Safety Effectiveness Evaluation of Median Cable Barriers on Freeways in Ohio

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16. Abstract

The Ohio Department of Transportation (ODOT) began installing median cable barriers in 2003 along highway medians for all roadways that were narrower than 59 ft. The central goal of this work was to prevent cross-median crashes (CMCs) that raised a concern due to their frequencies and severe injuries they caused when they occurred. Cross-median crashes occur when a vehicle leaves its travel way, enters or crosses the dividing median, and collides with vehicles moving in the opposite direction. This study received data from 41 locations totaling about 201 miles of installed median cable barriers in the years 2009-2014. These locations experienced 2,498 median related crashes before and after installation. The study involved a review of police reports to identify target crashes and the manner in which the vehicles hit or crossed the cable barriers. A detailed analysis of cable hits was also conducted. The study found that median cable barriers were effective in stopping vehicles from breaching the barrier; 95.4 percent of all cable median barrier crashes had no penetration of the cable barrier, i.e., the vehicles where stopped or bounced by the cables. This research study summarizes some key findings of safety effectiveness evaluation of the median cable barriers in Ohio. The findings of overall statewide crash reduction after the median cable barriers compared to before period are based on the safety effectiveness percentages computed by Empirical Bayes (EB) before-after study method using the Highway Safety Manual's (HSM) procedures. Safety effectiveness of Ohio's statewide cable barriers was found to be 73.9 percent for total crashes, 80.4 percent for fatal and injury (FI) crashes combined and 80.1 percent for fatal, incapacitating, and non-incapacitating injury (KAB) crashes combined. Therefore, the estimated crash modification factors (CMFs) for median cable barriers installed in Ohio's Interstate system for total, FI, and KAB crashes are 0.261, 0.196, and 0.199, respectively. Overall, the evaluation results show that the median cable barriers installed in Ohio's Interstate system are effective in reducing cross-median severe injury crashes, which was the main objective of ODOT's installing median barriers in their Interstate highway system.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation
CEM	Crash Estimation Model
CMCs	Cross Median Crashes
DF	Degree of Freedom
EB	Empirical Bayes
FHWA	Federal Highway Administration
FI	Fatal and Injury Crashes
GLM	Generalized Linear Model
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
ISPE	In-Service Performance Evaluation
KABCO	Injury Severity Classification Scale
ODOT	Ohio Department of Transportation
ODPS	Ohio Department of Public Safety
RDG	Roadside Design Guide
SPF	Safety Performance Function

CHAPTER I

INTRODUCTION

1.1 Introduction

According to the Federal Highway Administration (FHWA), the roadway departure crashes have resulted in substantial amount of fatalities: 18,779 from 2014 through 2016 (USDOT, 2018). These crashes represent 53 percent of all traffic fatalities. Additionally, Blincoe et al. (2015) point out a number of factors that cause cross-median crashes (CMC), also known as departure events, including distracted driving, drowsiness, impaired driving, and loss of control of a vehicle on roadways.

The authors of the Highway Safety Manual (HSM) estimate that using median barriers reduced fatal crashes by 43 percent and injury crashes by 30 percent. Despite that, median barriers have potentially increased crash frequencies by about 24 percent, predominantly increased property damage only (PDO) collisions (AASHTO, 2010)

The history of median cable barriers was stated in a study by McClanahan et al. (2004). The McClanahan et al. (2004) study state that high-tension cable barriers have been on highways nationwide as early as the 1930’s. The new system, which was developed in the 1960’s, utilizes three or four cables mounted on steel posts, and has been prevalent in many states. Cable barriers are known for lower cost than other preventive barriers and more often cause less damages to the involved vehicles (McClanahan et al., 2004).

A number of states that have installed these barriers have also attempted to evaluate their safety benefits. Some of the states that have performed before-after studies to quantify the safety benefits of installing cable median barriers include North Carolina (Lynch et al.,1993; Hunter et al., 2001), Oregon (Sposito and Johnston, 1999), Arizona (Mak and Sicking, 2002), Washington (McClanahan et al., 2004), Kentucky (Agent and Pigman, 2008), Texas (Cooner et al., 2009), Florida (Alluri et al, 2012), Michigan (Savolainen et al., 2014), Tennessee (Chimba, 2017), etc. Studies in Washington State, North Carolina, Texas, Michigan, Tennessee and other states have shown greatly diminished crashes, both fatal and injury crashes, after installing cable median barriers in their highways. The federal government has also recommended that states "review median crossover crash histories to identify locations where median barriers may benefit safety and consider use of cable median barriers where appropriate" (USDOT, 2018).

1.2 Problem Statement

The Ohio Department of Transportation (ODOT) began installing median cable barriers in 2003 along highway medians for all roadways that were narrower than 59 ft. The initial work covered sections of I-70 and SR 315 in central Ohio. In addition, cable barriers were installed on I-71 from Richland County to the north and along areas of I-75, I-76 and I-77 in various other parts of the state.

In 2010 ODOT installed median cable barriers along I-675 in the Dayton area and due to the successes already observed, in recent years ODOT announced that they will be adding additional median cable barriers in different locations in the state where there have been safety concerns. The central goal of this work was to prevent cross-median crashes (CMCs) that raised a concern due to their frequencies and severe injuries they cause when they take place. Cross-median crashes occur when a vehicle leaves its travel way, enters or crosses the dividing median, and collides with vehicles moving in the opposite direction. Since the main benefits of this installation was the reduction of vehicle-to-vehicle crashes traveling in opposite directions thereby reducing severe crashes, we should evaluate how well these installed types of barriers have met their expected purpose in the state of Ohio.

Since cable barriers are much cost efficient as compared to traditional concrete barriers, then they could become the preferred barrier type if found effective in their intended use and if existing geometric conditions allow for the installation of cable rails. It would be advantageous if it was determined that cable barriers were most effective in preventing severe crashes while saving money for Ohio’s tax payers. Although a number of states have evaluated median cable barriers installed in their freeways, and ODOT has been installing this type of median barriers for more than 15 years, Ohio has not performed formal rigorous analyses to quantify their economic and safety benefits.

1.3 Goals and Objectives of the Study

The intended purpose of this research project was to evaluate the effectiveness of median-installed cable barriers on Ohio freeways in preventing vehicle-to-vehicle cross-median crashes and reducing injury severity when vehicles encroach the median area.

The objectives of this research were two-fold: (1) to evaluate safety effectiveness with respect to the reduction in the number of cross-median crashes, as well as related injuries and fatalities; (2) to develop crash modification factors (CMF) for median cable barriers specific for Ohio.

1.4 Organization of the Report

This research report consists of six main chapters. The first chapter introduces the topic, the extent of the problem and the objectives of the study. The second chapter presents the literature review on the median cable barriers, and the third chapter contains the data collection efforts and describes the methodology in general. The fourth chapter presents the cable barrier strike analysis; the fifth chapter provides a summary and results of the research findings; and the last chapter summarizes the key findings and provides some recommendations.

CHAPTER II

LITERATURE REVIEW

2.1 Summary of Ohio-Based Literature Review

According to a study by Focke and Arnold (2006), the Ohio Department of Transportation (ODOT) proposed a project to install cable barrier systems in Ohio in 2002. In order to approve the project, the FHWA assigned ODOT to provide a three-year in-service performance evaluation (ISPE) study on the median cable system. Prior to installation, ODOT appraised the cost of installation of the high-tension cable system. The total cost was $1,045,000 for a 14.5 miles cable barrier installation as opposed to concrete barriers, which had an estimated cost of $4,500,000 based on a 2001 US dollar value (Focke and Arnold, 2006). Eventually ODOT conducted an ISPE study for evaluation purposes of high-tension cable barriers taking into account any maintenance or installation issues that might have occurred. This evaluation began in July of 2003 and concluded June 2006. Dean Focke, ODOT Standards Engineer, and Tom Arnold, District 8 Transportation Engineer, were the primary engineers in charge of this initiative. The first study by Focke (2005) mention that ODOT installed the first high-tension cable barriers on roadways in Ohio on I-75, north of Cincinnati, between Butler and Warren counties. The cable barrier system spanned 14.5 miles and was 14 feet from one edge line of a 60-foot depressed median with 6:1 slopes. Focke (2005) observed an annual average daily traffic (AADT) of 92,000 vehicles per day with 22 percent being trucks for 2003. His study shows that there was almost 1 crossover fatal crash per month in the before study period (11 crashes in 14 months). The crashes had no single cause, i.e., influencing factors for each crash were almost unique. Initially, ODOT District 8 initiated preventative measures to combat future crashes by first increasing police enforcement of speed limits and then shoulder rumble strips installation. However, the enforcement was reduced after the shoulder rumble strips were installed. Eventually median cable barriers were installed (Focke, 2005).

Focke and Arnold (2006) provide a report of the ISPE study conducted for three years on the installed high-tension system of cable barriers in Ohio. They report that out of 354 vehicle strikes on Briefen cable barriers in a 3-year period, only 39 of the crashes resulted into injuries where 64 percent were categorized as non-incapacitating, 31 percent as possible injuries, and 1 impact was not categorized. In addition, 28 percent of the total crashes involved hit and run crashes, perhaps resulting from the forgiving nature of these cables. Furthermore, 79 of the 354 total strikes were backside hits. Figure 2.1 shows a summary of total crashes before and after the installation of the cable barrier system including non-median based crashes (Focke and Arnold, 2006).

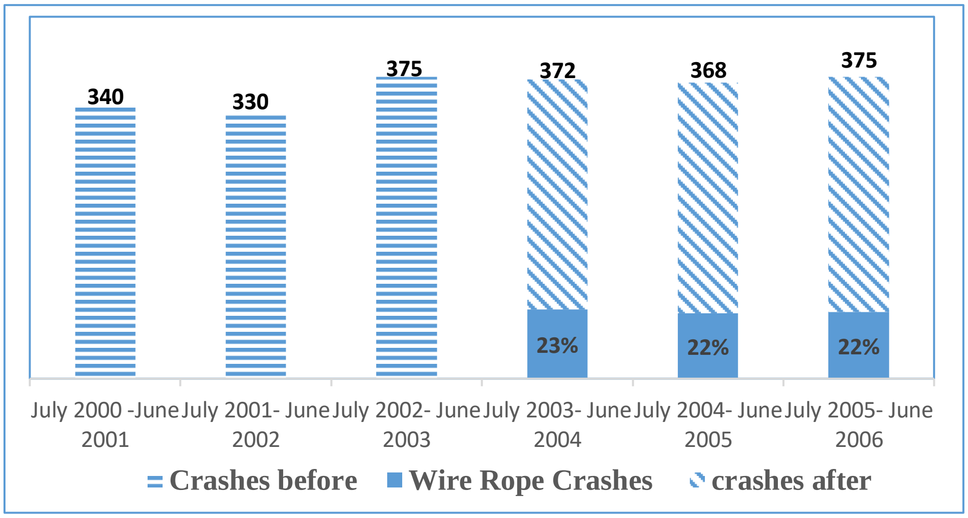


Figure 2.1: Total Crashes for Before and After Median Cable Installation, 2000-2006

The study by Focke and Arnold (2006) confirms the common conclusion that the cable barrier system increases property-damage only (PDO) type of crashes but decreases severity of injuries compared to other types of crashes statewide. Many state DOT agencies are concerned that interchanges may have an effect on cross-median crashes (Focke and Arnold, 2006). Merging traffic and weaving of exiting traffic, have been considered to be contributing factors to the occurrence of these types of crashes. However, it is important to note that within 2,000 feet of an interchange in the segment studied by Focke and Arnold (2006), cable ropes were less of a cause of cross-median collisions. In addition, they investigated the impacts of weather and road condition on the frequency and severity of collisions. More than half of the crashes occurred when snow, ice or wet pavement were present. Focke and Arnold (2006) report that 144 out of 256 crashes took place during these conditions. Their study shows that a cable barrier system has proved to be 96.9 percent successful in preventing penetration if a cable barrier impact occurred. In addition, most of the vehicles that penetrated decelerated once they encountered the cable barrier and hence less than 1 percent of the encroaching vehicles ended into a cross-median crash. Focke and Arnold (2006) found that about four crashes per year resulted into a penetration of the cable barrier. They concluded that before the installation of the cable system, there were significant fatalities each year over the period of 3 years. After cable barrier installation, fatal crashes were reduced from 21 to 4 at the end of the three-year evaluation period. However, none of the 4 fatalities involved cross-median crashes related to the cable barrier (Focke and Arnold, 2006).

2.2 Summary of Other States-Based Literature Review

Over a number of years, multiple states have conducted studies with a focus on evaluating safety performance of median cable barriers installed in their Interstate highways and freeways. North Carolina did investigations on cross-median crashes as early as the 1990s. Lynch et al. (1993) examined crashes that occurred on North Carolina's Interstate Highway System to assess cross median crashes. Then Hunter et al. (2001) analyzed ISPE cable median barriers in North Carolina, which were made of three strands that were installed in the year 1994. They eventually developed various models for different kinds of crashes.

Mak and Sicking (2002) report a program of developing the Arizona Department of Transportation (ADOT) study of continuous evaluation of in-service highway-safety feature performance. Among the roadway features studied, they included median cable barriers. Sicking et al. (2009) provide guidelines of implementation of cable median barriers on access-controlled highways in the state of Kansas. They reviewed crashes from 2002 to 2006 by analyzing 115 cross-median crashes and 525 cross median events. In their study, cross-median crashes were more likely to occur during winter months and their severities were likely to be lower. A correlation was found between the cross-median crash rate and the volume of freeway traffic with 60 feet median widths.

Agent and Pigman (2008) evaluated median cable barrier safety-performance on Kentucky Interstates in preventing cross-median collisions. They found that a median cable system was effective in the redirection of errant vehicles because only 0.9 percent of all cases failed, i.e., continued into the opposing lanes. Gabler et al. (2005) studied side impact injury risk for belted far side passenger vehicle occupants as the aftermath of the performance of three strands of median cable barrier system and other modified ones used in New Jersey.

Cooner et al. (2009) carried out an assessment on cable median barrier systems in the state of Texas. Texas started aggressively installing median cable systems almost the same time as Ohio in 2003. Cooner et al. (2009) contend that just prior to 2003, almost 96 percent of fatalities on Texas Interstate highways were due to cross-median crashes. Due to financial considerations, Texas DOT installed high-tension cable median barriers instead of concrete barriers simply because of economic reasons, i.e., more roadway miles could be protected by cable barriers by the same amount of funds available (Cooner et al. 2009). Knuiman et al. (1993) utilized Highway Safety Information System (HSIS) data from Illinois and Utah to develop a log-linear model to assess the median width/crash rates relationship and the crash data for the time when there were no cable barriers. But, with the cable barrier systems in Oregon, Sposito and Johnston (1999) observed a reduced fatality rate but yet five times growth in injury crashes, with additional vehicles hitting the barrier posts when entering the median.

The state of Michigan started installing median cable barriers in 2008 and by September 2013, they had completed 317 miles of high-tension median cable barriers on the state's freeways (Savolainen et al., 2014). Savolainen et al. (2014) investigated the safety and economic performance of these cable median barriers. Their study found that fatal and severe injury crashes were reduced significantly following cable median barrier installations. They conclude that cable median barrier installation is an effective approach to lower cross-median crashes experienced on Michigan's freeways.

In the state of Florida, Alluri et al. (2012) conducted a safety performance comparison study between the G4 (1S) W-beam guardrails and cable median barriers on Florida's freeways. Alluri et al. (2012) conclude that generally, guardrail barriers performed slightly better than cable barriers in terms of barrier and cross-median crashes. However, cable median barriers resulted into fewer severe injury crashes compared to guardrail barriers.

Ray et al. (2009) performed a safety evaluation of cable barrier system from several states. The study by Ray et al. (2009) reports that states that have installed cable median barrier systems have recorded a decrease of not less than 40 percent and in most cases reached 100 percent in severe crashes. According to the Ray et al. (2009) study, at least 88 percent of the cable systems stopped vehicles from crossing the median. In many instances, these captured crashes are not considered major, and very often the vehicle can be driven away.

The authors of the Highway Safety Manual (HSM) (AASHTO, 2010) appraise that using median barriers reduced fatal crashes by 43 percent, and injury crashes by 30 percent. Despite that, median barriers have potentially increased crash frequencies by about 24 percent, predominantly because of increased PDO collisions.

The American Association of State Highway and Transportation Officials (AASHTO) issued a new edition of Roadside Design Guide (RDG) in 2011 that provides guidelines to prevent CMCs by installing different safety features (AASHTO, 2011). The design guide mentions that FHWA surveyed more than 25 states in 2004 to assess the issue of cross-median crashes. Their results show that medians wider than 30 feet had high fatality rates caused by CMCs. According to the Roadside Design Guide (AASHTO, 2011), more than half of the CMCs occur over medians that were under 50 feet. High-tension cable barriers are mainly used as preventive measures against CMCs. A table in Appendix C summarizes some of the state research and findings on cable median barriers, listing by state, year, research intent and findings.

2.3 Median Cable Barrier Installation Guidelines

High-tension cable barriers were installed on freeways to prevent errant vehicles from crossing the median and encroaching into the opposing travelled way. ODOT has summarized all the important information, instruction, and approved proprietary products in the Roadside Safety Field Guide (ODOT, 2013). The Roadside Safety Field Guide was issued to assure that all barrier installations are constructed and maintained to meet all design expectations.

The Road Safety Field Guide (ODOT, 2013) identifies the following high-tension cable barrier systems that are being used in Ohio:

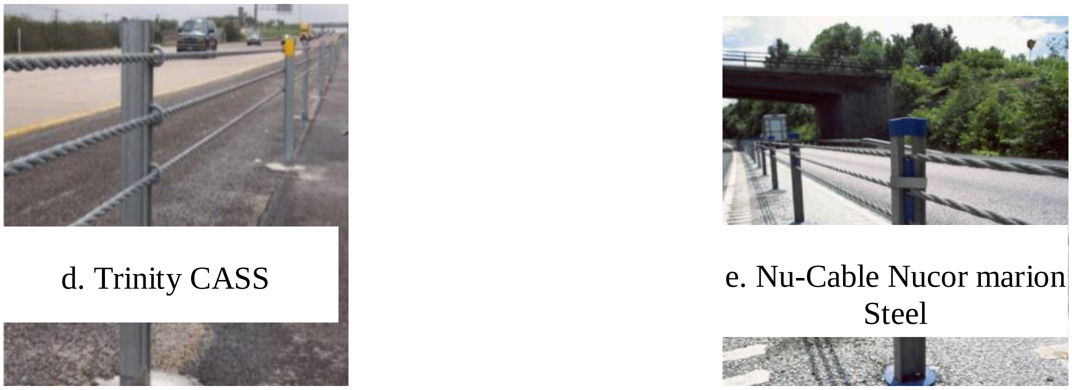
1. Brifen USA Wire Rope Safety Fence (WRSF)
2. Gibraltar Cable Barrier System
3. Safence by Gregory Highway Products
4. Trinity Industries Cable Safety System (CASS)
5. Nu-Cable by Nucor Marion Steel

According to the Road Safety Field Guide (ODOT, 2013), the high-tension cable barriers consist of either three or four cables/strands**.** Stephens (2005) states that most of the barrier systems that offer both Test-Level 3 (TL-3) and Test Level 4 (TL-4) are acceptable as prescribed by the National Cooperative Highway Research Program (NCHRP) Report 350**.** The Road Safety Field Guide (ODOT, 2013) points out that TL-3 systems are evaluated at 62 mi/h and TL-4 are evaluated at 50 mi/h with a 17,600-lb single-unit truck. Figure 2.2 illustrates a view of all the five cable barrier systems currently being used in Ohio.

a. Brifen

b. Gibratlar

c. Safence



d. Trinity CASS

e. Nu-Cable Nucor marion Steel

Figure 2.2: Types of High tension Cable Barrier Systems as Being Installed in Ohio

CHAPTER III

METHODOLOGY AND DATA COLLECTION

3.1 Introduction

This chapter includes: (1) data collection, (2) survey of first responders, (3), and statistical methodology used to perform data analysis. In the current study, data was primarily obtained from ODOT. A questionnaire was developed and ODOT personnel assisted in circulating the survey questionnaires to first responders throughout the state.

3.2 Identify Locations with Cable Barriers

Ohio installed the first median cable barriers on roadways with limited access in 2003. The subsequent median cable barriers have been installed on a yearly basis. To date, ODOT has already installed more than 406 miles of these barriers. The current study only includes in-service median cable barriers that were installed between 2009 and 2014. ODOT engineers chose specific locations of freeway segments of installed in-service median cable barriers to be used in the current study. The selected locations constituted freeway segments with median widths that ranged between 40 and 90 feet with a historic occurrence of cross median crashes. In total, this study received data from 41 locations that totaled 201 miles of installed median cable barriers in the years 2009-2014. The ODOT data included the start and end mile posts, dates of installation of median cable barriers, AADT, and median width for each segment. All Ohio based installations were high-tension cable barrier systems identified as CASS, Brifen or Gibraltar system. Table 3.1 shows all the locations and the construction dates at each of the 41 locations.

Table 3.1: Median Cable Barriers Construction Dates and Study Locations

Location Number	Roadway ID	Begin of Mile Post	End of Mile Post	Installation Length (mi)	ROUTE NAME	Actual Start Date	Actual End Date
1	SALLIR00075**C	0	3.02	3.02	I-75	9/13/2010	6/17/2011
2	SALLIR00075**C	9.6	23.15	13.55	I-75	9/13/2010	6/17/2011
3	SBELIR00470**C	0.49	6.33	5.84	I-470	4/2/2012	6/6/2013
4	SCLAIR00070**C	13.98	20.93	6.95	I-70	6/28/2010	9/19/2012
5	SCUYIR00090**C	0	0.45	0.45	I-90	7/12/2013	9/16/2013
6	SDELIR00071**C	1.6	11.5	9.9	I-71	5/15/2012	10/29/2012
7	SDELIR00071**C	11.5	17.23	5.73	I-71	9/16/2012	10/31/2014
8	SFRAIR00070**C	0	7.24	7.24	I-70	4/25/2011	9/2/2011
9	SFRAIR00270**C	2.6	9.62	7.02	I-270	8/7/2011	7/31/2014
10	SFRAUS00033**C	0	2.87	2.87	US-33	4/25/2011	9/2/2011
11	SGREIR00675**C	0	9.17	9.17	I-675	7/12/2010	5/31/2011
12	SHAMIR00071**C	19.35	19.81	0.46	I-71	7/12/2010	5/31/2011
13	SHAMIR00074**C	5.4	6.31	0.91	I-74	7/12/2010	5/31/2011
14	SHAMIR00074**C	7.94	9.02	1.08	I-74	7/12/2010	5/31/2011
15	SHAMIR00075**C	14.3	14.73	0.43	I-75	7/12/2010	5/31/2011
16	SHAMIR00275**C	6.8	7.61	0.81	I-275	7/12/2010	5/31/2011
17	SHAMIR00275**C	11.62	13.86	2.24	I-275	7/12/2010	5/31/2011
18	SHAMIR00275**C	15.42	21.52	6.1	I-275	7/12/2010	5/31/2011
19	SHAMIR00275**C	31.02	34.61	3.59	I-275	7/12/2010	5/31/2011
20	SHANIR00075**C	17.61	25.23	7.62	I-75	4/19/2010	8/24/2010
21	SHANIR00075**C	14.35	14.91	0.56	I-75	4/19/2010	8/24/2010
22	SHANIR00075**C	0	1.19	1.19	I-75	9/13/2010	6/17/2011
23	SLICIR00070**C	8.6	15.9	7.3	I-70	7/31/2009	10/30/2009
24	SLICIR00070**C	23.85	24.62	0.77	I-70	7/30/2010	10/30/2010
25	SLICIR00070**C	25.89	28.93	3.04	I-70	7/30/2010	10/30/2010
26	SMADIR00070**C	8.93	15.57	6.64	I-70	4/25/2011	9/2/2011
27	SMAHIR00076**C	0	0.9	0.9	I-76	10/20/2010	7/11/2011

28	SMEDIR00076**C	7.33	11.76	4.43	I-76	4/23/2012	1/28/2016
29	SMIAIR00075**C	10.97	19.95	8.98	I-75	8/10/2010	11/19/2010
30	SMOTIR00070**C	7.36	14.86	7.5	I-70	8/10/2010	11/19/2010
31	SMOTIR00675**C	2.27	7.44	5.17	I-675	8/10/2010	11/19/2010
32	SMRWIR00071**C	12.89	19.54	6.65	I-71	11/1/2011	11/7/2013
33	SMRWIR00071**C	3.17	12.19	9.02	I-71	3/20/2013	10/1/2015
34	SMRWIR00071**C	0	3.17	3.17	I-71	9/16/2012	10/31/2014
35	SMUSIR00070**C	0	1.23	1.23	I-70	7/30/2010	10/30/2010
36	SPORIR00076**C	0	21.2	21.2	I-76	10/20/2010	7/11/2011
37	SSUMIR00076**C	15.79	17.98	2.19	I-76	10/20/2010	7/11/2011
38	STRUSR00005**C	6.58	14.14	7.56	SR-05	8/18/2014	5/31/2015
39	STRUSR00082**C	13.89	16.35	2.46	SR-82	8/18/2014	5/31/2015
40	SUNIUS00033**C	24.37	25.11	0.74	US-33	4/25/2011	9/2/2011
41	SWOOIR00075**C	0	5.15	5.15	I-75	4/19/2010	8/24/2010

3.3 Cable Barrier Crash Data

As mentioned in the previous section, ODOT engineers provided the current study with the crash data required for analysis. With the assistance of MS Excel and SPSS, a manipulation of data was conducted. In order to conduct the analysis of safety performance, there are a number of variables that need to be considered for each road segment in the study. The variables that were available in the crash data include traffic crash frequency, traffic volumes, and median widths. Between 2007 and 2016, a total of 2498 crashes occurred at the 41 locations shown in Table 3.1. The 2007-2016 crash dataset was explored to determine the lengths of time for both before and after median cable barriers were installed on each segment site. For most cases, the period before construction of the median cable barriers consisted of 3 years of crash data, while the after period consisted of 3 to 5 years of crash data. In addition, the ODOT crash database included both injury severity and the number of vehicles in each crash event. In addition, other variables in the crash database included roadway, weather, and light conditions prevailing during the time of each crash.

The injury severity sustained by the individual is classified in terms of the KABCO injury scale. The KABCO injury scale classifies the injury severity into five distinct categories. These are fatal (denoted as K), incapacitating injury (denoted as A), non-incapacitating injury (denoted as B), possible injury (denoted as C), and no injury (denoted as O).

Since the main study objective was to analyze the effectiveness of a median cable barrier system in protecting the traveling public, therefore, it was important to identify target crashes for proper analysis. A target crash is the one which was potentially affected by the installation of median cable barriers. Consequently, target crashes include median-crossover crashes as well as all median-based crashes. Because identification of target crashes using electronic codes alone proved unreliable, a manual means was employed to review each crash occurrence on segments with cable barriers. Cable crashes were accessible for downloading from the Ohio Department of Public Safety (ODPS) website.

The crash data review assistants who performed this process were given a training on how to code every crash and place it in its correct target crash classification. Target crashes can be classified as under-ride, over-ride, penetration, contained, or redirected. An under-ride crash means the vehicle got under the lowest barrier cable. An over-ride crash means the vehicle passed over the highest barrier cable. A penetration crash means the vehicle passed through the barrier cables. A contained crash means a vehicle was stopped by the barrier cable upon colliding with it. A redirected crash means the vehicle becomes redirected back into travel lanes again upon colliding with the cable barrier. Figure 3.1 shows the classification of target crash categories.

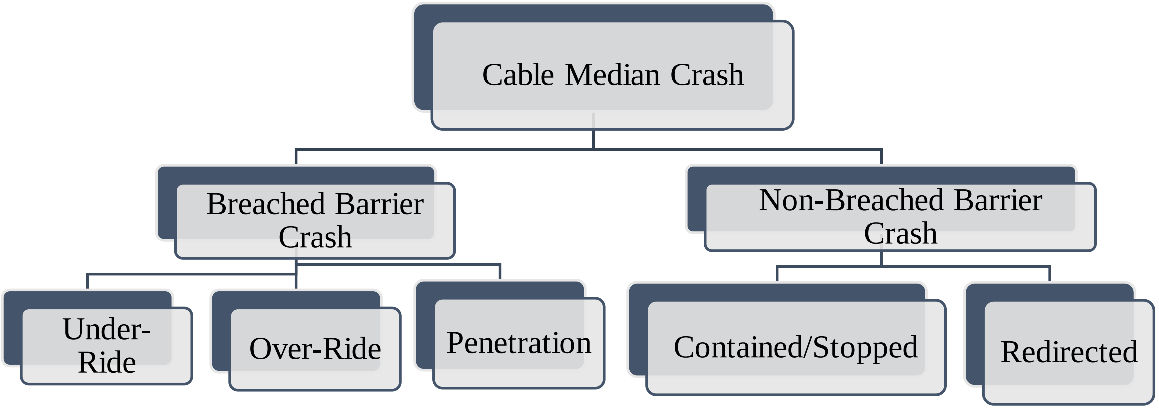
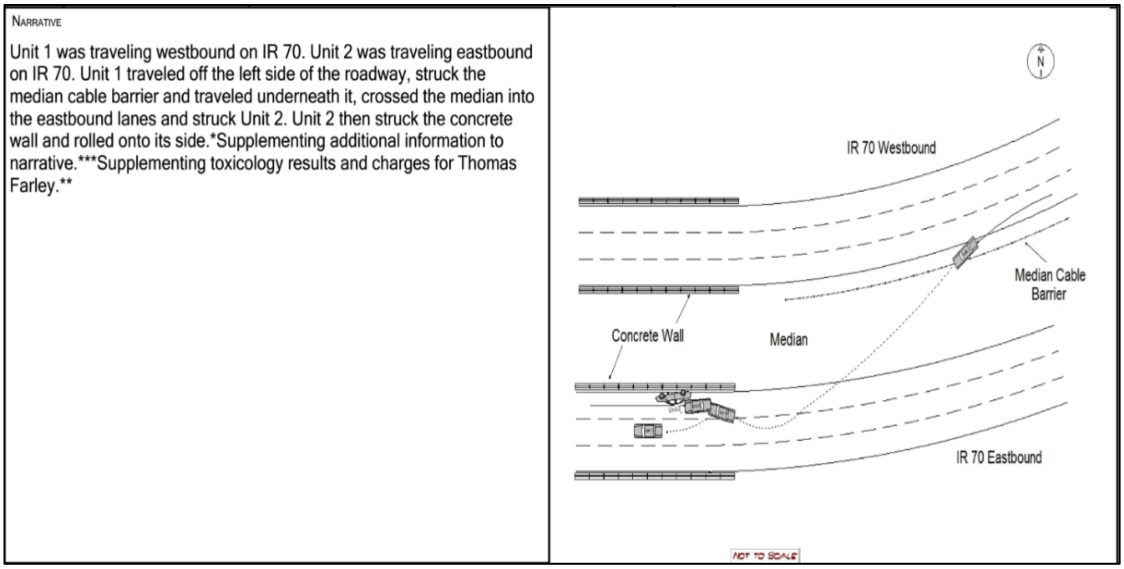


Figure 3.1: Target Crash Categories

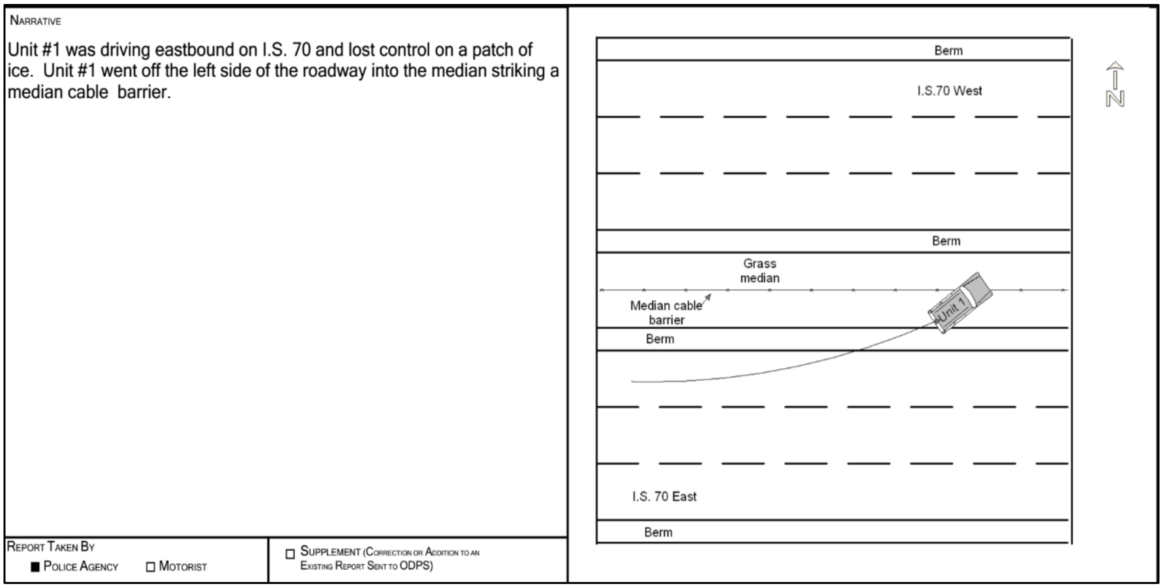
Generally, crash reviewers investigated crash diagrams for each report to find a target crash classification. In situations where the police narrative and diagram failed to pinpoint the target crash classification, crash reviewers reviewed the 'sequence of events' variable to assist in decision-making. For those crashes that did not meet criteria to be allocated under a target classification were eventually dropped from this analysis. Besides specifying the target classification, crash reviewers determined which vehicle got through the median and hit the cable barrier if multi-vehicles were involved in the crash. Finally, more than 2200 crashes were reviewed on a manual basis and identified to meet the cable crash categorizations. Figures 3.2 through 3.6 show some examples of the five-cable crash classifications.



NARRATIVE

Unit 1 was traveling westbound on IR 70. Unit 2 was traveling eastbound on IR 70. Unit 1 traveled off the left side of the roadway, struck the median cable barrier and traveled underneath it, crossed the median into the eastbound lanes and struck Unit 2. Unit 2 then struck the concrete wall and rolled onto its side.*Supplementing additional information to narrative.***Supplementing toxicology results and charges for Thomas Farley.**

Figure 3.3: Barrier Non-Breached Contained Crash Example



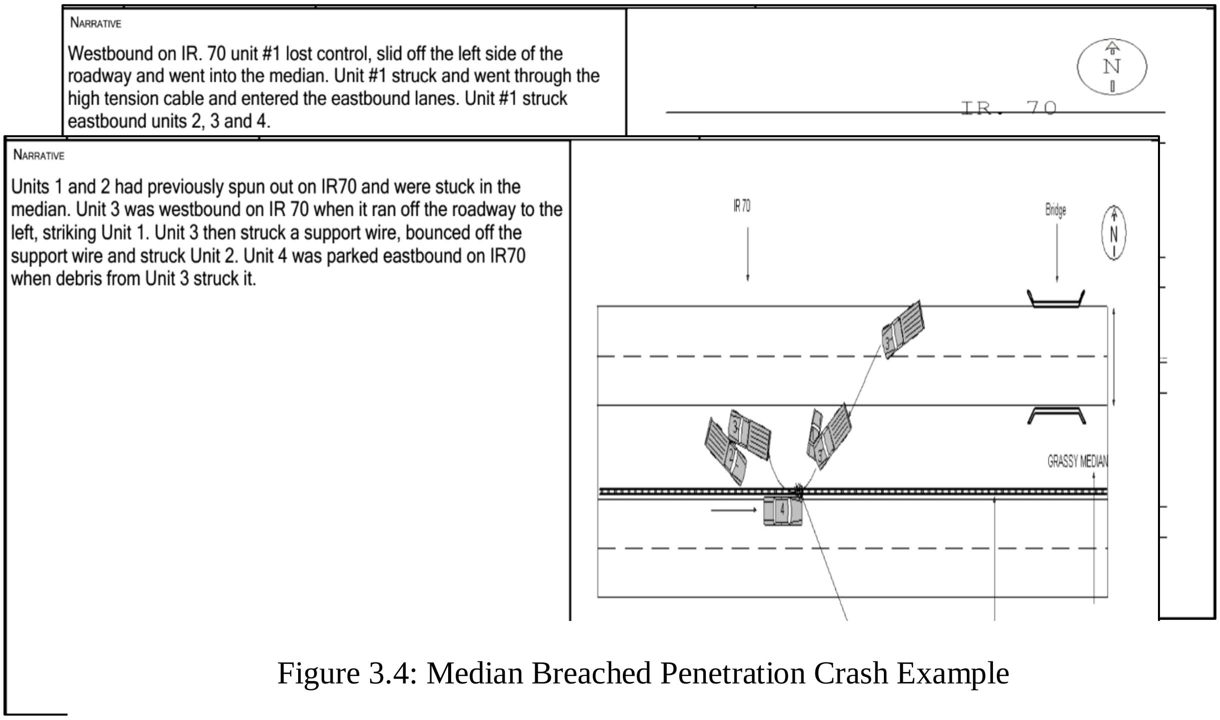
NARRATIVE

Unit #1 was driving eastbound on I.S. 70 and lost control on a patch of ice. Unit #1 went off the left side of the roadway into the median striking a median cable barrier.

REPORT TAKEN BY
■ POLICE AGENCY ☐ MOTORIST

☐ SUPPLEMENT (CORRECTION OR ADDITION TO AN EXISTING REPORT SENT TO ODPS)

Figure 3.2: Median Breached Under-Ride Crash Example



NARRATIVE

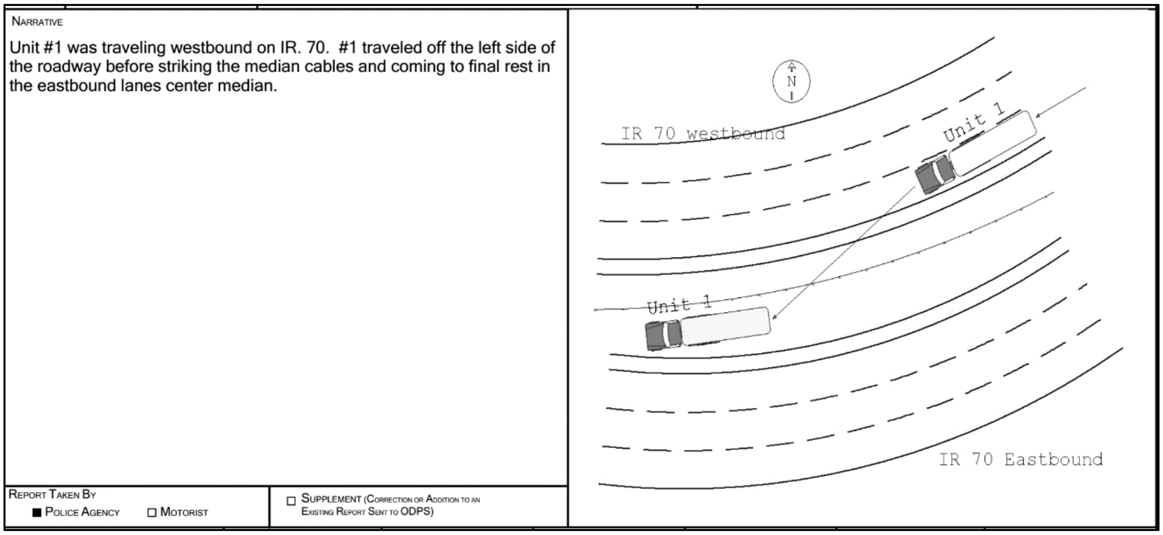
Westbound on IR. 70 unit #1 lost control, slid off the left side of the roadway and went into the median. Unit #1 struck and went through the high tension cable and entered the eastbound lanes. Unit #1 struck eastbound units 2, 3 and 4.

NARRATIVE

Units 1 and 2 had previously spun out on IR70 and were stuck in the median. Unit 3 was westbound on IR 70 when it ran off the roadway to the left, striking Unit 1. Unit 3 then struck a support wire, bounced off the support wire and struck Unit 2. Unit 4 was parked eastbound on IR70 when debris from Unit 3 struck it.

Figure 3.4: Median Breached Penetration Crash Example

Figure 3.5: Barrier Non-Breached Redirected Crash Example



NARRATIVE

Unit #1 was traveling westbound on IR. 70. #1 traveled off the left side of the roadway before striking the median cables and coming to final rest in the eastbound lanes center median.

REPORT TAKEN BY

■ POLICE AGENCY ☐ MOTORIST

☐ SUPPLEMENT (CORRECTION OR ADDITION TO AN EXISTING REPORT SENT TO ODPS)

Figure 3.6: Barrier Breached Over-Ride Crash Example

3.4 First Responder Questionnaire Survey

As part of the effort to evaluate the safety effectiveness of median cable barriers installed in some portions of freeways throughout the state, a survey was conducted to solicit experience of first responders who deal with crash scenes from time to time. The survey was developed so that the emergency responders (e.g., police agencies and fire departments) can tell us their experience and knowledge related to median cable barriers' safety. The feedback they provided was very helpful in understanding of freeway crash-related issues and the median cable barriers' performance in terms of their intended use and/or any known unintended disadvantages based on their experiences of attending the crash scenes.

ODOT personnel provided email addresses of potential respondents to whom the survey questionnaires were emailed to. We received 41 responses in total. Most of the responses (26) came from police agencies. Fire and medical agencies returned in 13 responses. There were only two responses from towing companies. Appendix A shows the survey questionnaire that was developed and used in this study.

More than 75 percent of the respondents (31 respondents) agreed that cable barriers have enhanced safety on Ohio’s freeways. Only less than 8 percent (3 respondents) disagreed with the notion that cable barriers have enhanced safety. However, some of the respondents indicated that cable barriers have made it difficult for emergency responders to reach the incidence scene when responding to an incidence. The respondents were asked to mention what they regarded as predominant issues with respect with their experiences of responding to attend the crash scenes on roadways with median cable barriers. Table 3.2 summarizes a list of challenges mentioned by respondents:

Table 3.2: List of Common Challenges in Responding to Crashes Related to Median Cable Barriers

Common responding challenges	Number of respondents (%)
Difficulty removing the entangled vehicle from the barrier	12 (29.3)
Difficulty to locate an emergency crossover or long distances between emergency crossovers.	17 (41.5)
Difficulty affording medical care to the injured persons because of the cable barriers	5 (12.2)
Cable barrier is located too close to the edge of the roadway which causes lane closure to clear the crash scene.	9 (21.9)
Other	5 (12.2)

The five respondents who checked ‘Other’ mentioned the following challenges/concerns:

- In the winter we must keep an eye on them because the cable becomes a weapon while we are trying to remove a vehicle and another vehicle hits the cable down the road.
- Lack of training for all emergency responders who relieve cables.
- Excessive damage to vehicles that contact the cable barriers.
- Had vehicles on both sides and had to leap or crawl over them multiple times.
- Hinders traffic enforcement and response time.

In brief, the majority of the respondents have a sense that installed median cable barriers have added a degree of difficulty when responding to an incidence, who are also in agreement that Ohio’s roadways have generally been safer due to the median cable barrier installation, which substantially have reduced dangerous freeway’s cross-median head-on crashes.

With respect to training on how to deal with median cable barrier-related crashes, almost 81 percent of the respondents mentioned that their agencies have neither guidelines nor training that can specifically be associated with cable barriers. Since the survey results reveal that most emergency responders received no training, further training opportunities may help to mitigate some of the issues the survey respondents have noted.

3.5 Development of Safety Performance Functions (SPFs)

The Highway Safety Manual (HSM) defines a Safety Performance Function (SPF) as an equation used to predict the average number of crashes per year at a location as a function of exposure and, in some cases, roadway or intersection characteristics (e.g., number of lanes, traffic control, or median type (AASHTO, 2010). For highway segments, exposure is usually represented by the segment length and annual average daily traffic (AADT) (AASHTO, 2010). An SPF is also sometimes known as the Crash Estimation Model (CEM) (Hovey and Choudhary, 2005; Eustace et al., 2010).

Prediction of crash frequency is properly done by using count data methods; the most popular ones being Poisson and negative regression models (Washington et al., 2011). According to Washington et al. (2011), Poison regression model is the more popular of the two models because it is used to model a wide range of transportation count data by estimating rare-event count data such as crash frequency or number of vehicles waiting in a queue. However, the Poisson distribution has one main requirement that sometimes poses a limitation to its use, the mean of the count numbers equals to its variance (Washington et al., 2011) and in some cases, the count data are overdispersed, that is, the variance is significantly larger than the mean and when this situation happens, Poisson distribution's principle is violated and hence these kind of count data are better modelled using the negative binomial model (Washington et., 2011; Srinivasan and Bauer, 2013).

Therefore, the Poisson and negative binomial regression models are statistical models traditionally used for fitting crash frequency estimation data. There are a number of model goodness-of-fit tests usually used to test and determine which of these models accurately fits the data at hand. The negative binomial model is a generalized form of a Poisson model, which allows the mean to differ from the variance. For a Poisson regression model, the probability of a road segment *i* that experiences non-negative integer number of crashes per year, y_i, is given by Equation (3.1) (Washington et al., 2011):

$$P(y_i) = \frac{EXP((-\lambda_i)\lambda_i^{y_i}}{y_i!} \text{ ....(3.1)}$$

Where:

$P(y_i)$ = probability of road segment i experiencing y_i crashes per year

λ_i = the Poisson parameter for road segment i, which equals to segment i's expected number of crashes per year, $E[y_i]$

The expected number of crashes per year (crash frequency) in Poisson regression model is thus estimated by specifying the Poisson parameter (λ_i) as a function of explanatory variables (Washington et al., 2011). A Generalized Linear Model (GLM) is usually used in specifying explanatory variables that may affect the crash frequency. The GLM has the advantage of providing a framework for using discrete variables as the response variable and incorporating the interacting parameters. In the current study, the SAS version 9.4 software GENMOD procedure was used to fit the models.

The relationship between the Poison parameter (i.e., the expected number of crash frequency in this case) and the explanatory variables (covariates) is a log-linear model (link function) represented as shown in Equation 3.2a or 3.2b, which are the same relationships but in different forms (Washington et al., 2011):

$$\lambda_i = EXP(\boldsymbol{\beta X_i}) \text{ ....(3.2a)}$$

$$Ln(\lambda_i) = \boldsymbol{\beta X_i} \text{ ....(3.2b)}$$

Where:

$\mathbf{X}_i$ = a vector of explanatory variables (covariates)

$\boldsymbol{\beta}$ = vector of estimable parameters

Whenever the Poisson distribution's property that restricts the mean and variance to be equal, i.e., $E[y_i] = Var[y_i]$ is violated, the count data are said to be either underdispersed, i.e., $E[y_i] > VAR[y_i]$ or overdispersed, i.e., $E[y_i] < VAR[y_i]$ and in both cases the Poisson distribution model will be biased, and thus the model will not fit well the data (Washington et al., 2011). Thus, as mentioned earlier, if overdispersion exists in the data, negative binomial regression model is used instead of Poisson regression model.

The negative binomial model is derived by rewriting Equations 3.2a or 3.2b by adding an error term as shown in Equations 3.3a and 3.3b:

$$\lambda_i = EXP(\boldsymbol{\beta X_i} + \varepsilon_i) \quad \text{……………………………………………………..(3.3a)}$$

$$Ln(\lambda_i) = \boldsymbol{\beta X_i} + \varepsilon_i \quad \text{……………………………………………………….(3.3b)}$$

Where:

$EXP(\varepsilon_i)$ = a gamma-distributed error term with mean 1 and variance α

Thus, this manipulation of the mean makes the variance to be different from the mean and the variance of the negative binomial regression model becomes as shown in Equation 3.4 (Washington et al., 2011):

$$VAR[y_i] = E[y_i] + \alpha E[y_i]^2 \text{……………………………………………(3.4)}$$

The negative binomial regression model is considered a general case whereby it becomes a Poisson regression model, which is a special case when the parameter α approaches zero. The parameter α is the one normally termed as the overdispersion parameter. Therefore, the selection between the Poisson regression model and the negative regression model to fit the crash frequency data is dependent upon the value of the overdispersion parameter, α (Washington et al., 2011).

According to Pedan (2001) if the overdispersion in the data is not captured when analyzing the data, the problem of underestimation of standard errors may occur and can lead into over-stating of significance in hypothesis testing. Consequently, using an inappropriate model to fit count data can greatly affect the statistical inferences and the resulting conclusions. Deviance (D), also known as the log-likelihood ratio G^2 statistic and Pearson chi-square statistic (χ^2) divided by the degrees of freedom (DF) are the two parameters commonly used to detect whether overdispersion or underdispersion exists in the count data and also used to indicate if an incorrectly specified model is used or the presence of outliers in the data (SAS, 2004).

The goodness of fit between the observed data and the estimated values from a Poisson distribution or a negative binomial distribution are usually measured by using the log-likelihood ratio G^2 statistic (i.e., the deviance) and the Pearson chi-square χ^2 statistics given as shown in Equations 3.5 and 3.6, respectively (White and Bennetts, 1996; Agresti and Finlay, 1997; SAS, 2004):

$$D = G^2 = 2\sum_i O_i ln\left(\frac{O_i}{E_i}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

Where:

O_i = observed frequency (in this case, equal to the number of observed crashes per year, y_i)

E_i = expected frequency based on the fitted model (in this case, predicted annual crashes, λ_i)

The criteria for assessing the goodness-of-fit is thus based on taking Equations 3.5 and 3.6 divided by the degree of freedom (DF) to obtain a nonnegative dispersion parameter, *k*, which is computed as shown in Equations 3.7 and 3.8 by using deviance and chi-square statistics:

$$k = \frac{D}{DF} \quad \text{(3.7)}$$

$$k = \frac{\chi^2}{DF} \quad \text{(3.8)}$$

Where:

k = a nonnegative dispersion parameter

D = deviance statistic

χ^2 = Pearson Chi-Square statistic

DF = degree of freedom.

If the results of the fitted Poisson model provide a *k* value close to one, this means that the Poisson model correctly fits the data. If a value of *k* is greater than one, this indicates that the data is over-dispersed, which means the variance is greater than the mean and if the value of *k* is less than one, it means the data is under-dispersed. If the data is over-dispersed or under-dispersed, the

Poisson model is not the right model to fit the data. In the case of over-dispersed data, the negative binomial model is a better model and if used, it is expected that the value of the k parameter generated will be close to one. For under-dispersed data, generalized Poisson or Hurdle models are suggested and if they are the correct models, again their resulting values of the k parameter will be close to one as well. In essence, for any model used to perform the prediction, if the resulting k value is not close to one, that model is not a good model for estimating that particular data.

3.6 Empirical Bayes Method (EB Before/After)

Evaluation of the change in crashes after a safety treatment or countermeasure has been implemented, is one of the most important steps in analyzing roadway safety (AASHTO, 2010). A before and after study is usually performed to assess how crash frequency or severity has changed due to the implementation of a countermeasure (treatment) or a set of treatments (Hauer, 1997; AASHTO, 2010). In addition, when a treatment is applied to multiple sites of similar traits and the effectiveness of the safety treatment is collectively evaluated, this analysis can also provide an estimate of a crash modification factor (CMF) due to the treatment (AASHTO, 2010).

Of all the statistical methods applicable for evaluating the safety effectiveness of before-after studies, the most suitable method selected in this study was the Empirical Bayes (EB) method. An EB method is a typical example of an observational before/after studies design used for safety effectiveness evaluations. The suitability of EB method is derived from the literature findings that suggest that the EB method is appropriate for this kind of analysis due to its ability to adjust and compensate for regression-to-the-mean (RTM) bias (Hauer & Persaud; 1983; Hauer, 1997;

AASHTO, 2010). Due to the correction of regression-to the mean and the application of the SPFs to estimate what the average crash frequency at the treated sites would have been during the time period after the treatment implementation, assuming the treatment was not implemented, these two capabilities make the EB method highly preferred (Hauer, 1997, AASHTO, 2010). Most researchers who previously performed the EB before-after safety effectiveness evaluation had used SPFs based on the negative binomial regression models due to the presence of overdispersion found in their crash data (e.g., Garber et al., 2005; Hovey and Chowdhury, 2005; Ossenbruggen and Linder, 2006; Miranda and Fu, 2007; Miller et al, 2006, Eustace et al., 2010; Srinivasan and Carter, 2011; Chimba, 2017).

The EB before-after safety evaluation method is essentially used to compare crash frequencies at a group of similar sites before and after a treatment is implemented (AASHTO, 2010) The change in safety performance at a treated site (roadway segment), i.e., after the installation of a median cable barrier is given as shown in Equation 3.9 (Hauer, 1997):

$$\Delta Safety = B - A \qquad (3.9)$$

Where:

ΔSafety = Change in the number of crashes (crash frequency)

B = Expected number of crashes (computed by EB method) in the after period without the treatment (in this case, installation of median cable barrier)

A = Actual (observed) number of crashes reported in the after treatment period

The first step in the EB before-after evaluation study involves the selection of treated sites. The next step in the study is the development of the SPF (CEM) as discussed in Section 3.5. The EB method addresses the regression-to-the mean (RTM) bias by simply incorporating crash data from a group of sites and utilizing the SPF and weighting the observed crash frequency at each site with the predicted average crash frequency based on the SPF estimates to obtain the expected average crash frequency (AASHTO, 2010).

The HSM (AASHTO, 2010) outlines the data needs as inputs in order to properly perform an EB before/after evaluation study as follows:

- At least 10-20 sites at which the treatment of interest has been implemented (such as median cable barriers have been installed)
- 3 to 5 years of crash and traffic volume data for the before treatment implementation period are available
- 3 to 5 years of crash and traffic volume data for the after treatment implementation period are available
- SPF for treatment site types (an SPF can be developed based on the available data from treatment sites or adopted and calibrated as outlined in the HSM).

In summary, the EB method computes the overall unbiased safety effectiveness of the treatment being evaluated, θ, expressed as a percentage change in crashes, and assesses its precision and statistical significance (Hauer 1997; AASHTO 2010). The EB before/after safety effectiveness evaluation study of median cable barriers was done by use of Excel spreadsheets by implementing the 14 steps of the analytical procedure as outlined in Chapter 9 of the HSM

(AASHTO, 2010). A detailed step-by-step description of the EB before-after safety effectiveness evaluation method is presented in Appendix B of this report.

According to AASHTO (2010), the Crash Modification Factors (CMFs) can be quantified as a result of a safety effectiveness evaluation as outlined above for countermeasures by evaluating a group of sites where the countermeasure is being evaluated. The CMF of the treatment being evaluated can be computed as shown in Equation 3.10 (AASHTO, 2010):

$$CMF = \left(100 - \frac{\theta}{100}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

Where:

CMF = crash modification factor due to the implementation of the treatment at a group of sites with similar traits

θ = an overall unbiased safety effectiveness as a percentage change in crash frequency across all sites as computed by the EB before/after safety evaluation study

According to Gross et al. (2010), a CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. Usually, the CMF is multiplied by the expected crash frequency without treatment to obtain an estimate of crash frequency if the treatment is implemented. While a CMF greater than 1.0 indicates an expected increase in crash frequency, a CMF value less than 1.0 indicates an expected reduction in crash frequency after a particular countermeasure has been implemented (Gross et al., 2010). As an example, a CMF of 0.9 indicates that there is an expected safety benefit of about 10 percent in crash frequency reduction due to the treatment. Likewise, a CMF of 1.1 indicates that there is an expected degradation in safety of about 10 percent increase in crash frequency.

CHAPTER IV

MEDIAN CABLE BARRIER CRASHES AND ANALYSIS

4.1 Analysis of Cable Barrier Hits

The characteristics of cable crashes and the effectiveness of a median cable barrier in preventing median crossovers with a chance of colliding with another vehicle on the opposite travel lanes was analyzed. All cable related crashes in the after period for all sites whereby a vehicle hits a median cable barrier were analyzed. Table 4.1 summarizes crash results by severity. In this case crash severity is synthesized in the form of KABCO scale normally used to classify the injury severity. That is, although crash severity is normally categorized into three levels of severity namely property damage only (PDO), injury, and fatal; but in this case the injury level is subdivided into 3 levels of injuries based on KABCO scale of injury levels, namely incapacitating injury (A), non-incapacitating injury (B), and possible injury (C) crashes.

Table 4.1 shows that the cable barriers were effective in stopping vehicles from reaching the oncoming traffic on the opposite side of the road. 95.4 percent of the total cable median barrier crashes had no penetration of the cable barrier, i.e., the vehicles were stopped by the cables. This reveals that the cable median barriers performed their role of preventing cross-median crashes successfully (e.g. the majority of cable hits were either stopped or redirected back into the travel lanes after striking the cable barrier). Furthermore, in an additional 2.9 percent of the crashes, vehicles managed to breach the cable barriers, but they were stopped short of reaching the opposite travel lanes, i.e., they were slowed down and stopped within the median. Finally, in only 1.7

percent of cable barrier strikes that vehicles ended up crossing the median all the way and entering the opposing lanes.

Table 4.1: Cable Barrier Crashes by Crash Severity and Crash Scenario

Cable Barrier Crash Event		After Period Cable Median Barrier Crashes by Severity						Percent of Total Cable Median Barrier Crashes
		PDO	C	B	A	K	TOTAL	
Stopped by Cable Barriers and Contained in Shoulder	No.	1474	144	170	48	7	1843	83.4%
	%	80.0%	7.8%	9.2%	2.6%	0.4%	100.0%	
Re-directed Back into the Travel Lanes upon Hitting Cable Barriers	No.	200	26	32	7	0	265	12.0%
	%	75.5%	9.8%	12.1%	2.6%	0.0%	100.0%	
Total Number of Crashes Which Didn't Breach Cable Median Barriers	No.	1674	170	202	55	7	2108	95.4%
	%	79.4%	8.1%	9.6%	2.6%	0.3%	100.0%	
Breached the Cable Barriers and Contained Within the Median	No.	44	13	4	1	1	63	2.9%
	%	69.8%	20.6%	6.3%	1.6%	1.6%	100.0%	
Breached the Cable Barriers and Entered Opposing Lanes (Crossover Crash)	No.	14	4	12	5	3	38	1.7%
	%	36.8%	10.5%	31.6%	13.2%	7.9%	100.0%	
Total: All Target Crashes	No.	1732	187	218	61	11	2209	100.0%
	%	78.4%	8.5%	9.9%	2.8%	0.5%	100.0%	

In terms of crash severity and as shown in Table 4.1, only 0.5 percent of all target crashes resulted into fatal injuries. And only 2.8 percent lead into incapacitating injuries. In general, most of the cable barrier strikes mainly lead into minor injuries with PDO crashes accounting for 78.4 percent of all target crashes. This is another evidence that median cable barriers have the potential of reducing injury severities of cross-median crashes. It is staggering to guess what percent of severe crashes would have been caused if all vehicles in these crash events were able to cross through the median and reach opposing travel lanes, with increases the probability of being involved in head-on type of crashes.

4.1.1 Vehicle Type

This study also evaluated cable barrier safety performance by looking at how they performed by vehicle type. If the cable crash involved more than one vehicle, the vehicle striking the cable was the sole one considered. A total of 1,696 cable hits were considered single crashes with the remaining crashes involving multiple vehicles. Crashes that involved more than one vehicle were excluded from the vehicle type analysis due to a lack of supporting information. Consequently, only single vehicle crashes are discussed in this section. Figure 4.1 shows the number of vehicles per crash involved in the target cable crash.

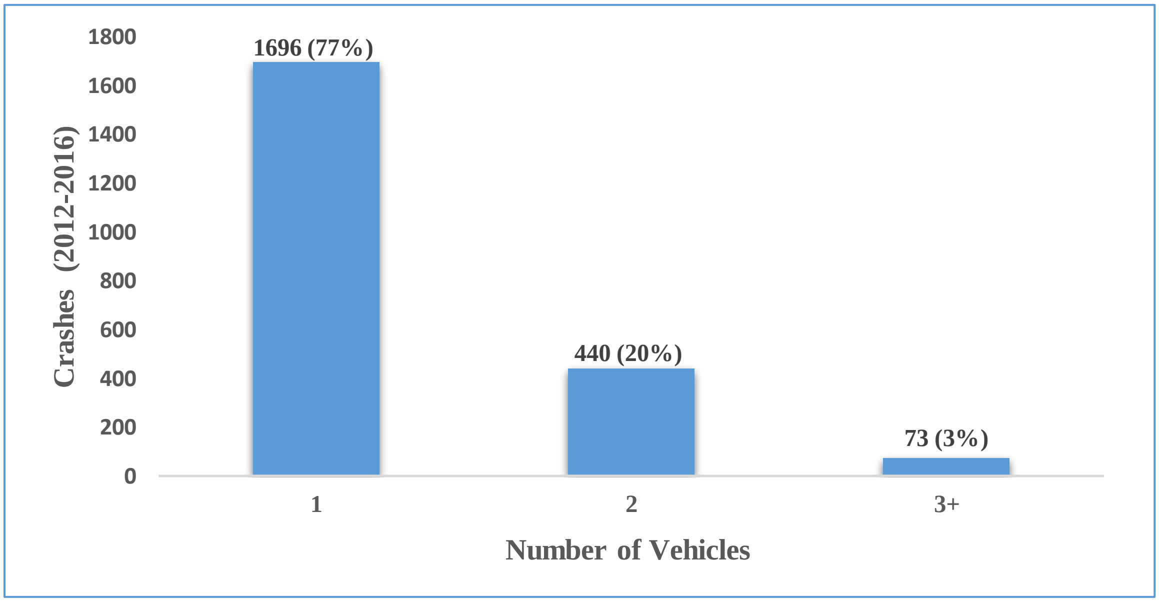


Figure 4.1: The Number of Vehicles Involved in Cable Barriers Crashes

The vehicle types found in the database include passenger cars, motorcycles, light trucks, medium trucks, heavy trucks, and others. Passenger cars include sub-compact, compact, mid-size, and full-size automobiles; light trucks include mini vans and sport utility vehicles (SUVs); heavy trucks include tractor-trailer combination trucks and vehicles with more than two rear axles. The vehicle types labeled as “other” consisted of vehicles whose type was undefined and those which had inadequate details in police reports.

Table 4.2 summarizes median cable barrier crashes (cable barrier hits) by vehicle type across all sites. Generally, 53 (3.1 percent) out of the 1696 cable median crashes were able to cut the cable and breached the median. However, these were effectively contained since they were stopped inside the median, could not reach the opposite travel lanes. Overall, only 21 vehicles (1.2 percent) were able to go through median all the way and caused crossover crashes. The cable median barriers were very effective in stopping passenger vehicles, motorcycles, and light trucks with a minimum of 95.5 percent containment (non-breached cables). Even for heavy trucks, the containment was fairly high with less than 15 percent of them breaching the median cable barriers. In general, 95.6 percent of all single vehicle cable crashes that did hit the cables did not breach (completely stopped by) the median cable barriers.

Table 4.2: Vehicle Type by Median Crash Type (Single-Vehicle Cable Crashes Only)

Vehicle Type	Crash Scenario				
	Crossover Crashes	Barrier Breached Crashes	Barrier Non-Breached Crashes	Total Crashes	% of Non-Breached
Passenger vehicle	9	29	1040	1078	96.5%
Motorcycle	0	0	6	6	100.0%
Light truck	6	17	489	512	95.5%
Medium truck	3	0	22	25	88.0%
Heavy truck	3	7	61	71	85.9%
Others	0	0	4	4	100.0%
Total	21	53	1622	1696	95.6%

4.1.2 Weather and Road Conditions

Figure 4.2 shows a summary of the number of median cable crashes by road condition when the crashes occurred. About 37.0 percent of median cable crashes occurred when the weather was cloudy or raining and about 34.0 percent occurred when the weather was clear. In addition, about 24.0 percent occurred during snowing days.

Moreover, as shown in Table 4.3, the cable-related crashes tended to be more severe in adverse weather i.e. snow, rain, sleet, fog, and severe crosswinds. This is because drivers are more likely to lose control and spin into the shoulder and hit the median cable barriers in wet and icy road conditions.

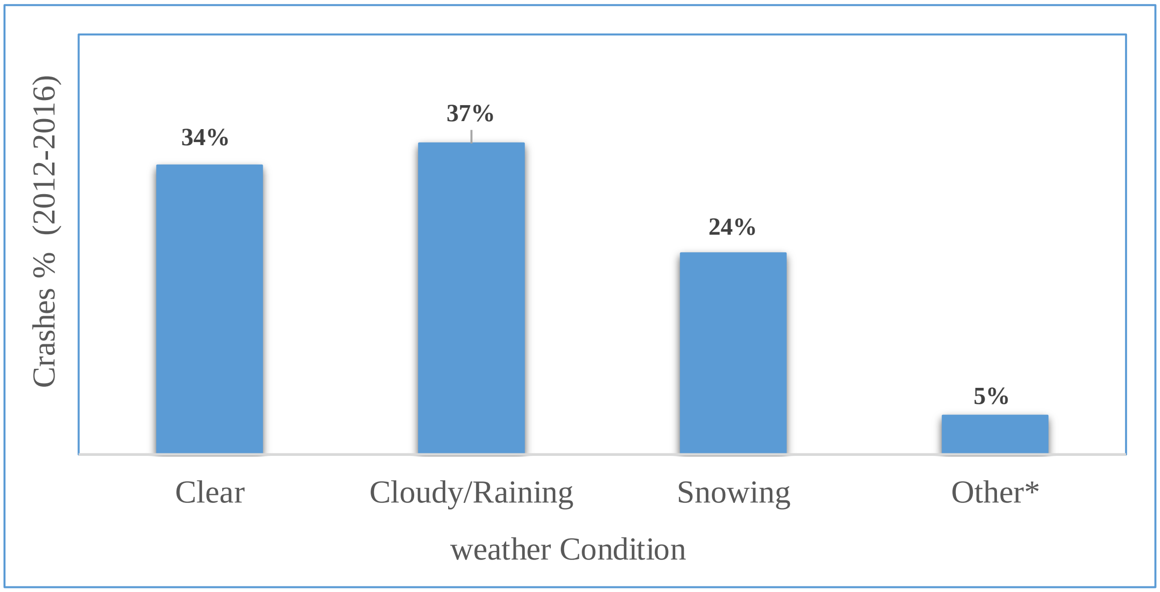


Figure 4.2: The Occurrences of Cable Crashes by Weather and Road Conditions.

Table 4.3: The Severity of Cable Crashes by Weather and Road Conditions.

Weather Condition		Level of Injury					Total
		PDO	C	B	A	K	
Clear	No.	543	78	109	28	2	760
	%	71.4%	10.3%	14.3%	3.7%	0.3%	100%
Cloudy/Raining	No.	638	70	80	26	4	818
	%	78.0%	8.6%	9.8%	3.2%	0.5%	100%
Snowing	No.	465	28	28	6	2	529
	%	87.9%	5.3%	5.3%	1.1%	0.4%	100%
Other*	No.	86	2	10	1	3	102
	%	84.3%	2.0%	9.8%	1.0%	2.9%	100%
Total	No.	1732	178	227	61	11	2209
	%	78.4%	8.1%	10.3%	2.8%	0.5%	100%

*Other includes some categories, such as fog, smog, smoke, sleet, hail and sever crosswinds

CHAPTER V

ANALYSIS AND DISCUSSION OF RESULTS

5.1 Final Study Locations and Crash Data Analyzed

This chapter presents the results of a before and after safety analysis of cable median barriers based on the cross-median related crashes. As previously defined, these crashes often take place when an errant vehicle leaves the travel lane and enters the median. As was shown in Table 4.1, most of the crashes that happened during the period following cable barrier installation were either stopped or redirected upon hitting the cable barriers. Because these types of crashes do not result in cross-median crashes (CMCs), these types of crashes were excluded. Some of the locations had less than three years of AADT data available in the before installation period and these sites were dropped from the analysis. Therefore, only 14 locations, which had three years of all data in the before period, were selected from a list of 41 locations (refer to Table 3.1) for the development of the SPFs. The 14 locations have a total of 206 crashes with 148 crossover median crashes occurring during the before period and 58 barrier breached crashes after the cable barrier system was installed. Table 5.1 lists the selected locations used to develop SPFs.

Table 5.1: Sites Used for the Before-After Study Evaluation Analysis

Location Number	Route Name	County	Installation Length (mi)	Number of Years	
				Before	After
6	I-71	Delaware	9.9	3	4
8	I-70	Franklin	7.24	3	5
11	I-675	Greene	9.17	3	5
16	I-275	Hamilton	0.81	3	5
17	I-275	Hamilton	2.24	3	5
23	I-70	Hancock	7.62	3	5
26	I-70	Madison	6.64	3	5
28	I-76	Medina	4.43	3	1
29	I-75	Miami	8.98	3	5
30	I-70	Montgomery	7.5	3	5
31	I-675	Montgomery	5.17	3	5
32	I-71	Morrow	6.65	3	3
36	I-76	Portage	21.2	3	5
41	I-75	Wood	5.15	3	5

5.2 Results of the Development of Safety Performance Functions (SPFs)

The safety effectiveness evaluation of median cable barriers utilized in the current study followed the procedure outlined in Chapter 9 of the Highway Safety Manual (AASHTO, 2010) and included in Appendix B of this research report. Developing a safety performance function (SPF) is the very first step that has to be undertaken in order to perform the Empirical Bayes (EB) safety evaluation methodology. Effective safety evaluation can only be undertaken successfully if good safety perfoamance functions are also developed and utilized. As defined by AASHTO (2010), an SPF is a model that can be used to estimate average crash frequency for a facility type with specific base conditions.

The SAS statistical software (version 9.4) was utilized to develop all models. The GENMOD Procedure in SAS allows the specification of a negative binomial distribution, Poisson distribution, etc., by fitting a generalized linear model (GLM) to the data by using the maximum likelihood estimation (MLE) techniques. The explanatory variables included in the models were AADT, median width in feet, installation length in miles, and the number of lanes.

Three separate models were developed: (i) total crashes, (ii) fatal and all injuries combined (FI), and (iii) fatal, incapacitating, and non-incapacitating injury (KAB) crashes combined. Table 5.2 presents the SPF parameter estimates from SAS output. Different forms and combination of independent variables were tested. It was observed that the natural log of AADT, installation length (mi), and number of lanes (with no change in before and after periods for all locations studied) were significant at $\alpha = 0.05$. Median width was not significant in all models.

Table 5.2: SAS Output of the SPFs Estimation Model Parameters

SPF Model	Parameter	Estimate	Std. Error	p-Value
Total Crashes	Intercept	-13.9203	5.6328	0.0135
	Ln(AADT)	1.5226	0.5462	0.0053
	Installation Length	0.041	0.0181	0.0234
	Number of Lanes	-0.3513	0.1152	0.0023
	Log-Likelihood	42.4004		
	Deviance/DF	1.2488		
	Chi-Square/DF	1.2361		
Fatal and Injury (FI) crashes	Intercept	-15.5926	7.3081	0.0329
	Ln(AADT)	1.6527	0.7075	0.0195
	Installation Length	0.0543	0.0223	0.0152
	Number of Lanes	-0.4196	0.1486	0.0047
	Log-Likelihood	-15.1668		
	Deviance/DF	1.2373		
	Chi-Square/DF	1.1971		
Serious Injury Crashes Only (KAB)	Intercept	-16.641	8.1669	0.0416
	Ln(AADT)	1.7291	0.7894	0.0285
	Installation Length	0.0695	0.024	0.0038
	Number of Lanes	-0.4387	0.1649	0.0078
	Log-Likelihood	-24.5328		
	Deviance/DF	0.9981		
	Chi-Square/DF	0.9707		

The SPFs for predicting annual crash frequency developed are as follows:

$$SPF_{TC} = EXP(-13.92 + 1.5226 * Ln(AADT) + 0.041 * Length - 0.35 * N)$$

$$SPF_{FI} = EXP(-15.59 + 1.6527 * Ln(AADT) + 0.0543 * Length - 0.4196 * N)$$

$$SPF_{KAB} = EXP(-16.64 + 1.73 * Ln(AADT) + 0.07 * Length - 0.44 * N)$$

Where:

TC = subscript for total crashes

FI = subscript for fatal and injury crashes

KAB = subscript for fatal, incapacitating and non-incapacitating injury crashes

AADT = Annual Average Daily Traffic

Length = length of median cable barriers (miles)

N = Number of lanes (in both directions; in this study N = 4 or 6)

The SPFs models are used to predict the annual number of crashes (or crash frequency) that would have occurred if the median cable barriers were not installed in the after-installation period for each site.

5.3 Results of the Before and After Empirical Bayes Safety Effectiveness Evaluation Analysis

For this research study, an Empirical Bayes (EB) design was found to be the most suitable method to be selected. The suitability was derived from the literature findings that suggested the EB method was appropriate for this kind of analysis due to its strengths in evaluating the safety effect of engineering treatments of roadway improvements similar to the one evaluated in the current study (Hauer and Persaud, 1983; Hauer, 1997; Eustace et al., 2010; AASHTO 2010; Srinivasan and Bauer, 2013; Chimba, 2017). Among its strengths, is its ability to correct for regression-to-the mean (RTM) bias, which is normally due to the natural fluctuations of crash frequencies that cause average values over a short period of time to be either higher or lower than the mean over a long period (Hauer, 1997; Eustace et al., 2010; AASHTO 2010; Srinivasan and Bauer, 2011; Chimba, 2017). Appendix B provides a detailed outline for the implementation of the EB before-after safety effectiveness evaluation procedure according to the Highway Safety Manual's methodology (AASHTO, 2010). An Excel spreadsheet was used in implementing all the computational procedures. Separate Excel spreadsheet tabs were developed to implement EB before-after analyses for (1) total crashes; (2) fatal and injury crashes, and (3) fatal, incapacitating, and non-incapacitating crashes.

The results of three EB before-after analyses for the three crash severity levels studied (i.e., total, FI, and KAB) in the current study are summarized in Table 5.3. The treatment safety effectiveness is presented for each crash severity level considered, and this is the average change in crash frequency between before and after the period that the data has been obtained. If the value of OR equals one, there is no change in crashes following median cable installation. Values of less than one indicate a potential decrease in crashes while values greater than one indicate an increase in crashes at that specific crash severity level being analyzed.

Table 5.3: The Before and After Empirical Bayes Estimation Results

Safety Effectiveness Parameter	Safety Electiveness Evaluation Models		
	Total Crashes	Fatal and Injury (FI) Crashes	Serious Injury (KAB) Crashes
Overall Unbiased Estimate of Treatment (OR)	0.261	0.196	0.199
Safety Effectiveness	73.9%	80.4%	80.1%
Variance of Overall Unbiased Effectiveness Var(OR)	0.001	0.002	0.002
Standard Error of the Variance SE(OR)	0.038	0.041	0.044
SE (Safety Effectiveness)	3.8%	4.1%	4.4%
Abs [Safety Effectiveness/SE (Safety Effectiveness)]	19.23	19.74	18.02
CMF	0.261	0.196	0.199
Statistical Significance Confidence Level	95%	95%	95%

As shown in Table 5.3, the evaluation results show that installation of median cable barriers at the fourteen Interstate locations used for this study reduced total cross-median crash frequency by 73.9 percent and reduced fatal and injury crashes by 80.4 percent. In addition, the median cable barriers reduced fatal, incapacitating and non-incapacitating cross-median crashes by 80.1 percent. All these reduction results are statistically significant at the 95 percent confidence level. These findings indeed highlight that the median cable barriers installed in Ohio’s Interstate system are key in the reduction of cross-median crashes and especially severe (fatal and injury) crashes.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This research study summarizes some key findings of safety effectiveness evaluation of the median cable barriers in Ohio. The findings of overall statewide crash reduction after the median cable barriers compared to before period are based on the safety effectiveness percentages computed by Empirical Bayes (EB) before-after study method using the Highway Safety Manual (HSM) procedures. The findings from the current study will be the first rigorous analysis that ODOT needs to evaluate whether the cable barriers they have been installing in various locations in the Interstate system throughout the state have been effective in terms of safety benefits.

The major concern for cross-median crashes is that they tend to be severe, that is, they mainly cause fatalities, incapacitating and non-incapacitating injuries when these crashes occur. The main interest for ODOT from the onset when they started installing these median cable barriers was to mitigate these kinds of crashes and hence reduce the resulting deaths and injuries.

Although ODOT provided 41 Interstate locations where median cable barriers have been installed since 2010, but only 14 locations were used for developing the safety performance functions (SPFs) and hence used in the EB before-after study safety effectiveness evaluations because the other locations did not have the recommended minimum years of crash and AADT data available in the before period. Although the 14 locations used meet the minimum number of sites recommended by the HSM (AASHTO, 2010) procedure and therefore, the evaluation results from the current study are statistically acceptable, but we strongly believe that if good data were available for all 41 sites, the results would be even more robust. The more the data, the better the model.

The following are the findings from the Ohio's statewide median cable barriers safety effectiveness results:

- Safety effectiveness of the median cable barriers for total crashes is 73.9 percent, which translates into a CMF of 0.261.
- Safety effectiveness of the median cable barriers for fatal and injury crashes combined is 80.4 percent, which leads into a CMF of 0.196.
- Safety effectiveness of the median cable barriers for fatal, incapacitating and non-incapacitating injury crashes combined is 80.1 percent, which means a CMF of 0.199.

These results show that the median cable barriers installed in Ohio's Interstate system are more effective in reducing cross-median severe injury crashes, which was the main objective of ODOT of installing the median barriers.

6.2 Recommendations

The following recommendations are suggested for further studies in Ohio using in-service installed median cable barriers:

- This short one-year project with only 14 sites should be taken as a pilot study. ODOT is recommended to conduct a more robust, multi-year project study, well-funded to collect better and more reliable data, which can build and expand on the results of the current study.

- Exploring the effects of lateral offset, horizontal and vertical alignments, cable barrier type (3- or 4-cable strings) on median-related crashes after median cable barrier installation.
- Investigation of the type of impacts to include frequency and spacing of emergency crossovers, safety effectiveness for motorcyclists, and the overall effects of weather and roadway conditions.
- Perform an economic analysis of installing median cable barriers; with respect to the agency costs (installation and maintenance costs) and safety benefits in terms of reducing the crash frequency and severe crashes.

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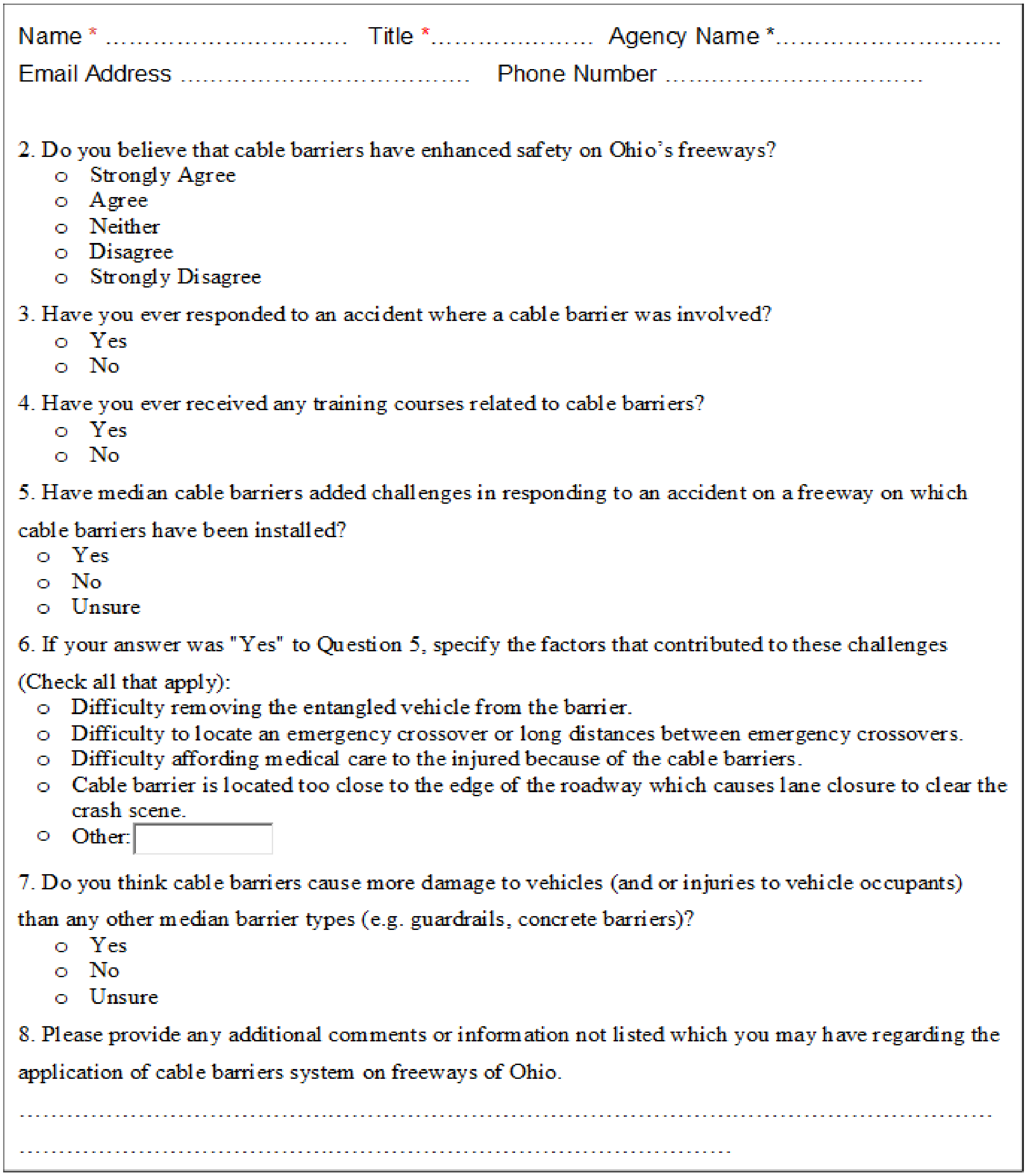
APPENDIX A

The First Responders' Survey Questionnaire



Name * .... Title *...................... Agency Name *..............................

Email Address .... Phone Number ....

2. Do you believe that cable barriers have enhanced safety on Ohio's freeways?
   - ○ Strongly Agree
   - ○ Agree
   - ○ Neither
   - ○ Disagree
   - ○ Strongly Disagree

3. Have you ever responded to an accident where a cable barrier was involved?
   - ○ Yes
   - ○ No

4. Have you ever received any training courses related to cable barriers?
   - ○ Yes
   - ○ No

5. Have median cable barriers added challenges in responding to an accident on a freeway on which cable barriers have been installed?
   - ○ Yes
   - ○ No
   - ○ Unsure

6. If your answer was "Yes" to Question 5, specify the factors that contributed to these challenges (Check all that apply):
   - ○ Difficulty removing the entangled vehicle from the barrier.
   - ○ Difficulty to locate an emergency crossover or long distances between emergency crossovers.
   - ○ Difficulty affording medical care to the injured because of the cable barriers.
   - ○ Cable barrier is located too close to the edge of the roadway which causes lane closure to clear the crash scene.
   - ○ Other: ☐

7. Do you think cable barriers cause more damage to vehicles (and or injuries to vehicle occupants) than any other median barrier types (e.g. guardrails, concrete barriers)?
   - ○ Yes
   - ○ No
   - ○ Unsure

8. Please provide any additional comments or information not listed which you may have regarding the application of cable barriers system on freeways of Ohio.

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APPENDIX B

Empirical Bayes Method

The Computational Procedure for Implementing the EB Before/After Safety Effectiveness Evaluation method

The analytical process for the cable barrier before and after EB analysis followed the procedure outlined in the Highway Safety Manual (AASHTO, 2010). The calculations process has 14 steps as outline below.

Expected Average Crash Frequency in the Before Period from EB Estimate

Step 1

Using appropriate SPF, calculate the predicted average crash frequency, $N_{predicted}$, for site type x during each year of the before period. For roadway segment, the predicted average crash frequency are expressed as crashes per site per year; for intersections, the predicted average crash frequency is expressed as crashes per intersection per year. See Equation 1 below:

$$N_{predicted} = N_{spf} \times \left(CMF_{ix} \times CMF_{2x} \times \ldots \times CMF_{yx}\right) \times C_x \qquad (1)$$

Step 2

Calculate the expected average crash frequency, $N_{expected}$, for each site i summed over the entire before period. The expected average crash frequency for roadway segment is expressed as crashes per site and for intersections are expressed as crashes per intersection. See Equation 2 below.

$$N_{expected,B} = w_{i,B} N_{predicted} + \left(1 - w_{i,B}\right) N_{observed,B} \tag{2}$$

But weight $w_{i,B}$ per site i is found using the Equation 3 shown below:

$$w_{i,B} = \frac{1}{1 + k * \sum_{Before\ years} N_{predicted}} \tag{3}$$

Where

$N_{expected,B}$ = Expected average crash frequency per site for the whole before period

$N_{spf=}$ Predicted average crash frequency for SPF, step 1

$N_{observed,B}$ = Observed crash frequency per site for the total before period

k = Parameter for over dispersed SPF

Expected Mean Crash Frequency in the After Period from EB Estimate

Step 3

Using applicable SPF, calculate the predicted average crash frequency, $PR_{i,y,A}$, for each site i per each year y of the after period.

Step 4

Calculate the adjustment factor r_i responsible for the before-after periods variation in terms of duration and traffic volume per site using Equation 4:

$$r_i = \frac{\sum_{After\ years} N_{predicted,A}}{\sum_{\boldsymbol{Before}\ years} N_{predicted,B}} \tag{4}$$

Step 5

Calculate the expected mean crash frequency $N_{expected}$ per site i for the total after period without the treatment as shown in Equation 5:

$$N_{expected,A} = N_{expected,B} \times r_i \tag{5}$$

Estimating Treatment Effectiveness

Step 6

Calculate the treatment safety effectiveness for observed crash frequency in an estimate per site i in terms of odds ratio OR_i as shown in Equation 6:

$$OR_i = \frac{N_{observed,A}}{N_{expected,A}} \tag{6}$$

Step 7

Calculate the effectiveness of safety in the form of percentage of crash change per site i and determined as per Equation 7:

$$Safety\ Effectiveness = 100 \times (1 - OR_i) \tag{7}$$

Step 8

Calculate the overall effectiveness of treatment for all sites combined, in the form of an odds ratio, OR' as shown in Equation 8:

$$OR' = \frac{\sum_{All\,sites} N_{observed,A}}{\sum_{All\,sites} N_{expected,A}} \tag{8}$$

Step 9

The odds ratio computed in Step 8 is potentially biased, it needs adjustment to obtain an unbiased approximation of treatment effectiveness in terms of an adjusted odds ration OR as per Equation 9:

$$OR = \frac{OR'}{1+\frac{Var\left(\sum_{All\,sites} N_{expected,A}\right)}{\left(\sum_{All\,sites} N_{expected,A}\right)^2}} \tag{9}$$

Where

$$Var\left(\sum_{All\ sites} N_{expected,A}\right) = \sum_{All\ sites}\left[(r_i)^2 \times N_{expected,B} \times \left(1 - w_{i,,B}\right)\right]$$

Step 10

Calculate the overall unbiased safety effectiveness as a percentage change in crash frequency across all sites as shown by Equation 10:

$$Safety\ Effectiveness = 100 \times (1 - OR)$$

Estimating the Precise Treatment Effectiveness

The precision of the estimated safety effectiveness of the treatment is calculated to determine whether it is statistically significant. This is achieved by first calculating the precision of the odds ratio, *OR*, in Equation 9.

Step 11

The variance of the unbiased estimated safety effectiveness is calculated and expressed as an odds ratio, OR, as shown by Equation 10:

$$Var\ (OR) = \frac{(OR')^2\left[\frac{1}{N_{observed,A}} + \frac{Var\left(\sum_{All\ sites} N_{expected,A}\right)}{\left(\sum_{All\ sites} N_{expected,A}\right)^2}\right]}{\left[1 + \frac{Var\left(\sum_{All\ sites} N_{expected,A}\right)}{\left(\sum_{All\ sites} N_{expected,A}\right)^2}\right]} \qquad (10)$$

Step 12

The standard error is calculated as the square root of its variance to obtain a measure of the precision of the odds ratio (OR) as shown by Equation 11 below:

$$SE(OR) = \sqrt{Var(OR)} \qquad (11)$$

Step 13

Using the relationship OR and Safety Effectiveness, the standard error of Safety Effectiveness, SE(Safety Effectiveness), is calculated as shown in Equation 12:

$$SE(Safety\ Effectiveness) = 100 \times SE(OR) \tag{12}$$

Step 14

Assessment of the statistical significance of the estimated safety effectiveness is done by making comparisons with the measure *Abs* [(Safety Effectiveness/SE (Safety Effectiveness)] and drawing conclusions based on the following criteria:

- If Abs [Safety Effectiveness/SE (Safety Effectiveness)] < 1.7, conclude that the treatment effect is not significant at the (approximate) 90 percent confidence level.
- If Abs [Safety Effectiveness/ SE (Safety Effectiveness)] ≥ 1.7, conclude that the treatment effect is significant at the (approximate) 90 percent confidence level
- If Abs [Safety Effectiveness/SE (Safety Effectiveness)] ≥ 2.0, conclude that the treatment effect is significant at the (approximate) 95 percent confidence level

APPENDIX C

Summary of State Research Findings on Cable Median Barriers

Author & Year	State	Intent	Findings
Sposito & Johnston (1998)	Oregon	Evaluate the effectiveness of the three-cable barrier in preventing crossover crashes on I-5, Oregon Highway 1, and evaluates the maintenance and repair costs in order to make recommendations for future installations	• Cable median barrier system proved to be cost-effective when compared to the concrete median barrier system and the system performed well, decreasing crossover crashes in the area. • The cable median barrier system works well in medians with a minimum of 7 m width, where it is used to prevent the infrequent potentially catastrophic CMCs • Unfortunately, there is not much information concerning the maintenance and repair costs of the cable barrier system..
Hunter et al. (2001)	North Carolina	Evaluate crash effectiveness of cable median barrier installed on a segment of I-40 between Davis Drive in the Research Triangle and Wade Avenue in Raleigh, North Carolina	• Increase ROR-left and hit-fixed object crashes • improved overall safety due to reduced serious & fatal crashes and head-on crashes • overall severity index value greatly reduced
Makk & Sicking (2002)	Arizona	Study to develop a program for the continuous in-service evaluation of highway safety features	Developed a conceptual framework of an in-service evaluation program that includes four major subsystems: • Level I - Continuous monitoring • Level II - Supplemental data collection • Level III - In-depth investigation • New product evaluation
Gabler et al. (2005)	New Jersey	Evaluate the post-impact performance of two different median barrier systems installed in New Jersey: (1) a three-strand cable	• Both barriers are viable solutions to reduce the occurrence of cross median collisions on divided highways. • Although there is typically an increase in the total number of collisions, the installation of the

		median barrier system installed on I-78, and (2) a modified thrie beam median barrier system installed on I-80.	barrier typically results in an overall reduction of crash severity. • Maintenance of the system appears to be a problem: the barrier was slow to be repaired after damaged. • Cables were frequently left on the ground for weeks after the crash, and were hence not always available to contain an encroaching vehicle.
Agent Pigman (2008)	Kentucky	Evaluate the effectiveness of the Brifen TL-4 and Trinity CASS median cable barrier systems in preventing cross-median collisions on sections of I-64, I-71, and I-264, and KY-4	• The cable system was successful in redirecting the vehicles • A wide range of types of vehicles hit the cable at consistently high speeds • In only 0.9% of the crashes, a vehicle was able to go through the cable system and into the opposing travel lanes.
Sicking et al (2009)	Kansas	Study to use crash data to develop median barrier warrants that might be representative of states in the Midwestern region.	• Winter driving conditions significantly increase CMC rates but crash severities decrease • A relationship was found between cross-median crash rate and traffic volume for Kansas freeways with median widths of 60 ft. • This relationship was combined with encroachment rate and lateral extent of encroachment data from the Roadside Safety Analysis Program to develop general guidelines on the use of cable median barriers along Kansas freeways
Cooner et al. (2009)	Texas	Performance evaluation of various cable barrier systems in Texas by evaluating TxDOT's experience with cable barrier systems by analyzing installation cost, recurring maintenance costs	• A cable barrier is an attractive option compared to concrete barrier. • Lack of coordination between TxDOT and emergency responders during the project planning and maintenance phases of cable barrier system projects. • Maintenance costs and personnel requirements for cable barrier systems can be substantial and

		and experiences, crash history before and after implementation, and field performance	constrained maintenance budgets and personnel availability for frequent repair needs are issues. • Cable barriers are performing extremely well and have had very few cases of penetration unless there were nonstandard impact conditions. • The installation of cable barriers has produced significant benefits that equate to an almost $46 million economic benefit • .Due to problems experienced in Texas and other states, soil conditions should be considered as part of the project development process for cable barrier system installations.
Savolainen et al. (2014)	Michigan	Conduct a comprehensive evaluation of the effectiveness of cable barrier systems that have been installed to date	• Cable barriers were 96.9% effective in preventing penetration in the event of a cable barrier strike. • Weather and road conditions play a role in the frequency and severity of crashes, and cable barrier performance. • An economic analysis was conducted to determine the cost-effectiveness of the cable barrier system, • Guidelines were developed to assist in prioritizing candidate locations for cable barrier installation
Alluri et al. (2015)	Florida	Evaluate the safety performance of cable median barriers on limited access facilities in Florida and compare its performance with G4 (1S) type of strong-post W-beam guardrails	• Overall, 98.1% of cars and 95.5% of light trucks that the cable barrier were prevented from crossing the median • Cable median barriers reduced fatal crash rate by 42.2%, severe injury crate by 20.1%, and minor injury crash rat by 11.6% • But increased possible injury and PDO by 53.1% and 88.1%, respectively

			• Overall, guardrails performed slightly better than cable barriers in terms of barrier and median crossover crashes. However, cable median barriers were found to result in fewer severe injury crashes
Chimba (2017)	Tennessee	Evaluate the median cable barrier safety effectiveness as experienced on Tennessee highways. Provide guidance for site selection, safety evaluation, and CMFs of median cable barriers in Tennessee	• Statewide cable barriers Safety Effectiveness for fatal crashes was 94%, incapacitating injury crashes was 92% and fatal and incapacitating injury crashes combined was 92%. • The safety effectiveness for fatal and all injury crashes combined was 85%. • Fatal crashes were reduced by 82% after the cable barriers were installed while incapacitating injury crashes were reduced by 76%. • Head-on crashes went down by 96% and crashes involving two or more vehicles went down by 92%. • CMF for fatal crashes was found to be 0.04, fatal and incapacitating injury 0.07, and 0.14 for fatal and all injury crashes. • The developed CMFs translate into crash reduction of 96% and 86% for fatal only and fatal and all injuries combined respectively. • Wider cable offsets from the travel lane and wider inside shoulders were found to help reduce the number of severe median crossover crashes