Evaluation of High-Tension Cable Barriers in Wisconsin

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16. Abstract

A cross median crash (CMC) is a typically violent collision with a disproportionately high probability of fatalities and severe injuries. To mitigate the devastating effects of CMCs, the Wisconsin Department of Transportation (WisDOT) installed median cable barriers at several locations on state highway sections where a number of CMCs have occurred. This study evaluated the safety effectiveness and performance of four different cable barrier systems used as a CMC countermeasure, namely CASS, Brifen, and Gibraltar, all considered high-tension cable barriers, and a common low-tension cable barrier system.

The results of this study are based on a before-and-after crash comparison as well as cable maintenance log data. Key findings are:

1) An appreciable portion of Wisconsin's cable barrier crashes are weather- and road condition-related;

2) Cable barriers are effective in reducing CMCs and crash severities;

3) High-tension cable barriers perform better than low-tension cable barriers in all categories (maintenance cost, repair time, post-collision conditions).

A cost-benefit analysis exhibits high safety benefits (B/C ratios ranged from 3.2 to 13.0) of the implementation of median cable barriers at the test locations. In addition, cost per hit and unit cable operation and maintenance cost per mile generated from Wisconsin data can assist WisDOT in planning future cable barrier installations and developing predictive cable median barrier warrants.

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Executive Summary

A cross median crash (CMC) is a typically violent collision with a disproportionately high probability of fatalities and injuries. Median barrier is a commonly used countermeasure for CMCs. Past studies in other states overwhelmingly indicate that installing cable barriers can drastically reduce the occurrence of CMCs. The Traffic Operations and Safety (TOPS) Laboratory at the University of Wisconsin-Madison, conducted an evaluation of several cable barriers used by the Wisconsin Department of Transportation (WisDOT) to determine their effectiveness as a CMC countermeasure.

Three types of high-tension cable barrier (HTCB): Brifen, CASS and Gibraltar, were evaluated along with a low-tension cable system. Seven sites on USH 41 (in Fond du Lac and Winnebago counties) and I-94 (in Waukesha County) were included in the study. Three years of crash data from prior to the installation in these locations were compared with the crash data collected after the cable installation. Three types of crashes were included in the before data: median entries (ME), cross median events (CME), and CMCs. In order to obtain an unbiased performance evaluation and cost-benefit analysis, all police crash reports were reviewed manually to ensure the accuracy of this data. Cable maintenance and repair logs were also collected and analyzed.

Data analysis showed that median-related crashes are frequently weather- and road condition-related (either during snowy weather or icy pavement), although less severe than crashes on dry pavement. Before and after comparisons of crash counts and crash rates indicate that more median-related crashes, especially property damage only (PDO) crashes, occurred after the installation of median cable barrier, but overall crash severities were reduced significantly. A Chi-squared (χ^2) statistical test confirmed that cable barriers contributed to a significant crash severity reduction. A series of statistical tests were conducted to compare different cable barrier systems in terms of man-hours for repair, number of posts replaced and total maintenance cost per hit. In general, Brifen and CASS are superior to low-tension cable while Gibraltar is superior to low-tension only in man-hours used. The cost-benefit analysis showed high values of benefit to cost ratios (ranging from 3.2 to 13.0), demonstrating that high-tension cable barriers are an excellent solution for mitigating CMCs and reducing crash severities. Finally, the cost per hit and unit cable operations and maintenance cost per mile generated from Wisconsin data can assist WisDOT in planning future cable barrier installations and developing predictive cable median barrier warrants.

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INTRODUCTION

A cross median crash (CMC) is a crash in which a vehicle crosses the median and hits vehicle(s) in the opposing travel direction. The American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide* recommends two countermeasures for preventing CMCs: widening medians to a sufficient width to provide an adequate clear zone for a running-off-the-road vehicle to recover; or installing median barriers when the median is less than 30 feet wide and annual daily traffic (ADT) is greater than 20,000 vehicles (*1*). Recently, several states have reconsidered the *Roadside Design Guide* in light of their own crash experiences and have developed guidelines calling for a more aggressive provision for barriers or provisions for installing median barriers in medians greater than 30 feet (*2*).

Previous research has shown that CMCs, although less frequent, are responsible for a disproportionately high number of fatalities and serious injuries because CMCs are typically high-speed violent collisions (*3, 4*). Many of these crashes could be prevented with adequate median barrier protection. However, installation of median barriers can lead to barrier collisions caused by vehicles encroaching into the median, thereby increasing the frequency of crashes, although the barrier crashes are typically less severe than CMCs. The tradeoff between reduced CMCs and median barrier crashes demands a comprehensive assessment of the benefits of median barriers.

The objective of this study was to evaluate the performance of high-tension cable barrier (HTCB) and low-tension cable barrier (LTCB) systems installed on Wisconsin state highways.

LITERATURE REVIEW

The literature review found a great number of studies on median-related issues. Literature review presented here primarily focuses on performance of cable barriers and their cost effectiveness.

The study of cable barriers on New York State roads found that over a three-year period from 1967 to 1969, there were 125 police-reported cable guardrail related crashes per year. In 27 percent of these crashes, the cable system was penetrated. There were 1.3 fatalities and 6.0 injury crashes per year. During the three-year period, two of the fatalities involved penetrating the barrier. In spite of the penetrations, New York’s study still concluded the weak-post cable barrier resulted in less severe crashes than strong post W-beam guardrail systems (*5*).

Another early cable evaluation in Iowa studied cable guardrail effectiveness in 1977 and 1978. There were 16 police-reported crashes per year. In 23 percent of the crashes, the cable system was penetrated. Twenty-nine cable barrier repairs per year were reported with the average repair cost per crash of $543 ($90 per post). The study concurred with New York study that cable barrier impacts were less costly and less severe than impacts with other barriers, and the cable system performed adequately (*5*).

Low-tension and weak post cable barrier systems installed in the 1960s or 1970s have a relatively high penetration rate, which has been substantially reduced with the recent high-tension cable systems. In a Florida median barrier pilot study, there were 20 reported impacts from May 2005 to April 2006 (*6*). All impacts successfully restrained crashed vehicles and prevented them from encroaching on opposing lanes with no median crossover fatalities reported within cable barrier areas. Another study in Illinois reported an almost flawless result of high-tension cable barrier: only one penetrated crash was found out of a total 198 median barrier crashes (*7*). All vehicles were retained within the median and only two out of the 198 cable crashes resulted in a cable snapping. A large tractor-trailer truck was involved in one of the cable snapping crashes. It should be noted that cable barriers are not designed to stop the weight of a large truck, although examples of successful stoppages exist.

An Oregon study evaluated the effectiveness of the three-cable barriers in preventing crossover crashes on Interstate 5 and Oregon Highway 1, and estimated the maintenance and repair costs in order to make recommendations for future installations (*8*, *9*). The cable median barrier system worked well in medians with a minimum width of seven meters, where it prevented the infrequent but potentially catastrophic CMC. According to the research results, the cable median barrier system proved to be cost-effective when compared with concrete median barrier system, and decreased CMCs in the area.

The North Carolina Department of Transportation (NCDOT) is one of a few agencies that decided to implement system-wide cable median barriers as a countermeasure for CMCs. Cable barriers were installed for the entire Interstate highway network with median widths of 70 feet or less. Their maintenance and repair costs, sampled along an 8.5 miles long section on I-40, showed that there were 71 cable barrier impacts/repairs per year without any fatal crashes. The estimated repair cost per post was $86 for the subject section (*10*). More recently, Hunter *et al*. studied in detail the effectiveness of the cable barrier system in North Carolina. The researchers developed negative binomial regression models and used a reference population of the North Carolina Interstate highways to predict the expected number of crashes. They found that the high-tension barriers successfully reduced CMCs. They also found an increase in crashes from pre to post-treatment, but only to a level equivalent to the rest of the interstate system (*11*). However, overall safety was enhanced (*11*). Hunter's findings are supported in a later study by Texas Transportation Institute (TTI) (*12*). In a follow-up study on a larger scale, NCDOT reported a reduction of 54 fatal crossover crashes. One hundred thirty three fatal crashes occurred in a before study period (1994-1998) while 79 occurred in an after study period (1999-2003). In the same period, fatalities reduced from 198 to 104 on 238 miles of freeway that were monitored (*13*). A study from Missouri Department of Transportation (MoDOT) yielded similar results: merely two fatalities occurred in 2006 after an accumulated 179 miles of cable barrier was installed compared with 24 fatalities with only 18 miles of cable barrier installed in 2002 (*14*).

Following the same philosophy as NCDOT, South Carolina Department of Transportation equipped their state highways with more than 470 miles of cable barriers by mid-2006, which decreased fatal CMCs to 4 in 2006 from 27 in 2000. Given the $902 per hit maintenance cost, the study reaffirmed that installing median cables to prevent severe crashes is a cost effective solution (15).

Cable median barrier installation cost in Washington State was calculated to be approximately $44,000 per mile. The average cost per repair was found to be $733 and the maintenance repair cost per mile was found to be $2,570 annually. The societal benefit of this cable median barrier installation was calculated to be $420,000 per mile annually. Given the societal benefits associated with the use of a cable median barrier at locations having substantial prior CMCs, cable median barriers have been found to be a cost effective solution to CMCs (*16*, *17*).

A research study funded by the Kansas Department of Transportation examined crashes on an access-controlled freeway in Kansas from 2002 to 2006 in order to assess the need for cable median barriers. A total of 126 CMCs and 527 CME were identified. CMCs were found to be more frequent and less severe in winter months. This finding indicates that median barrier warranting criteria may need to be adjusted to accommodate regional climate differences. Cable crash rates and maintenance costs from Missouri were used for the Kansas cost-benefit study because of a lack of these data for Kansas (Kansas had not installed cable median barriers yet). The study concluded that implementing cable median barrier may be cost beneficial (*18*).

Although overwhelming evidence and evaluations support median cable barriers as an effective approach to reducing CMCs and their severities, one exception appeared in a study report based on data collected from I-5 in Maryville, Washington, suggesting that cable barriers may negatively impact overall safety. Prior to installing cable barrier systems, the fatal median collision rate was 0.27 fatalities per million vehicle miles traveled (MVMT). After the installation of cable barrier the fatal median collision rate was 0.28 fatalities per MVMT. The reasons for this slight increase were unclear. This one roadway section in Washington State is atypical of cable barrier performance in other locations within Washington State. Overall cable barrier performance in Washington State resulted in a 63 percent reduction in the CMC rate (including both fatal and non-fatal) (*20*). The atypical performance of cable barrier on I-5 near Maryville signaled a possible failure within the system and encouraged further investigation and evaluation of candidate locations for cable barrier.

Reported installation costs for high-tension cable barrier range from $54,000 to $125,000 per mile and the average reported maintenance cost per hit varies from approximately $312 to $1,795 (*5, 8, 9, 12, 15, 16, 17 and 23*). Overall, the severity of median related crashes reduced significantly after high-tension median barrier installation. As expected, the number of total crashes tends to increase, especially total property damage only crashes, because of the new object in the right-of-way. Table 1 provides cost lists from various states, with dollar values adjusted to 2008 dollars assuming an interest rate of four percent. Given the wide range of installation and maintenance costs, it is necessary to quantify these values in Wisconsin to obtain a realistic and reliable cost estimate for the WisDOT future planning and investment decisions.

WISCONSIN CABLE MEDIAN BARRIERS

Types of Median Barriers

Median barriers are generally classified into three categories: flexible, semi-rigid and rigid barriers. Flexible systems have the greatest dynamic deflection and are the most forgiving barrier systems. The maximum deflection during an impact for a flexible system ranges from eight to twelve feet. Cable and weak post W beam are usually included in this category. Flexible barriers are generally considered good solutions for rural locations with wide open, unprotected median, free of woody or mounding vegetation and median slope of 6:1 or flatter (*21*).

Table 1 Installation Cost and Maintenance Cost in Various States*

States	Installation Cost $/Mile	Maintenance Cost $/Hit ($/Post)	 $/Mile/year
Colorado	$71,280	$1000	NA
Illinois	$114,217	$748	NA
Indiana	$125,090	$312	NA
Iowa	$105,600	$904 ($114)	NA
Louisiana	$92,400	NA	NA
Missouri	$60,000-$100,000	NA	$6,000-$10,000
New York	NA	$415	
North Carolina	NA	($104)	$6804
Oregon	$55,725	$1795 ($405)	$3596
South Carolina	NA	$1015	NA
Washington	$53,333	$892	$3127

* adjusted to 2008 dollars at 4% Interest Rate.

The semi-rigid systems include three types of barriers: strong post W beam, Thrie beam and box beam. Strong post W beam and Thrie beam belong to strong post system, but box beam is considered a weak post system. Strong post W beam deflects approximately two to four feet during a typical impact. Strong post W beam is very effective and typical along narrow medians. Thrie beam barriers deflect as little as one foot with a full impact and can accommodate a larger range of vehicles than W beam. Thrie beams are an effective solution at very narrow median locations. Box beam barriers deflect about three feet and are relatively inexpensive to repair.

Rigid systems, typically concrete barriers, are usually placed where there is not enough space to accommodate the magnitude of dynamic deflection without affecting the opposing traffic. Because the rigid concrete barriers do not have any dynamic deflection, injuries are usually more severe than the semi-rigid system because of more energy being absorbed by the vehicle and occupants during contact. Rigid concrete barriers are usually used on highways and freeways with high posted speed limits and high traffic volumes with narrow or no medians.

Wisconsin Cable Barrier Types and Placement

Before the high-tension cable barrier systems were developed and approved for use, Wisconsin installed low-tension median cable barriers at locations warranted by the WisDOT Facility Development Manual (FDM). WisDOT began installing high-tension cable barrier with the increase in traffic and advancement of cable technologies. Starting from a pilot project approved by FHWA, WisDOT initially installed two types of HTCB systems, Brifen and CASS, in the median of USH 41 in Fond du Lac County. Installation locations are shown in Figure 1.

Once a decision has been made to shield a median highway section, the type of barrier (rigid, semi-rigid, or flexible) and the location of the barrier (edge of shoulder versus middle of median) must also be decided. The WisDOT *Facilities Development Manual* (referencing the AASHTO *Roadside Design Guide*) provides guidance for how to place various barrier systems (*26*).

Gary *et al*. reconstructed several CMCs to produce estimates of the impact severity at the edge of the shoulder and at the center of the median (*20*). The findings indicate that placing a barrier in the center of the median increases the probability that a vehicle will hit the barrier at an angle steeper than what barrier systems are designed for, than placing the barrier on the shoulder edge. This in turn means that the impact severity of the resulting collision may exceed the test level specified in NCHRP Report 350 *(22)*. In addition, placing barriers on the shoulder edge also provides an easier identification of median entry crashes than placing barriers in the center of median (*22*). However, more cable barrier impacts could be expected. A study performed by the Pennsylvania Department of Transportation admitted that it was hard to identify how many median related crashes will become cable collisions after cable installation if cable barriers are placed in the center of median (*20*). Therefore, the decision to place high-tension cable barrier along the shoulder or in the center of the median must consider the trade-offs cited above. In Wisconsin, initial installation of high-tension cable barriers were installed at the edge of the shoulder (as shown in Figure 1) in one travel direction at the pilot locations. In other words, single run cable barriers (versus double run cable along both shoulders) were installed.

Figure 1 Locations and Typical High-Tension Cable Barrier Installation at the Edge of Shoulder.

Median Width

The median widths at the study locations are between 15 and 50 feet. These locations satisfy the median width requirements for installing cable barrier as AASHTO warrants median barrier installations for median widths of less than 70 feet, given the traffic volume at this location (*1*). Figure 1 shows the cable barrier locations and Table 1 provides median widths of study locations in Wisconsin by cable type.

Table 2 Median Widths for the Study Locations

Cable Barrier System	Median Width (feet)	Median Width (feet)
Brifen	50 (N. of Fond du Lac)	50 (S. of Fond du Lac)
CASS	48 (N. of Fond du Lac)	50 (S. of Fond du Lac)
Low-tension	30 (N. of Fond du Lac)	15 (S. of Fond du Lac)
Gibraltar	50 (Waukesha)	

DATA COLLECTION

Study Locations

In this study, both high-tension and low-tension cable barriers were considered for analysis. In Wisconsin, high-tension cable barriers were installed at the initial test site on USH 41 in Fond du Lac County, as well as additional sites in Winnebago and Dodge Counties, and on I-94 in Dunn, Juneau, Waukesha, and Dane Counties. These installations included several types of high-tension cable barrier, including CASS, Brifen, SafeFence, Nucor, and Gibraltar. Due to limited after data for several of the cable barrier installations, not every installation was evaluated in this study. The installations that were evaluated in this study include Brifen and CASS median barriers in Fond du Lac and Winnebago Counties on USH 41, and Gibraltar median barriers in Waukesha County on I-94. The length of Brifen installation is 7.7 miles in total, including 4.07 miles south and 3.63 miles north of the City of Fond du Lac. The length of CASS installation is 6.91 miles in total, including 2.60 miles south and 4.31 miles the north of the city. The length of Gibraltar installation is 5.90 miles in total, including 3.57 miles in Dunn County and 2.33 miles in Waukesha County. The section of Gibraltar in Dunn County was not included in this study because of insufficient cable maintenance data collection. Due to different construction stages, between one and two years of data were available for each study location. A low-tension system was also evaluated for comparison purposes. The total length of the common low-tension cable system is 2.34 miles, including one 1.30 mile-long segment and the other was a 1.04 mile segment. The location information of three cable types is summarized in Table 3.

Table 3 Cable Barrier Locations and Lengths

Barrier Types	Total Length	Location	North of Fond du Lac		
			Start RP	End RP	Length
Brifen	7.7 mi	N. of Fond du Lac	83+1.18	88M+0.01	3.63 mi
		S. of Fond du Lac	65M+1.08	71M+00	4.07 mi
CASS	6.91 mi	N. of Fond du Lac	88M+0.01	91+1.81	4.3 mi
		S. of Fond du Lac	71M+00	73M+1.03	2.60 mi
Gibraltar	5.90 mi	Dunn	283M+0.0	287G+0.0	3.57 mi
		Waukesha	52G+0.0	54K+0.0	2.33 mi
Low-tension	2.34 mi	N. of Fond du Lac	77+0.53	78+0.71	1.04 mi
		S. of Fond du Lac	73M+1.25	76+0.34	1.30 mi

Maintenance Log Design

Data were needed to evaluate the costs associated with high-tension and low-tension cable barriers; specifically the installation, maintenance, and repair costs. In collaboration with WisDOT project engineers, the TOPS Laboratory developed a WisDOT Maintenance/Repair Log for cable barrier systems. Three components of data were required to complete the log. The first data component was a description of the incident related to cable hit. After a hit was recorded, the results of an inspection of the condition of the cables were recorded in the log. The second component of the data collection was repair information where traffic control and actual labor, material, and machinery use were recorded. The first and the second data components were collected by county highway staff which inspected and repaired the damaged cable barriers. The last component of the data collection included the estimated cost for traffic control and cable barrier repair and was completed by WisDOT regional office staff. A sample log is illustrated in Figure 2.

Crash Data Collection

Study Period

Three years of data were collected for the before implementation period for all high-tension cable study locations. The before period began on January 1, 2003 and ended on December 31, 2005. No before study period overlapped with a cable construction period.

The USH 41 south and north projects were completed in 2006 and 2007, respectively, resulting in different study periods for the after data collection. After a careful review of maintenance logs and construction schedules, researchers found that portions of the construction areas were open to public traffic prior to completion of the entire project. This resulted in a one and a half month overlap between the construction period and the after study periods in order to include all cable barrier crashes. The after study period began on October 19, 2006 for the south project and on September 11, 2007 for the north project. For all locations, the after study period ended on December 31, 2008. The after period for evaluation of the low-tension system was from July 22, 2006 to December 31, 2008.

To be completed by county maintenance staff and sent to WisDOT Region Office

CRASH INFORMATION

County ____________ Highway ________ Mile marker ________

Date ____________ Direction ☐N ☐S ☐E ☐W

Time ____________ On curve ☐Yes ☐No

Road condition ☐Dry ☐Wet ☐Snow/Slush ☐Ice Other________

Vehicle type ☐Passenger car ☐Pick up/SUV ☐Bus ☐Semi truck ☐Motorcycle ☐Unknown Other________

Vehicle penetrated system ☐Yes ☐No Cable on ground ☐Yes ☐No

Concrete footing damaged ☐Yes ☐No Cable damaged, broken, or cut ☐Yes ☐No

Cable maintained tension ☐Yes ☐No

REPAIR INFORMATION*

Date ________ Approx.Outside temp (°F) ____ Time (________ to ________)
Arrival at site time Departure time

Concrete footing replaced (qty) ________

Posts replaced/repaired/reset (#) ________

Cable replaced (ft) ________

Cable repaired (e.g., spliced) ☐Yes ☐No

Cable re-tensioned? ☐Yes ☐No

End terminal repaired ☐Yes ☐No

# of employees ________

Total # of man-hours ________

Cable Barrier Type (Check box that applies)	
Gibraltar (3-cable)	☐
Dunn County	
(TL-4 system)	
Gibraltar (3-cable)	☐
Waukesha County	
(TL-3 system)	

*Briefly describe repair and comment on problems encountered:

Traffic control ☐Lane closure ☐Shoulder closure ☐None

Duration of closure (hours) ________

Recorded by ____________________ Date ____________

To be completed by WisDOT Regional Staff Only

1. Crash report # (MV4000 document number) ____________

2. County repair # (CR) ____________

3. Total cost of repair including traffic control, labor and equipment costs ____________

Recorded by ____________________ Date ____________

Please fax to (608) 262-5199 Xiao(Shaw) Qin(Chin), Ph.D., P.E.Traffic Operations and Safety (TOPS) Laboratory, University of Wisconsin-MadisonPhone: (608) 262-3649 Email : xqin@engr.wisc.edu

Figure 2 Sample Log of Wisconsin Cable Barrier Maintenance and Repair.

Definition of Median-Related Crashes

Median related crashes for the before period were extracted from the WisTransPortal database by reviewing all corresponding police crash records between January 1, 2003 and December 31, 2005. Median related crashes include median entry (ME), cross median event (CME), and cross median crash (CMC). An ME crash was one that involved a vehicle entering the median but not the opposing lane of travel. Since a vehicle entered the median but did not impact the cable barrier, this crash event was not included in the evaluation. A CME crash is an incident where a vehicle completely crosses the median and entered the opposing travel lanes without contacting any vehicles in the opposite direction. A CMC is an incident in which a vehicle completely crosses the median and collides with opposing traffic. The difference between a CME crash and a CMC lies in the fact that a CME crash is a single vehicle crash but a CMC is a multi-vehicle crash. As illustrated in Figure 3, three types of median-related crashes are counted and the fourth one is excluded in the before period because no median cable would be installed on the side; therefore, not preventing the crash from happening. The same crash-type principle is applied for the after data collection which considered only those median entry crashes occurring on the same side as of cable installation.

Selecting the appropriate crash types is an apparent flaw in several of the previous studies that considered only CMCs in the before period. Some researchers included CMEs in their before-and-after crash data analysis but none of them included ME crashes (*23*). In fact, ME crashes may become a cable barrier crash collision if the cable is installed on the side of the travel direction. Failure to account for them will potentially overestimate the safety benefit of the barrier systems. The rigorous data collection for a before-and-after comparison must include median entries with the knowledge of which side of the roadway cable barrier will be installed. It ensures that the before-and-after crash comparison is comprehensive and complete.

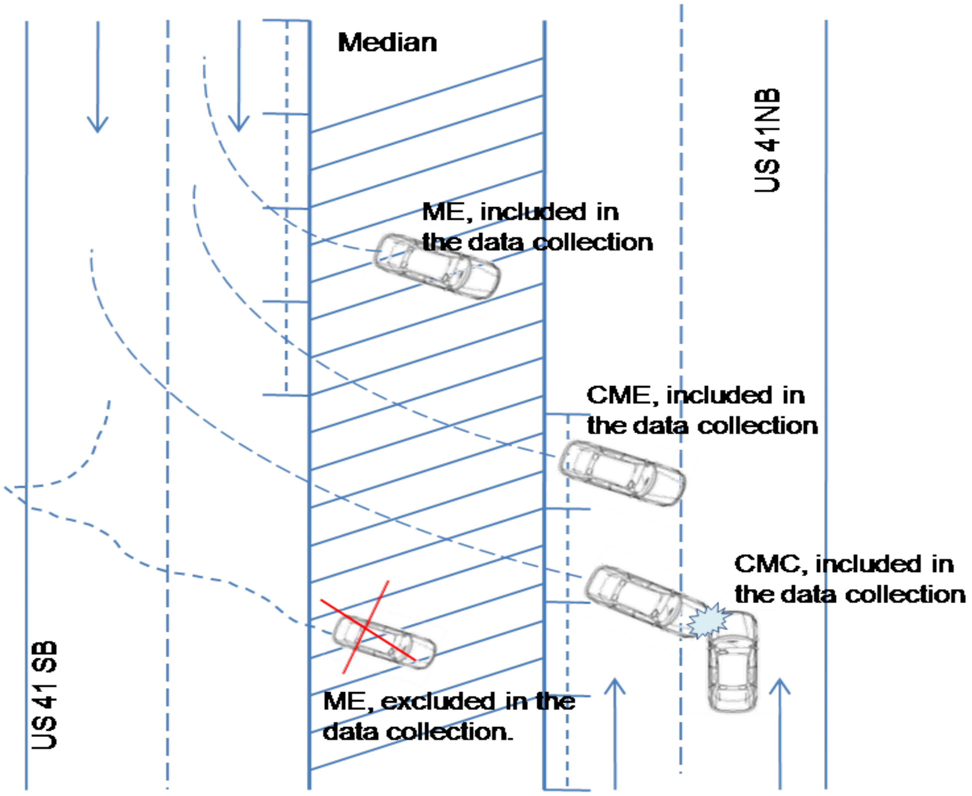

Figure 3 Types of Median Related Crashes in Before Period Included in the Study.

The after period crash data were obtained directly from the maintenance logs and crash reports were retrieved from the WisTransPortal database. Data for 123 cable related crashes including several hit-and-run crashes (only including hit-and-run crashes that resulted in cable repairs) were collected in Fond du Lac, Waukesha and Winnebago Counties. Figure 4 shows the after period crash types included.

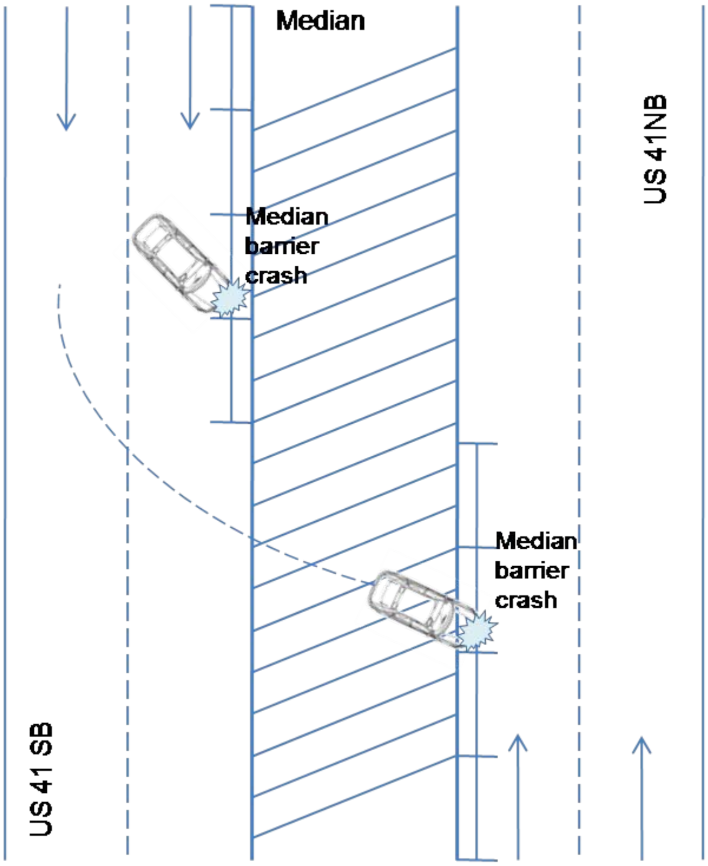

Figure 4 Types of Median Related Crashes in After-Period Included in the Study.

Crash Data Quality Assurance

All median-related crashes in the before period were identified through manually reviewing crash reports. Because cable barriers were installed on one side of the shoulder edge of medians, median entries were easily identified. The median entries that occurred from the side of the highway where cable barrier was not installed were excluded from the before crash data collection if the vehicle's travel distance in the median is not given in the crash report. To make the after period data collection consistent, WisDOT provided data collection training to county maintenance crews. The TOPS Laboratory research team also reviewed all the crash reports in order to verify data provided in the maintenance logs. The research team conducted meetings with WisDOT engineers and county maintenance crews to verify the maintenance data. Necessary adjustments of maintenance data were made according to police reports, meeting minutes, and other available sources. Hit-and-run crashes were identified only when the crash resulted in cable repairs. All hit-and-run crashes were classified as PDO because it was assumed that drivers with injuries could not have left without medical attention.

OVERVIEW OF CRASH DATA INFORMATION

Crash Patterns and Trends

The initial data analysis consisted of crash distribution by month, pavement surface, and light conditions. This analysis aimed to find median crash patterns in Wisconsin. Recognizable crash patterns can be identified from Tables 4 through Table 7. It should be noted that 99 after crashes are shown because 24 out of 123 crashes were not reported and did not result in a crash report.

From Tables 4 and 5, it is clear that crashes are more frequent in winter months than non-winter months. For both before and after periods, more crashes (but with less severity) occurred between November and March than April through October.

Table 4 Crash Data by Month and Severity

Month	Before Crash Data						After Crash Data				
	K	A	B	C	PDO	Total Crashes	A	B	C	PDO	Total Crashes
Jan			1	1	5	7		2	1	14	17
Feb			1	2	6	9		1	3	17	21
Mar		1	2		3	6		2	1	6	9
Apr	1	2	1		1	5				1	1
May	1	1	1	1	3	7				1	1
Jun	1		2	0	2	5				1	1
Jul			2	1	3	6	1	1	1	1	4
Aug		1	1		1	3		1	1	1	3
Sep		1	1	1	0	3		1	1	2	4
Oct					2	2		2		6	8
Nov			2	1	9	12		2	1	6	9
Dec		2	1	1	10	14			1	20	21
Total	3	8	15	8	45	79	1	12	10	76	99

Table 5 Crash Counts and Percentages by Severity and Winter/Non-winter Season

		K	**A**	**B**	**C**	**PDO**	**Total Crashes / percentage**
Before	Nov ~ Mar (5 months)	0 0%	3 6.3%	7 14.6%	5 10.4%	33 68.8%	48 100%
	Apr ~ Oct (7 months)	3 9.7%	5 16.1%	8 25.8%	3 9.7%	12 38.7%	31 100%
After	Nov ~ Mar (5 months)	0 0%	0 0%	7 9.1%	7 9.1%	63 81.2%	77 100%
	Apr ~ Oct (7 months)	0 0%	1 4.6%	5 22.7%	3 13.6%	13 59.1%	22 100%

Table 5 shows that snow/ice covered or wet roads are major reasons for crashes, especially for after period crashes. Snow covered roads experienced more crashes than other road conditions.

Table 6 Crash Counts by Pavement Condition and Severity

Road Condition	**Before Crash Data**						**After Crash Data**				
	K	**A**	**B**	**C**	**PDO**	**Total Crashes**	**A**	**B**	**C**	**PDO**	**Total Crashes**
Ice			2	1	8	11		1	2	18	21
Snow	1	2	3	3	10	19		1	4	38	43
Wet			1	2	3	6		2		5	7
Dry	2	6	9	2	24	43	1	8	4	15	28
Total	3	8	15	8	45	79	1	12	10	76	99

Table 7 Crash Counts by Weather Condition and Severity

Weather Condition	Before Crash Data						After Crash Data				
	K	A	B	C	PDO	Total Crashes	A	B	C	PDO	Total Crashes
Cloudy	1	3	5	1	11	21	1	3	3	16	23
Clear	1	3	5	1	15	25		8	2	14	24
Rain			1	2	1	4			1	2	3
Sleet					2	2				2	2
Snow	1	2	3	4	14	24		1	4	35	40
Wind					2	2				7	7
Xwind			1			1					0
Total	3	8	15	8	45	79	1	12	10	76	99

Tables 6 and 7 indicate that inclement weather or slick pavement conditions contributed to more crashes (with lower severity) in winter.

Cable Collision Frequencies and Rates

Tables 8 through 13 present before and after average annual crash counts and annual crash rates per one hundred million vehicle miles traveled (100MVMT) by severity with and without heavy vehicle (HV) crashes. Although cable barriers can sometimes stop large trucks, as captured in a picture taken by Wisconsin State Patrol (Figure 5), cable barriers are generally not designed for truck impacts. Most roadside barriers are designed following NCHRP 350 TL3 crash testing criteria (test vehicles are limited to compact cars or pickups) (*22*). Therefore, tables below excluding truck crashes provide extra information for cable performance by design. In each table, K denotes a fatal crash, A denotes an incapacitating injury crash, B denotes a non-incapacitating injury crash, C denotes a possible injury crash, and PDO represents a reportable property damage only crash where damage was above $1,000. N indicates the north cable section while S indicates the south section in comparison to the City of Fond du Lac.

Figure 5 A Semi-Truck Stopped by Cable Barriers (Brifen).

Cable Collision Frequencies

Tables 8 and 9 show before and after average annual crash counts with and without trucks (i.e., heavy vehicles (HV)). Comparing before and after crash counts, one can see that:

1) There are more annual crashes in the after study period than in the before period.

2) The severity of crashes in the after period is significantly lower than that in the before period and no fatalities occurred in the after period. Corresponding crash rates can be found in Figure 6 and Table 12.

Table 8 Average After Annual Crash Counts by Site and Severity with and without Heavy Vehicles

	N Brifen		N CASS		S Brifen		S CASS		Gibraltar	
After	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV
K	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0	0	0	0.45	0.45	0	0
B	1.54	1.54	1.54	0.00	0.91	0.91	0.45	0.45	1.38	0.00
C	1.54	1.54	0.00	0.00	0.45	0.00	0.91	0.91	1.38	1.38
PDO	5.85	4.49	7.93	6.79	10.63	7.80	7.81	7.81	8.28	7.59
Sub-total	8.93	7.57	9.47	6.79	12.00	8.71	9.62	9.62	11.03	8.97
Years	1.30		1.30		2.20		2.20		1.45	

Table 9 Average Before Annual Crash Counts by Site

2003-2005 (3 yrs)	N Brifen		N CASS		S Brifen		S CASS		Gibraltar	
	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV
K	0.33	0.33	0.33	0.33	0.33	0.00	0	0.00	0.33	0.33
A	1.00	0.67	0.33	0.00	1.33	1.00	0	0.00	0.33	0.00
B	1.33	1.00	0.67	0.67	2.33	1.33	0.33	0.33	0.67	0.33
C	0.00	0.00	0.67	0.67	0.33	0.00	0.67	0.33	0.67	0.00
PDO	4.00	1.67	2.33	1.00	5.00	2.67	1.33	0.67	1.00	1.00
Subtotal	6.67	3.67	4.33	2.67	9.33	5.00	2.33	1.67	3.00	1.67

Figure 6 summarizes the tables above and shows that the number of crashes after cable barrier installation is consistently higher than before installation.

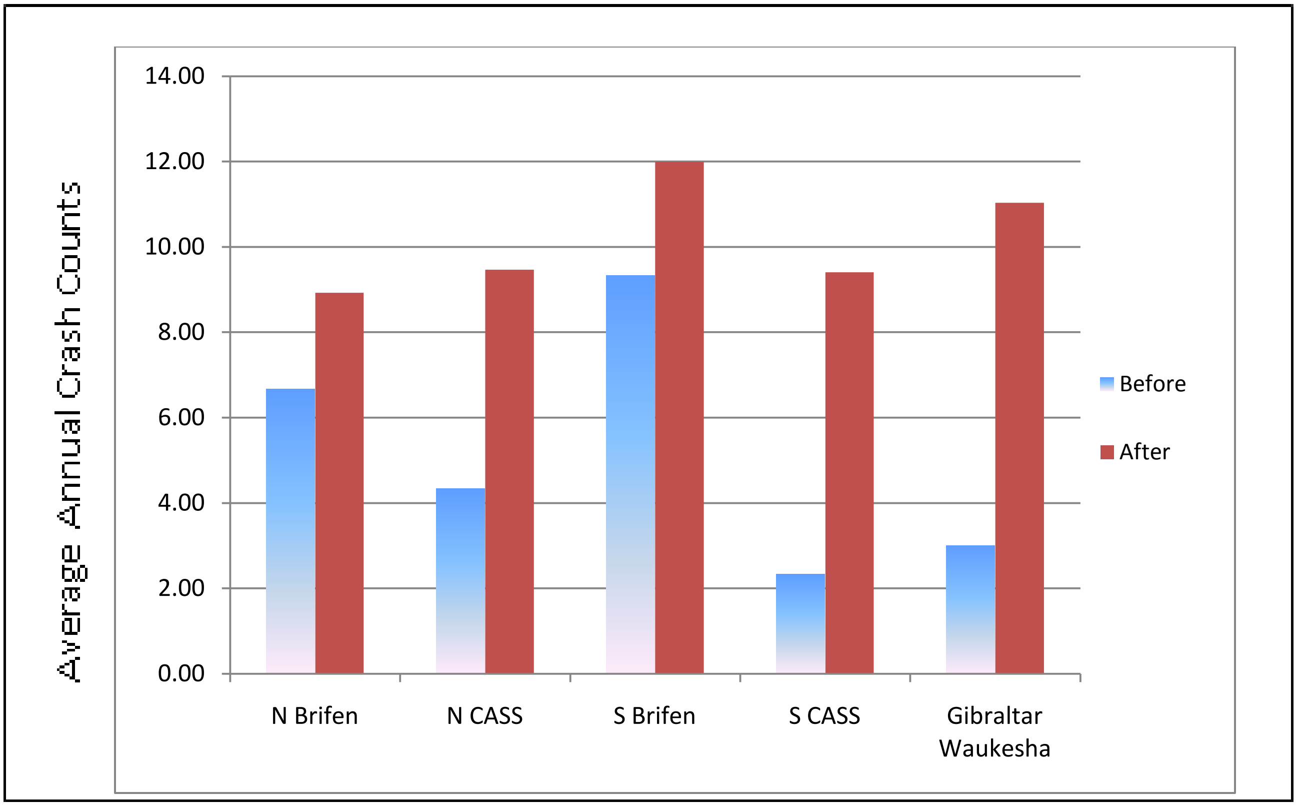

Figure 6 Average Annual Crash Count Comparison (with heavy vehicles).

Cable Collision Rates

Cable crash rates were calculated by dividing annual crash counts by 100MVMT. Tables 10 and 11 show average crash rates in the before and after study periods with and without trucks (i.e., heavy vehicles).

Table 10 Average After Crash Rates by Barrier Site with and without Heavy Vehicles

After Crash Rates (per 100 MVMT)	**N Brifen**		**N CASS**		**S Brifen**		**S CASS**		**Gibraltar**	
	W/ HV	**W/O HV**	**W/ HV**	**W/O HV**	**W/ HV**	**W/O HV**	**W/ HV**	**W/O HV**	**W/ HV**	**W/O HV**
K	0	0	0	0	0	0	0	0	0	0
A	0	0	0	0	0	0	3.15	3.15	0	0
B	8.86	8.86	7.46	0	3.70	3.70	3.15	3.15	2.62	2.62
C	8.86	8.86	0	0	1.85	0	6.30	6.30	2.62	0
PDO	33.70	25.88	38.46	32.94	43.30	31.76	52.58	54.10	34.95	24.51
Subtotal	51.43	43.61	45.93	32.94	48.85	35.46	65.18	66.70	40.19	27.51

Table 11 Average Before Crash Rates by Barrier Site with and without Heavy Vehicles

Before Crash Rates (per 100 MVMT)	N Brifen		N CASS		S Brifen		S CASS		Gibraltar	
	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV	W/ HV	W/O HV
K	1.50	1.50	1.28	1.28	1.39	0.00	0.00	0.00	2.70	2.70
A	4.50	3.00	1.28	0.00	5.55	4.16	0.00	0.00	2.70	0.00
B	6.00	4.50	2.56	2.56	9.72	5.55	2.16	2.16	5.40	2.70
C	0.00	0.00	2.56	2.56	1.39	0.00	4.32	2.16	5.40	0.00
PDO	17.99	7.50	8.95	3.83	20.82	11.10	8.65	4.32	8.11	8.11
Subtotal	29.98	16.49	16.62	10.23	38.86	20.82	15.14	8.65	24.32	13.51

Table 12 computes differences between before and after crash rates. There are considerable reductions on fatal (K) and serious injury (A) crashes (shaded cells indicate increase in average crash rate) except for a slight increase in serious injury crashes (A) in the south CASS location.

Table 12 Crash Rate Differences between After and Before Periods with trucks

Crash Rate Differences (per 100 MVMT)	N Brifen	N CASS	S Brifen	S CASS	Gibraltar
K	-1.50	-1.28	-1.39	0	-2.70
A	-4.50	-1.28	-5.55	3.15	-2.70
K+A	-6.00	-2.56	-6.94	3.15	-5.40
B	2.87	4.91	-6.01	0.99	-2.79
C	8.86	-2.56	0.46	-2.70	-2.79
PDO	15.72	29.52	22.48	43.93	26.85

Figure 7 shows a clear reduction in the fatal and serious injury crash rates as a result of cable barrier systems and a considerable increase in the total number of crashes.

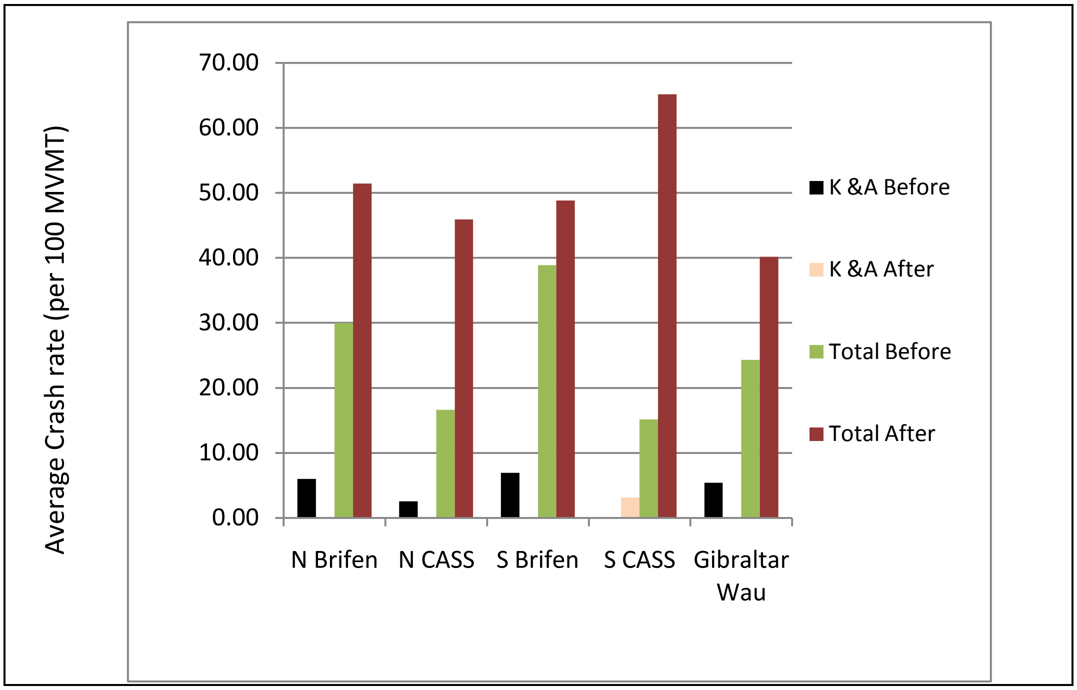

Figure 7 Average Crash Rate Comparison by Cable Type (with heavy vehicles).

After closely monitoring cable barrier performance at four of the pilot locations, it was found that these highway sections experienced a larger number of crashes. Most of these crashes resulted in property damage only incidents. Vehicles simply drifting from the travel lane were more likely to impact the cable barrier. However, sustainable benefits in saving people lives and preventing them from being severely injured underscore the benefits of installing cable barriers in areas where high number of CMCs occurred.

Cable Performance Evaluation

Although crash facts and previous research affirm the strong safety benefits resulting from median cable barriers, the installation adds new facilities to highway medians and their operational and maintenance costs cannot be neglected in the WisDOT project planning and programming process. More importantly, cable barrier performance (after being struck by vehicles) needs to be carefully evaluated from several aspects to understand the further impact: whether or not the cable will deflect vehicles back to the traffic, which may incur a secondary crash; will the cable lose tension or how easily the broken cable/posts can be fixed or repaired so the damaged section will not provide a gap for an errant vehicle to go across to the opposing lanes. Efforts were made to acquire the requisite data and analyze median barrier performance in the following aspects:

- Collision result after a contact with the cable barrier;
- Cable barrier performance versus collision consequence;
- Number of posts replaced after a vehicle's contact; and
- Man-hours incurred.

After colliding with a cable barrier, there are three consequences for the vehicle and occupants: penetrate, redirect, or capture/stop. In this study, penetration is defined as: vehicle hits the cable barrier, breaks through it completely, and enters the median area. The narrative and pictorial sections in the police crash report were used to identify if a cable barrier penetration occurred. From the maintenance data collected by the TOPS Laboratory, all cable crash records marked as penetrated were reviewed manually for identification of penetrations. As shown in Table 13, all cable barrier types produced very low penetration rates and most vehicles were restrained or stopped by the cable barriers. For all types of cable barrier studied, there were no associated CMCs or CMEs in the after study period.

Table 13 Cable Collision Results*

Cable Type	Penetrated	Redirected	Stopped
Brifen	0	5	22
CASS	1	5	14
Gibraltar	0	2	8
Low-tension	1	3	29
Total	2	15	73

* Could not determine cable collision outcome for 9 crashes

Tables 14 through 16 present cable performance evaluations from a maintenance perspective. The number of posts replaced depends on the magnitude of the impact and the cable barrier system installed. As Table 15 indicates, some collisions resulted in replacement of 16 or more posts. Man-hours for maintenance is correlated with the number of posts replaced as well as the ease of replacement. Winter conditions add considerable amount of time to the maintenance. Both posts replaced and man-hours contribute to the amount of recovery cost. Table 16 presents the maintenance cost histogram by cable barrier type.

Table 14 Number of Posts Replaced by Cable Barrier Type

Number of posts replaced	W/ Heavy Vehicles				W/O Heavy Vehicles			
	Brifen	CASS	Gibraltar	Low-Tension	Brifen	CASS	Gibraltar	Low-Tension
0	1	1	0	5	1	1	0	5
1	10	9	4	10	10	9	4	10
2	6	8	5	6	5	7	3	6
3	6	7	3	3	6	7	3	3
4	9	0	0	3	9	0	0	2
5	2	0	1	5	2	0	1	4
6	2	4	2	0	2	3	1	0
7	0	2	1	0	0	2	1	0
8~15	1	3	0	2	1	3	0	1
>=16	2	0	0	0	1	0	0	0
Total crashes	39	34	16	34	37	32	13	31

Table 15 Man-hours for Crash Recovery by Cable Barrier Type

Number of man-hours (hrs)	W/ Heavy Vehicles				W/O Heavy Vehicles			
	Brifen	CASS	Gibraltar	Low-Tension	Brifen	CASS	Gibraltar	Low-Tension
0-1	5	3	0	0	5	3	0	0
1-2	3	3	7	0	2	3	7	0
2-3	4	6	2	8	4	5	2	8
3-4	11	6	4	3	11	6	2	3
4-5	5	8	0	6	5	8	0	6
5-6	2	0	0	7	2	0	0	7
6-7	0	2	0	0	0	2	0	0
7-8	5	1	1	1	5	1	1	1
>8 hrs	4	5	2	9	3	4	2	6
Total	39	34	16	34	37	32	13	31

Table 16 Maintenance Cost Histogram by Cable Barrier Type*

Cost ($)	W/ Heavy Vehicles				W/O Heavy Vehicles			
	Brifen	CASS	Gibraltar	Low-Tension	Brifen	CASS	Gibraltar	Low-Tension
0-100	2	0	0	0	2	0	0	0
100-200	7	5	4	6	6	5	4	6
200-300	15	12	1	5	15	12	1	5
300-400	6	6	3	6	6	5	2	6
400-500	5	0	2	6	5	0	2	6
500-600	0	2	3	3	0	2	1	3
600-700	1	3	0	2	1	3	0	2
700-800	1	2	0	0	1	2	0	0
800-900	0	1	0	1	0	1	0	1
900-1100	0	1	0	1	0	1	0	1
1100-1200	1	0	1	1	1	0	1	1
>1200	1	1	1	3	0	0	1	0
Total	39	33	15	34	37	31	12	31

* *Cost for one CASS and one low-tension cable barrier crash is unknown.

Table 17 exhibits the means and standard errors in the cost per hit, man-hours used and the number of posts replaced for Brifen, CASS, Gibraltar and low-tension cable barriers. The average cost per hit and mean man-hours for low-tension are less predictable because of the large variation. It is worth noting that according to this data, the maintenance cost per hit for cable barriers in Wisconsin is lower than that of any other state reported in the literature (5, 10, 15, 16, 17).

Table 17 Mean, Standard Error for Maintenance Cost, Man-hours Used, Posts Replaced

		Mean				**Standard Error**			
		Brifen	**CASS**	**Gibraltar**	**Low-Tension**	**Brifen**	**CASS**	**Gibraltar**	**Low-Tension**
With HV	Costs ($)	377.07	408.59	441.90	589.53	436.75	301.14	362.84	622.13
	Man-Hours (hrs)	5.34	5.10	4.47	7.68	5.68	2.87	4.10	7.76
	Posts Replaced	4.08	3.18	2.94	2.47	5.51	3.02	1.68	2.63
Without HV	Costs ($)	319.88	422.90	446.08	418.58	219.94	240.17	404.71	303.28
	Man-Hours (hrs)	5.40	4.76	4.27	7.78	3.05	2.79	4.62	3.82
	Posts Replaced	4.14	3.25	2.31	2.55	3.22	3.12	2.18	1.97

Table 18 shows the number of cable barrier crashes, total maintenance cost, and cost per hit for each of the cable barrier types. Cost per hit is a very important measure because it can be used to estimate the future maintenance cost provided that the number of cable collisions is known. Note that low-tension cable barrier has the highest cost per hit among the four cable systems. Between the high-tension cable systems, the difference in the cost per hit is marginal regardless of the involvement of heavy vehicles in crashes.

Table 18 Cost per Hit by Cable Type

Cost	**Brifen**	**CASS**	**Gibraltar**	**Low-Tension**	**Total**
Total crashes	39	34	16	34	123
Total cost ($)	14,705.75	13,603.84	6,691.18	20,044.01	55,044.78
Cost with HV($)	2,870.22	2,828.59	1,388.41	7,068.16	14,155.38
Cost W/O HV($)	11,835.53	10,775.25	6,691.18	12,975.85	40,889.40
Cost per hit($)	377.07	400.11	446.08	589.53	451.19
Cost W/O HV per hit($)	319.88	336.73	353.52	418.58	355.56

In general, the observational statistics strongly support that high-tension cable barrier outperformed low-tension cable barrier while marginal difference exists between HTCB systems. To get more rigorous results, a statistical analysis was conducted. In particular, two levels of analyses were performed: determine if the installation of high-tension cable barriers makes statistically significant changes in crash severity, and test if statistically significant differences exist among the cable barriers studied.

Because the number of crashes is relatively low in each severity category, annual crash counts for types K and A were grouped together, types B and C were grouped together, while

PDO was considered independently. The test statistic Chi-squared (χ^2) of 32.72 is greater than the reference value of 9.21 at a significance level of 0.01 with two degrees of freedom, rejecting the null hypothesis that there is no statistically significant difference between crash severity distribution before and after installation of cable barriers. In other words, the reduction in the fatal and Type A injury crashes and the increase in PDO crashes are statistically significant at 0.01 level of significance. Similar Chi-squared (χ^2) test was performed for crash rate and high-tension cable barriers were found to be effective in preventing severe crash occurrences.

The next evaluation was designed to compare cable effectiveness of different systems. Brifen, CASS, Gibraltar and low-tension systems were tested from the standpoints of maintenance costs, man-hours used, and number of posts replaced. Though the distribution of observed sample of maintenance cost, man-hour, or number of posts does not strictly follow a normal distribution due to its small size, the population may be normally distributed. The *t* test statistics given in Table 19 indicate that when all crashes are considered, there is no statistically significant difference between the three high-tension cables systems Brifen, CASS and Gibraltar in maintenance costs, posts replaced, and man-hours used. Brifen performed better than low-tension in all the three respects. CASS performed better than low-tension in maintenance costs and man hours used while it was similar to low-tension in posts replaced. Gibraltar has no significant difference with low-tension except for man hours used.

Table 19 Paired Comparisons for Maintenance Cost, Man-hours Used, Posts Replaced

		Comparison Pairs	Equal Variance used (Y/N)	Degrees of Freedom	t value	Critical t value	Significant or not (Y/N)
With HV	Mainte-nance Costs	Brifen Vs CASS	N	67	0.361	1.296	N
		Brifen Vs Low-tension	N	58	1.665	1.299	Y
		Brifen Vs Gibraltar	Y	52	0.510	1.299	N
		CASS Vs Low-tension	N	47	1.522	1.303	Y
		CASS Vs Gibraltar	Y	46	0.333	1.303	N
		Low-tension Vs Gibraltar	N	43	1.040	1.303	N
	Posts Replaced	Brifen Vs CASS	N	60	0.880	1.296	N
		Brifen Vs Low-tension	N	56	1.620	1.299	Y
		Brifen Vs Gibraltar	N	50	1.165	1.299	N
		CASS Vs Low-tension	Y	66	1.028	1.296	N
		CASS Vs Gibraltar	N	46	0.358	1.303	N
		Low-tension Vs Gibraltar	N	43	0.757	1.303	N
	Man-Hours Used	Brifen Vs CASS	N	57	0.227	1.299	N
		Brifen Vs Low-tension	N	59	1.454	1.299	Y
		Brifen Vs Gibraltar	Y	53	0.556	1.299	N
		CASS Vs Low-tension	N	41	1.817	1.303	Y
		CASS Vs Gibraltar	Y	48	0.636	1.303	N
		Low-tension Vs Gibraltar	N	47	1.914	1.303	Y
Without HV	Mainten-ance Costs	Brifen Vs CASS	Y	67	1.859	1.296	Y
		Brifen Vs Low-tension	N	53	1.510	1.299	Y
		Brifen Vs Gibraltar	N	13	1.032	1.35	N
		CASS Vs Low-tension	Y	61	0.063	1.296	N
		CASS Vs Gibraltar	N	14	0.187	1.345	N
		Low-tension Vs Gibraltar	Y	41	0.243	1.303	N
	Posts Replaced	Brifen Vs CASS	Y	67	1.154	1.296	N
		Brifen Vs Low-tension	N	60	2.489	1.296	Y
		Brifen Vs Gibraltar	Y	48	1.892	1.303	Y
		CASS Vs Low-tension	N	52	1.070	1.296	N
		CASS Vs Gibraltar	Y	43	0.992	1.303	N
		Low-tension Vs Gibraltar	Y	42	0.358	1.303	N
	Man-Hours Used	Brifen Vs CASS	Y	68	0.913	1.296	N
		Brifen Vs Low-tension	Y	66	2.863	1.296	Y
		Brifen Vs Gibraltar	Y	48	0.998	1.303	N
		CASS Vs Low-tension	N	54	3.602	1.299	Y
		CASS Vs Gibraltar	N	15	0.357	1.341	N
		Low-tension Vs Gibraltar	Y	42	2.617	1.303	Y

Delays in Maintenance

Delays for cable barrier maintenance were determined from maintenance logs. Tables 20 and 21 provide general information for delays. The longest delay for maintenance was 103 days and the shortest delay was zero (i.e., repaired the same day the cable was hit). At five crash locations, barrier repairs took place over two months after the barrier was hit, and at two (out of the five) crash locations barrier repairs took place over three months after they were hit. The two longest delays occurred in the first summer after the data collection began (they were all in low-tension sites). Table 20 shows that mean delays in winter months were smaller than mean delays for the full year. Although this may be counterintuitive, the two longest delays (103 days and 95 days) occurred in the first summer of data collection and increased the mean delay by over two days. The standard deviation was also higher due to this reason. Table 21 shows the distribution of delays. Over one-fourth of the maintenance tasks took more than a month to be repaired whether for all data or winter data only. Figure 8 shows that the delay in maintenance in the non-winter period was greater than in the winter period.

Table 20 Mean Delays, Standard Errors, and Confidence Intervals*

	Total Crashes	**Mean Delay (days)**	**Standard Error**	**Confidence Interval**	
				Lower Limit	**Upper Limit**
All	97	21.38	22.84	0.00	66.60
Winter only	77	20.61	20.30	0.00	60.81

* Could not determine delays for rest of the crashes.

Table 21 Distribution of Delays*

Delay Days		**0~10 days**	**11~20 days**	**21~30 days**	**30+ days**	**Total**
All Maintenance	Counts	41	18	13	25	97
	Percentage	42.3%	18.6%	13.4%	25.8%	100.0%
Winter only	Counts	31	12	13	21	77
	Percentage	40.3%	15.6%	16.9%	27.3%	100.0%

* Could not determine delays for rest of the crashes.

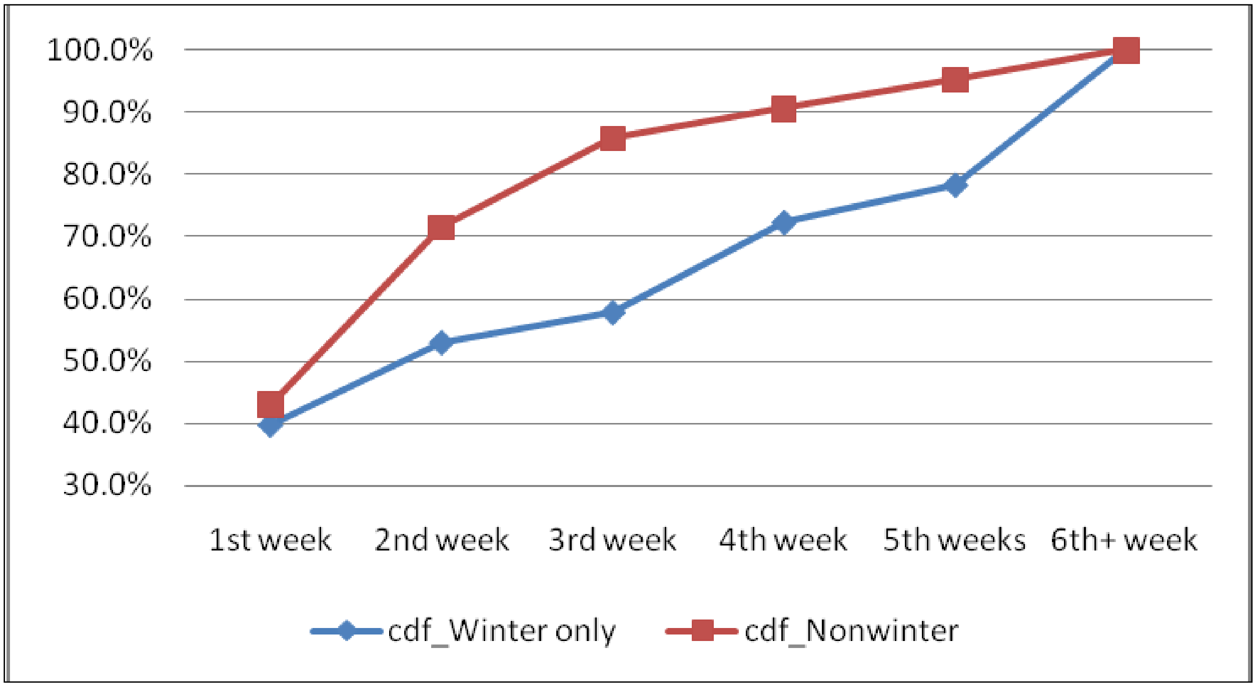

Figure 8 Cumulative Density Functions for Winter and Non-Winter Repairs

COST-BENEFIT ANALYSIS

A cost-benefit analysis consists of the ratios of savings accrued from reduction in crash severity to costs in constructing, operating, and maintaining safety treatments. Note that the construction cost did not include the cost of grading, modifying drainage systems, and traffic control items. Research from TTI was considered that not only developed models for estimating median-related crashes under different scenarios, but also did cost-benefit analysis and sensitivity analysis (*27*, *28*). For performing cost-benefit analysis, cost (construction, operation and maintenance) and crash savings were required.

Cable Barrier Construction and O&M Costs

Costs used in the cost-benefit analysis include installation and maintenance costs. Installation cost consisted of the cost of cables, posts, anchors and other parts, cost of site preparation, and cable installation. User delay costs caused by work zone traffic control were also included in the installation cost. According to WisDOT project managers and contractors, however, there was no delay observed and thereby no user costs were involved. Maintenance cost included costs for parts, related labor, equipment rentals, and traffic control during repairs. The total annual cable cost was the sum of annual depreciation cost and annual maintenance cost.

Following the WisDOT planning guide, a 20-year service life and three percent inflation rate were applied to the analysis. The interest rate in the analysis was equivalent to the three percent inflation rate (*25*). The annual depreciation cost was calculated using the following formula and the results are presented in Table 22.

$$\text{Depreciation cost per year} = \frac{TC * i * (1+i)^{20}}{(1+i)^{20} - 1}, \qquad (1)$$

where TC denotes total installation cost and i represents the interest rate.

Table 22 Depreciation Cost by System and Location

	Total Installation Cost ($)	Years in Service (year)	Length of Cable (mile)	Interest Rate	Annual Depreciation Cost ($)	Annual Depreciation Cost/Mile ($)
Brifen	872,055.40	20	7.7	3%	56,908.56	7,390.72
North	389,092.78	20	3.63	3%	25,391.40	6,994.88
South	482,962.62	20	4.07	3%	31,517.16	7,743.77
CASS	587,256.95	20	6.91	3%	38,323.20	5,546.05
North	353,106.77	20	4.31	3%	23,043.03	5,346.41
South	234,150.18	20	2.6	3%	15,280.17	5,876.99
Gibraltar	237,524.10	20	2.33	3%	15,500.34	5,731.31

Cost information is further broken down in Table 23 where detailed information regarding maintenance cost at each location by system is provided, including the annual maintenance cost per mile.

Table 23 Annual Maintenance Cost per Mile

Cable Type	Total Maintenance Cost ($) (W/ HV)	Total Maintenance Cost ($) (W/O HV)	Study Period (years)	Cable Length (mile)	Annual Maintenance Cost/Mile ($) (W/ HV)	Annual Maintenance Cost/Mile ($) (W/O HV)
Brifen	14,705.75	11,835.53	1.78	7.7	1,075.53	863.53
North	3,278.24	3,278.24	1.30	3.63	694.69	694.69
South	11,427.51	8,557.29	2.20	4.07	1,276.25	955.69
CASS	13,603.84	10,775.25	1.64	6.91	1,201.43	950.84
North	6,702.33	1,581.06	1.30	4.31	1,196.20	858.70
South	6,901.51	4,860.24	2.20	2.6	1,206.56	1,206.56
Gibraltar	6,691.18	5,302.77	1.45	2.33	1,980.52	1,569.56

Safety Benefits

Benefits were defined as expected crash savings from the reduction in the total crash costs before and after the cable barrier installation and the total crash cost the sum of the products of unit crash cost by severity and corresponding crash counts. Federal Highway Administration (FHWA) unit crash cost, listed in Table 24, were adopted in the study and converted to 2008 values (*24*). Note, these costs are the same unit crash costs used by the Division of Transportation Investment Management (DTIM) for planning purpose in WisDOT.

Table 24 FHWA Crash Cost Inflated to 2008 Values.

Severity	Fatal	Incapacitating injury (type A)	Evident injury (type B)	Possible (type C)	Property Damage Only
2008 $ Value	$3,494,668	$241,939	$48,388	$25,538	$2,688

Annual benefits were calculated from the following relationship:

Expected Crash Savings = Expected Before Crash Cost - Expected After Crash Cost (2)

B/C Ratios

B/C ratios are the ratios of crash savings to total cable costs and are calculated as follows:

B/C Ratio =

(3)

A B/C ratio greater than 1.0 indicates that the benefits from crash savings due to the safety improvement are monetarily greater than the total costs. Table 25 provides B/C ratios by system and location with and without truck crashes. Note that if grading and drainage items are included in the analysis, the B/C ratio will be lower.

All B/C ratios calculated found ratios greater than one except for the CASS installation in south Fond du Lac County. A B/C ratio less than 1.0 at this location resulted from 1) the lack of fatal CMCs before the cable barrier project, 2) one incapacitating injury crash occurred in the after period which could be a random event and, 3) the short period of after crash data collection. The B/C ratio would have been higher if the truck crashes were omitted. Since the HTCB system is not designed for trucks, all sites with a B/C ratio greater than one considered only non-heavy vehicle related crashes. In short, the B/C ratios calculated from the Wisconsin maintenance and crash data for high-tension cable barriers unanimously identify significant safety benefits at all study locations.

Table 25 B/C Ratios by System/Location with and without Truck Crashes

Cable Type	W/ HV			W/O HV		
	Benefit ($)	Annual Cable Cost Per Mile ($)	Ratios (B/C)	Benefit ($)	Annual Cable Cost Per Mile ($)	Ratios (B/C)
Brifen	382,201.44	8,466.25	12.98	198,856.48	8,466.25	8.45
N Brifen	373,542.23	7,689.57	8.80	345,154.38	7,689.57	8.35
S Brifen	377,728.23	9,020.02	12.63	56,178.29	9,020.02	3.21
CASS	173,236.70	6,747.48	6.39	159,555.77	6,747.48	9.54
N CASS	280,230.20	6,542.62	9.94	260,687.17	6,542.62	26.08
S CASS	-25,330.54	7,083.54	-0.64	-29,293.92	7,083.54	-0.68
Gibraltar	443,128.01	7,689.57	3.62	394,286.49	7,689.57	3.21

CONCLUSIONS

In an effort to reduce the number of cross median crashes (CMCs) and the severities of such crashes, WisDOT retrofitted several unprotected median areas with median cable barriers. The TOPS Laboratory conducted an evaluation of these median barrier locations considering cable barrier maintenance data and crash data collected for each of the selected study sites.

Because median barriers were installed primarily as a countermeasure for CMCs, three years of before data for median-related crashes, along with all available after median cable barrier installation collision data, were collected and manually reviewed to verify the locations and types of crashes. Specifically, the inclusion of median entry crashes during the before data collection period avoided the overestimation of median cable barrier safety benefits. In addition to crash data, cable maintenance information was collected by the county highway departments. After synthesizing all the information, both descriptive and statistical analyses were conducted to identify cable barrier crash patterns, compare before and after crash variations, and evaluate the performance of different cable systems.

Data analysis showed that before and after crashes appear to be weather- and road condition related. During winter months, a very high percentage of crashes occurred on reportedly snow or ice-covered roads. Comparing crash severities on dry roads with the other seasons, less severe crashes were found. This finding was consistent with the findings from other states with similar weather conditions.

Data analysis of before and after crash counts and rates indicated that more median barrier crashes, especially PDO crashes, occurred at every location under evaluation. The overall crash severities, however, reduced significantly when compared with the before crash severities. This safety benefit of median cable barrier is in line with the national goal of reducing fatal and serious injury crashes and the “vision zero” in the State of Wisconsin. No fatalities and only one type A injury crash were found across all the study sites after the installation of cable barriers. In the before period, however, three of four locations had fatal and several type A crashes. The observations were further confirmed by a statistical test in which Chi-squared (χ^2) test statistics support the conclusion that cable barriers reduce severe crashes associated with median encroachments.

In addition to the safety benefits, cable barrier construction and future operation and maintenance costs cannot be ignored and the overall cost may vary from one cable system to another. A series of statistical tests were conducted to compare cable barriers by repair man-hours, number of posts replaced, and total maintenance cost per hit. The results show that there is no difference in the performance of Brifen, CASS and Gibraltar. In general, Brifen and CASS are superior to low-tension cable barrier, while Gibraltar is superior to low-tension cable barrier only in man-hours used. Though the observed data shows marginal benefits of using CASS over Brifen by posts replaced and man-hours used, statistical tests cannot distinguish the two from each other.

The benefit-cost ratios for the installation of high-tension median cable barrier ranged from 3.62 to 12.98 when heavy vehicle-related crashes were considered and range from 3.21 to 9.54 when heavy vehicle-related crashes were excluded. Note that the benefit-cost analysis depends appreciably on the number of hits sustained by the system per mile and the crash severity, which may vary from site-to-site and from system-to-system. The crash data and cost-benefit analysis provide strong evidence that high-tension cable is overall a cost-effective approach for preventing severe median-related crashes. Finally, the cost per hit and operation and maintenance cost per mile generated from the data obtained can assist WisDOT in assessing future cable implementations and developing predictive cable median barrier warrants.

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