DEPARTMENT OF TRANSPORTATION

High-Tension Cable Median Barrier Safety Effectiveness Evaluation

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16. Abstract (Limit: 250 words)

The objective of this study was to evaluate the change in crash frequency or severity of varying lateral offset distances of high-tension cable median barriers in Minnesota. Crash and traffic data from 2016 to present were conjoined with roadway cross-sectional data and high-tension cable barrier locations to perform cross-sectional analyses for interstate segments equal to or greater than 0.05-miles long. Negative binomial regression models were estimated and used to develop crash modification factors (CMFs) for the following crash types: total crashes, target crashes, and barrier crashes. In addition to evaluating the impact of lateral offset, a naïve before-after evaluation was completed to quantify the impact of installing high-tension cable barrier.

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HIGH-TENSION CABLE MEDIAN BARRIER SAFETY EFFECTIVENESS EVALUATION

FINAL REPORT

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EXECUTIVE SUMMARY

High-tension cable median barriers (HTCMB) are a crash safety countermeasure tool used to reduce the frequency and severity of cross-median vehicular crashes. They are generally installed in the center median near the roadway shoulder or near the ditch bottom and may consist of three or four strands of cable. The purpose of the HTCMB is to absorb a vehicle's impact when struck and redirect the vehicle so it continues in the direction it was traveling. When vehicles depart from the travel lane and collide with the HTCMB, the barrier posts break while the cables absorb a large amount of the vehicle's kinetic energy at the point of collision. In this way, the vehicle speed is reduced, the travel path is redirected away from opposing traffic, and the vehicle either remains in the median or continues moving in the original direction of travel.

The objectives of this report were to: (1) study the change in crash frequency or severity after installing HTCMB, and (2) study the change in crash frequency or severity associated with the offset, i.e., the distance between the road and cable barrier.

To address these objectives, this study used a combination of cross-sectional regression analysis and naïve before-after methods to investigate the safety impact of HTCMB. Cross-sectional regression analysis was used to develop crash modification factors (CMFs) for the offset distance, i.e., distance between the barrier and inside edge line. Naïve before-after methods were used to develop CMFs for installation of cable barrier. The cross-sectional analysis was conducted only for interstate roads with two-lanes in each direction with segments 0.05 miles or longer. The naïve before-after analysis included all facility types.

Evaluations were conducted for total crashes, as well as target crashes and barrier crashes. Target crashes, also referred to as median crashes in this document, were defined as any crash that included a cable median barrier as a first harmful event in addition to descriptions such as "ran off the road into the median" in the narrative. They also included any crashes that involved overturning of vehicles in the median. A median barrier crash, also referred to as barrier crashes in this document, was a subset of median crashes. A median carrier crash was defined as a crash that specifically included a cable median barrier as a first harmful event in addition to a cable or median barrier in the narrative. The difference between a median crash and barrier crash was that median crashes included additional criteria related to relative trafficway location (the median), manner of collision (ran off road) and first harmful events described as cross median for vehicles involved in the crash. Target crashes were crashes that either were or could have been impacted by HTCMB, whether HTCMB was present or not, while barrier crashes were directly impacted by HTCMB.

For offset, measured in feet, the recommended CMFs (base Condition: offset = 8 feet) for the three crash types that could be investigated were:

Total Crashes

- $CMF = \left(\frac{offset}{8}\right)^{-0.1438}$
- Where:
  - Offset = distance between the inside edge line of the road and the cable barrier; feet
  - Base condition is offset = 8 feet
  - Note: Only applicable for offset greater than 0 feet

Target Crashes

- $CMF = \exp[-0.0186 \times (offset - 8)]$
- Where:
  - Base condition is offset = 8 feet

Barrier Crashes

- $CMF = \exp[-0.0204 \times (offset - 8)]$
- Where:
  - Base condition is offset = 8 feet

As the barrier was placed farther away from the inside edge line, total crashes, target crashes, and barrier crashes re expected to decrease. These CMFs can be used by practitioners to determine the impact to crash frequency by changing the barrier's position in the median.

Regarding the effectiveness of installing a barrier to reduce crash frequency and severity, Table ES-1 shows the CMFs that were estimated using naïve before-after analysis. Crash types listed in the table are based on the KABCO injury classification scale:

- K – Fatal Injury
- A – Incapacitating injury or suspected serious injury
- B – Non-incapacitating injury or suspected minor injury
- C – Possible injury
- O – No injury

Crash types designated as KA include fatal injury and incapacitating injury crashes. Crash types designated as KAB include fatal, incapacitating, and non-incapacitating injury crashes. The KABC designation includes all injury and possible injury crashes. Total crashes includes crashes of all severities, including no injury. All the CMFs were statistically different from 1.0 at the 5% significance level (95% confidence level). Total and target crashes increased when barriers were installed, while KA, KAB, and KABC crashes decreased (CMFs for K crashes were not estimated due to small samples). In reviewing these CMFs, it was important to consider that the definition of A and B crashes changed in 2016, and the naïve analysis did not explicitly account for these changes. The definition of A and B crashes was modified from being called "incapacitating injury" to "suspected serious injury" and "non-incapacitating injury" to "suspected minor injury." The modification only impacted the associated names of A and B crashes and how law enforcement reported crash severity. As such, caution should be used with interpreting KAB and KA CMFs.

Table ES-1: CMFs Based on Naïve Before-After Method for High-Tension Cable Barrier

Crash Type	Crashes in the After Period	Expected Crashes in the After Period Without Treatment	CMF	S.E. of CMF
KA	73	103.5	0.682	0.021
KAB	583	630.4	0.920	0.006
KABC	1410	1718.7	0.819	0.002
Total	7398	5741.0	1.288	0.001
Target Crashes	2690	1391.4	1.930	0.009
Target KA	17	41.6	0.377	0.017
Target KAB	137	222.9	0.605	0.008
Target KABC	309	528.3	0.581	0.003

CHAPTER 1: BACKGROUND

High-tension cable median barriers (HTCMB) are a crash safety countermeasure tool used to reduce the frequency and severity of cross-median vehicular crashes. They are generally installed in the center median near the roadway shoulder or near the ditch bottom and may consist of three or four strands of cable. The purpose of the HTCMB is to absorb a vehicle's impact when struck and redirect the vehicle to continue in the same direction it was traveling. When vehicles depart from the travel lane and collide with a HTCMB, the barrier posts break while the cables absorb a large amount of the vehicle's kinetic energy at the point of collision. In this way, vehicle speed is reduced and the travel path is redirected away from opposing traffic so the vehicle either remains in the median or continues moving in the original direction of travel without over-redirecting into same directional traffic. In Minnesota, HTCMB are typically installed on high-speed, divided, multi-lane highways with two lanes in each direction, and as of December 2018, there were 705 miles of HTCMB installed throughout the state (MnDOT, 2021).

The Minnesota Department of Transportation (MnDOT) reports that from 2004 to 2016, the implementation of HTCMB has reduced "fatal and life-changing crashes caused by vehicles crossing the median into oncoming traffic" by 95 percent and "there are few safety devices available that virtually guarantee consistent success in saving lives every year on divided highways" (MnDOT, 2021). From 2004 to 2016, MnDOT reported that 148 lives were saved by HTCMB.

The objective of this study was to evaluate the relationship between anticipated crash reduction and the lateral offset from the travel lanes at which HTCMB are installed, as well as verify the effectiveness of HTCMB in reducing the severity of crashes. The need for this study was identified by MnDOT district staff as they deal with the issues of deciding where to place HTCMB. In the past, district staff have had to weigh the costs of changing the median design to place the barrier farther away from the travel lanes. However, there has been limited information available to estimate the expected benefit (i.e., crash reduction) to understand the tradeoff between construction costs and safety benefits. Therefore, the goal of this research was to provide MnDOT with information that would allow it to estimate changes in crashes based on the lateral placement of HTCMB.

CHAPTER 2: LITERATURE REVIEW

2.1 SUMMARY OF HTCMB COUNTERMEASURES STUDIES IN CMF CLEARINGHOUSE

This literature review primarily focuses on existing studies for installation of cable barriers available in the Federal Highway Administration's (FHWA) Crash Modification Factor (CMF) Clearinghouse. The CMF Clearinghouse is a web-based database for countermeasures, associated CMFs and supplemental resources about CMFs. The Clearinghouse identified 15 studies related to HTCMB. All 15 studies were reviewed except for one (Handbook of Road Safety Measures by Rune Elvik). For each study reviewed, a brief summary is provided about the statistical method used for the evaluation along with the results of the evaluation.

Chandler, B. (2007). Eliminating Cross-Median Fatalities: Statewide Installation of Median Cable Barrier in Missouri

Chandler (2007) evaluated the impact on cross-median fatalities of the statewide installation of high-tension cable median barriers in Missouri. Missouri Department of Transportation (MoDOT) started researching options to improve safety by preventing cross median crashes in the 1980s. Initially high-tension cable median barriers were installed on interstates. However, success of these installations led to a beginning of systemwide installations starting in 2002. An internal MoDOT study determined that high-tension cable median barriers caught 95 percent of vehicles entering the median and kept them from entering opposing lanes. On Interstate 70, using a simple before-after analysis Chandler found a 92 percent decrease in cross-median fatalities with the installation of 179 miles of high-tension cable median barrier, effectively reducing cross-median fatalities from 24 fatalities in 2002 (highest peak) to only 2 cross-median fatalities in 2006.

Villwock, N., N. Blond, and A.P. Tarko. (2009). Safety Impact of Cable Barriers on Rural Interstates

Villwock *et al*. (2009) assessed the safety impacts of low- and high-tension cable barriers on rural interstates using data from eight states (Indiana, Colorado, Illinois, Missouri, New York, Ohio, Oregon, and Washington) using a combination of a before-after analysis with negative binomial and logistic regression. They found that properly installed low- and high-tension cable barriers effectively eliminate over 90 percent of cross-over crashes (multi-vehicle opposing direction crashes). This reduction in cross-over crashes is accompanied by an 80 percent increase in single vehicle crashes with the installation of a cable barrier. With respect to crash severity, they found that installation of low-tension cable barriers decreased the proportion of fatal and injury crashes by 8 percent, whereas the effect of high-tension cable barriers on crash severity was negligible relative to no HTCMB being present.

Cooner, S., Y. Rathod, D. Alberson, R. Bligh, S. Ranft, and D. Sun. (2009). *Performance Evaluation of Cable Median Barrier Systems in Texas*

Cooner *et al*. (2009) evaluated the impact of high-tension cable median barrier systems in Texas. Prior to the installation of high-tension cable median barriers, almost all fatalities on the interstate systems in

Texas were a result of cross-median crashes. Using a simple before-after analysis, they found that the installation of cable barriers resulted in a reduction of 18 fatalities and 26 incapacitating injuries in the first full year. This equates to almost $46 million in economic benefit based on crash cost value of $1,040,000 for fatal and incapacitating injuries.

Olsen, A. N., G.G. Schultz, D.J. Thurgood, and C.S. Reese. (2011). *Hierarchical Bayesian Modeling for Before and After Studies*

Olsen *et al*. (2011) looked at the safety impacts of cable barriers installed on the freeway system in the state of Utah. They used hierarchical Bayesian method (an extension to the commonly used empirical Bayesian method) and found cable barriers to be associated with a 62 percent reduction in all cross median crashes and a 44 percent reduction in severe crashes.

Alluri, P., K. Haleem, and A. Gan. (2012). In-Service Performance Evaluation (ISPE) for G4 (1S) Type of Strong-Post W-Beam Guardrail System and Cable Median Barrier: Volume II

Alluri *et al*. (2012) evaluated the safety performance of high-tension cable median barriers on both limited and non-limited access roadways in Florida. Using a simple before-after analysis, they found that high-tension cable median barriers were effective in preventing 97 percent of vehicles from travelling into the opposing lanes of traffic. With respect to crash severity, they found that high-tension cable median barriers led to a 42.2 percent reduction in fatal crash rates, accompanied by a 20.1 percent reduction in incapacitating injury crash rates and 11.6 percent reduction in non-incapacitating crash rates.

Olsen, A. N., G.G. Schultz, D.J. Thurgood, and C.S. Reese. (2011). *Hierarchical Bayesian Modeling for Before and After Studies*

Olson *et al*. (2013) summarized the evolution and accomplishments of the Washington State Department of Transportation's (WSDOT's) high-tension cable median barrier program. Using a simple before-after analysis, they found high-tension cable median barriers were effective in reducing the fatal crash rates by almost 50 percent. High-tension cable median barriers were also effective at reducing the cross-median collision by 58 percent. Rollover crashes in the median also saw a 53 percent reduction.

Coulter, Z.C., and K. Ksaibati. (2013). Effectiveness of Various Safety Improvements in Reducing Crashes on Wyoming Roadways

Coulter and Ksaibati (2013) looked at the effects of high-tension cable median barriers on crash severity in Wyoming. Using a simple before-after analysis, they found a 79 percent reduction in critical cross-median crashes with vehicles on the other road along with a 41 percent reduction in critical crashes in the median.

Srinivasan, R., B. Lan, D. Carter, B. Persaud, and K. Eccles. (2016). Safety Evaluation of Cable Median Barriers in Combination with Rumble Strips on the Inside Shoulder of Divided Roads

Srinivasan *et al*. (2016) evaluated the application of high-tension cable median barriers in combination with rumble strips on the inside shoulder of divided roads in Illinois, Kentucky, and Missouri using the empirical Bayes before-after method. The evaluation using Illinois and Kentucky data determined the effectiveness in crash reduction associated with implementing cable barrier along sections that already had rumble strips and found a 48.2 percent reduction in cross-median crashes. The evaluation using Missouri data determined the safety effect of implementing cabler barrier and inside shoulder rumble strips around the same time and found an 88.1 percent reduction in cross median indicator plus head on crashes.

Russo, B., P. Savolainen, and T. Gates. (2016). Development of Crash Modification Factors for Installation of High-Tension Cable Median Barrier.

Russo *et al*. (2016) evaluated the safety impacts of approximately 317 miles of high-tension cable median barriers installed in Michigan. They used the empirical Bayes method to develop crash modification factors as a function of median width. Their findings suggest that cable barriers significantly reduced the frequency of fatal and severe injury crashes, although substantial increases in less severe crashes were also observed. The cable barrier was found to have greater impacts on crashes across nearly all severity levels when used on narrow medians (i.e., 26 to 50 ft) compared with wider medians (50 to 94 ft).

Chimba, D., E. Ruhazwe, S. Allen, and J. Waters. Digesting the Safety Effectiveness of Cable Barrier Systems by Numbers

Chimba *et al*. (2017) looked at the safety impacts of cable barrier systems in Tennessee using the empirical Bayes before-after method. They found a 94 percent reduction in median related fatal crashes after installation of high-tension cable median barriers. This was accompanied by a 92 percent reduction in incapacitating injury crashes and an 84 percent reduction in non-incapacitating crashes.

Bryant, A., D. Chimba., and E. Ruhazwe. (2018). Crash Modification Factors for Median Cable Barriers in Tennessee

Bryant et al. (2018) also looked at the safety impacts of high-tension cable median barriers in Tennessee using the before-after with comparison group method. They found a 96 percent reduction in median related fatal crashes because of high-tension cable median barriers. This was accompanied by a 91 percent reduction in incapacitating injury crashes and 93 percent reduction in non-incapacitating crashes.

Dissanayake, S. and U. Galgamuwa. (2017). Estimating Crash Modification Factors for Lane Departure Countermeasures in Kansas

Dissanayake and Galgamuwa (2017) evaluated safety impacts of various lane departure countermeasures including high-tension cable median barriers on four-lane divided road segments in Kansas using cross-sectional regression. They found a 50 percent reduction in all lane departure crashes, and an 18 percent reduction in fatal and injury lane departure crashes with the installation of high-tension cable median barriers.

Savolainen, P. T., T. J. Kirsch, R. Hamzeie, M. U. M. Johari, and E. Nightingale. (2018). *In-Service Performance Evaluation of Median Cable Barriers in Iowa*

Savolainen *et al.* (2018) conducted an in-service performance evaluation to assess the efficacy of high-tension cable median barrier systems in Iowa. Using cross-sectional regression, they found high-tension cable median barriers were effective in reducing K-, A-, and B-level crashes by 61.6, 30.8, and 25.8 percent, respectively. However, reduction in fatal and severe injury crashes were accompanied by 11.2 percent and 108.3 percent increases in C- and O-level crashes, respectively.

Eustace, D. and M. Almothaffar. (2018). Safety Effectiveness Evaluation of Median Cable Barriers on Freeways in Ohio

Eustace and Almothaffar (2018) evaluated the safety effectiveness of high-tension cable median barriers on freeways in Ohio using the empirical Bayes before-after method. They found a 73.9 percent reduction in fatal crashes because of high-tension cable median barriers accompanied by an 80.1 percent reduction in KAB crashes and an 80.4 percent reduction in KABC crashes.

2.2 SUMMARY OF HTCMB CMF CLEARINGHOUSE VALUES

In the CMF Clearinghouse, there are currently a total of 13 CMFs for installing high-tension cable median barriers (see Table 1 for summary), and 65 CMFs for installing low- or high-tension cable median barriers (see Table 2 for summary). These tables present a summary of CMFs from the studies discussed in Section 2.1. The associated crash severity, CMF value and maximum star rating is provided in the summaries below as well. The star ratings indicate the quality or confidence in CMF values for a study with five stars being the highest rating.

Overall, the studies indicated a safety benefit due to the implementation of cable barriers, especially for cross-median crashes, and severe crashes. The CMF Clearinghouse does not currently have any CMFs for the effects of lateral placement (i.e., distance from edge of road).

Table 1. Summary of High-Tension Cable Median Barrier CMFs in the CMF Clearinghouse

Crash Type	**No. of CMFs**	**CMF Range**	**Max. Star Rating**
Median Related Crashes	13	0 – 2.63	5 Stars
Crash Severity	**No. of CMFs**	**CMF Range**	**Max. Star Rating**
KABCO	4	0.04 – 1.72	3 Stars
KA	2	0.47 – 0.76	4 Stars
K	1	0.58	2 Stars
A	1	0.80	1 Star
B	2	0.91 – 1.02	3 Stars
CO	2	2.51 – 2.63	5 Stars
O	1	1.88	2 Stars

Table 2. Summary of Low- or High-Tension Median Barrier CMFs in the CMF Clearinghouse

Crash Type	**No. of CMFs**	**CMF Range**	**Max. Star Rating**
All Crashes	19	0 – 1.34	3 Stars
Median Related Crashes	46	0 – 2.08	4 Stars
Crash Severity	**No. of CMFs**	**CMF Range**	**Max. Star Rating**
KABCO	20	0 – 1.91	4 Stars
KABC	6	0.14 – 1.07	3 Stars
KAB	1	0.19	3 Stars
KA	5	0.07 – 0.94	3 Stars
ABC	3	0.15 – 0.74	3 Stars
AB	2	0.12 – 1.10	3 Stars
BC	3	0.19 – 0.89	3 Stars
K	10	0 – 0.48	3 Stars

CHAPTER 3: DATA SOURCES AND DATABASE DEVELOPMENT

3.1 DATA SOURCES

The data used in this evaluation consist of HTCMB specific data, roadway attribute data, traffic volume data, and crash data. HTCMB specific data were gathered from direct correspondence with MnDOT, while roadway attribute data were obtained through MnDOT's Geocommons website (MnDOT, 2021a). A summary of data used is shown in Table 3.

Table 3. Summary of Data Sources

Category	Dataset	Description	Source	Format
HTCMB Data	"MNDOT_HTCB.gdb"	Locations and characteristics of high-tension cable barrier	Direct email correspondence with MnDOT	Geodatabase
Roadway Attribute	"MnDOT_Interchanges"	Locations and areas of influence of interchanges	Direct email correspondence with MnDOT	Shapefile
Roadway Attribute	"PavementPaintStriping"	Linework for pavement striping roadway delineation	Direct email correspondence with MnDOT	Shapefile
Roadway Attribute	"RoadwaySurface"	Linework for edge of pavement	Direct email correspondence with MnDOT	Shapefile
Roadway Attribute	"trans_functional_class"	Federal function classification	MnDOT Geocommons	Geodatabase
Roadway Attribute	"trans_lanes"	Roadway lane information	MnDOT Geocommons	Geodatabase
Roadway Attribute	"trans_roads_centerlines"	Road centerlines	MnDOT Geocommons	Geodatabase
Roadway Attribute	"trans_roads_characteristics"	Roadway details including road width, access control, and public status	MnDOT Geocommons	Geodatabase
Roadway Attribute	"shp_trans_roads_structure"	Median widths and median types	MnDOT Geocommons	Geodatabase
Roadway Attribute	"trans_shoulders"	Shoulder widths and shoulder types	MnDOT Geocommons	Geodatabase
Crash Data	"MNStateCrashData2019"	Crash data for 2019	Direct email correspondence with MnDOT	Shapefile
Crash Data	Additional Crash Tables (2009-2018)	Crash data for 2009-2018	Constructed for previous evaluations completed as part of the Traffic Safety Evaluation contract	Oracle database
Traffic Volumes	Trans_aadt_traffic_segments	Most recent estimates of traffic volumes	MnDOT Geocommons	Geodatabase
Traffic Volumes	Trans_historic_aadt	Historical estimates of traffic volumes	MnDOT Geocommons	Geodatabase

3.2 DATABASE DEVELOPMENT

The data for HTCMB, roadway attributes, crashes, and traffic volumes were joined spatially within a Structured Query Language (SQL) Server database. The data were joined using either latitude and longitude coordinates or reference milepoints along road routes in MnDOT's Transportation Information System (TIS) or Linear Referencing System (LRS). The output resulted in two spreadsheet files – one containing roadway attribute data and another containing crash details. Summaries of roadway and crash output fields and their associated descriptions are provided in Table 4 and Table 5 respectively. Field Descriptions indicating "see section 3.2.X" are provided for fields where calculations can be found in that designated section.

Table 4. Roadway Output Fields (Provided for Increasing and Corresponding Decreasing Segment)

Field Name	Field Description
Roadway ID	Unique identifier for each .1-mile segment
Year	Source year for roadway detail
Changed	Yes/No indicator whether one of the following field values changed from the previous year's value (Thru Lane, Shoulder Type Left , Shoulder Width Right Paved)
Roadway	Roadway description
Direction	I/D (Increasing/Decreasing)
Begin	Begin mile marker
End	End mile marker
Mid	Midpoint mile marker
Facility Type	Facility type
Functional Class	Functional class
Access Control	Access control
Additional Left	Additional left
Additional Left Type	Additional left type
Additional Right	Additional right
Additional Right Type	Additional right type
Pavement Type	Pavement type
Side of Road - Curb	Side of road - curb
Curb Type	Curb type
Turn Lane Left Type	Turn lane left type
Turn Lane Left	Turn lane left
Turn Lane Right Type	Turn lane right type
Turn Lane Right	Turn lane right
Median Width	Median width
Median Width - Calculated	Median width - calculated
Median Type	Median type
Median Structure Type	Median structure type
Shoulder Type Left	Shoulder type left
Shoulder Width Left Paved	Shoulder width left paved
Shoulder Type Right	Shoulder type right
Shoulder Width Right Paved	Shoulder width right paved
Thru Lane	Thru lane
Travel Width	Travel width
Shoulder Type Left UnPaved	Shoulder type left unpaved
Shoulder Width Left UnPaved	Shoulder width left unpaved
Shoulder Type Right UnPaved	Shoulder type right unpaved
Shoulder Width Right UnPaved	Shoulder width right unpaved
Cable Barrier Offset (Same Side) - Inside Paint Edge Line	Calculated (see section 3.2.1)
Cable Barrier Offset (Same Side) - Paved Surface	Calculated (see section 3.2.1)
Cable Barrier Offset (Opposite Side) - Inside Paint Edge Line	Calculated (see section 3.2.1)
Cable Barrier Offset (Opposite Side) - Paved Surface	Calculated (see section 3.2.1)
Cable Barrier Present	Yes/No indicator whether cable barrier was installed at this location in the current year or years prior
Treatment	Yes/No indicator whether cable barrier exists at this location currently
AADT - Both Directions	AADT – Both Directions
AADT - Single Direction	AADT – Both Directions / 2
Intersection	Yes/No indicator whether an intersection is within 250ft of the segment
Interchange	Yes/No indicator whether an interchange is within 250ft of the segment
Rumble Strip	Yes/No indicator whether the segment includes rumble strips

Table 5. Crash Output Fields

Field Name	Field Description
Target Crash	Yes/No indicator (see section 3.2.4)
Barrier Crash	Yes/No indicator (see section 3.2.5)
Incident ID	Unique identifier for each crash reported
Roadway ID	Unique identifier for each .1 mile segment
Roadway	Roadway description
Direction	When crash direction is S or W, direction is D (Decreasing) When crash direction is N or E, direction is I (Increasing) (see section 3.2.6)
Direction (Assumed)	When crash direction is S or W, assumed direction is D (Decreasing) All other crash directions (including Unknown), assumed direction is I (Increasing) (see section 3.2.6)
Severity	Severity
Year	Source year for roadway detail
Date	Date
# Vehicle	Number of vehicles involved in incident
First Harmful Event	First harmful event that contributed to the crash
Collision Type	Collision type
Relative Location Trafficway	Relative location trafficway
Unit 1 - Type	Unit 1 - type
Unit 1 - Description	Unit 1 - description
Unit 1 - Maneuver	Unit 1 - maneuver
Unit 1 - Maneuver Description	Unit 1 - maneuver description
Unit 1 - First Harmful Event	Unit 1 - first harmful event
Unit 2 - Type	Unit 2 - type
Unit 2 - Description	Unit 2 - description
Unit 2 - Maneuver	Unit 2 - maneuver
Unit 2 - Maneuver Description	Unit 2 - maneuver description
Unit 2 - First Harmful Event	Unit 2 - first harmful event
Unit 3 - Type	Unit 3 - type
Unit 3 - Description	Unit 3 - description
Unit 3 - Maneuver	Unit 3 - maneuver
Unit 3 - Maneuver Description	Unit 3 - maneuver description
Unit 3 - First Harmful Event	Unit 3 - first harmful event
Unit 4 - Type	Unit 4 - type
Unit 4 - Description	Unit 4 - description
Unit 4 - Maneuver	Unit 4 - maneuver
Unit 4 - Maneuver Description	Unit 4 - maneuver description
Unit 4 - First Harmful Event	Unit 4 - first harmful event

3.2.1 High-Tension Cable Median Barrier Offset Calculations

To conduct the HTCMB evaluation, the offset of the HTCMB from the travel lanes was needed but not readily available from MnDOT. As such, the HTCMB offset was computed using SQL and GIS methods.

As shown in Figure 1, a perpendicular measurement was taken from the HTCMB to the edge of pavement and median yellow striping for both travel directions at 0.01-mile intervals for every location with HTCMB present.

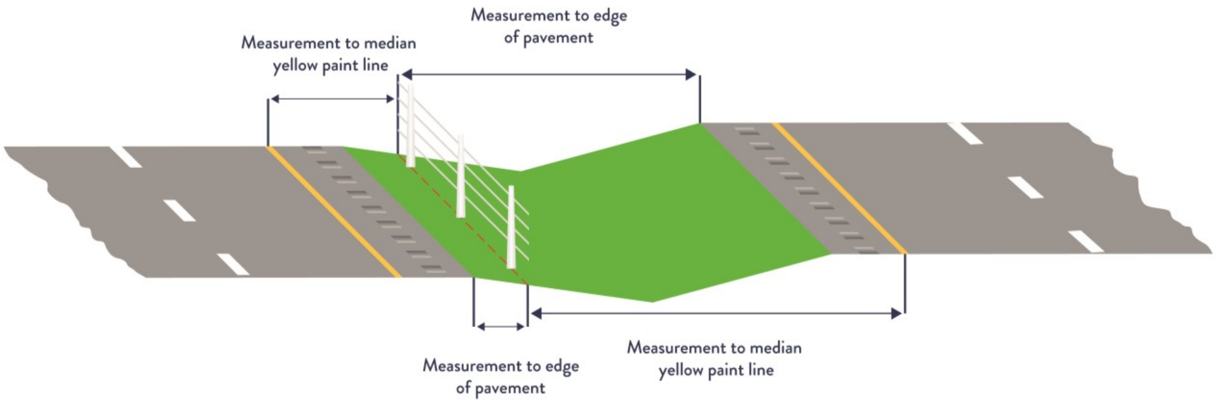

Figure 1. Offset Calculation

A measurement tolerance was implemented, in which the measurement was recorded only where it deviated from the previous measurement by more than one foot. This was done to reduce the amount of noise in the data and only record data where a design level difference existed. For instance, a difference in measurement of 0.05 feet is not indicative of a difference in designed roadway cross section.

After initially running the offset calculations, the data were evaluated to assess the accuracy and reasonableness of the calculated offset distances. MnDOT confirmed that in most cases, the HTCMB should be relatively close to the edge of a travel lane on one side of the road. As such, wherever a HTCMB offset was measured on the near side as greater than 30 feet, that data were removed from the database. This occurred in four percent of the offset calculations. It was verified that measurements from the HTCMB to the median yellow edge line were always less than measurements to the white outside edge line.

Additional preliminary challenges were identified with the data related to distance requirements, roadway characteristics, and associated digital information tied to datapoints during collection. Cable Barrier data that experienced one or more of the following attributes were excluded from the analysis, resulting in 508 exclusions of the 1,418 total cable barrier records:

- Manually digitized
- CADD imported

- Asset ID unknown
- Test section
- Distance from HTCM to yellow exceeding 30 feet
- Paint distance less than surface distance to HTCMB
- Difference between distance from HTCMB to yellow max and min exceeding 2 feet
- Status (not in place)
- Non-divided roadway
- MnDOT override

Once offset calculations were complete, a sample of measurements were spot-checked against aerial photography. In addition, reports were created and sent to MnDOT District Traffic Engineers for verification if the calculations seemed accurate based on their knowledge.

3.2.2 High-Tension Cable Median Barrier Data Issues

In correspondence with MnDOT, it was agreed to exclude certain stretches of HTCMB from the database. While the majority of HTCMB locations in relation to the roadway were obtained through LiDAR, some locations were obtained through review of as-builts, field collections, manually digitized data, and CADD imported data. The LiDAR data is accurate within a meter, while the as-built and field collection data is assumed to be relatively accurate. However, in looking through the manually digitized and CADD imported data, the location of the HTCMB in relation to the roadway did not appear as accurate as anticipated. As such, the manually digitized and CADD imported data were removed from the database. In addition, if the data collection method at a location of HTCMB was unknown, that data were removed.

In the pavement marking data, there were locations found in which the wrong color of paint was entered in the data. For instance, in some locations the data indicated a white pavement marking was present when a yellow marking was expected. In other locations, the pavement marking was missing where one was expected. There were also locations where the pavement markings were not parallel and were expected to be so. In all these locations, the data were removed.

3.2.3 Merging Roadway Attribute Data into a Combined Table

For the years 2009-2018, roadway attribute data were provided by MnDOT in the form of shapefiles and text files that provided detailed roadway information at a segment level, such as lane widths, shoulder widths, and median widths. In 2019, the data became stored in the Geocommons site as separate datasets. To synthesize the data in the database, the roadway datasets from the Geocommons site were merged in GIS to create a combined table with all roadway attribute data in the same format as the 2009-2018 data. A new segment was created in the table wherever an attribute changed. For instance, a new segment was created where the lane width changed from 12 feet to 10 feet and the median width changed from 30 feet to 35 feet. This resulted in a combined table in which the attributes are homogeneous within each defined segment (or row in the table).

3.2.4 Defining a Median Crash

A crash record was defined as a Median Crash (Target Crash) when one or more of the criteria in Table 6 were met.

Table 6. Median Crash

Applies To	Criteria
Crash	First Harmful Event = High-tension cable median Barrier (or MEDIAN SAFTY BAR)
Unit1 (2, 3, or 4)	First Harmful Event = High-tension cable median Barrier (or MEDIAN SAFETY BAR)
Crash	Relative Trafficway Location = On Median
Crash	Manner of Collision = RAN OFF RD-LEFT
Unit1 (2, 3, or 4)	First Harmful Event = Ran Off Roadway Left
Unit1 (2, 3, or 4)	First Harmful Event = Cross Median
Crash	The word "cable" appears in the narrative
Crash	The phrase "median barrier" appears in the narrative
Crash	The phrase "center median" appears in the narrative.
Crash	A narrative review of all K and A severity crashes that were captured using only keyword searches in the narratives. Ensure these apply to median barrier, or median, or cross-median crashes.

3.2.5 Defining a Cable Barrier Crash

A crash record was defined as a Cable Barrier Crash (Barrier Crash) when one or more of the criteria in Table 7 were met.

Table 7. Cable Barrier Crash

Applies To	Criteria
Crash	First Harmful Event = High-tension cable median Barrier (or MEDIAN SAFTY BAR)
Unit1 (2, 3, or 4)	Most Harmful Event = High-tension cable median Barrier (or MEDIAN SAFETY BAR)
Crash	The word "cable" appears in the narrative
Crash	The phrase "median barrier" appears in the narrative

3.2.6 Crash Direction

In 2016, MnDOT changed systems from TIS to LRS causing a difference in the format of the Roadway field values (ex. I-35: TIS – 0100000035, LRS - 0100000000000035-I). Because the TIS format does not include an Increasing/Decreasing indicator, it was necessary to create a method to derive this value from other information. The assumption was made that any crash with a roadway direction value of North or East were “Increasing” and South or West were “Decreasing”.

3.2.7 Synthesizing Data from TIS and LRS Systems

It was necessary to perform analysis on homogenous segments from year to year. Because roadways do not remain the same over time, maintaining long segments would increase the chance that the segment would experience some sort of physical change over time. Therefore, the corridors were broken into 0.1-mile segments to minimize the chance that a change occurred at some point in time. This allowed the evaluation to control for other factors and isolate the offset to the HTCMB.

CHAPTER 4: STATISTICAL ANALYSIS

As mentioned in the beginning of this document, MnDOT is interested in two major objectives: (1) the effect of the installation of the high-tension cable median barrier on crashes, especially, severe crashes, and (2) in the locations that have high-tension cable median barriers, investigate the effectiveness the offset, i.e., the distance between the road and cable barrier, has in reducing crashes and severity. As discussed in the literature review section, many studies have conducted evaluations in other States to determine the safety impact of the barrier. So, the second objective was considered more important for MnDOT, and was addressed first in this study.

4.1 SAFETY EFFECT OF CABLE OFFSET DISTANCE

For observational studies, the evaluation could be cross-sectional or before-after. The following will discuss the methodology behind each and how the analysis was conducted.

4.1.1 Before-After Analysis Methodology

Initially, the project team investigated the possibility of conducting a before-after study to determine the effectives of cable barrier offset in reducing crash frequency and severity. Based on the literature review, there seemed to be a consensus that properly conducted before-after studies provide more reliable estimates of safety effects compared to cross-sectional studies (Carter et al., 2012). This methodology is considered rigorous in that it accounts for the possible bias due to the RTM using a reference group of similar but untreated sites, safety performance functions (SPFs) to account for changes in exposure, time trends, and has been found to reduce the level of uncertainty in the estimates of the safety effect. Since the offset is rarely changed after the installation of the cable barrier, the intent was to use a two-step process. Step 1 was to estimate the safety effect of the cable barrier using the EB method, and Step 2 was to estimate crash modification functions to determine the specific safety effect associated with the offset. Investigation of the crash data revealed that until 2015, a certain percentage of crashes could not be reliably assigned to a particular direction of the road, and these crashes were removed from the evaluation. The project team then proceeded to estimate safety performance functions (SPFs) using the untreated segments (without the barrier). The cumulative residual (CURE) plots revealed that the SPFs did not fit the data very well. It is possible that removing crashes that did not have the direction variable created bias that prevented the development of quality SPFs. For this reason, it was decided that this investigation will be limited to data from 2016 onwards. Due to this limitation, any before-after evaluation would have to be based on sites where high-tension cable median barriers were installed after 2016 with at least one year of before and after data. This further limited the data available making a before-after evaluation not reliable. Instead, a cross-sectional analysis was performed by including those years (2016 and later) after the cable barrier was installed.

4.1.2 Cross-Sectional Analysis Methodology

For the cross-sectional analysis, the offset distance was defined as the distance between the inside edge line of the road and the cable barrier, shown in Figure 2.

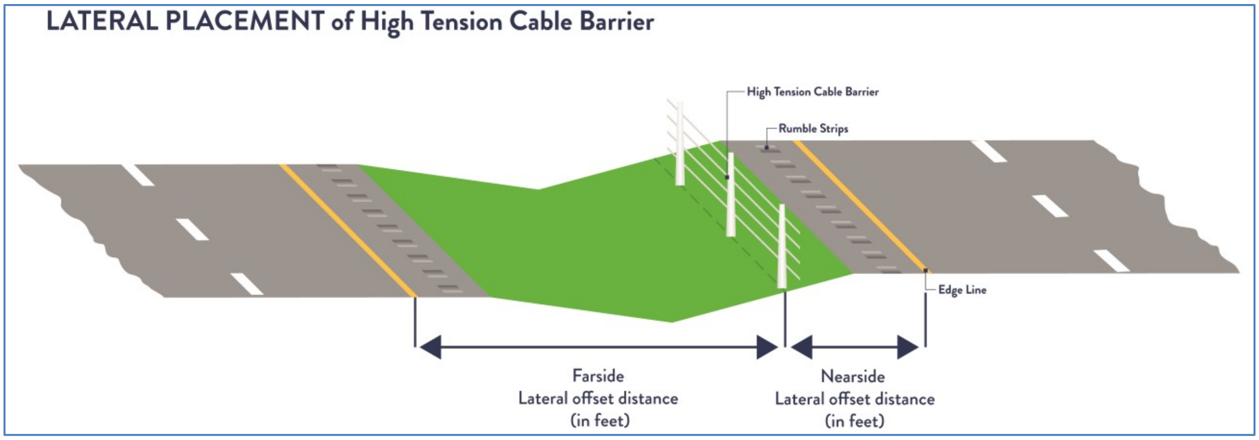

Figure 2. Lateral Placement of HTCMB Example

These results are only valid for situations where the cable barrier was already present. Cable median barriers are installed in the roadway median and are associated with a different offset for each side of the road. With this in mind, to investigate the safety effect of the offset, the two sides of a road need to be considered independently. This was done by evaluating the results separately for the decreasing and increasing direction of the study segments. Only interstates with two lanes in each direction were included in this analysis. In addition, as mentioned earlier, only data from 2016 onwards at locations where cable barriers were installed were included in this evaluation. Segments with length $\geq$ 0.05 miles were included; shorter segments were excluded.

The analysis was conducted to evaluate Total Crashes, Target Crashes, and Barrier Crashes. Using cross-sectional models for estimating CMFs has been criticized for many reasons including the fact that cross-sectional models represent correlation, and not causation. From that perspective, the CMFs for target crashes and barrier crashes could be considered more reliable, because it is possible to envision the effect of the offset distance on these types of crashes.

4.1.3 Cross-Sectional Analysis Descriptive Statistics

Table 8 and Table 9 provide summary statistics for the decreasing and increasing direction of the study segments.

Table 8. Summary Statistics for Decreasing Direction

Variable	Minimum	Maximum	Mean	Std Dev	Sum
Total crash	0	8	0.258	0.631	1119
KABCO	0	8	0.257	0.63	1111
KABC	0	2	0.038	0.2	164
KAB	0	2	0.018	0.137	76
KA	0	1	0.003	0.057	14
K	0	1	0.001	0.03	4
Target Crash	0	5	0.131	0.41	567
Barrier Crash	0	5	0.124	0.397	535
Shoulder width_left (feet)	2	4	3.425	0.494	NA
Shoulder width_right (feet)	8	10	9.237	0.961	NA
Median width (feet)	28	153	64.907	14.208	NA
Offset (feet)	4	59	25.197	17.189	NA
Segment Length (miles)	0.052	0.099	0.098	0.003	425.501

Note: This included 4329 segments.

Table 9. Summary Statistics for Increasing Direction

Variable	Minimum	Maximum	Mean	Std Dev	Sum
Total crash	0	6	0.221	0.535	925
KABCO	0	6	0.22	0.533	922
KABC	0	3	0.038	0.204	161
KAB	0	3	0.021	0.15	88
KA	0	1	0.003	0.051	11
K	0	1	0.001	0.035	5
Target Crash	0	3	0.089	0.314	372
Barrier Crash	0	3	0.08	0.299	337
Shoulder width_left (feet)	0	6	3.275	0.461	NA
Shoulder width_right (feet)	4	10	9.425	1.057	NA
Median width (feet)	2	153	64.2	15.711	NA
Offset (feet)	6	113	33.371	19.529	NA
Segment Length (miles)	0.053	0.099	0.098	0.003	411.785

Note: This included 4192 segments.

Negative binomial regression models were estimated for the following crash types: total crashes, target crashes (total only), and barrier crashes (total only, injury crash models either did not converge or the offset variable was not significant). Independent variables included annual average daily traffic (AADT), offset distance, and pavement type. Offset distance was included as a continuous variable as well as a categorical variable. Regarding categories for offset distance, the following two options were investigated:

Option 1

- ≤ 10 feet
- 11-20 feet
- 21-30 feet
- 31-40 feet
- 41-50 feet
- >50 feet

Option 2

- ≤ 6 feet
- 7-12 feet
- 13-16 feet
- 17-20 feet
- 21-30 feet
- 31-40 feet
- 41-50 feet
- >50 feet

Option 1 consisted of ten-foot bins to have enough data samples for reliable results. Option 2 was created to reflect typical freeway cross-section design and placement of high-tension cable barrier.

4.1.4 Cross-Sectional Analysis Crash Modification Factors

Goodness of fit statistics (GOF) were computed to compare the performance of the different models. The Akaike's Information Criterion (AIC) is a GOF of particular interest when comparing the performance of continuous and categorical options. In general, a lower value of AIC implies a more efficient model because the AIC penalizes a model with more parameters. Based on the AIC, the model with offset distance as a continuous variable was considered more efficient. For comparison purposes, the results from both continuous and categorical options are provided here.

Appendix A provides the parameter estimates of the models that were estimated. Examples for how to calculate predicted crashes using the SPFs are described in Appendix A. The remainder of this section summarizes the CMFs that were generated from these models.

4.1.4.1 Total Crashes

Total Crashes — Offset assumed to be continuous

- $CMF = offset^{-0.1438}$
- Where:
  - Offset = Distance between the inside edge line of the road and the cable barrier; feet
  - Base Condition is Offset = 1 foot
  - Note: Only applicable for offset greater than 0 feet
- AIC = 9936.6

Using this equation, it would be possible to calculate the CMF associated with changing the offset from 1 foot to a particular value (i.e., base condition is 1 foot). For example, the CMF associated with changing the offset from 1 foot to 10 feet would be $10^{-0.1438}$ = 0.718 (see Table 10):

Table 10. CMF for Total Crashes Assuming a Continuous Offset

Offset (ft)	CMF
1	1.000
4	0.819
5	0.793
10	0.718
15	0.677
20	0.650
25	0.629
30	0.613
35	0.600
40	0.588
45	0.578
50	0.570
55	0.562
60	0.555

The results from the Table can also be used to estimate the CMF associated with other changes in the offset. For example, if the offset is changed from 5 feet to 15 feet, the CMF is 0.677/0.793 = 0.854. Based on MNDOT's policy, offsets need to be 8 foot or longer unless there is a design exception. The equation for the CMF given above can be modified as follows to show the safety effect associated with a base condition of 8 feet:

$$CMF \text{ (for base condition of 8 feet)} = \frac{offset^{-0.1438}}{8^{-0.1438}} = \left(\frac{offset}{8}\right)^{-0.1438}$$

CMF based on Option 1

For Option 1, the base condition is offset < 10 feet (see Table 11 for the CMFs). The resulting model has an AIC value of 9943.6; which is higher than the continuous model's value.

Table 11. CMF for Total Crashes Assuming Option 1

Offset (ft)	CMF
<10	1.000
11-20	*0.95**
21-30	0.762
31-40	*0.791*
41-50	0.837
>50	0.743

* Note: In the CMFs provided for Options 1 and 2, the CMFs in italics are not significantly different from 1.0 at the 5 percent significance level. This applies to all the crash types.

The results from the Table can also be used to estimate the CMF associated with other changes in the offset. For example, if the offset is changed from 43 feet (in the category 41 to 50 feet) to 60 feet (> 50 feet), the CMF is 0.743/0.837 = 0.888.

CMF based on Option 2

For this Option 2, the base condition is offset < 6 feet (see Table 12 for the CMFs). The resulting model has an AIC value of 9945.0; which is higher than the values for the continuous model and option 1 for the categorical model.

Table 12. CMF for Total Crashes Assuming Option 2

Offset (ft)	CMF
<6	1.000
7-12	0.706
13-16	*0.775*
17-20	*0.724*
21-30	0.604
31-40	0.609
41-50	0.617
>50	0.567

The results from the table can also be used to estimate the CMF associated with other changes in the offset. For example, if the offset is changed from 43 feet (in the category 41 to 50 feet) to 60 feet (> 50 feet), the CMF is 0.567/0.617 = 0.919.

Figure 3 shows the CMFs from the continuous and both categorical models. The schematics show that the general trend for the categorical and continuous models are quite similar, providing further validity to the results.

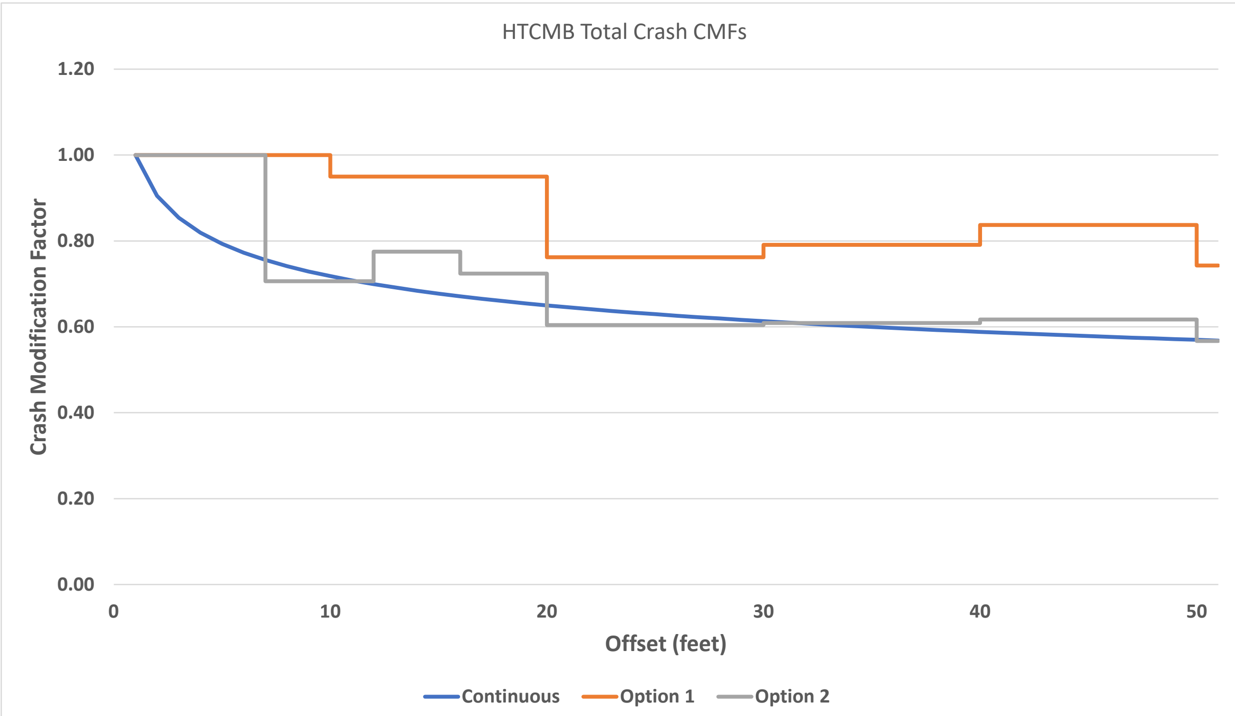

Figure 3. CMF Schematic Comparison for Total Crashes

4.1.4.2 Target Crashes

Target Crashes — Offset assumed to be continuous.

- $CMF = \exp(-0.0186 \times offset)$
- Where:
  - Base condition is offset = 0 foot
- AIC = 5885.8

Using this equation, it would be possible to calculate the CMF associated with changing the offset from 0 foot to a particular value (i.e., base condition is 0* foot). For example, the CMF associated with changing the offset from 0 foot to 10 feet would be $\exp(-0.0186 \times 10) = 0.830$ (see Table 13):

* The reference level is different in this model because of the difference in the functional form.

Table 13. CMF for Target Crashes Assuming a Continuous Offset

Offset (ft)	CMF
0	1.000
4	0.928
5	0.911
10	0.830
15	0.757
20	0.689
25	0.628
30	0.572
35	0.522
40	0.475
45	0.433
50	0.395
55	0.360
60	0.328

As discussed earlier with Total Crashes, the CMF associated with a base condition of 8 feet is the following:

$$CMF \text{ (for base condition of 8 feet)} = \frac{\exp(-0.0186 \times offset)}{\exp(-0.0186 \times 8)} = \exp[-0.0186 \times (offset - 8)]$$

Target Crashes — Categorical Offset Assessment

CMFs based on Option 1

For this Option 1, the base condition is offset $\leq$ 10 feet (see Table 14 for the CMFs). The resulting model has an AIC value of 5898.1; which is higher than the continuous model's value.

Table 14. CMF for Target Crashes Assuming Option 1

Offset (ft)	CMF
≤10	1.000
11-20	*1.001*
21-30	*0.749*
31-40	0.602
41-50	0.510
>50	0.469

CMFs based on Option 2

For this Option 2, the base condition is offset < 6 feet (see Table 15 for the CMFs). The resulting model has an AIC value of 5901.4; which is higher than the values for the continuous model and option 1 for the categorical model.

Table 15. CMF for Target Crashes Assuming Option 2

Offset (ft)	CMF
<6	1.000
7-12	*1.007*
13-16	*0.953*
17-20	*0.895*
21-30	*0.734*
31-40	*0.591*
41-50	0.501
>50	0.461

Figure 4 shows the CMFs from both the continuous and categorical models. Especially for offsets that exceed 20 feet, the schematics show that the general trend for the categorical and continuous models are quite similar, providing further validity to the results.

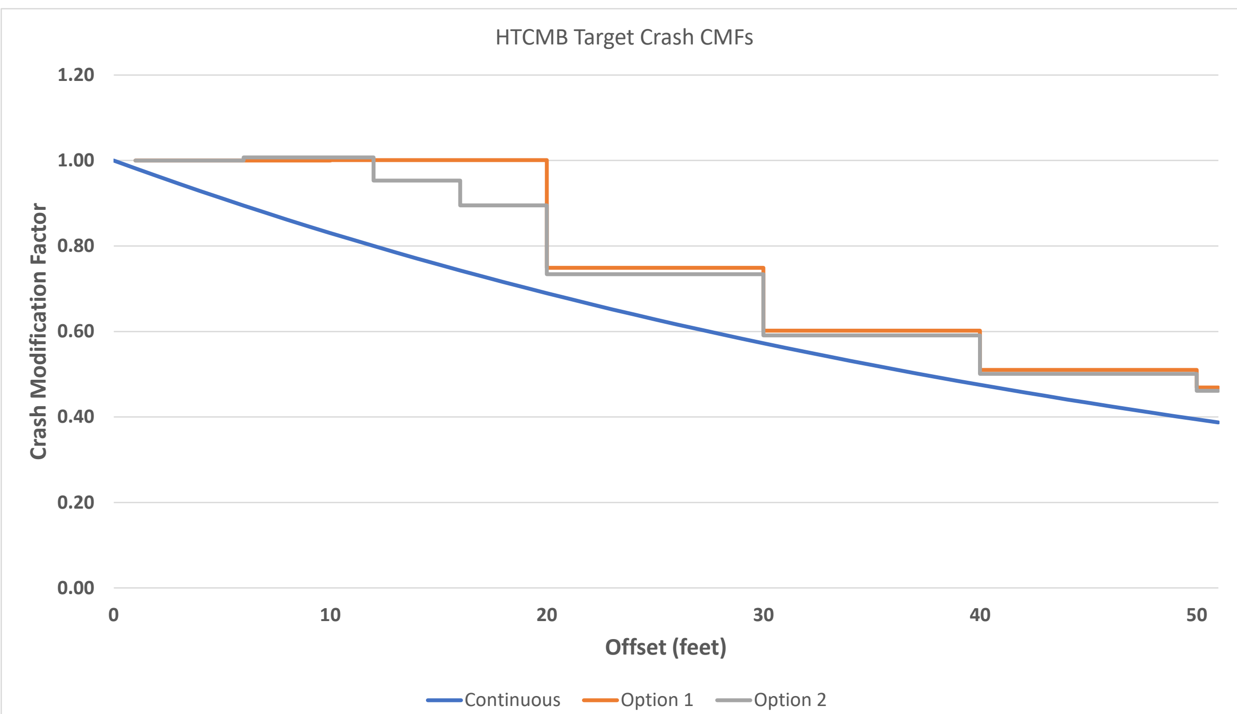

Figure 4. CMF Schematic Comparison for Target Crashes

4.1.4.3 Barrier Crashes

Barrier Crashes — Offset assumed to be continuous

- $CMF = \exp(-0.0204 \times offset)$
- Where:
    - Base condition is offset = 0 foot
- AIC = 5572.1

Using this equation, it would be possible to calculate the CMF associated with changing the offset from 0 foot to a particular value (i.e., base condition is 0 foot). For example, the CMF associated with changing the offset from 0 foot to 10 feet would be $\exp(-0.0204 \times 10) = 0.815$ (see Table 16).

As discussed earlier with Total Crashes, the CMF associated with a base condition of 8 feet is the following:

$$CMF \text{ (for base condition of 8 feet)} = \frac{\exp(-0.0204 \times offset)}{\exp(-0.0204 \times 8)} = \exp[-0.0204 \times (offset - 8)]$$

Table 16. CMF for Barrier Crashes Assuming a Continuous Offset

Offset (ft)	CMF
0	1.000
4	0.922
5	0.903
10	0.815
15	0.736
20	0.665
25	0.600
30	0.542
35	0.490
40	0.442
45	0.399
50	0.361
55	0.326
60	0.294

CMFs based on Option 1

For this Option 1, the base condition is offset $\leq$ 10 feet (see Table 17). The resulting model has an AIC value of 5584.2; which is higher than the continuous model's value.

Table 17. CMF for Barrier Crashes Assuming Option 1

Offset (ft)	CMF
≤10	1.000
11-20	*1.021*
21-30	0.681
31-40	0.562
41-50	0.486
>50	0.442

CMFs based on Option 2

For this Option 2, the base condition is offset $\leq$ 6 feet (see Table 18). The resulting model has an AIC value of 5587.7; which is higher than the values for the continuous model and option 1 for the categorical model.

Table 18. CMF for Barrier Crashes Assuming Option 2

Offset (ft)	CMF
≤6	1.000
7-12	*1.088*
13-16	*1.042*
17-20	*0.982*
21-30	*0.712*
31-40	*0.589*
41-50	0.510
>50	0.465

Figure 5 shows the CMFs from both the continuous and categorical models. Especially for offsets that exceed 20 feet, the schematics show that the general trend for the categorical and continuous models are quite similar, providing further validity to the results.

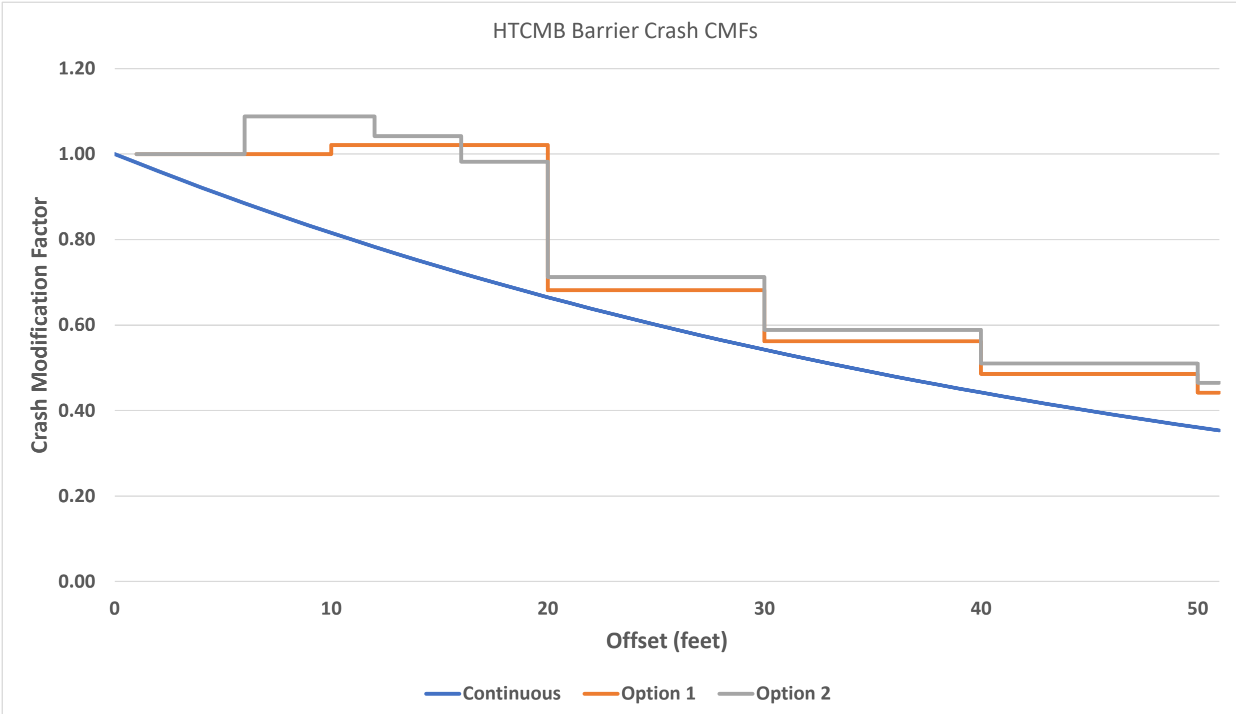

Figure 5. CMF Schematic Comparison for Barrier Crashes

4.1.5 Recommended CMFs for HTCMB Offset

Based on the AIC values, the models with offset included as a continuous variable are considered more efficient. Furthermore, it was also determined that the CMFs with a base condition of 8 feet for the lateral offset is the most relevant to MnDOT staff. Therefore, the following are the recommended CMFs for the three crash types that could be investigated:

Total Crashes

- $CMF = \left(\frac{offset}{8}\right)^{-0.1438}$
- Where:
    - Offset = Distance between the inside edge line of the road and the cable barrier; feet
    - Base Condition is offset = 8 feet
    - Note: Only applicable for offset greater than 0 feet

Target Crashes

- $CMF = \exp[-0.0186 \times (offset - 8)]$
- Where:
    - Base condition is offset = 8 feet

Barrier Crashes

- $CMF = \exp[-0.0204 \times (offset - 8)]$
- Where:
    - Base condition is offset = 8 feet

Figure 6 shows the CMFs from all three continuous models where the base condition was translated to 8-foot offset. The schematics show that the general trend for the Target and Barrier crashes are quite similar and generally smaller than the CMFs for Total crashes. Since the CMFs were translated to a base condition where lateral offset is 8 feet, all three lines have a value of 1.0 when the offset is 8 feet.

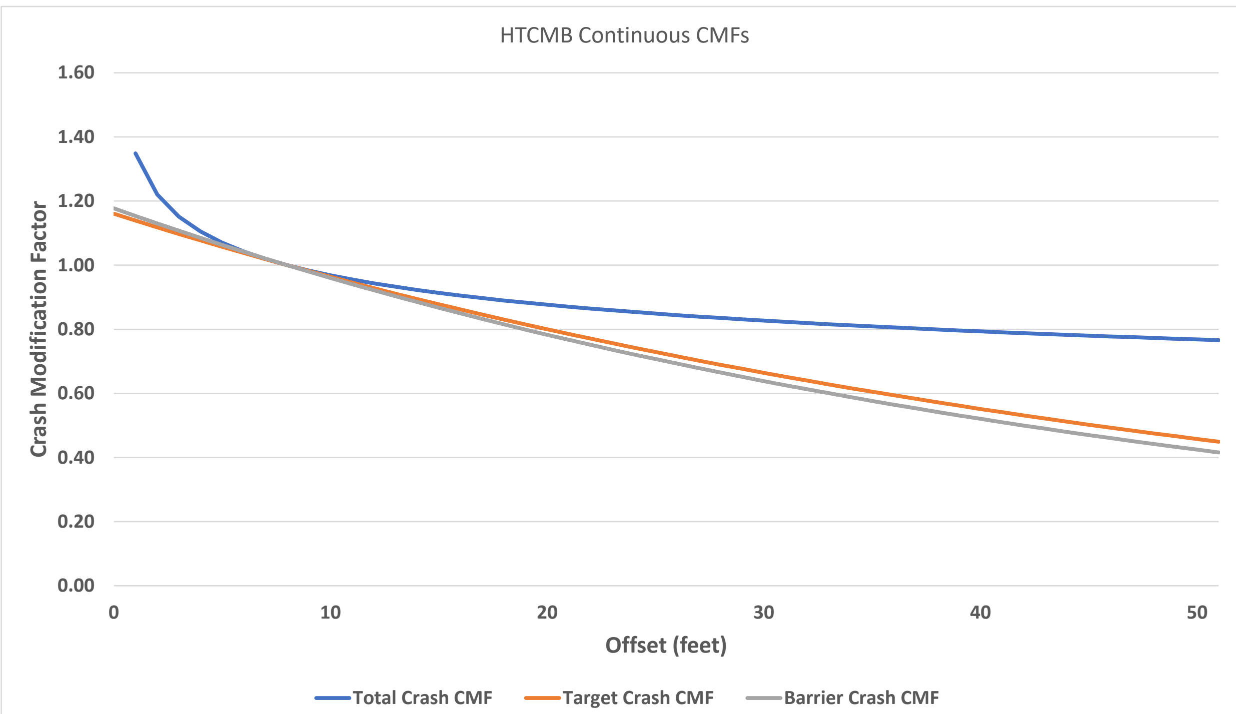

Figure 6. CMF Schematic Comparison for Continuous CMFs (Base Condition equals 8 feet)

4.2 NAÏVE BEFORE-AFTER EVALUATION OF INSTALLING OF CABLE BARRIER

A naïve before-after evaluation was conducted to examine the safety of installing a cable barrier. For this evaluation, all years of data were utilized, and the total number of crashes from both directions for a segment were included. Unlike the cross-sectional analysis, the naïve before-after analysis included data from all facility types.

4.2.1 Descriptive Statistics

Table 19 provides the summary statistics for the sites that were included in the naïve before-after evaluation.

Table 19. Summary Statistics for Before & After Periods

Variable	Minimum	Maximum	Mean	Standard Deviation	Sum
Length	0.022	0.099	0.097	0.009	214.1
AADT (before)	94	60000	12594	8272.55	NA
AADT (after)	94	60000	13765	9532.27	NA
Median Width (before)	2	190	67.25	19.04	NA
Median Width (after)	2	190	64.81	1770	NA
Total Crashes (before)	0	115	2.6	6.761	5746
Total Crashes (After)	0	118	3.348	6.677	7398
KABC Before	0	30	0.689	1.713	1522
KABC After	0	33	0.638	1.764	1410
KAB Before	0	12	0.25	0.674	552
KAB After	0	16	0.264	0.773	583
KA Before	0	3	0.038	0.202	83
KA After	0	2	0.033	0.184	73
Target Crashes (Before)	0	28	0.646	1.648	1427
Target Crashes (After)	0	31	1.217	2.003	2690
Target KABC (Before)	0	8	0.189	0.548	417
Target KABC (After)	0	7	0.14	0.49	309
Target KAB (Before)	0	6	0.078	0.324	173
Target KAB (After)	0	4	0.062	0.281	137
Target KA (Before)	0	1	0.013	0.112	28
Target KA (After)	0	1	0.008	0.087	17

Note: This included 2210 segments.

4.2.2 Crash Modification Factors

CMFs estimated using the naïve before-after method are provided in Table 20. In the table, the expected crashes in the after period without treatment was estimated in the following manner:

$$\begin{aligned} &Expected\ crashes\ in\ after\ period\ without\ treatment \\ &= \frac{Duration\ of\ after\ period}{Duration\ of\ before\ period} \times Crashes\ in\ before\ period \end{aligned}$$

Table 20. CMFs Based on Naïve Before-After Method for High-Tension Cable Barrier Installation

Crash Type	Crashes in the After Period	Expected Crashes in the After Period Without Treatment	CMF	S.E. of CMF
KA	73	103.5	0.682	0.021
KAB	583	630.4	0.920	0.006
KABC	1410	1718.7	0.819	0.002
Total	7398	5741.0	1.288	0.001
Target Crashes	2690	1391.4	1.930	0.009
Target KA	17	41.6	0.377	0.017
Target KAB	137	222.9	0.605	0.008
Target KABC	309	528.3	0.581	0.003

All the CMFs are statistically significant at the 0.05 significant level. As expected, KA, KAB, and KABC crashes decreased following the installation of the cable barrier, and total and target crashes increased following the installation of the cable barrier. In reviewing these CMFs, it is important to consider that the definition of A and B crashes changed in 2016, and the naïve analysis does not explicitly account for these changes. The definition of A and B crashes was modified from being called "Incapacitating Injury" to "Suspected Serious Injury" and "Non-Incapacitating Injury" to "Suspected Minor Injury." The modification only impacted the associated names of A and B crashes and how law enforcement reported crash severity. As such, caution should be used with any interpreting of KAB and KA CMFs.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 SAFETY EFFECT OF HTCMB OFFSET DISTANCE

This study used a combination of cross-sectional regression analysis and naïve before-after methods to investigate the effectiveness of reducing crash frequency and severity associated with high-tension cable median barriers. Cross-sectional regression analysis was used to develop CMFs for the offset distance, i.e., distance between the barrier and inside edge line. Interstates with two lanes in each direction with segment lengths of 0.05 miles or longer were included in this analysis. Examples for how to calculate predicted crashes using the SPFs were described in Appendix A.

For offset, measured in feet, the recommended CMFs (Base condition: offset = 8 feet) for the three crash types that could be investigated are:

Total Crashes

- $CMF = \left(\frac{offset}{8}\right)^{-0.1438}$
- Where:
    - Offset = Distance between the inside edge line of the road and the cable barrier; feet
    - Base condition is offset = 8 feet
    - Note: Only applicable for offset greater than 0 feet

Target Crashes

- $CMF = \exp[-0.0186 \times (offset - 8)]$
- Where:
    - Base condition is offset = 8 feet

Barrier Crashes

- $CMF = \exp[-0.0204 \times (offset - 8)]$
- Where:
    - Base condition is offset = 8 feet

As expected, as the barrier was placed farther away from the inside edge line, total crashes, target crashes, and barrier crashes decreased. These CMFs can be used by practitioners to determine the safety impact of changing placement of a HTCMB.

5.2 SAFETY EFFECT OF INSTALLING A HTCMB

Regarding the effectiveness in reducing crash frequency and severity due to installing a barrier where previously there was none, Table 21 shows the CMFs that were estimated using naïve before-after analysis. All these CMFs were statistically significant at the 0.05 significant level. Total and target crashes increased when barriers were installed, while KA, KAB, and KABC crashes decreased. In reviewing these

CMFs, it is important to consider that the definition of A and B crashes changed in 2016, and the naïve analysis did not explicitly account for these changes.

Table 21. CMFs Based on Naïve Before-After Method for High-Tension Cable Barrier

Crash Type	Crashes in the After Period	Expected Crashes in the After Period Without Treatment	CMF	S.E. of CMF
KA	73	103.5	0.682	0.021
KAB	583	630.4	0.920	0.006
KABC	1410	1718.7	0.819	0.002
Total	7398	5741.0	1.288	0.001
Target Crashes	2690	1391.4	1.930	0.009
Target KA	17	41.6	0.377	0.017
Target KAB	137	222.9	0.605	0.008
Target KABC	309	528.3	0.581	0.003

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APPENDIX A
Cross-Sectional Regression Models

This Appendix provides the results of the regression models that were estimated to determine the CMFs for offset. The models were estimated for interstates with 2 lanes in each direction with segment lengths 0.05 miles or longer. The regression models were estimated using negative binomial regression with a log-linear functional form. With this form, the relationship between the predicted number of crashes at the site characteristics can be expressed as follows:

$$Y = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots \ldots\ldots \beta_n X_n)$$

Where, Y is the predicted number of crashes per mile per year, X_1 through X_n are site characteristics, and β_1 through β_n are parameters that are estimated.

For each model that was estimated, the goodness of fit (GOF) statistics are provided along with the parameter estimates, standard error of the parameter estimates, the Wald Chi-square values, and the p values.

While the primary purpose of these models was to estimate the CMFs, these models can also be used to predict the number of crashes that may be expected based on the characteristics of the sites. Examples illustrating the use of the models for prediction are provided after the Tables showing the parameter estimates for the continuous offset.

Total Crashes

Table A1.1: Total Crashes (continuous offset)—8379 observations—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	4968.307	0.5932
Scaled Deviance	4968.307	0.5932
Pearson Chi-Square	9270.884	1.107
Scaled Pearson X2	9270.884	1.107
Log Likelihood	-4565.16	
Full Log Likelihood	-4963.31	
AIC (smaller is better)	9936.622	
AICC (smaller is better)	9936.629	
BIC (smaller is better)	9971.789	

Table A1.2: Total Crashes (continuous offset)—8379 observations

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-6.8261	0.5360	162.21	<.0001
Bituminous related	-0.1715	0.0542	10.01	0.0016
Concrete related (reference)	0.0000	0.0000	.	.
***ln*(AADT)**	0.8846	0.0570	240.52	<.0001
***ln*(offset)**	-0.1438	0.0345	17.34	<.0001
k	1.2530	0.1132		

The parameter estimates in Table A1.2 can be used to predict the total number of crashes that may be expected based on the characteristics of a site. The equation for the predicted number of total crashes is the following:

Y (total number of crashes per mile per year in one direction) =

$$\exp(-6.8261 - 0.1715\ (for\ bituminous) + 0\ (for\ concrete) + 0.8846 \times \ln(AADT) - 0.1438 \times \ln(offset))$$

In this equation, AADT refers to the AADT in a particular direction. Suppose a section has an AADT of 10,000 in one direction; it has a bituminous pavement, and an offset of 10 feet. The predicted number of total crashes per mile per year in one direction =

$$\exp(-6.8261 - 0.1715\ + 0.8846 \times ln(10{,}000) - 0.1438 \times ln(10)) = 2.268.$$

For the same conditions, instead of a bituminous pavement, if it is a concrete pavement, the predicted number of total crashes per mile per year in one direction =

$$\exp(-6.8261 + 0.8846 \times ln(10{,}000) - 0.1438 \times ln(10)) = 2.692.$$

Table A2.1: Total Crashes (Option 1)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	4971.625	0.594
Scaled Deviance	4971.625	0.594
Pearson Chi-Square	9305.088	1.1117
Scaled Pearson X2	9305.088	1.1117
Log Likelihood	-4563.63	
Full Log Likelihood	-4961.78	
AIC (smaller is better)	9943.554	
AICC (smaller is better)	9943.581	
BIC (smaller is better)	10013.89	

Table A2.2: Total Crashes (Option 1)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-7.4204	0.5617	174.54	<.0001
Bituminous related	-0.1553	0.0578	7.21	0.0072
Concrete related (reference level)	0.0000	0.0000	.	.
***ln*(AADT)**	0.8711	0.0587	220.49	<.0001
Left shoulder width	0.1184	0.0565	4.40	0.0359
Offset ≤ 10 (reference level)	0.0000	0.0000	.	.
Offset 11 to 20	-0.0515	0.0770	0.45	0.5036
Offset 21 to 30	-0.2713	0.1217	4.97	0.0257
Offset 31 to 40	-0.2345	0.1617	2.10	0.1470
Offset 41 to 50	-0.1781	0.0763	5.46	0.0195
Offset > 50	-0.2969	0.0924	10.32	0.0013
k	1.2461	0.1130		

Table A3.1: Total Crashes (Option 2)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	4970.043	0.5939
Scaled Deviance	4970.043	0.5939
Pearson Chi-Square	9254.203	1.1058
Scaled Pearson X2	9254.203	1.1058
Log Likelihood	-4563.37	
Full Log Likelihood	-4961.52	
AIC (smaller is better)	9945.037	
AICC (smaller is better)	9945.068	
BIC (smaller is better)	10022.41	

Table A3.2: Total Crashes (Option 2)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-6.6398	0.5791	131.45	<.0001
Bituminous related	-0.1653	0.0582	8.07	0.0045
Concrete related	0.0000	0.0000	.	.
***ln*(AADT)**	0.8607	0.0587	215.15	<.0001
Offset $\leq$ 6 (reference level)	0.0000	0.0000	.	.
Offset 7 to 12	-0.3482	0.1627	4.58	0.0323
Offset 13 to 16	-0.2552	0.1749	2.13	0.1447
Offset 17 to 20	-0.3236	0.1906	2.88	0.0895
Offset 21 to 30	-0.5048	0.1861	7.36	0.0067
Offset 31 to 40	-0.4953	0.2165	5.24	0.0221
Offset 41 to 50	-0.4822	0.1632	8.73	0.0031
Offset > 50	-0.5672	0.1721	10.87	0.0010
k	1.2472	0.1130		

Target Crashes

Table A4.1: Target Crashes (continuous offset)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	3299.201	0.3939
Scaled Deviance	3299.201	0.3939
Pearson Chi-Square	8805.74	1.0513
Scaled Pearson X2	8805.74	1.0513
Log Likelihood	-2841.12	
Full Log Likelihood	-2938.92	
AIC (smaller is better)	5885.838	
AICC (smaller is better)	5885.843	
BIC (smaller is better)	5913.972	

Table A4.2: Target Crashes (continuous offset)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-4.7698	0.7444	41.05	<.0001
***ln*(AADT)**	0.5797	0.0799	52.70	<.0001
Offset	-0.0186	0.0021	80.30	<.0001
k	1.5089	0.2358		

The parameter estimates in Table A4.2 can be used to predict the number of target crashes that may be expected based on the characteristics of a site. The equation for the predicted number of target crashes is the following:

Y (target crashes per mile per year in one direction) =

$$\exp(-4.7698 + 0.5797 \times \ln(AADT) - 0.0186 \times offset)$$

In this equation, AADT refers to the AADT in a particular direction. Suppose a section has an AADT of 10,000 in one direction and an offset of 10 feet, the predicted number of target crashes per mile per year in one direction =

$$\exp(-4.7698 + 0.5797 \times \ln(10000) - 0.0186 \times 10) = 1.467.$$

Table A5.1: Target Crashes (Option 1)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	3298.881	0.394
Scaled Deviance	3298.881	0.394
Pearson Chi-Square	8791.713	1.0501
Scaled Pearson X2	8791.713	1.0501
Log Likelihood	-2843.23	
Full Log Likelihood	-2941.03	
AIC (smaller is better)	5898.057	
AICC (smaller is better)	5898.074	

Table A5.2: Target Crashes (Option 1)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-4.8770	0.7599	41.19	<.0001
***ln*(AADT)**	0.5687	0.0827	47.32	<.0001
Offset ≤ 10 (reference level)	0.0000	0.0000	.	.
Offset 11 to 20	0.0005	0.0951	0.00	0.9958
Offset 21 to 30	-0.2895	0.1522	3.62	0.0571
Offset 31 to 40	-0.5069	0.2262	5.02	0.025
Offset 41 to 50	-0.6741	0.1092	38.14	<.0001
Offset > 50	-0.7577	0.1363	30.90	<.0001
k	1.5196	0.2369		

Table A6.1: Target Crashes (Option 2)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	3298.705	0.3941
Scaled Deviance	3298.705	0.3941
Pearson Chi-Square	8810.441	1.0526
Scaled Pearson X2	8810.441	1.0526
Log Likelihood	-2842.88	
Full Log Likelihood	-2940.68	
AIC (smaller is better)	5901.356	
AICC (smaller is better)	5901.382	
BIC (smaller is better)	5971.69	

Table A6.2: Target Crashes (Option 2)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-4.9739	0.8166	37.10	<.0001
***In*(AADT)**	0.5810	0.0826	49.43	<.0001
Offset ≤ 6 (reference level)	0.0000	0.0000	.	.
Offset 7 to 12	0.0071	0.2329	0.00	0.9757
Offset 13 to 16	-0.0483	0.2480	0.04	0.8454
Offset 17 to 20	-0.1106	0.2653	0.17	0.6766
Offset 21 to 30	-0.3094	0.2603	1.41	0.2346
Offset 31 to 40	-0.5251	0.3105	2.86	0.0908
Offset 41 to 50	-0.6921	0.2393	8.37	0.0038
Offset > 50	-0.7735	0.2545	9.24	0.0024
k	1.5183	0.2368		

Barrier Crashes

Table A7.1: Barrier Crashes (continuous offset)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	3151.109	0.3762
Scaled Deviance	3151.109	0.3762
Pearson Chi-Square	8890.682	1.0614
Scaled Pearson X2	8890.682	1.0614
Log Likelihood	-2694.63	
Full Log Likelihood	-2782.03	
AIC (smaller is better)	5572.067	
AICC (smaller is better)	5572.071	
BIC (smaller is better)	5600.2	

Table A7.2: Barrier Crashes (continuous offset)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-4.7747	0.7689	38.56	<.0001
***ln*(AADT)**	0.5768	0.0825	48.87	<.0001
Offset	-0.0204	0.0022	88.24	<.0001
k	1.5269	0.2502		

The parameter estimates in Table A7.2 can be used to predict the number of barrier crashes that may be expected based on the characteristics of a site. The equation for the predicted number of barrier crashes is the following:

Y (barrier crashes per mile per year in one direction) =

$$\exp(-4.7747 + 0.5768 \times \ln(AADT) - 0.0204 \times offset)$$

In this equation, AADT refers to the AADT in a particular direction. Suppose a section has an AADT of 10,000 in one direction and an offset of 10 feet, the predicted number of barrier crashes per mile per year in one direction =

$$\exp(-4.7747 + 0.5768 \times \ln(10000) - 0.0204 \times 10) = 1.396$$

Table A8.1: Barrier Crashes (Option 1)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	3151.824	0.3765
Scaled Deviance	3151.824	0.3765
Pearson Chi-Square	8871.29	1.0596
Scaled Pearson X2	8871.29	1.0596
Log Likelihood	-2696.71	
Full Log Likelihood	-2784.11	
AIC (smaller is better)	5584.22	
AICC (smaller is better)	5584.237	
BIC (smaller is better)	5640.488	

Table A8.2: Barrier Crashes (Option 1)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-4.9088	0.7842	39.18	<.0001
***ln*(AADT)**	0.5657	0.0853	43.95	<.0001
Offset ≤ 10 (reference level)	0	0	.	.
Offset 11 to 20	0.0207	0.0973	0.05	0.8315
Offset 21 to 30	-0.3843	0.1611	5.69	0.0171
Offset 31 to 40	-0.5767	0.2387	5.84	0.0157
Offset 41 to 50	-0.7213	0.1135	40.41	<.0001
Offset > 50	-0.8163	0.1428	32.67	<.0001
k	1.5356	0.2512		

Table A9.1: Barrier Crashes (Option 2)—Criteria for Assessing Goodness of Fit

Criterion	Value	Value/DF
Deviance	3151.61	0.3765
Scaled Deviance	3151.61	0.3765
Pearson Chi-Square	8893.284	1.0625
Scaled Pearson X2	8893.284	1.0625
Log Likelihood	-2696.45	
Full Log Likelihood	-2783.86	
AIC (smaller is better)	5587.716	
AICC (smaller is better)	5587.742	
BIC (smaller is better)	5658.051	

Table A9.2: Barrier Crashes (Option 2)

Parameter	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	-5.1112	0.8432	36.74	<.0001
lnaadt	0.5823	0.0852	46.67	<.0001
Offset ≤ 6 (reference level)	0.0000	0.0000	.	.
Offset 7 to 12	0.0840	0.2448	0.12	0.7315
Offset 13 to 16	0.0408	0.2596	0.02	0.8752
Offset 17 to 20	-0.0183	0.2766	0.00	0.9472
Offset 21 to 30	-0.3390	0.2754	1.52	0.2183
Offset 31 to 40	-0.5293	0.3279	2.61	0.1065
Offset 41 to 50	-0.6735	0.2520	7.15	0.0075
Offset > 50	-0.7655	0.2682	8.15	0.0043
k	1.5348	0.2511		