installed to date. Statistical analyses showed that fatal and incapacitating injury crashes were reduced by 33 percent after cable barrier installation. The analysis also showed the median-crossover 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 vehicle striking the cable barrier was also conducted. The results showed that cable barriers were 96.9 percent effective in preventing penetration in the event of a cable barrier strike. Weather and road conditions were also found to play a role in the frequency and severity of crashes, as well as cable barrier performance. An economic analysis was conducted to determine the cost-effectiveness of the cable barrier system, and guidelines were developed to assist in prioritizing candidate locations for cable barrier installation.

17. Key Words	18. Distribution Statement No restrictions. This document is available to the public through the Michigan Department of Transportation

19. Security Classification - report	20. Security Classification - page	21. No. of Pages	22. Price
Unclassified	Unclassified	93	N/A

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EXECUTIVE SUMMARY

PROBLEM STATEMENT AND OBJECTIVES

Median-crossover crashes are among the most hazardous events that can occur on freeways. These crashes are caused by a variety of factors including drowsiness, driver distraction, impaired driving, and loss of control on horizontal curves or slippery road surfaces. According to the AASHTO *Roadside Design Guide* (*RDG*), the primary countermeasure to reduce the opportunity for such crashes is the installation of median barriers (*1*). 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.

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 when selecting the most 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" (*1*).

In recent years, high-tension cable 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 (*2*). Michigan is one of several states that have recently begun implementing 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 September 2013.

Given the capital costs required for this initial cable barrier installation program, as well as the anticipated annual maintenance and repairs costs, a comprehensive evaluation was conducted to ascertain the efficacy of cable barrier systems that have been installed in Michigan to date. The primary objectives of this analysis included:

- Determining the effectiveness of high-tension cable barriers in reducing median-crossover crashes in Michigan.
- Comparing the relative safety performance among cable barrier, thrie-beam guardrail, and concrete barriers.
- Exploring 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.
- Performing an economic analysis to gain insight into the cost-effectiveness of cable median barriers.
- Developing guidelines to assist in screening freeway locations as candidates for cable barrier installation.

BEFORE AND AFTER CRASH EVALUATION

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. The results of a statistical analysis showed that low severity (i.e., PDO/C) crashes increased 155 percent after cable barrier installation, B-injury level crashes were virtually unchanged (increased 1 percent), and severe and fatal (K/A) injury crashes decreased 33 percent after cable barrier installation. These changes are comparable with those experienced in recent evaluations that were conducted in other states. The analysis also showed a significant reduction in cross-median crashes after cable barrier installation as demonstrated by an 86.8 percent reduction in the median cross-over crash rate. The rate of rollover crashes was also reduced by 50.4 percent.

The data contained in this report illustrates the number of crashes involving cable median barrier, as well as the severity of those crashes. It is important to note the relationship between the crash data and cable barriers is primarily a corollary relationship, not a direct relationship. While cable barriers were involved in these crashes, they should not be construed as the cause of these crashes or the resulting injuries.

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 case of a cable barrier strike. Additionally, a number of vehicles which penetrated the cable barrier still came to rest in the median, and only 0.7 percent of crashes involving a cable barrier strike resulted in a cross-median event or crash.

The performance of cable median barriers in the event of a strike was also compared with thrie-beam median guardrail and concrete median barrier. While thrie-beam guardrail and concrete barrier were slightly more effective in preventing penetration in the event of a barrier strike; they were significantly more likely to re-direct vehicles back into the travel lanes, which increased the potential for a secondary crash event. 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 27.2 percent and 31.4 percent for thrie-beam guardrail and concrete barriers, respectively.

The effects of frequency and spacing of emergency vehicle (EV) median crossover locations were examined through a survey of emergency responders and the analysis of crash data at crossover locations. Emergency responders indicated that the greatest difficulty introduced by cable barrier was an inability to locate a median cross-over due to the relative infrequency of crossover/turnaround locations. The crash analysis showed that the number of crashes occurring at turnaround locations was significantly reduced after cable barrier installation. It was also found that the majority of such crashes were caused by motorists attempting to illegally use the crossovers.

Weather and road conditions were also found to play a role in the frequency or severity of crashes, as well as cable barrier performance. 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 90.4 percent when crashes occurred during wet/icy/snowy road conditions. While the frequency of crashes may increase during periods of adverse weather conditions, the cable barriers still perform effectively during these periods.

ECONOMIC ANALYSIS

An economic analysis was conducted to determine the cost-effectiveness of the cable barrier system. This analysis consisted of a time of return (TOR) analysis, which is consistent with the methodology used by MDOT for determining the economic effectiveness of safety initiatives. TOR is defined as the amount of time that must pass after implementation, typically gauged in years, for the expected benefits of the initiative to equal the costs of the initiative. The TOR analysis was conducted for cable barrier installations in Michigan through 2012 (2013 installations were excluded due to lack of post-installation crash data). Engineering, construction, and maintenance costs were considered as part of the TOR analysis, as well as the benefits realized by reductions in severe crashes. Ultimately the TOR for cable median barrier installation in Michigan was found to be 13.38 years.

CABLE BARRIER INSTALLATION GUIDELINES

Guidelines were developed to assist the Michigan Department of Transportation (MDOT) in the prioritization of candidate locations for the installation of cable median barrier. Various factors were considered as screening criteria for identifying candidate locations. These included average daily traffic, median width, number of lanes, lateral clearance of the cable barrier from edge of travel lanes, annual snowfall, and horizontal curvature. Predictive models were developed to allow for the prediction of the number of target crashes per mile per year 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 were estimated for number of lanes, lateral clearance, snowfall ranges, and horizontal curvature 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.

CONCLUSIONS AND RECOMMENDATIONS

Ultimately, the results of this study show that installation of cable median barrier is an effective strategy for reducing cross-median crashes on freeways. However, the reductions in serious and fatal injuries are offset to a degree by increases in PDO and minor injury crashes due to the proximity of the barriers to the travel lanes.

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. Consequently, it is important to note that while cable barrier can be an effective countermeasure, site-specific factors should be considered when screening candidates for barrier installation.

1.0 INTRODUCTION

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 (*3*). 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 (*4*). 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 this same five-year period (2009 to 2013), resulting in 27 fatalities and 61 incapacitating injuries; rates that are significantly higher than other crash types (*3*).

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 (*1*). 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 (*5*). 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 (*3*).

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 (*1*), 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" (*1*).

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 (*2*). 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 September 2013.

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.

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. 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. Compare the relative safety performance among cable barrier, thrie-beam guardrail, and concrete barriers.
- 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.

2.0 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 (*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*).

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.

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 (*1*) 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.

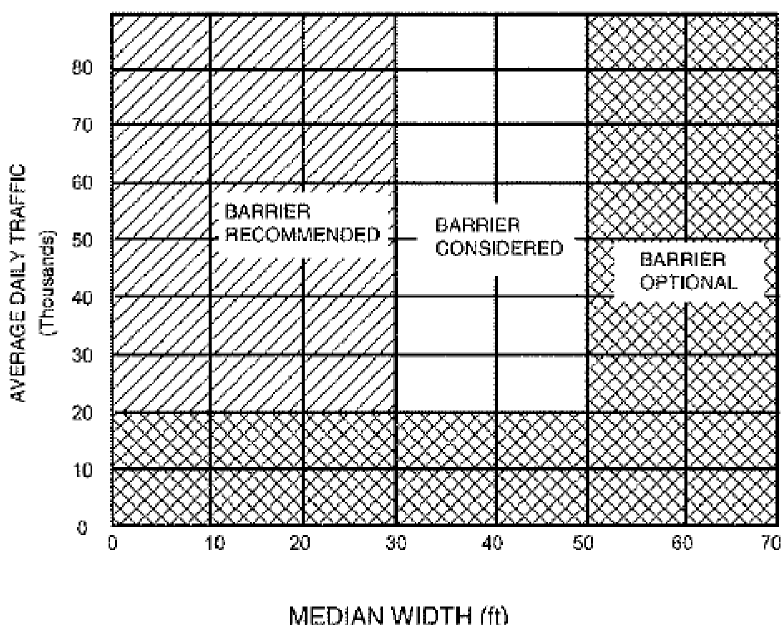


Figure 1. AASHTO Median Barrier Guidelines (*1*)

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 (*1; 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.

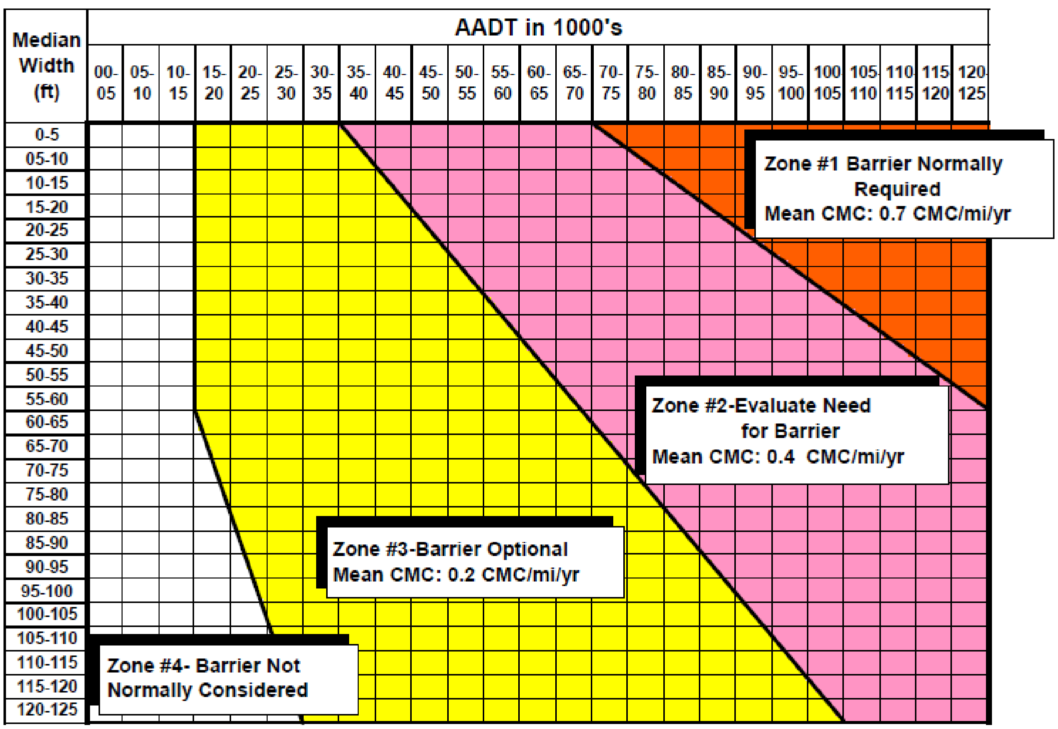


Figure 2. Guideline for Installing Median Barriers on Texas Interstates and Freeways (*26*)

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 (*1*) 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.

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.

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.

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

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 installed?		
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 barrier?		
<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%**

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

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 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

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.

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.

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; 30*) 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 (*31*). 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, these results 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.

3.0 ROADWAY SEGMENT DATA COLLECTION AND ANALYSIS

Cable Median Barrier Segment Data

Segments of roadway in which cable median barrier have been installed (as of September 2013) 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 (*32*) 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 every year through 2013. As of September 2013, 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 September 2013. 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.

Cable Barrier Installation Data

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.

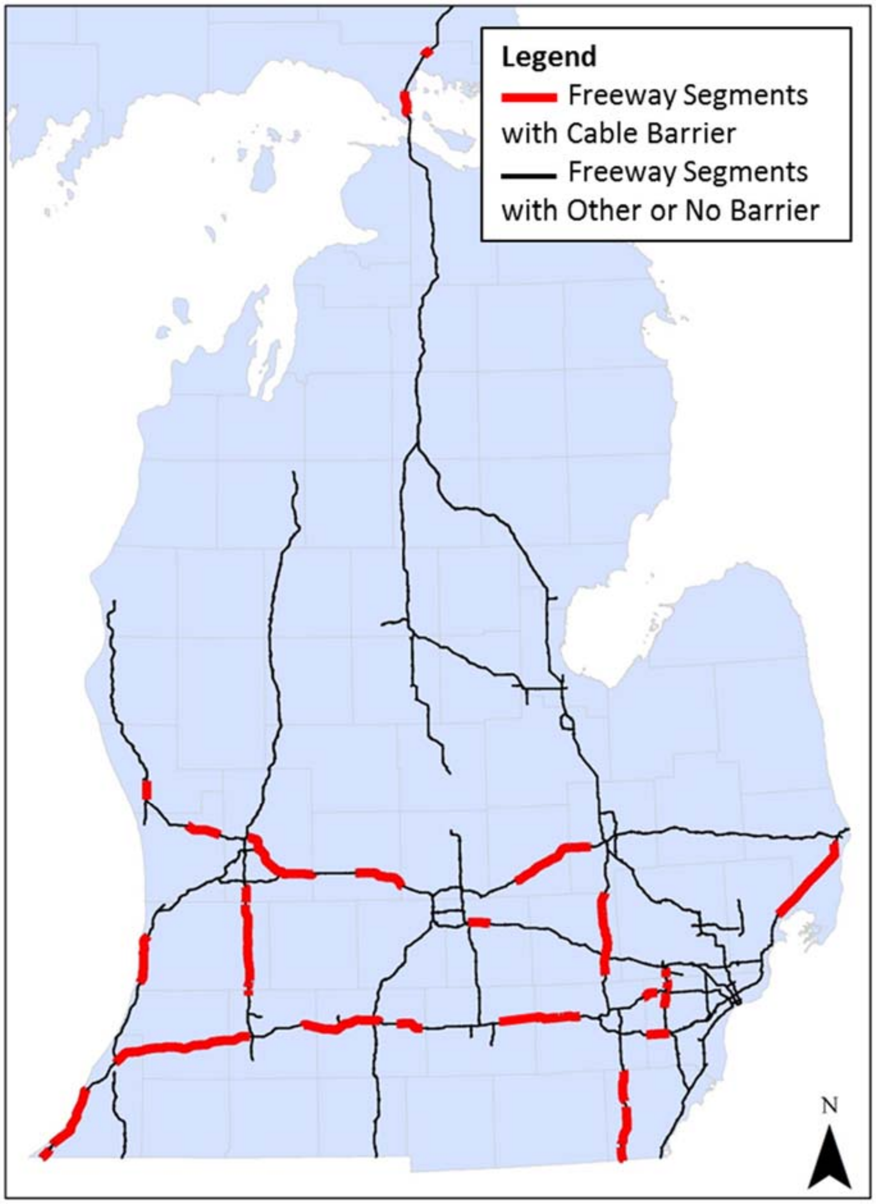


Figure 4. Map Showing Cable Barrier Installation Locations

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**

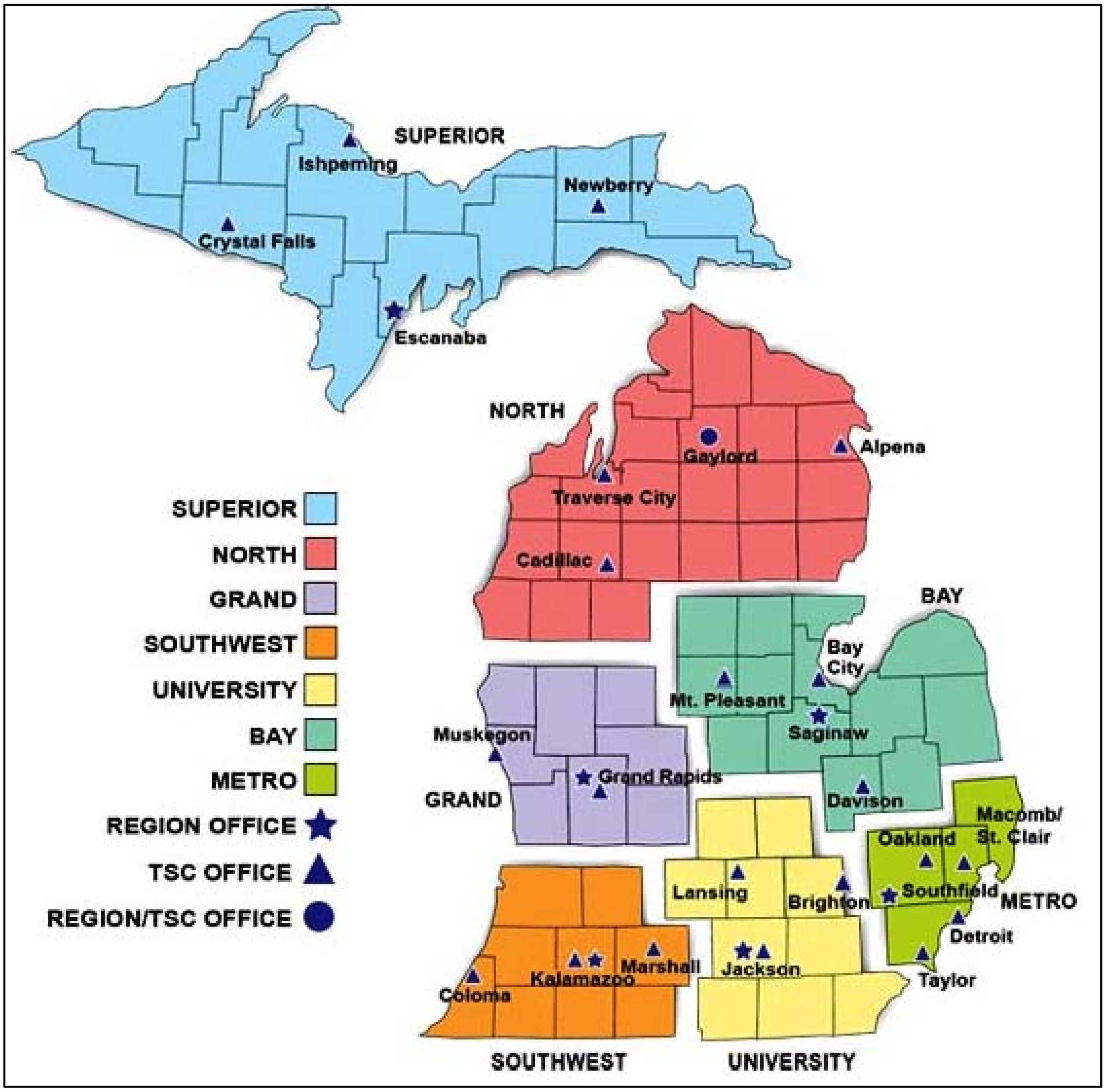


Figure 5. Map Showing MDOT Regions (Source: MDOT)

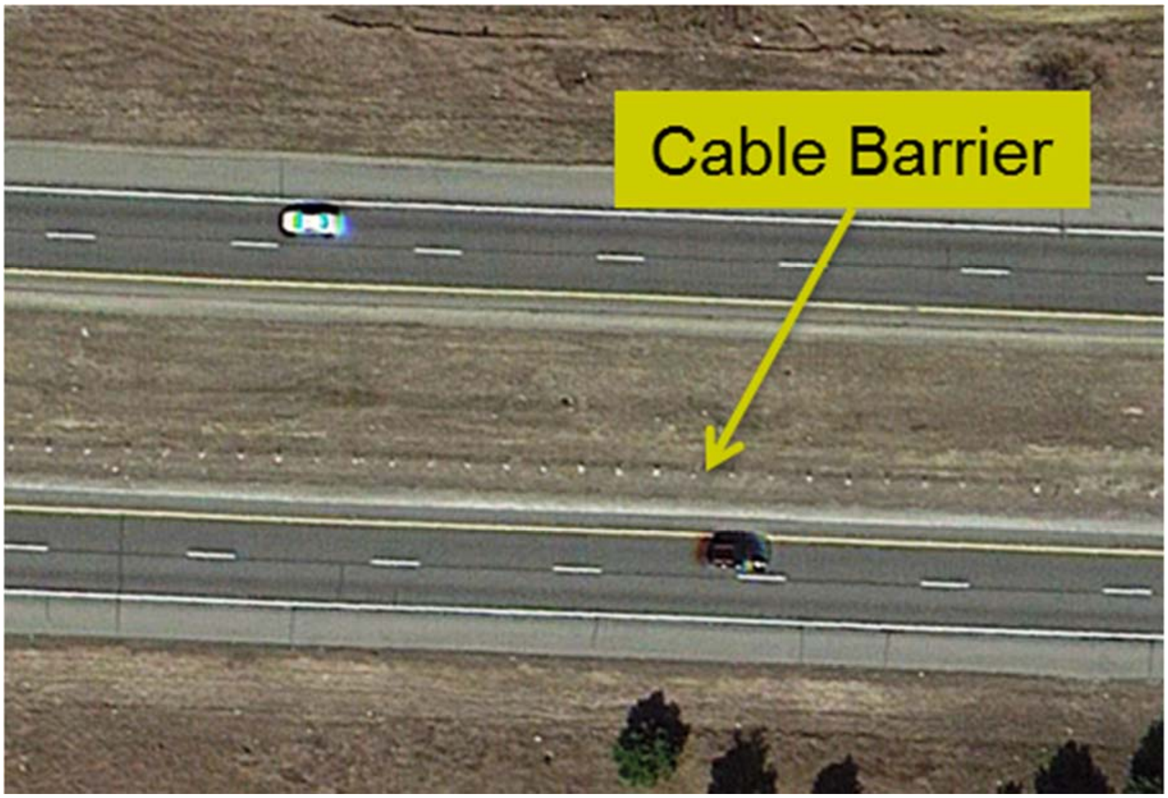


Figure 6. Screen Shot from Google Earth Showing Cable Median Barrier (*32*)

Roadway Geometry 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.

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.

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

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 (*33*). 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.

Control Segment Roadway Information

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 control 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

Table 7. Summary of Cable Barrier Roadway Segments

Characteristic		3-Cable Sections		4-Cable Sections		All Cable Barrier Sections	
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	
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%)	
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.							

The control 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. The geometric, traffic, crash, and snowfall data were obtained for each control segment in the same manner as the cable barrier segments described previously. However, only the most recent 5 years (2009-2013) of data were examined for the control segment analysis (there are no 'before and after' periods for the control segments as there are for the cable barrier segments). Table 8 shows a summary of the no barrier, thrie-beam guardrail, and concrete barrier roadway 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.

Table 8. Summary of Control Roadway Segments

Characteristic		No Barrier Segments (median < 100 ft)	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	7.2	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	26.0	12.0	6.0
	Max	94.0	70.0	70.0
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%)
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)		44.72	36.97	38.12
*'No curve' includes curved segments with radii greater than 3,500 ft.				

4.0 CRASH DATA COLLECTION AND ANALYSIS

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 Crash

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 Crash

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.

Narrative

Driver of vehicle #1 stated that an unknown semi entered her lane, causing her to take evasive action. Driver #1 stated that she over-corrected, lost control, and rolled her vehicle in the median.

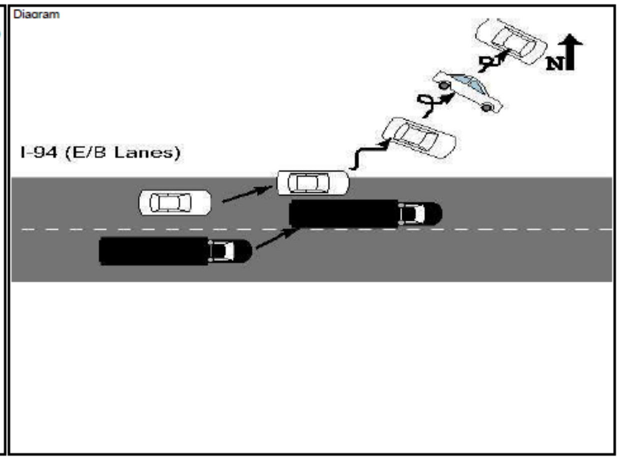


Figure 7. Target 1 Crash – Median Crash

Narrative

#1 crossed through the median overturning and landing on its roof in the west bound lanes. #1 admitted he fell asleep. #1 was cited for careless driving.

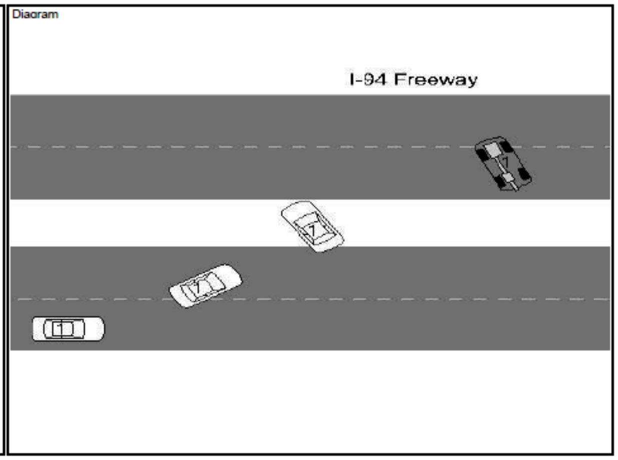


Figure 8. Target 2 Crash – Cross-Median Event

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.

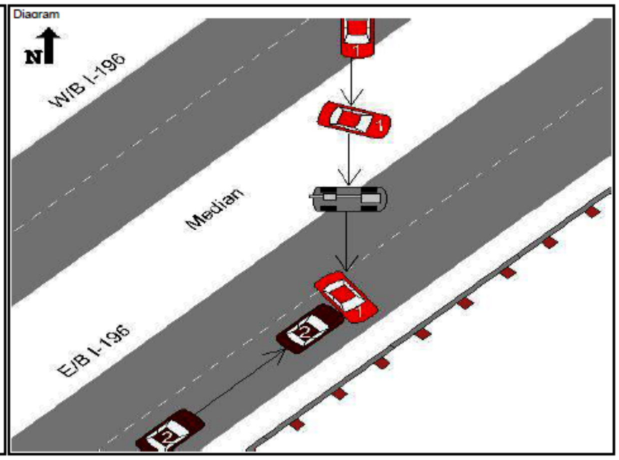


Figure 9. Target 3 Crash – Cross-Median Crash

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.

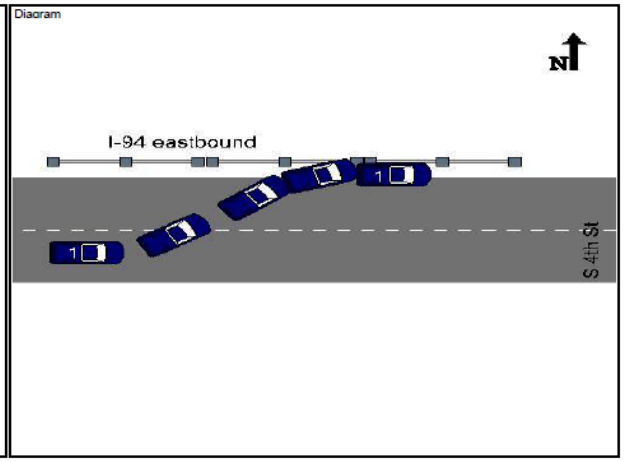


Figure 10. Target 4 Crash – Contained by Cable Barrier

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.

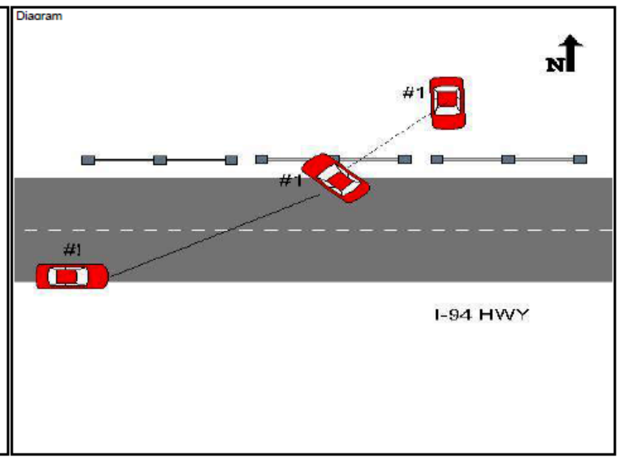


Figure 11. Target 5 Crash – Penetrated Cable Barrier but Did Not Enter Opposing Lanes

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.

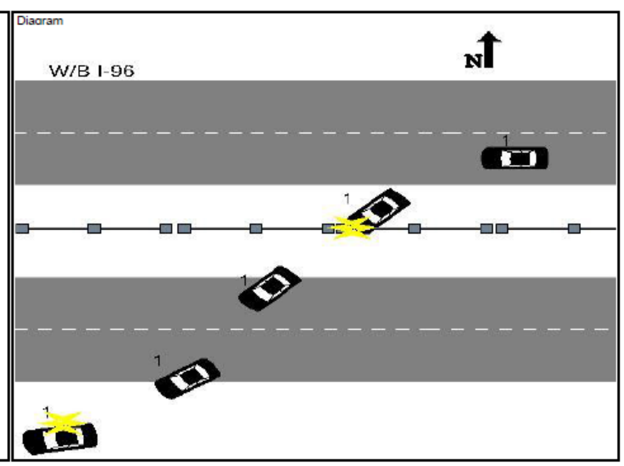


Figure 12. Target 6 Crash – Penetrated Cable Barrier and Entered Opposing Lanes, but Did Not Strike Opposing Vehicle

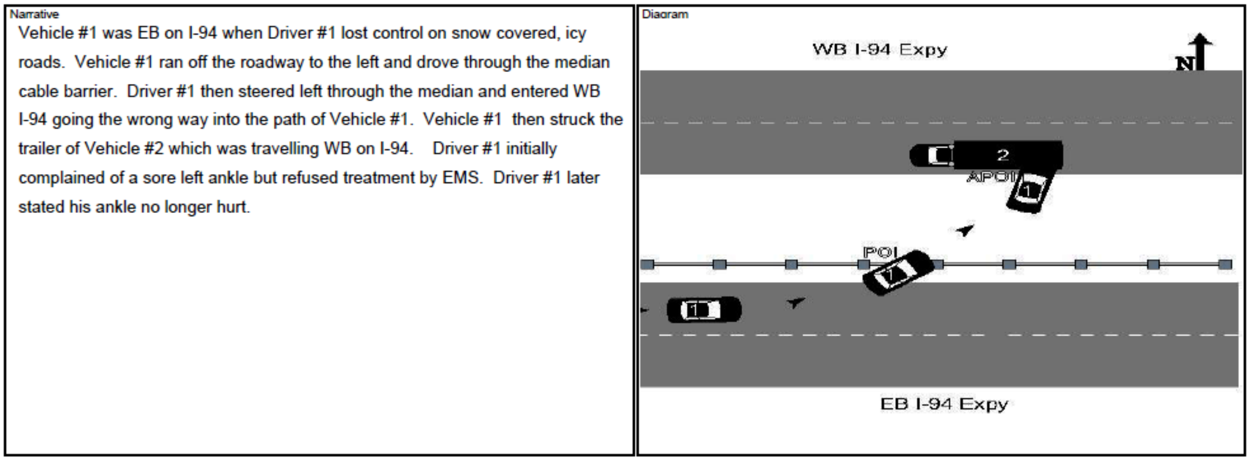


Figure 13. Target 7 Crash – Penetrated Cable Barrier and Entered Opposing Lanes, and Struck Opposing Vehicle

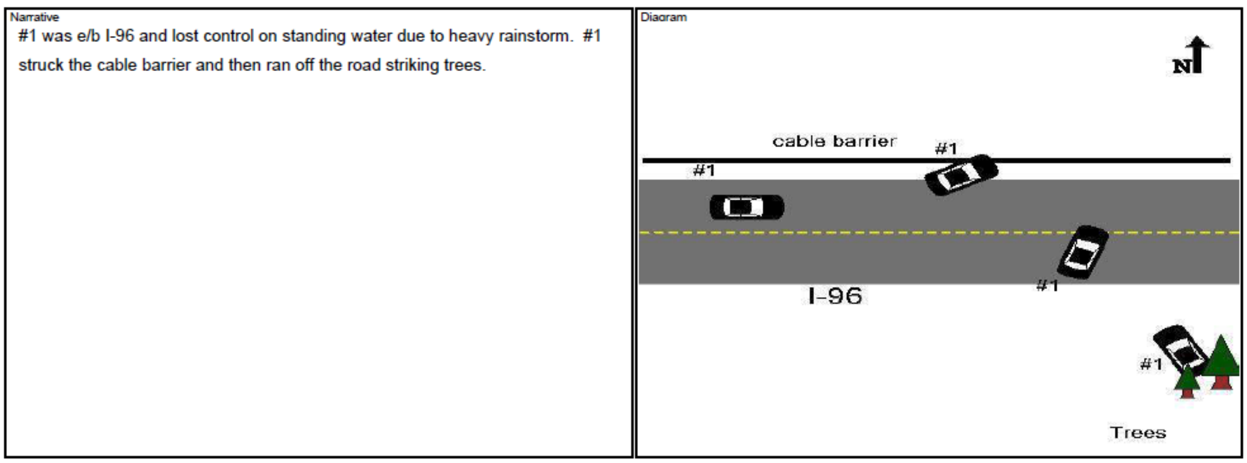


Figure 14. Target 8 Crash – Struck Cable Barrier and Re-Directed Onto Travel Lanes

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 (*3*):

- 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)

Control Segment Crash Data

The crash data for the control 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 control segment crashes in a similar manner previously described for the cable barrier segments. The target crash coding for the control segments were similar to those for the cable barrier segments:

<u>Median or Median Crossover Crash</u>

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 control segments. Further details of the before-and-after cable barrier crash analysis and the control segment crash analysis is presented in the following sections of this report.

5.0 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.

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.

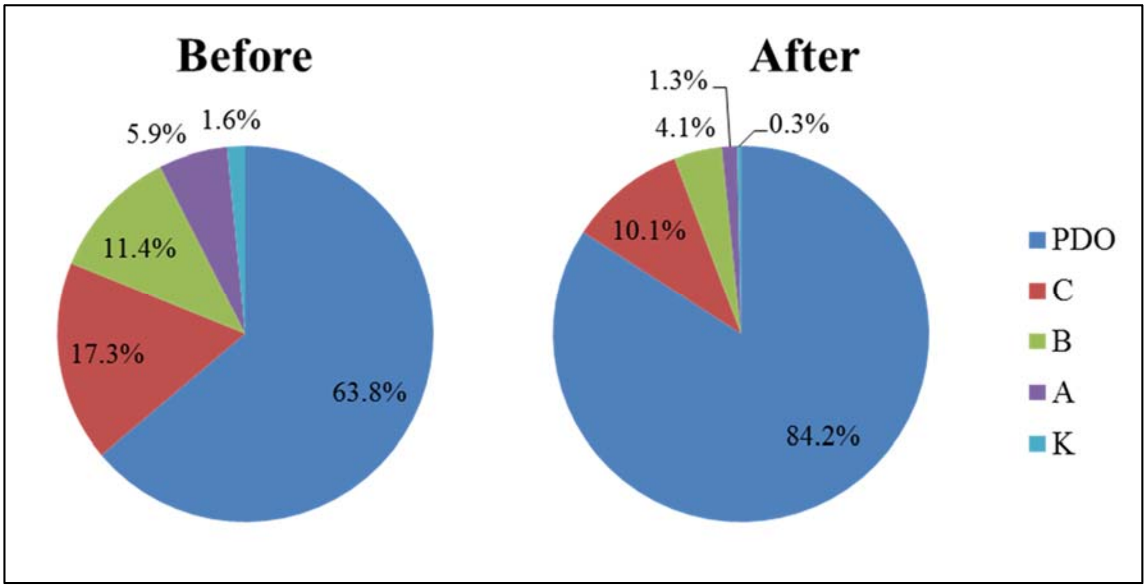


Figure 15. Percent of Target Crashes by Crash Severity and Analysis Period

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**

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.

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.

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%

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 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 Period	1,212	32.0%	2,572	68.0%	3,784	100.0%
After Period	263	6.4%	3,827	93.6%	4,090	100.0%

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 (*34*) 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%

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 (*35*) 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" (*35*). Other states such as Missouri have recommended spacing EV crossovers no more than 2.5 miles apart (*36*). 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

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
	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.

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. 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%

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 (*37*), 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; 30*). 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 (*38*). 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 control 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 control 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

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

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.

Comparison with Other 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 control segments. The details of the identification and crash review for the thrie-beam guardrail and concrete barrier segments were described previously in this report. All target crashes for both control 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 identified. These crashes were summarized by crash severity and crash outcome scenario (contained/penetrated/re-directed). Table 21 presents a summary of thrie-beam median guardrail crashes and Table 22 presents a summary of concrete median barrier crashes.

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 (*39*), indicating both thrie-beam guardrail and cable barrier in Michigan outperform the w-beam guardrail analyzed in Florida.

Table 21. 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.	1,475	317	109	45	5	1,951	83.4%
	%	75.6%	16.2%	5.6%	2.3%	0.3%	100.0%	
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.**	**1,696**	**409**	**142**	**65**	**9**	**2,321**	**99.2%**
	%	**73.1%**	**17.6%**	**6.1%**	**2.8%**	**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 (struck opposing veh.)	No.	0	0	1	2	0	3	0.1%
	%	0.0%	0.0%	33.3%	66.7%	0.0%	100.0%	
Penetrated thrie-beam and entered opposing lanes (did not strike opposing veh.)	No.	4	0	3	2	0	9	0.4%
	%	44.4%	0.0%	33.3%	22.2%	0.0%	100.0%	
Total thrie-beam crashes	No.	1,704	411	146	69	9	2,339	100.0%
	%	72.9%	17.6%	6.2%	2.9%	0.4%	100.0%	

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 (31.1 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 23 which shows the percentage of single- vs. multi-vehicle crashes for cable barrier strike, thrie-beam strike, and concrete barrier strike crashes.

Table 22. 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.	5,893	1,656	546	105	13	8,213	68.9%
	%	71.8%	20.2%	6.6%	1.3%	0.2%	100.0%	
Struck concrete barrier and re-directed back onto travel lanes	No.	2290	940	356	102	16	3,704	31.1%
	%	61.8%	25.4%	9.6%	2.8%	0.4%	100.0%	
Total concrete barrier strikes which did not penetrate concrete barrier	**No.**	**8,183**	**2,596**	**902**	**207**	**29**	**11,917**	**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	0.02%
	%	0.0%	50.0%	50.0%	0.0%	0.0%	100.0%	
Penetrated concrete barrier and entered opposing lanes (struck opposing veh.)	No.	0	0	0	0	0	0	0.00%
	%	N/A	N/A	N/A	N/A	N/A	N/A	
Penetrated concrete barrier and entered opposing lanes (did not strike opposing veh.)	No.	3	1	2	0	0	6	0.05%
	%	50.0%	16.7%	33.3%	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 23. Percent of Single- vs. Multi-Vehicle Crashes by Barrier Type

Crash Type	Cable Barrier		Thrie-Beam Guardrail		Concrete Barrier	
	No.	**%**	**No.**	**%**	**No.**	**%**
Single-Vehicle	3,214	87.5%	1,891	80.8%	9,244	77.5%
Multi-Vehicle	460	12.5%	448	19.2%	2,681	22.5%
Total	3,674	100.0%	2,339	100.0%	11,925	100.0%

In terms of injury severity distributions, 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 16 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.

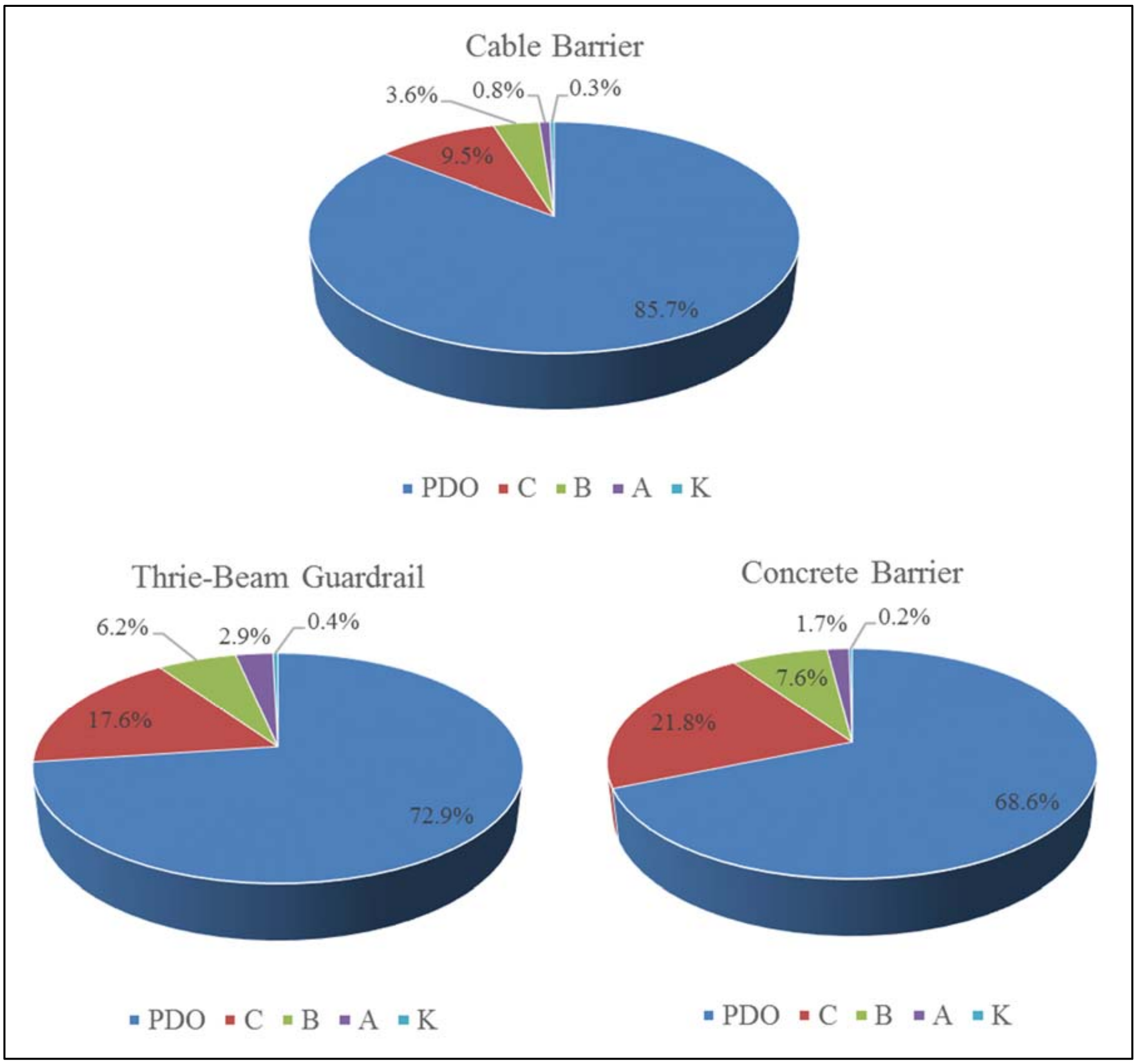


Figure 16. Comparison of Severity Distributions by Median Barrier Type

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" (*5*) . 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 control 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 (*40*). 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 (*40*). As such, negative binomial regression modeling was used to develop all SPFs as a part of this study. A detailed description of negative binomial regression models is included in the Appendix A of this report.

Before and After Cable Barrier SPFs

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 road segments were presented previously in Table 7. Table 24 shows a summary of before and after annual target crashes per segment by severity.

Table 24. 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

The models were developed using SPSS statistical software (*41*). 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.

Table 25. Before and After SPFs for Cable Barrier Road Segments

Dependent Variable	Parameter	Before Period			After Period		
		β	Std. Error	P-Value	β	Std. Error	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		

To illustrate the effect of installing cable median barriers, predicted crashes were calculated for the before and after periods using the SPFs from Table 25 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 17, 18, and 19, 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 17-19, 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.

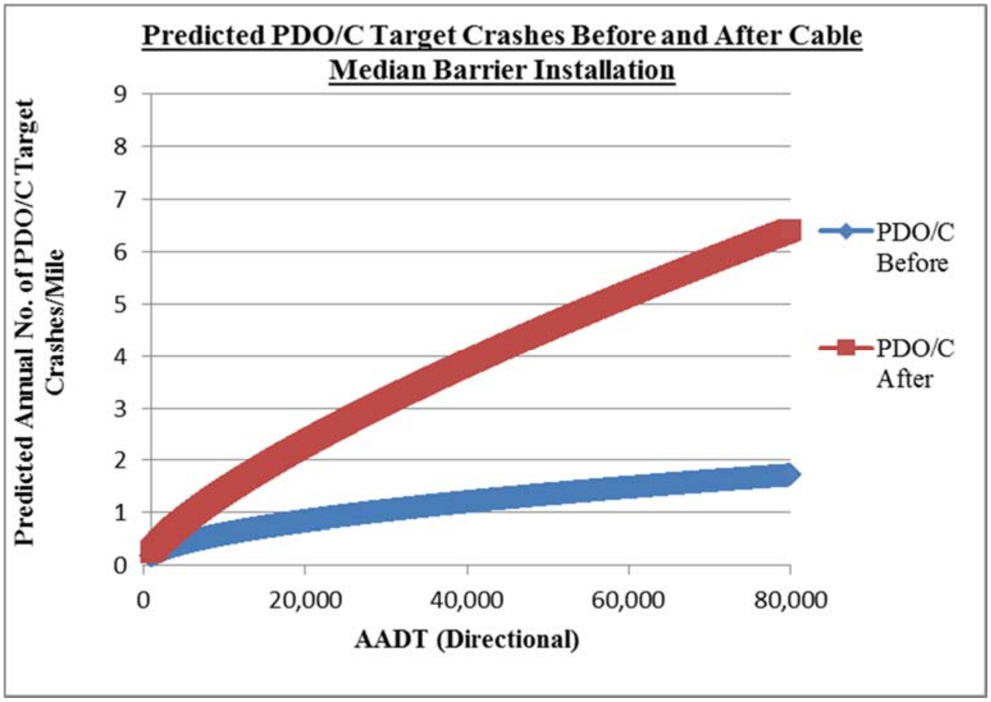


Figure 17. Before and After Cable Barrier SPF Predicted PDO/C Crashes

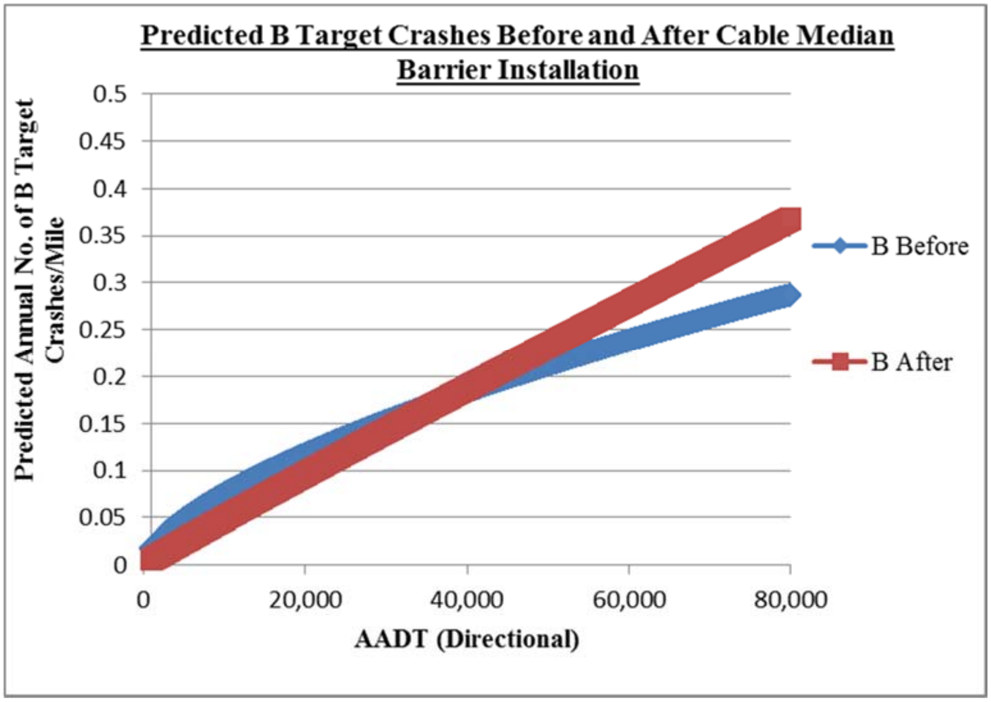


Figure 18. Before and After Cable Barrier SPF Predicted B Crashes

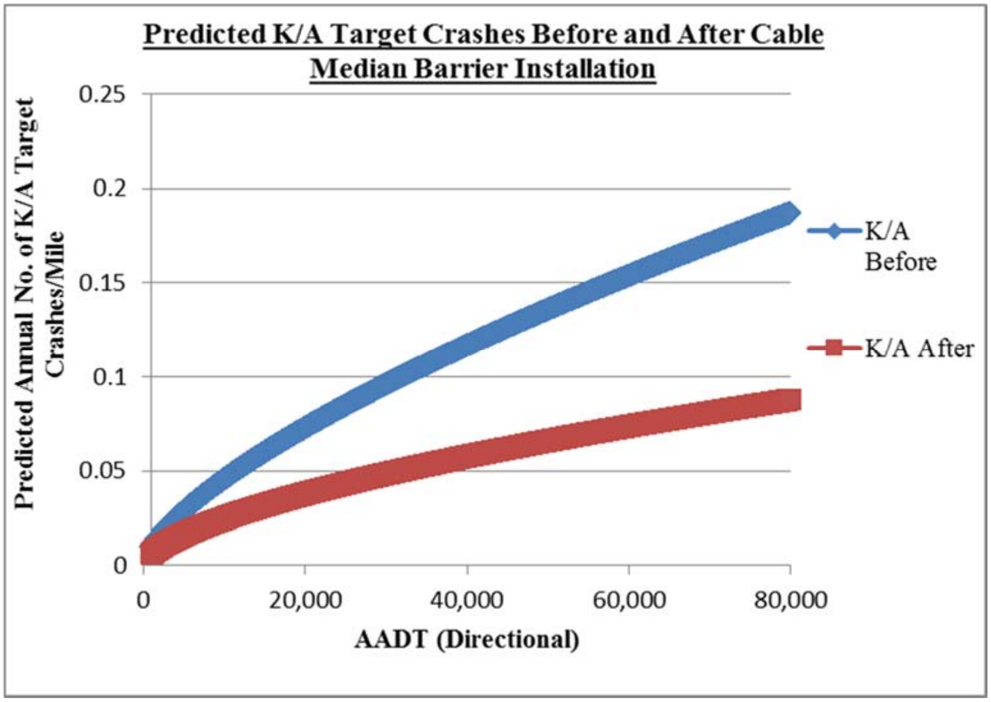


Figure 19. Before and After Cable Barrier SPF Predicted K/A Crashes

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 26.

The parameter outputs for the no barrier SPFs are shown in Table 27. 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 20, 21, and 22, 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 20, 21, and 22 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 26. No Barrier Control Segments Average Annual Target Crashes Per Segment by Severity

Crash Type	Parameter	Average Annual Crash Frequency Per No Barrier Segment
		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 27. 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		

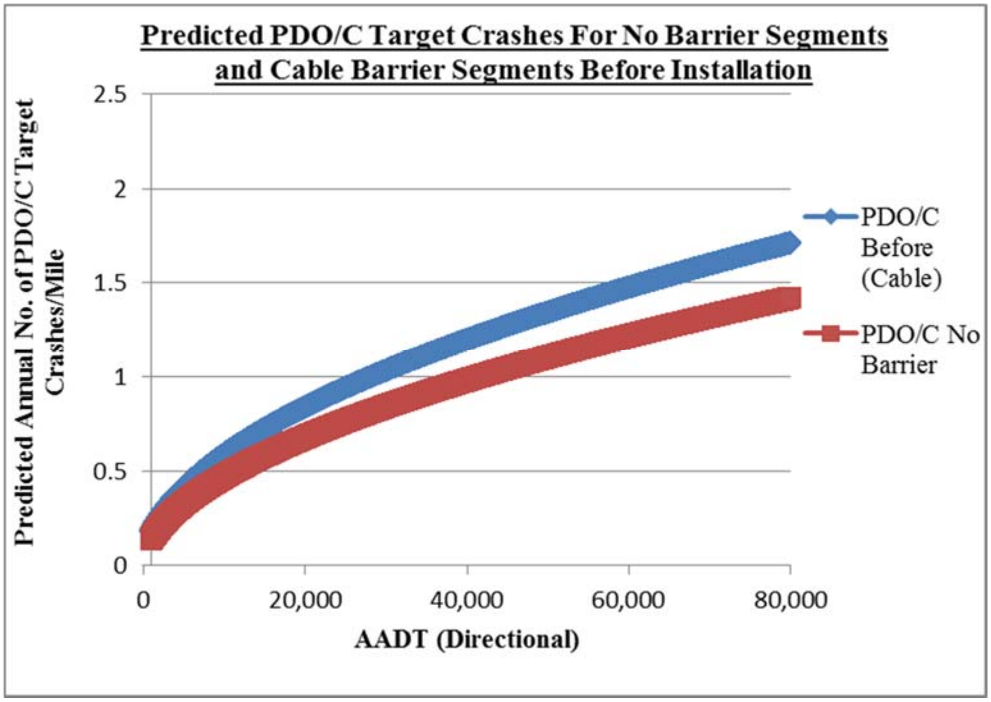


Figure 20. No Barrier and Cable Barrier (before) SPF Predicted PDO/C Crashes

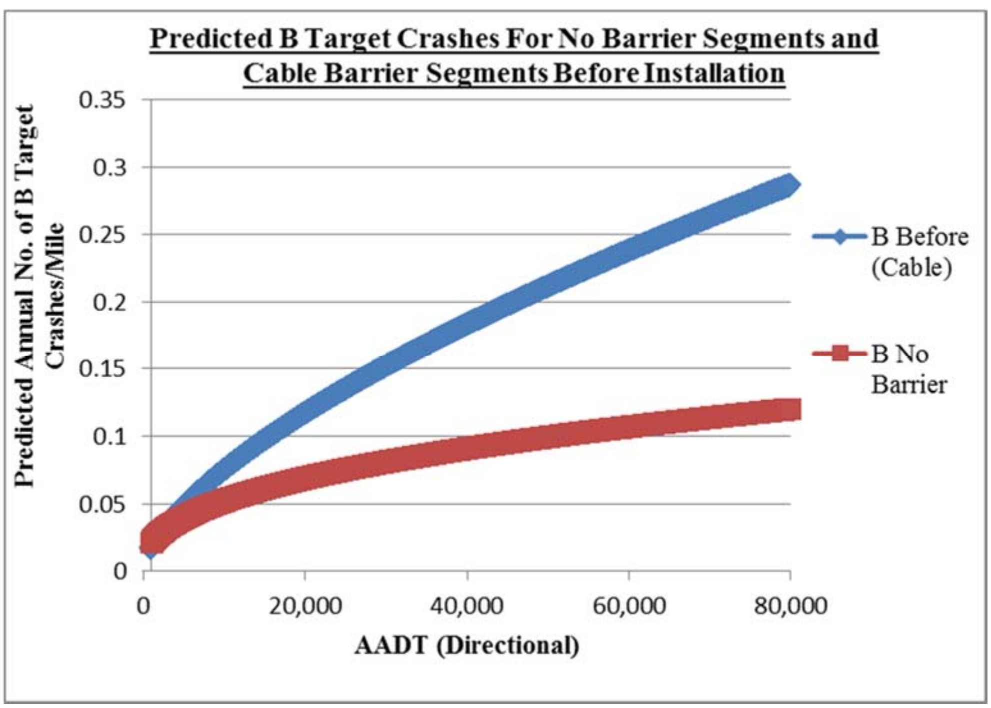


Figure 21. No Barrier and Cable Barrier (before) SPF Predicted B Crashes

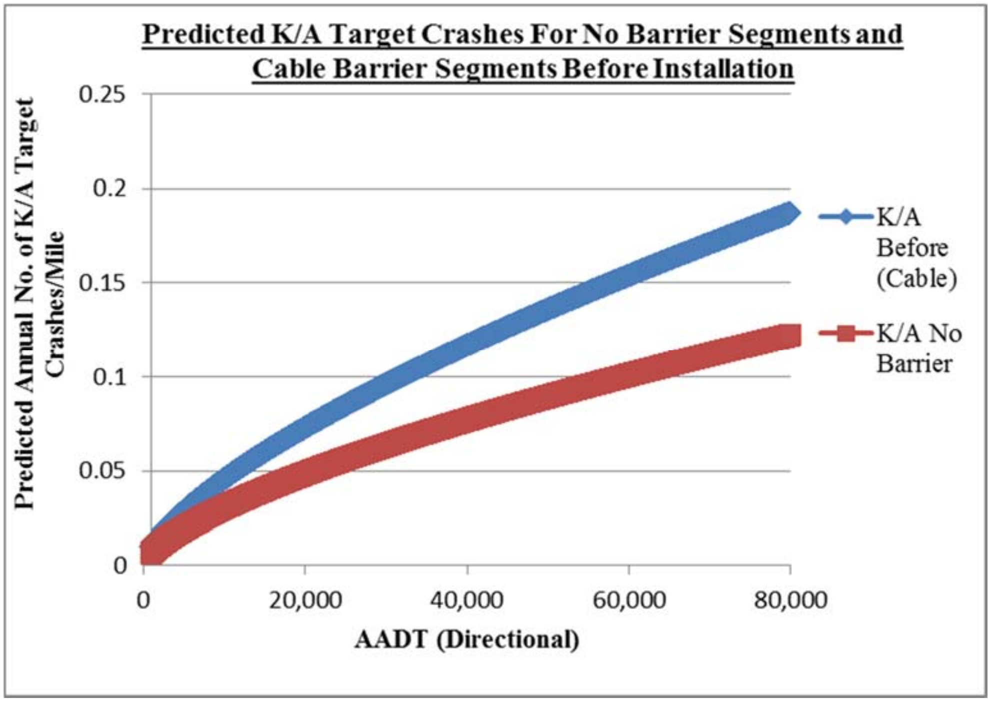


Figure 22. No Barrier and Cable Barrier (before) SPF Predicted K/A Crashes

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; 42; 43*). 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 (*44*). 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 23. 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.

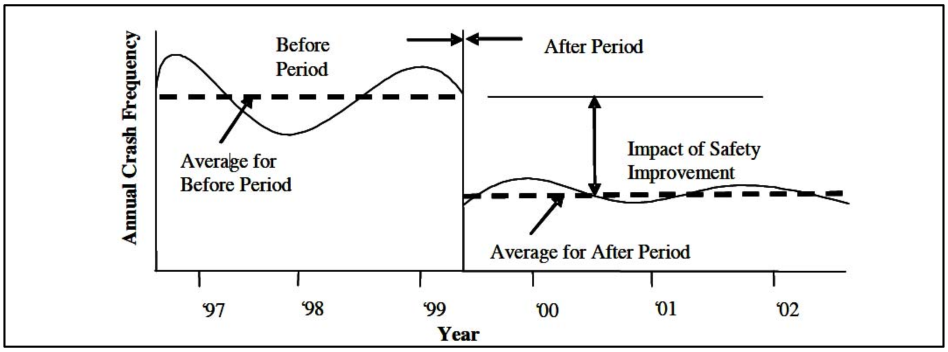


Figure 23. Example of Fluctuation in Crashes Before and After Countermeasure Implementation (*45*)

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 (*5*). 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 (*5*). 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 when the variance in crash rate is smaller for the control group. The crash rate for the control group of similar locations can be in the form of either a mean rate (in the case of before-and-after with control) or a safety performance function (SPF)/regression equation (in the case of the EB procedure).

For this study, an Empirical Bayes design was adopted to account for selectivity bias and potential regression-to-the-mean effects. The reader is referred to the Appendix A of this report for further details of the EB procedure. 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:

<u>PDO/C Crashes</u>: θ = 2.55 (155 percent increase after cable barrier installation)
Standard deviation (θ) = 0.02

<u>B Crashes</u>: θ = 1.01 (1 percent increase after cable barrier installation)
Standard deviation (θ) = 0.08

<u>K/A Crashes</u>: θ = 0.67 (33 percent decrease after cable barrier installation)
Standard deviation (θ) = 0.12

These results are slightly different compared to the reductions observed using simple before and after crash rates presented in Table 11 of this report (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.

6.0 ECONOMIC ANALYSIS

Cable Barrier Installation 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 28. 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 28. 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 Maintenance/Repair Data

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*).

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 (*46*). MDOT utilizes these economic crash costs in their time of return (TOR) worksheet which is described in the subsequent section of this report. MDOT blends the costs of PDO, C and B injury crashes, as well as incapacitating (A) and fatal (K) injuries. Table 29 shows the blended costs utilized by MDOT for time of return analyses.

Table 29. Average Crash Costs by Injury Severity (Source: MDOT TOR Worksheet)

Injury Severity	**Blended Economic Costs**
PDO, C or B Injury	$9,100 per crash
A Injury or Fatality (K)	$258,300 per injured or killed person

Time of Return (TOR) Analysis

In order to determine the economic impacts of Michigan's cable median barrier program, a time of return (TOR) economic analysis was conducted. This is consistent with the methodology used by MDOT for determining the economic effectiveness of safety initiatives. TOR is defined as the amount of time that must pass after implementation, typically gauged in years, for the expected benefits of the initiative to equal the costs of the initiative. Therefore, initiatives with lower TOR values are considered to be more favorable from an economic standpoint compared to those with higher TOR values. MDOT utilizes a TOR calculation spreadsheet (which can be found on their website). This spreadsheet was utilized for the purpose of this study. As mentioned previously, the MDOT TOR worksheet utilizes blended costs based on weighted averages for PDO/C/B crashes and K/A injuries, and these costs were presented in Table 29.

Since there were no 'after' data available for cable barrier installations completed in 2013, these installations were excluded from the TOR analysis. Consequently, the analysis included a total of 302.9 miles of cable barrier. It should be noted that the total installation cost and number of crashes in the before period utilized for the TOR analysis will not match the total values presented previously in Tables 6 and 9 because the 2013 installations are excluded.

In order to complete the TOR analysis using MDOT's calculation spreadsheet, the total present value project cost must be entered. For cable median barrier, this includes installation costs (engineering and construction), as well as the present value for future maintenance costs. It should be noted that an iterative procedure was necessary in order to estimate the maintenance costs for the purposes of the TOR analysis. Since the project costs are inputted in terms of their present value, annual maintenance costs must be converted to present value. Since the present value of maintenance costs will be dependent upon the time-of-return (i.e., maintenance costs will be higher for a longer period), iteration will be necessary to converge to a solution where TOR converges to the nearest year. A summary of the inputs for the TOR analysis are as follows (for 2008-2012 installations):

- Installation (engineering + construction) costs: $47,020,662.95
- Maintenance costs: 1,314 average annual total crashes in the after period x $848.58 per crash = $1,113,034.12 per year. This annual maintenance was converted to present value using an iterative process. Ultimately, 13 years of maintenance costs were converted to present value using a series present worth (spw) factor with 2.5% interest rate (spw factor for i=2.5% and n=13 years = 10.983). The total present value for maintenance costs was $1,113,034.12 x 10.983 = $12,224,453.74
- Total present value cost = $47,020,662.95 + $12,224,453.74 = $59,245,116.69
- Total average annual crashes in before period = 616.3 crashes
- Total average annual PDO/C/B crashes in before period = 570.3
- Total average annual K/A injuries in before period = 68.0 (56.9 A-injuries and 11.1 fatalities)
- Percent reduction PDO/C/B crashes based on raw before-after data: -126.0%
- Percent reduction K/A injuries based on raw before-after data: 55.1%
- Default values of ADT growth (10%) and rate of inflation (2.5%) were utilized
- Area type was coded as 'between'

Table 30 presents a summary of the TOR analysis. 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. The TOR for the cable barrier installations in

Michigan was found to be 13.36 years. This finding indicates that high-tension cable barrier provides a cost-effective alternative to reduce cross-median crashes on Michigan freeways.

Table 30. Summary of Time of Return Analysis

Injury Severity	Observed Total Average Annual Crashes/ Injuries Before Installation	Observed Total Average Annual Crashes/ Injuries After Installation	Percent Reduction
PDO/C/B (crashes)	570.3	1289.0	-126.0%
K/A (injuries)	68.0	30.5	55.1%

Economic Factors	Present Value Costs
Installation Costs	$47,020,662.95
Maintenance Costs	$12,224,453.74
Time of Return	**13.36 years**

7.0 CABLE 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 (*1*). 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 (*1*). 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.

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 24 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.

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

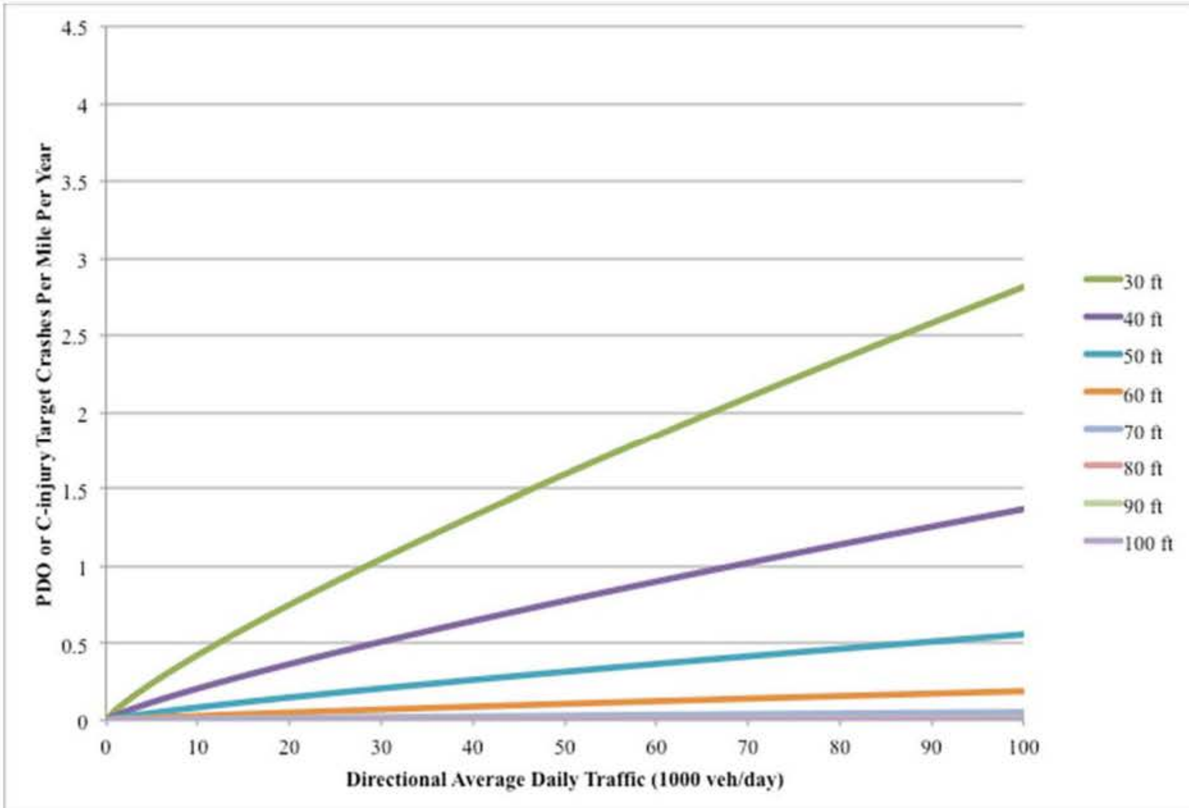
$$Crashes_{K/A\ AFTER} = ADT^{0.613} exp(-9.343).$$

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:



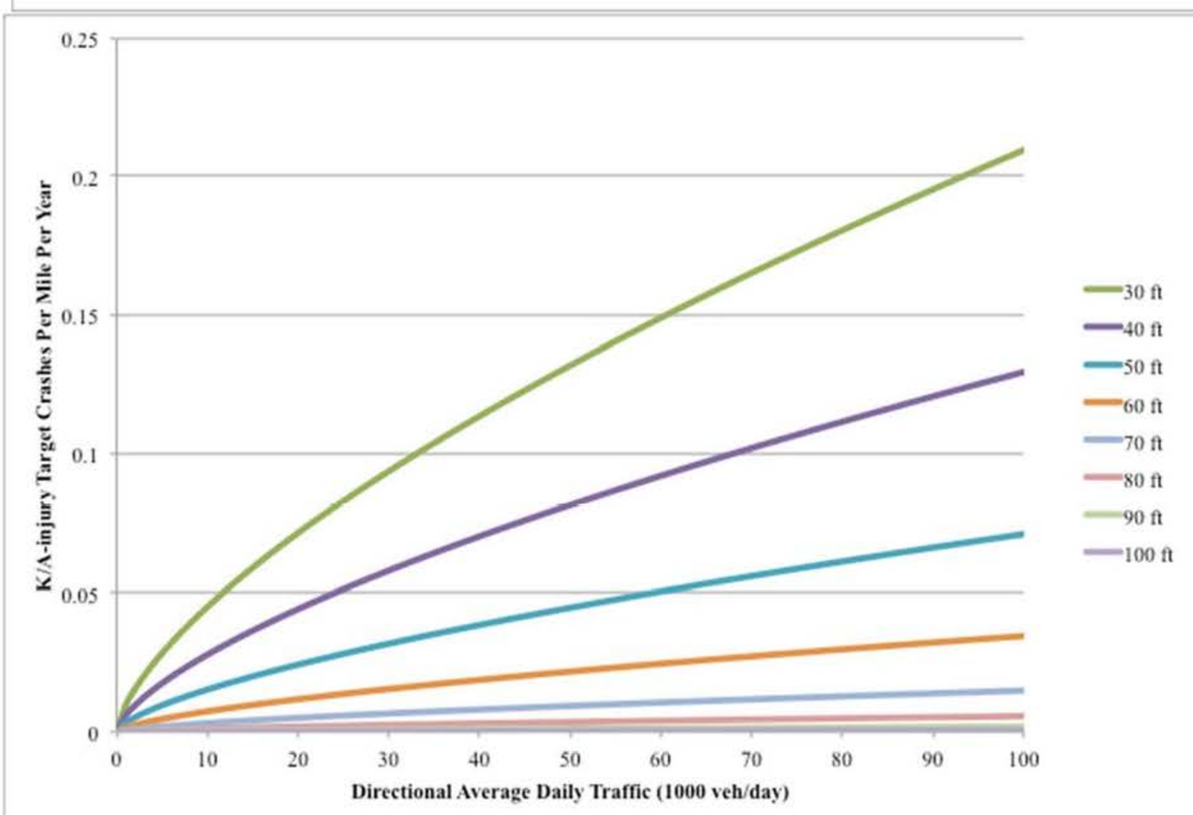


Figure 24. Predicted Number of Target Crashes by Severity Level (PDO/C and K/A) Based upon Directional Average Daily Traffic and Median Width

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 safety performance function (SPF) for PDO/C-injury crashes at locations where cable barrier has been installed is as follows:

$$Crashes_{PDO/C\ AFTER} = ADT^{1.028} exp(-9.535 - 0.006 \times WIDTH)$$

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 31 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.

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.

Table 31. PDO/C-injury SPF 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 > 3,500 feet	Baseline
	Curve w/ radius 2,500-3500 feet	70.2% increase
	Curve w/ radius <2,500 feet	104.2% increase

Effects of 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 25 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.

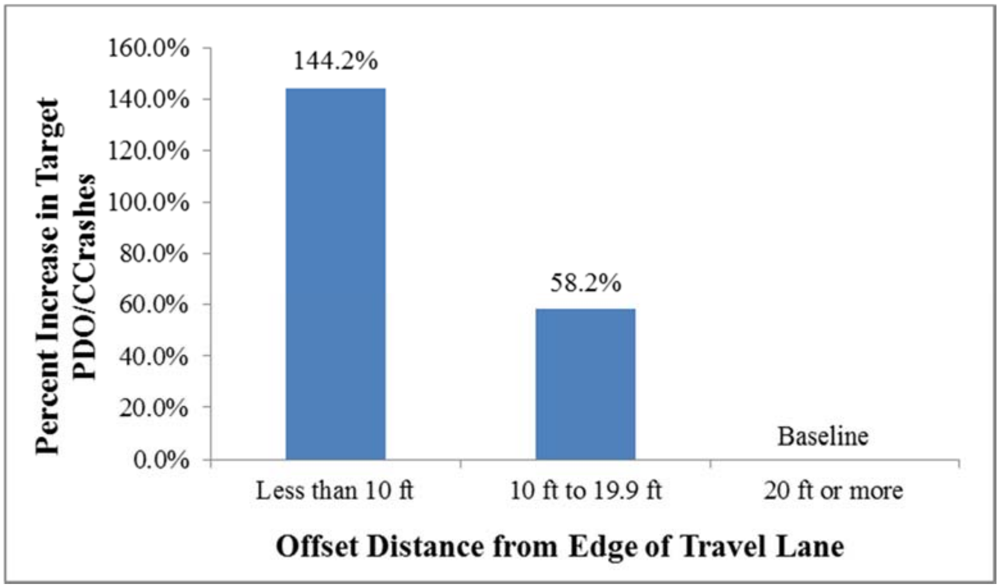


Figure 25. Effects of Offset Distance on Target PDO/C Crash Frequency

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 26 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.

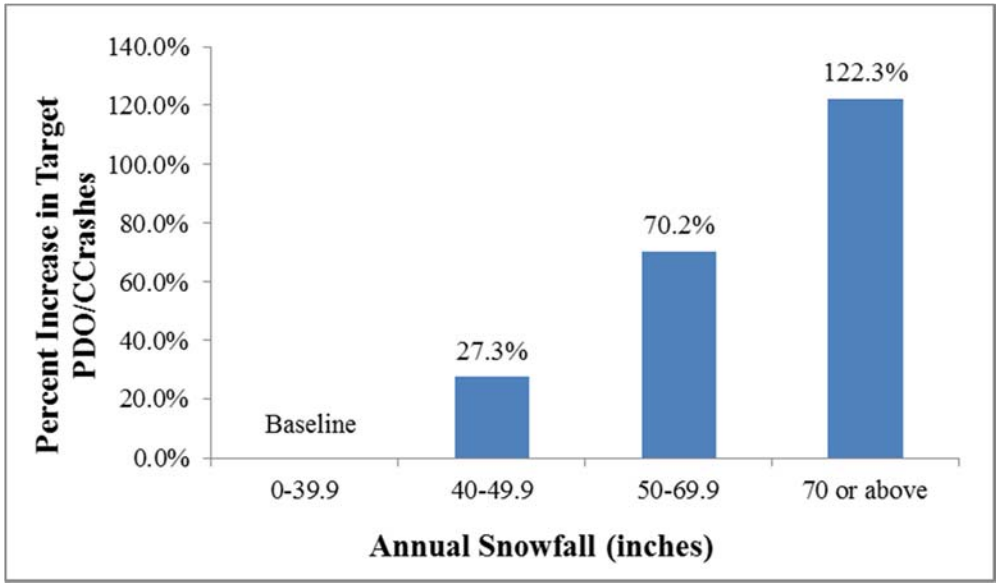


Figure 26. Effects of Snowfall on Target PDO/C Crash Frequency

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 27 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* (*47*) which found increased median-related crash rates on horizontal curves with radii less than 3000 feet.

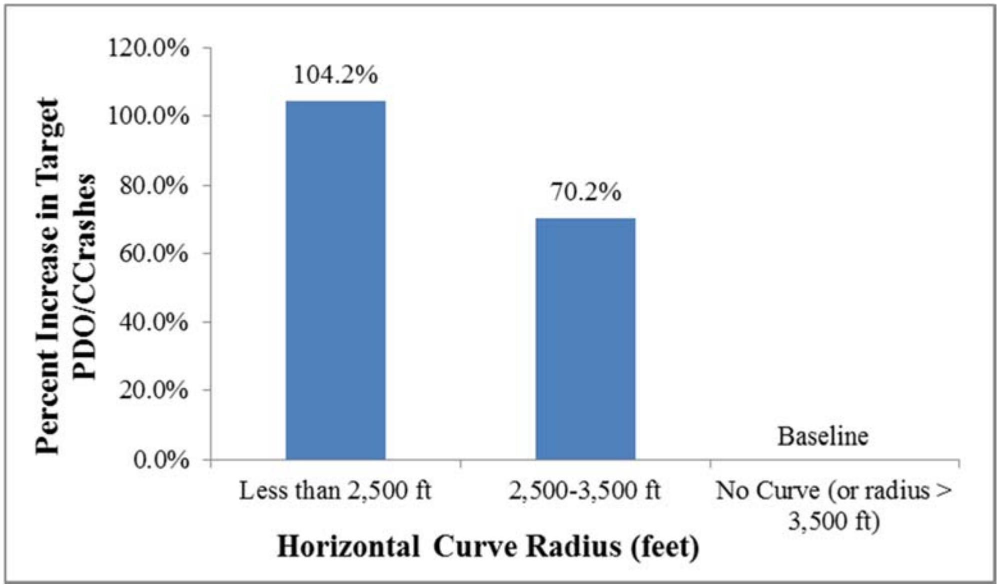


Figure 27. Effects of Horizontal Curvature on Target PDO/C Crash Frequency

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. Appendix B of this report presents an example case study of guideline application.

8.0 RESULTS 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 September 2013. 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.

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. This analysis consisted of a time of return (TOR) analysis, which is consistent with the methodology used by MDOT for determining the economic effectiveness of safety initiatives. TOR is defined as the amount of time that must pass after implementation, typically gauged in years, for the expected benefits of the initiative to equal the costs of the initiative. The TOR analysis was conducted for cable barrier installations in Michigan through 2012 (2013 installations were excluded due to lack of post-installation crash data). Engineering, construction, and maintenance costs were considered as part of the TOR analysis, as well as the benefits realized by reductions in severe crashes. Ultimately the TOR for cable median barrier installation in Michigan was found to be 13.38 years.

One of the main goals of this study 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 (*1*), “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.

APPENDIX A – STATISTICAL METHODS

Negative Binomial Regression Model

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 (*40*):

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

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 (*40*).

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 $VAR[y_i] = E[y_i] + \alpha E[y_i]^2$ (*40*). The α term is also known as the over-dispersion parameter, and will be utilized during the before and after Empirical Bayes 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.

Empirical Bayes

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 section of this report 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.

APPENDIX B – EXAMPLE GUIDELINE APPLICATION

This appendix provides an example application of the cable median barrier guidelines. A case study is provided for a section of US-131 between 84th Street and 100th Street south of the City of Grand Rapids in MDOT's Grand Region. Cable barrier was installed at this location in 2009.

Required input data:

The characteristics of this segment are included here:

- Segment length = 2.0 miles
- Length of before period = 5 years

Crashes/Injuries by Severity Level	2004	2005	2006	2007	2008	SUM	AVG.
Number of Crashes*	4	11	5	6	9	35	7.00
PDO+Minor Inj Crashes*	4	8	4	5	8	29	5.80
Number of K/A Crashes	0	3	1	1	1	6	1.20
A-Injured or Killed Persons*	0	6	1	2	2	11	2.20

*These values are entered directly on the TOR worksheet

Note that only 'target' (i.e. median-related) crashes should be included in the analysis.

- The percent reduction (increase) for PDO/C crashes is -155% (entered directly on TOR worksheet)
- The percent reduction for K/A injuries is 44% (entered directly on TOR worksheet)
- The percent reduction for K/A crashes is 33% (used only for estimating annual maintenance costs)

Required cost estimation procedure:

Estimate costs for installing cable barrier: $155,621.49 per mile x 2.0 miles = $311,242.98.

At this point, an initial TOR can be calculated using the TOR worksheet to estimate a starting point for the number of years of maintenance costs to include in the analysis (Initial TOR = 1.31 years).

Estimate annual costs for maintaining/repairing cable barrier:

Estimate annual crashes in after period:

PDO/C: 5.80 x 2.55 = 14.79 (155% increase)

K/A = 1.20 x 0.67 = 0.80 (33% decrease)

Total = 14.79+0.80=15.59

Annual maintenance cost = 15.59 crashes x $848.58 per repair = $13,229.36

Convert annual maintenance cost to present value: try n=1 year (based on the initial TOR starting point) conversion using series present worth (spw) factor with i=2.5%:

$spw = [(1+i)^n - 1]/[i(1+i)^n] = [(1+0.025)^1 - 1]/[0.025(1+0.025)^1]$ = 0.976

Present worth of maintenance cost = \$13,229.36 x 0.976 = \$12,911.86

Total estimated present worth of project cost = \$324,154.84

<u>Enter all corresponding values into TOR worksheet:</u>

NUMBER OF CRASHES OR INJURED PERSONS.

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
	2004	2005	2006	2007	2008
- -	-	-	-	-	-
		-155%	%REDUCTION		
Number of Crashes	4.00	11.00	5.00	6.00	9.00
PDO+Minor Inj Crashes	4.00	8.00	4.00	5.00	8.00
A-Injured or Killed Persons					
- -	-	-	-	-	-
		44%	%REDUCTION		
Number of Crashes	4.00	11.00	5.00	6.00	9.00
PDO+Minor Inj Crashes					
A-Injured or Killed Persons	0.00	6.00	1.00	2.00	2.00

# of **A-injuries**:	0	For reference only	**TOR =**
# of **Fatalilties**:	0	For reference only; "Q" accounts for the risk of a fatality.	1.37
PROJECT **COST** ESTIMATE :	\$324,155	If unknown, enter "0" (zero).	
ADTb (before-volume)	1.0	You may change these default ADT rate values	
ADTa (after-volume)	1.1		
# OF **YEARS** OF DATA:	5	**3 to 5** years should be used.	
RATE OF **INFLATION**:	2.50%		
AREA TYPE:	3	(**1** = RURAL, **2** = URBAN, **3** = BETWEEN)	

Check the TOR output and confirm that the assumed number of years of maintenance costs is within one year of the output TOR. If the TOR differs from the assumed number of years of maintenance, another iteration should be performed with an adjusted assumption of maintenance years until the values converge to within one year.

This example outlines the general process for estimating the TOR for installing cable median barrier on a given segment of freeway. The percent reductions applied in this example are average reductions, and engineering judgment should be practiced based on the specific conditions for a particular freeway segment. The percent reductions can be adjusted based on engineering judgment and/or using SPFs and other adjustment factors presented in Chapter 7.0 of this report.

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