High-tension Median Cable In-service Performance Evaluation and Cost Effectiveness Analysis

Xiao Qin, PhD, PE*
Assistant Professor
Department of Civil and Environmental Engineering
South Dakota State University
Brookings, SD 57007
Email: Xiao.Qin@sdstate.edu

Maria (Fenghuan) Wang
Transportation Engineer
Traffic Operations and Safety (TOPS) Laboratory
Department Civil and Environmental Engineering
University of Wisconsin-Madison
Madison, WI 53706
Phone (608) 265-8582
Email fwang6@wisc.edu

Revised and resubmitted for Presentation and Publication for the 89th Annual meeting of the Transportation Research Board

January, 2010

*: Corresponding Author

ABSTRACT

Cross median crashes (CMC) are typically violent collisions with a disproportionately high probability of fatalities and injuries. Applying median barriers might be a potential solution to reduce the number of CMCs and their severities. Past studies overwhelmingly indicate that installing cable barriers is the right choice for preventing CMCs from occurring. As part of the exploration of system-wide cable implementation and development of predictive cable median barrier warrants, a comprehensive cable barrier evaluation was conducted in Wisconsin.

Initial data analysis shows that median-related crashes, a portion of run-off-the-road crashes, are frequently weather related (usually during snow or ice conditions), but less severe. Before and after comparisons of crash counts and crash rates imply that more median related crashes, especially property damage only (PDO) crashes, occurred after cable installation, but overall crash severities were reduced significantly. Moreover, median cable in-service performance with the emphasis on several high tension cable guards (HTCG) was thoroughly assessed through analyzing archived cable maintenance logs. In most categories, high-tension cable systems outperformed low-tension cable in repaired man-hours, average cost per hit and vehicle penetration rate. Cost benefit analysis shows high values of benefit to cost (B/C) ratios at almost all tested sites, recommending high-tension cables as an excellent solution for preventing CMC and reducing crash severities. Finally, the generation of cost per hit and unit cost of cable operations and maintenance (O&M) per mile can assist Wisconsin Department of Transportation (WisDOT) in making an informed decision about system-wide cable installation.

Key Words: Cross Median Crash, Cable Median Barrier, In-service Performance, Benefit-cost analysis

INTRODUCTION

Cross-median crashes (CMCs) are crashes in which a vehicle crosses the median and hits a vehicle in opposing traffic. Because of the violent impact, these collisions frequently result in a disproportionately high probability of fatalities and injuries. The *Roadside Design Guide* recommends two countermeasures for preventing cross-median crashes: first, widening medians to a sufficient width to provide adequate clear zone for an out-of-control vehicle to recover; and second, 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 more aggressive provision for barriers or for increased median widths (2). However, installation of median barriers may trigger barrier collisions for vehicles veering off the roadway, thereby increasing the frequency of overall crashes, although less severe. The compromise between crashes and median barriers demands a justification and a comprehensive assessment of safety benefits for the installation.

The objective of this paper was to present a comprehensive in-service performance evaluation of cable barrier systems installed on Wisconsin state highways with the emphasis on the high-tension cable guard (HTCG). The safety benefits of implementing cable systems were primarily estimated through a before-and-after crash comparison. The ad hoc maintenance effort to repair the cable barriers were also assessed for three types of HTCG: CASS, Brifen, and Gibraltar systems. The evaluation and associated cost not only help public agencies to prioritize competing safety needs but also comparing the overall benefits between the system-wide implementation of cable barrier and spot treatments. In addition, the cable system comparison responds directly to the questions of endorsing the appropriate cable system on state highways.

The paper is organized as follows: A review of previous studies related to median barriers follows the introduction; then a data section provides Wisconsin cable system information and crash data, supported by descriptive data and statistical analysis; next, the cost benefit analysis is detailed and followed by a conclusion with recommendations and future extensions.

LITERATURE REVIEW

Varying in study designs and evaluation perspectives, the median cable barrier studies have been conducted at different times, on different scales, and in different manners. To be consistent with the objective of the study, this review primarily focused on the cable in-service performance and cost effectiveness.

The pioneering studies of cable barriers in use on New York State roads and Iowa roads concluded that the weak-post cable barrier resulted in less severe crashes than strong post W-beam guardrail systems even though cable penetrations existed in the former system (5). It was also reported that the average repair cost per accident was around $543 ($90 per post) in Iowa. The old cable barriers, low-tension and weak post systems, installed in the 1960's or 1970's, have a relatively high penetration rate which has been substantially reduced with the latest, high-tension cable systems. For example, in a Florida median barrier pilot study, there were 20 reported impacts from May 2005 to April 2006 (6). All impacts were successfully restrained with no median crossover fatalities reported within cable barrier areas. Another study in Illinois reported an almost flawless result of cable barriers, only one penetrated crash was found out of 198 total median barrier crashes (7). All vehicles were retained within the median and only two of 198 cable crashes resulted in a cable snapping, one by means of a semi-truck crash. An Oregon study evaluated the effectiveness of the three-cable barriers in preventing crossover accidents on Interstate 5 and Oregon Highway 1, and estimated the maintenance and repair costs in order to make recommendations for future installations (8). The cable barrier system worked well in medians at least seven meters wide, where used to prevent the infrequent but potentially catastrophic cross-median crashes. According to the results, the cable median barrier system proved to be cost-effective when compared to the concrete median barrier system.

North Carolina Department of Transportation (NCDOT) is one of the few agencies who implemented system-wide median cable barriers as an ultimate solution to CMCs. Cables were installed for the entire Interstate highway network with medians narrower than 70 feet. Their maintenance and repair costs, sampled along a 13.7 kilometer-long (8.5 miles) section on I-40, showed that there were 71 repairs per year. The estimated repair cost per post was $86 for the subject section (9). More recently, Hunter *et al*. studied the effectiveness of the cable barrier system in North Carolina (11). The researchers developed negative binomial regression models and used a reference population of the North Carolina Interstate Highways to predict crashes and found that the barriers did indeed reduce cross median collisions and improve safety even though an increase in run-off-the-road left crashes existed. Hunter's findings are supported by the Texas Transportation Institute (TTI) whose outcome conveyed similar messages (11). In a larger scale follow-up study, NCDOT reported a reduction of 54 fatal crossover crashes from 133 in the before study period (1994-1998) to 79 in the after study period (1999-2003), saving 94 lives (a reduction from 198 to 104 fatalities) through a five-year before and after crash study on 238 miles of freeway (13). Missouri Department of Transportation (MoDOT) also found a system-wide cable barrier implementation was significant, reducing fatalities from 24 in 2002 to 2 in 2006 (14). Following the same path as NCDOT, the South Carolina Department of Transportation (SCDOT) equipped their state highways with more than 470 miles of barriers by mid-2006, which significantly decreased crossover fatalities from 27 median crossover fatalities in 2000 to 4 crashes in 2006 (15). Given a maintenance cost of $902 per hit, the study reaffirmed that installing median cables to prevent severe crashes is a cost effective solution. Consistently, the societal benefit of Washington state cable barrier was calculated to be an annual $420,000 per mile with approximately $733 per repair, $44,000 installation cost per mile and $2,570 annual maintenance cost per mile (16).

Although overwhelming evidence supports median cable barriers as an effective approach to reducing CMCs and their severities, one exception appeared in a study report based on a section on I-5 in Maryville, Washington where four fatal cross-median crashes resulting in seven deaths involved penetrating median barriers (17). Prior to installing cable barrier systems the fatal CMC rate was 0.089 per Million Vehicle Miles Traveled (MVMT). After the installation of cable barriers the fatal CMC rate was 0.120 per MVMT. As a result, a concrete barrier was recommended for that section (17). It should be noted that this roadway section in Washington State is atypical to cable barrier performance within Washington State. Overall cable barrier performance in Washington State indicates a 63 percent reduction in the CMC rate (both fatal and non-fatal) (18). Not as successful as the rest of the state, I-5 stretch signaled possible issues with the barrier system and the installation, which encouraged further investigation and evaluation of cable candidate locations.

In summary, reported installation costs range from $44,000 to $125,000/mile and the average maintenance cost per hit varies from $312 to $1,795 (5, 8, 10, 11, 15, and 16). The severity of median related crashes has been reduced significantly after median barrier installation, but the number of total crashes, especially property damage only crashes, was significantly increased.

DATA COLLECTION

Before the high-tension systems, Wisconsin installed low-tension median cable barriers at the locations warranted by the WisDOT Facility Development Manual (FDM) (19). WisDOT started to install HTCG with the increase of traffic, the awareness of the public toward median cross-over collisions, and the advancement of cable technologies. Starting from a pilot project approved by the Federal Highway Administration (FHWA), WisDOT uses three types of HTCG systems, Brifen, CASS, and Gibraltar.

Study Locations

In this study, both high-tension and low-tension cable barriers are considered for analysis with low-tension cable as a baseline comparison. Three high-tension cable barrier systems, Brifen, CASS, and Gibraltar, were installed on USH 41 in Fond du Lac County, Winnebago County and Dodge County, and on I-94 in Dunn County, Juneau County, Waukesha County and Dane County. The length of Brifen installation is 7.7 miles in total, 4.07 miles south of, and 3.63 miles north of the city of Fond du Lac. CASS installation is 6.91 miles in total, 2.60 miles south of, and 4.31 miles north of the city. The length of Gibraltar installation is 5.90 miles, 3.57 miles in Dunn County and 2.33 miles in Waukesha County. Due to different construction stages, over one year of data is available for both north projects and more than two years' data for both south projects. Existing low-tension cable barriers on USH 41 near the city of Fond du Lac were used as a comparison. The total length of low-tension cable system is 2.34 miles, one 1.30 mile-long segment and a 1.04 mile segment.

Maintenance Log's Design

In order to evaluate the costs associated with cable barriers, specifically: installation, maintenance, and repair costs, a Maintenance/Repair Log for cable barrier systems was designed from other states' templates such as Illinois, Ohio, Texas, and Washington but modified and customized to reflect the needs for Wisconsin. The Wisconsin log used three data components: a description of cable hit incidents, a list of materials and labor used to repair damaged barriers, and finally a total cost of these repairs. The first and second components are collected by county highway officials while the third component is completed by the WisDOT regional office. A sample log is illustrated in Figure 1.

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 1 Sample log of Wisconsin cable rarrier maintenance and repair.

Crash Data Collection

Though cable barriers are installed to reduce CMCs, they themselves are fixed roadside objects. Without overemphasizing their positives, cable barriers reduce the area in which an errant vehicle is allowed to recover without encountering an object. Therefore, crashes have to be carefully reviewed to identify the real changes happening before and after the cable installation.

Study Period

Three-year data has been 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, never overlapping with the cable construction period.

The projects were completed in 2006 and 2007, causing different study periods for the after data collection. Also, researchers found that a portion of the construction areas were open to traffic prior to completion. Hence, the after study periods overlap the construction period by 50 percent of the construction period in order to include all cable barrier crashes. The after study period began on October 19, 2006 for the south project, on September 11, 2007 for the north project, and on July 18, 2007 for Gibraltar in Waukesha and ended on December 31, 2008 for all locations. The after period for low-tension system is from July 22, 2006 to December 31, 2008.

Definition of Median-related Crashes

A study performed by the Pennsylvania Department of Transportation admitted that it was difficult 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). Mak and Sicking applied a probabilistic approach to estimate the distance of vehicle encroachment to obtain the number of "possible" cable collisions (21). At the pilot locations in Wisconsin, single run cable barriers were installed on the shoulder edge close to the traveled way. Hence, it is relatively safe to assume that all left-encroached vehicles may trigger cable collisions.

Median related crashes for the before period were extracted from WisDOT crash database by manually reviewing all corresponding police crash records between January 1, 2003 and December 31, 2005. Modified from a study conducted by Miaou et al. (9), median related crashes were classified by median entries (ME), cross median events (CME), and cross median crashes (CMC). The difference between CME and CMC is that CME is a single vehicle crash but CMC is a multi-vehicle crash. As illustrated in Figure 2a, three median-related crashes are counted and the fourth is excluded in the before period because no median cable would be installed on this side. An apparent flaw in many previous studies is only the crossover median crashes were considered in the before period. Some researchers included CME in the before-and-after crash data analysis, but none of them included ME crashes (21). In fact, ME crashes may be converted to cable collisions assuming the cable barrier is installed on the same side of the median as the vehicle entry point. Failure to account for these crashes will potentially underestimate the safety benefit of the barrier systems. The data collection for a before-and-after comparison should include median entries with the knowledge of exact side the installed cable barrier to ensure that the comparison is comprehensive and complete. The after period crash data was obtained directly from the maintenance logs and reviewed manually along with crash reports from the state's crash database. Data for 123 cable related crashes including hit-and-run crashes that resulted in cable repairs were collected in Fond du Lac, Waukesha, and Winnebago counties. Figure 2b shows the types of after period crash data in the study.

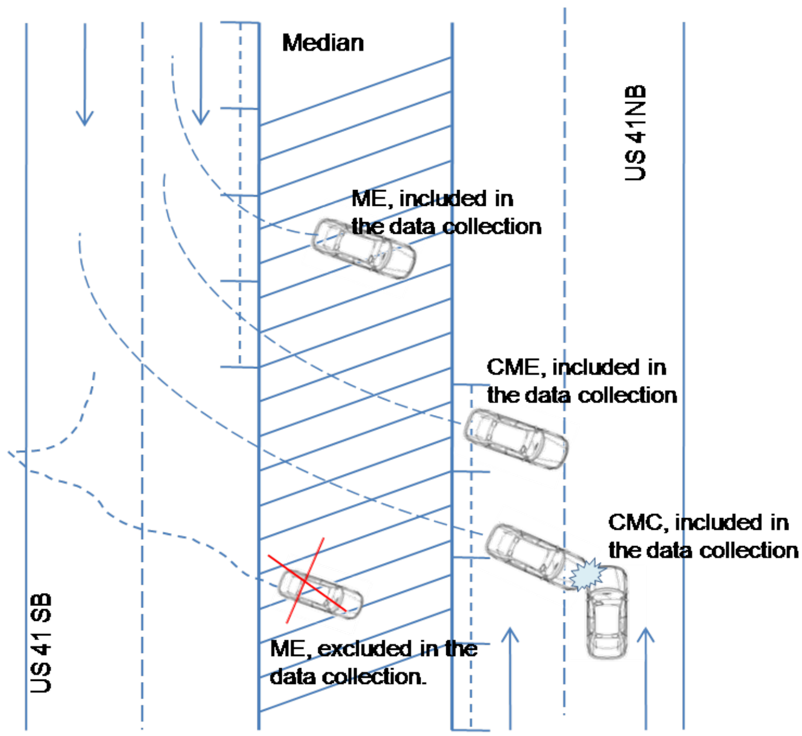

Figure 2a Types of median related crashes in before period included in the study.

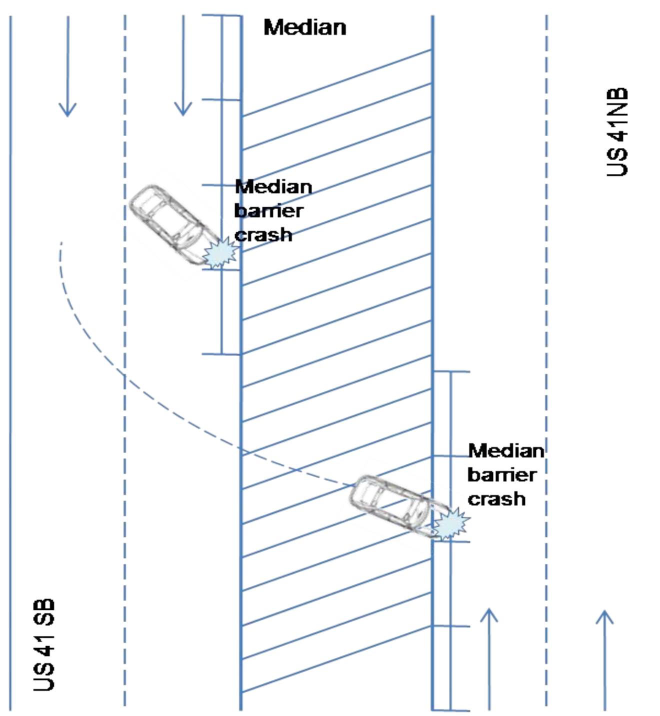

Figure 2b Types of median related crashes in after period included in the study.

OVERVIEW OF CRASH DATA INFORMATION

Crash Patterns by Season

Mother Nature contributes to a considerable portion of run-off-the-road incidents including CMCs and the seasonal factor should not be overlooked when considering any safety improvement countermeasures (20, 21). The safety consequence of installing median cable barrier is different in Texas than Wisconsin. For example, more cable collisions may be expected due to more left-encroached vehicles during the prolonged winter season in Wisconsin. The initial data analysis consists of crash distributions by month and pavement surface, summarized by winter versus non-winter seasons in Table 2. From Table 1 it is clear that crashes increased about 60 percent in winter while decreased about 26 percent in non-winter seasons after the installation of cable barriers, making the crash count ratio between winter and non-winter more than tripled. The large increase of cable collisions in winter accounts for an increase in overall "after" crashes, but usually less severe.

Table 1 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%

Cable Collision Rates

In order to describe the characteristics of data in all aspects, both descriptive data analysis and more complicated comparisons for the before and after data were conducted. Most roadside barriers are designed following NCHRP 350 TL3 crash testing criteria and are generally not designed for semi-trucks (22). Therefore, tables below excluding truck crashes provide extra information for the cable performance by design. Table 2a and 2b present before and after annual crash rates per one hundred million vehicle miles traveled (100MVMT) by severities with and without truck crashes.

The differences between crash rates show significant reductions of fatal (K) and serious injury (A) crashes while the results are rather mixed for types B and C. On the other hand, PDO increased at all locations after installing the cable barriers. However, the sustainable benefits in saving lives and preventing severe injuries underscore the importance of installing cable barriers in the areas where high numbers of CMCs happened.

Table 2a After Crash Rates by Site with and without Trucks

After Crash Rates	N Brifen		N CASS		S Brifen		S CASS		Gibraltar	
	W/ Truck	W/O Truck	W/ Truck	W/O Truck	W/ Truck	W/O Truck	W/ Truck	W/O Truck	W/ Truck	W/O Truck
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	0.00	3.70	3.70	3.15	3.15	2.62	2.62
C	8.86	8.86	0.00	0.00	1.85	0.00	6.30	6.30	2.62	0.00
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 2b Before Crash Rates by Barrier Site and Severity

Before Crash Rates	N Brifen		N CASS		S Brifen		S CASS		Gibraltar	
	W/ Truck	W/O Truck	W/ Truck	W/O Truck	W/ Truck	W/O Truck	W/ Truck	W/O Truck	W/ Truck	W/O Truck
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

K denotes a fatal crash,
A denotes an incapacitating injury crash,
B denotes a non-incapacitating injury crash,
C denotes a possible injury crash,
PDO represents a reportable property damage only crashes whose damage is above $1,000, and
N means the north cable section and S means the south section.

Cable Collision Results

Cable performance after being struck by vehicles needs to be carefully evaluated from several aspects to understand whether or not the cable will deflect vehicles back to the traffic, which may incur a secondary crash. Effort has been made to acquire and analyze the median barrier performance based recorded crashes.

After colliding with the cable, the vehicle can either penetrate, or be redirected or stopped. In this study, penetration should be defined as when a vehicle hits the cable barrier, breaks through it completely and enters the median area. The narrative and pictorial section in the police accident report helps to identify and confirm whether a cable barrier penetration happened or not. From the maintenance data collected, all cable crash records marked as penetrated have been reviewed manually for identifying the real penetrations. Some crashes might be marked as penetrations such as the tire tracks on the other side of cable; however, this recorded penetration may only be deflection. As shown in Table 3, all cable barriers produce very low penetration rates and most vehicles are restrained or stopped by the cable barriers. No CMCs or CMEs are associated with vehicle penetrations for all types of cables in the after study period.

Table 3 Cable Collision Results

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

MEDIAN CABLE BARRIER IN-SERVICE PERFORMANCE EVALUATION

Although crash facts confirm the strong safety benefits resulting from cable barriers, the installation adds new facilities to highway medians and their operation and maintenance costs cannot be neglected. More importantly, the cable barrier's in-service performance needs to be addressed after the collision as to whether or not the system can handle another crash before it is fixed entirely. From the maintenance log, relevant information can be retrieved and the assessment was performed in three areas: 1) Cable's performance versus collision consequence; 2) Number of posts replaced after a vehicle's contact; and 3) Man-hours incurred.

Cable in-service Performance

Crash severity is categorized by cable system and by performance with and without truck-related crashes in Table 4. Truck impacts may significantly affect cable performance, causing grounded or slightly damaged cables. The Brifen cable system shows slightly better results than CASS. Low-tension is not able to continue to function after being struck.

Table 4 Collision Safety Consequence and Severities

Cable Type	W/ Truck			W/O Truck		
	Vehicle Penetration	Cable on Ground	Cable Damaged	Vehicle Penetration	Cable on Ground	Cable Damaged
Brifen	0	1 PDO	0	0	0	0
CASS	1B	2B	1B	1B	1B	0
Low Tension	1C	1C, 1 B and 7 PDO	0	1C	1B and 5 PDO	0
Gibraltar	0	2 PDO	0	0	2 PDO	0
Total	2	12	1	2	7	0

Table 5 presents cable performance evaluations from the maintenance perspective. The number of posts replaced is not only decided by the magnitude of the impact but also by system type. The man-hours are correlated to the number of posts replaced and the ease of replacement, which can add a considerable amount of time. Both posts replaced and man-hours attribute to the amount of recovery cost. Comparatively, the most frequent cost figure for both Brifen and

CASS is between $200 and $300 and the most frequent cost for Gibraltar is between $100 and $500, while the cost for low-tension cable is more evenly distributed.

Table 5 Mean, Standard Error for Maintenance Cost, Man-hours Used, Posts Replaced

		Mean				Standard Error			
		Brifen	CASS	Low Tension	Gibraltar	Brifen	CASS	Low Tension	Gibraltar
With Truck	Costs	377.07	408.59	589.53	441.90	436.75	301.14	622.13	362.84
	Man Hours	5.34	5.10	7.68	4.47	5.68	2.87	7.76	4.10
	Posts Replaced	4.08	3.18	2.47	2.94	5.51	3.02	2.63	1.68
With-out Truck	Costs	319.88	422.90	418.58	446.08	219.94	240.17	303.28	404.71
	Man Hours	5.40	4.76	7.78	4.27	3.05	2.79	3.82	4.62
	Posts Replaced	4.14	3.25	2.55	2.31	3.22	3.12	1.97	2.18

The average cost per hit becomes available once the man-hours and parts to be replaced are known. It is worth noting that the maintenance cost per hit for cables is lower than any state in the literature (5, 8, 15, and 16). Cost per hit is a very important measure because it projects the future maintenance estimate provided that the number of cable collisions is known. Considering all the high-tension cables without truck impacts, the performance of Brifen system is associated with low figures in costs, man hours and replaced posts.

In general, the observed statistics strongly support that HTCG substantially outperformed LTCG while marginal difference exists between two HTCG systems. To get more rigorous results, statistical analysis was conducted to test whether or not a significant difference exists among the cables studied. Brifen, CASS, low-tension, and Gibraltar cable systems were tested from the standpoints of the maintenance costs, man-hours used, and number of posts replaced. Though the distribution of the 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. Otherwise, to relax the normality assumption, a non-parametric alternative to the *t* test such as Mann-Whitney-Wilcoxon (MWW) test or signed-rank test should be used. The *t* test statistics given in Table 6 indicate that there is no statistically significant difference between high-tension cables systems Brifen and CASS, and between low tension and Gibraltar; but both high-tension cables Brifen and CASS outperformed low-tension and Gibraltar. Gibraltar shows no significant difference with low tension except for the man hours used, but Gibraltar slightly outperformed low tension cable. Brifen outperformed CASS in maintenance cost without trucks involved.

Table 6 Paired Comparisons for Maintenance Cost, Man-hours Used, Posts Replaced

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

Cable Repair Delay

It is critical to repair and replace the malfunctioned cables after collisions to avoid further median intrusions. However, the repair can be delayed due to a variety of reasons such as unknown crash locations, parts and staff availability, weather, and so on. Information for delays was derived from the maintenance logs. The longest delay for maintenance was 103 days and the shortest one is zero as the barriers were repaired in the same day. There are a total of five cable crash locations which took over two months to repair. The two longest delays occurred in the first summer after the data collection began (both at low tension sites), and, as expected, the mean delay in winter months is larger than the in the non-winter months. Note that the two longest delays (103 days and 95 days) are treated as outliers and excluded from the analysis. Figure 3 shows that the maintenance delay is not normally distributed since over a quarter of the maintenances took more than a month to repair regardless of the season.

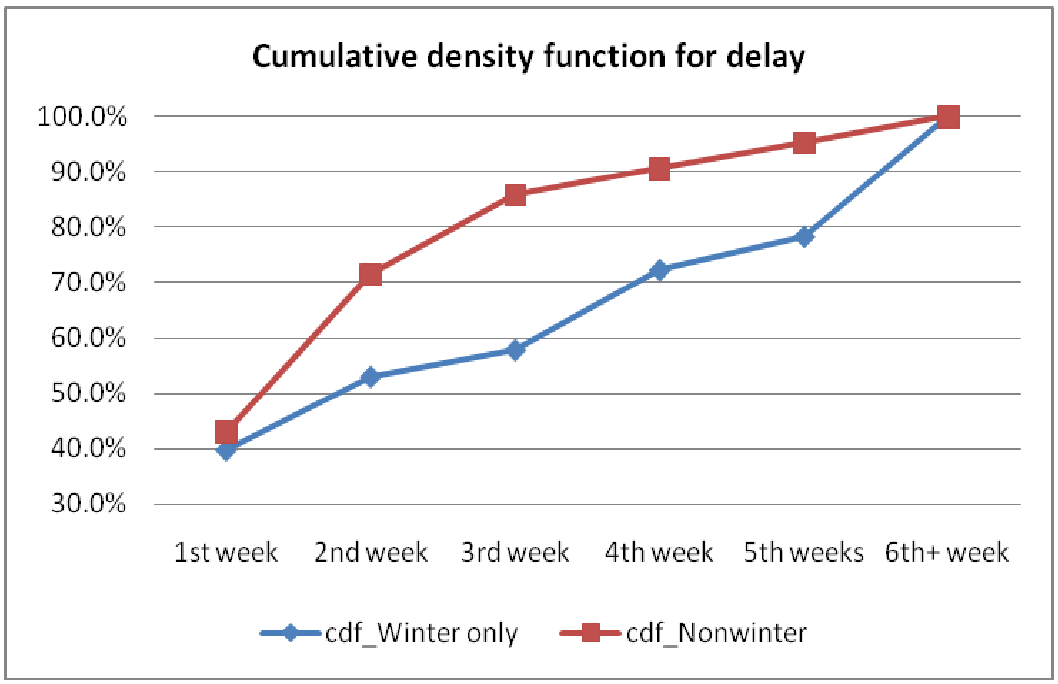

Figure 3 Cumulative density functions for winter and non-winter delays.

COST BENEFIT ANALYSIS

A median cable is designed to contain and deflect an errant vehicle to an acceptable deceleration and angle so that the collision severity can be reduced. In determining whether it is cost-effective to install a barrier, this benefit of reduced injury severities is compared against the "nuisance hits", as well as the cable installation and maintenance cost. Note that the construction cost does not include the cost of providing grading, modification drainage systems and traffic control items. Previous cost-benefit analysis was performed only based on crash savings using a median related crash prediction model (9). Including cable barrier construction, maintenance and operational costs provides a realistic budget estimate and economically justifiable performance measure against other safety needs.

Cable Barrier Construction and O&M Costs

Installation cost consists of purchases of cables, posts, anchors, and other parts, and the cost of site preparation and cable installation. User costs and delay costs caused by work zone traffic control should be also included in the installation cost. However, no delays were observed for the Wisconsin projects so these costs were ignored. Maintenance cost includes costs for parts, related labor, equipment rentals, and traffic control during repairs. So the total annual cable cost is the sum of annual depreciation cost and annual maintenance cost.

Following the WisDOT planning guide, 20-year in service for cable barrier and three percent inflation rate were applied. And the interest rate used here is 3%, which is usually the inflation rate (23). The annual depreciation cost was calculated using the following formula and the results are presented in Table 7.

$$\text{Depreciation cost per year} = \frac{TC * i * (1+i)^{20}}{(1+i)^{20} - 1}, \frac{\text{Expected Annual Crash Savings}}{\text{Expected Annual Total Cable Costs}} \quad (1)$$

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

Based on the installation costs and maintenance costs occurred in this study, Table 7 gives the annual budget if all interstate highways are installed cable barriers in Wisconsin for the cable choices of Brifen, CASS, and Gibraltar, given the three percent interest rate and the twenty service years for cables. The budget for each of these cable types will be roughly five million to six and a half million dollars each year.

Table 7 Total Annual Cost for WI if All Interstate Highways Are Installed Cable Barriers.

Barrier Type	Installation Cost/(Year*Mile)	Maintenance Cost//(Year*Mile)	Cost /(Year*mile)	Total Mileage	Total Cost per Year
Brifen	7,390.72	1,075.53	8,466.25	743	6,290,427.20
CASS	5,546.05	1,201.43	6,747.48	743	5,013,379.73
Gibraltar	6,652.51	1,980.52	8,633.02	743	6,414,337.22

Safety Benefits

Benefits are expected savings from the reduction in the total crash costs before and after the cable installation, where the total crash cost is the sum of the unit crash cost multiplied by severity and corresponding crash counts. It is also the same unit crash cost used by the Division of Transportation Investment Management (DTIM) for planning purpose in WisDOT. Annual benefits are calculated from the following formula according to the definition.

$$\text{Expected Crash Savings} = \text{Expected Before Crash Cost} - \text{Expected After Crash Cost} \quad (2)$$

B/C Ratios

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

$$\text{B/C Ratio} = \frac{\text{Expect Annual Crash Savings}}{\text{Expect Annual Total Cable Costs}} \quad (3)$$

A ratio greater than one indicates that the benefits from the safety improvement are monetarily greater than the total costs, proving the project to be economically justifiable, while the converse is true for a B/C ratio less than one. Table 8 provides B/C ratios by system and location with and without truck crashes. Note if grade or drainage items are included in the analysis, the B/C ratio will be lower.

Table 8 B/C Ratios by System/Location with and without Truck Crashes*

Cable Type	W/ Truck			W/O Truck		
	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

*FHWA Crash Cost Inflated to 2008 Values. The FHWA unit crash cost, listed in Table 13, was adopted in the study and inflated to 2008 value.

All B/C Ratios calculated are satisfactory except for the one for CASS in the south Fond du Lac County, which may result from 1) the lack of fatal CMC crashes 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. Brifen is shown to have a consistent high B/C ratio on average. In short, the ratios calculated from the Wisconsin maintenance and crash data for high-tension cables unanimously assert safety benefits at all study locations.

CONCLUSIONS

In an effort to reduce the number of median cross-over crashes and their severities, WisDOT is retrofitting the unprotected areas with cable barriers. Since median barriers were installed primarily for their safeguard against CMCs, three-year before median-related crashes along with all available after cable collisions were collected and manually reviewed to verify the location and crash type. Particularly, the inclusion of median entry crashes during the before data collection period can avoid the underestimate of cable safety benefits. Besides crash data, cable maintenance information was collected by the Fond du Lac County Highway Department. After synthesizing all of the information, both descriptive and statistical analyses were conducted to identify cable crash patterns, compare before and after crash variations, address potential cable deficiencies and evaluate different cable systems' performance.

Initial data analysis shows that before and after crashes are more weather and road condition related. In winter, a very high percentage crashes occurred on snow or ice covered roads, compared to less severe crash severities on dry roads in other seasons. This is consistent with findings from other states with similar weather conditions.

Data analysis of before and after crash rates indicate that more median barrier crashes, especially PDO crashes, were found at every location under evaluation, likely due to the close proximity of the barriers to the traveled way. However, overall crash severity decreased significantly as no fatalities and only one type A injury crash were found in all sites after installation compared several fatal and type A crashes in the before period. The observations were further confirmed by a statistical test in which χ^2 test statistics support cable barrier's function of preventing severe crashes. In addition to safety benefits, cable construction and future O&M 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 cables by the repair man-hours, number of posts replaced and total maintenance cost per hit and the results show that the high-tension cables are superior to low-tension cable in every category. Truck impacts may be significant to cable's performance since most systems are designed using cars and pickup trucks as test vehicles.

It is suggested that the B/C ratio without truck-related crashes be used since the systems are not designed for large trucks. As a result, all except for one testing sites display large cost-benefit effectiveness. Note that the benefit-cost analysis depends appreciably on the number of hits sustained by the system per mile along with 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 a cost-effective approach to preventing severe median related crashes. Finally, the cost per hit and unit cable O&M cost per mile generated from Wisconsin data can assist WisDOT in assessing the option of system wide cable implementation or spot treatment and in developing predictive cable median barrier warrants.

ACKOWLEDGMENTS

The assistance of engineers in the central office and Fond du Lac County from WisDOT is acknowledged for providing the maintenance data and other necessary information to complete the study. Madhav Chitturi, Andrea Bill and Michael Runnels are also acknowledged for proofreading of this report.

REFERENCES

1. *Roadside Design Guide.* AASHTO, Washington, D.C., 2002.
2. *Improved Guidelines for Median Safety: Draft Report of Analysis Findings.* Prepared for NCHRP Project 17-14(2). BMI-SG, Vienna, Va., 2003.
3. Noyce, D. A. *Reducing Median Crossover Crashes in Wisconsin*. Institute of Transportation Engineering, Annual Meeting and Exhibit. 2006.
4. Donnell, E. T. and Mason, J. M. Jr. *Methodology to Develop Median Barrier Warrant Criteria.* Journal of Transportation Engineering. April 2006, pp. 55-63.
5. Ray, M. H, and R. G. McGinnis. *NCHRP Synthesis 244: Guardrail and Median Barrier Crashworthiness*. National Academy Press, Washington, D.C, 1997. Chapter 3, pages 29-37.
6. Cook, W. H. and Johnson, R. B. *Median Cable Barrier Pilot Project Design.* Florida Department of Transportation. 2006.

7. Benda, J and Stukel, G. *Cable Median Barrier System Deployment Operation and Maintenance.* IBTTA – Facilities Management Workshop. Illinois Department of Transportation. May 22, 2007.
8. Monsere, C. M., Sposito, B., and Johnston, S. *Safety Effectiveness and Operating Performance of Three-Cable Median Barrier on Interstate 5 in Oregon.* Compendium of Technical Papers, Institute of Transportation Engineers 2003 Annual Meeting, Seattle, Washington, August 2003.
9. Miaou, S. P., Bligh, R. P. and Lord, D. *Developing Guidelines for Median Barrier Installation: Benefit–Cost Analysis with Texas Data. Transportation Research Record: Journal of the Transportation Research Board, No. 1904,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 2-19.
10. Mustafa, M. B. *Use of Three-Strand Cable Barrier as a Median Barrier*. North Carolina Department of Transportation. August 1997.
11. Hunter, W. W., Stewart, J. R., Eccles, K. A., Huang, H. F., Council, F. M. and Harkey, D. L. *Three-Strand Cable Median Barrier in North Carolina*. . In *Transportation Research Record: Journal of the Transportation Research Board, No. 1743,* Transportation Research Board of the National Academies, Washington, D.C., 2001, pp. 97-103.
12. Cooner, S. A., Alberson, D. C., Bligh, R. P., Ranft, S. E., Rathod, Y. K., and Sun, D. *0-5609: In-Service Evaluation of Cable Median Barrier Performance.* TTI, Feb 2008.
13. Bennett, J. A. and Murphy, B. *Median Barriers in North Carolina AASHTO Subcommittee on Design – 2006.* North Carolina Department of Transportation. June 2006.
14. Chandler, B**.** *Research paid off: Eliminating Cross-Median Fatalities--Statewide*
15. *Interstate Cable Barriers.* South Carolina Department of Transportation. 2007
16. McClanahan, D., Albin, R. B. and Milton, J. C. *Washington State Cable Median Barrier In-Service Study*. WSDOT, Nov 2003.
17. Ray, M. H. Chapter 1: An Evaluation WSDOT's Cable Median Barrier Policy (2007 Cable Median Barrier Report). Washington Department of Transportation. 2007
18. Albin, R. B. *Washington State Cable Median Barrier*. AASHTO TIG. Washington Department of Transportation. 2007.
19. FDM 11-45-1, http://roadwaystandards.dot.wi.gov/standards/fdm/11-45-001.pdf, Accessed on Mar 12, 2009.
20. Mason, J. M. Jr., Donnell, E. T., Harwood, D. W., Bauer, K. M., Sada, J. M. and Pitrucha, M. T. *Median Safety Study (Interstates and Expressways.)* Final report, Pennsylvania Department of Transportation. June 2001.
21. Mak, K. K., Sicking, D. L. and Polivka, K. A. *Roadside Safety Analysis Program (RSAP), Engineer's Manual.* National Cooperative Highway Research Program report 492, Transportation Research Board, Washington D.C., 2003.
22. Ross, H. E., Jr., D. L. Sicking, R. A. Zimmer, and J. D. Michie. *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.* TRB, National Research Council, Washington, D.C., 1993.
23. Kellison, S. G. *The Theory of Interest*. Second Edition, International Edition 2005, McGraw Hill.