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Safety Effectiveness of Cable Median Barriers in Louisiana

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13. Abstract

The primary objective of this research was to investigate the safety effectiveness of cable median barriers (CMB) installed on Louisiana freeway medians. This study performed a comprehensive evaluation to ascertain the performance of CMB from traffic safety and economic standpoints. A three-year observational before-and-after crash analysis for total and targeted crashes (by severity, manner of collision, testing level, and other relevant factors) was conducted for 23 CMB segments consisting of 275 miles throughout the state. Furthermore, crash modification factors were developed to better understand the impact of CMB on crash outcomes. Finally, a comprehensive benefit-cost analysis was performed to assess CMB's cost-effectiveness. The results revealed that cross-median crashes for all severity levels and head-on crashes significantly decreased after CMB implementation (100% reduction for fatalities and serious injuries). Median-related fatal and serious injury crashes also decreased significantly. However, an increase in property damage only (PDO) crashes was observed in the cases of total and median-related crashes. The benefit-cost ratios calculated using economic crash unit costs for both total and targeted crashes were higher than one. Notably, when using the comprehensive crash unit costs, the estimated benefit-cost ratios were considerably greater. The CMB were found to be effective in reducing cross-median crashes and mitigating crash severities. They were also proven to be cost-effective countermeasures despite the increase in PDO crashes, justifying the continuous use of CMB in Louisiana.

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Abstract

The primary objective of this research was to investigate the safety effectiveness of cable median barriers (CMB) installed on Louisiana freeway medians. This study performed a comprehensive evaluation to ascertain the performance of CMB from traffic safety and economic standpoints. A three-year observational before-and-after crash analysis for total and targeted crashes (by severity, manner of collision, testing level, and other relevant factors) was conducted for 23 CMB segments consisting of 275 miles throughout the state. Furthermore, crash modification factors were developed to better understand the impact of CMB on crash outcomes. Finally, a comprehensive benefit-cost analysis was performed to assess CMB's cost-effectiveness. The results revealed that cross-median crashes for all severity levels and head-on crashes significantly decreased after CMB implementation (100% reduction for fatalities and serious injuries). Median-related fatal and serious injury crashes also decreased significantly. However, an increase in property damage only (PDO) crashes was observed in the cases of total and median-related crashes. The benefit-cost ratios calculated using economic crash unit costs for both total and targeted crashes were higher than one. Notably, when using the comprehensive crash unit costs, the estimated benefit-cost ratios were considerably greater. The CMB were found to be effective in reducing cross-median crashes and mitigating crash severities. They were also proven to be cost-effective countermeasures despite the increase in PDO crashes, justifying the continuous use of CMB in Louisiana.

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Implementation Statement

This project performed a comprehensive analysis to evaluate the safety effectiveness and benefit-cost ratio of cable median barriers in Louisiana. The results of this research revealed that CMB is an effective and economically justified crash countermeasure, which warrants continuing implementation on freeways and expressways. This study will provide DOTD with a deeper understanding of CMB effectiveness with quantified evidence on targeted crashes and economic benefits. The findings will help DOTD to make informed decisions and justify highway safety investments essential for the Louisiana Highway Safety Improvement Program. Furthermore, the results of this project can be used as part of Destination Zero Deaths' efforts to reach the goal of zero fatalities on Louisiana roadways.

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Introduction

Cross-median crashes are considered one of the most serious hazards to road safety in freeway traffic operations. Crashes where an errant vehicle crosses the median and traverses to the opposite travel lane are referred to as cross-median crashes. Although the occurrences of cross-median crashes are rare, these crashes tend to result in more fatalities, severe injuries, and vehicular damage. While only less than 5% of divided interstate crashes are cross-median crashes, almost 30% of these cross-median crashes result in either death or incapacitating injury [1]. A study in Atlanta found that 54.5% of the cross-median crashes had one or more injuries, while this number was only 29.8% for non-crossing crashes, which is significantly lower [2]. According to Fatality Analysis Reporting System (FARS), 8% of all fatalities on divided highways are attributed to head-on crashes, which primarily occurs when vehicles cross the median into the opposite direction. Therefore, greater significance should be given to countermeasures aimed at preventing cross-median crashes.

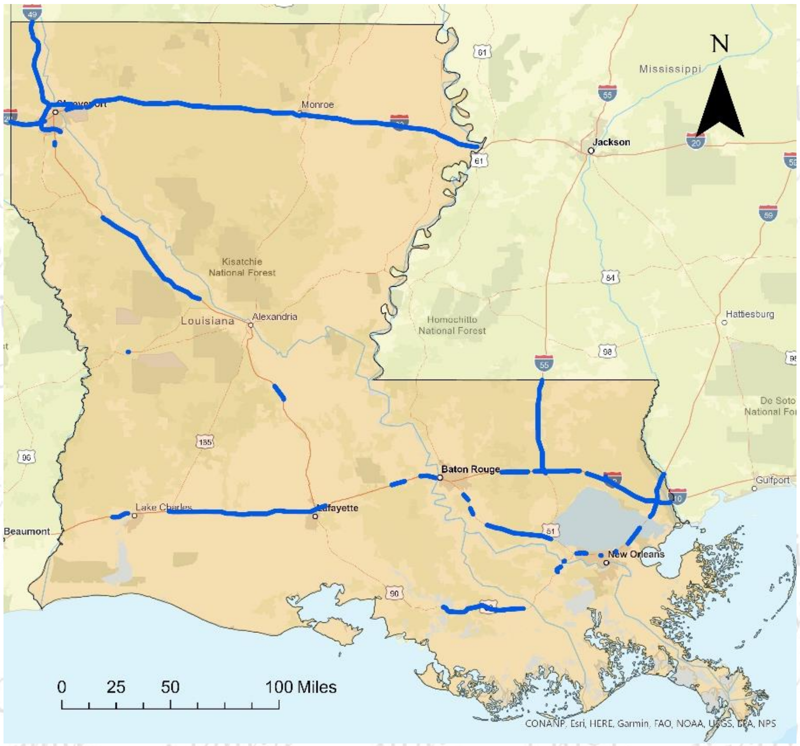
The Federal Highway Administration (FHWA) included median barriers in the list of proven safety countermeasures for roadway departure; therefore, transportation agencies are encouraged to consider implementing median barriers to reduce fatalities and serious injuries on divided highways to achieve safety goals [3]. Implementation of median barriers is identified by the American Association of State Highway and Transportation Officials (AASHTO) as the primary countermeasure for preventing cross-median crashes [4]. Median barriers are longitudinal barriers designed to prevent cross-median crashes on the freeways. A Pennsylvania study [5] found that approximately 57% of the cross-median crashes occurred on specific highway sections even though the median width in those sections was more than 50 ft., indicating the necessity of median barrier installation on wider medians. Furthermore, according to the NCHRP Report 794, median barriers are found to prevent almost 97% of the total cross-median crashes in rural four-lane freeways [6]. However, the small number of cross-median crashes that cannot be prevented usually causes catastrophic results in terms of fatalities and injuries.

Among the different types of median barriers such as concrete barrier (rigid), metal beam guardrail (semi-rigid), and cable median barrier (flexible) [6], [7], cable median barriers (CMB) are gaining popularity because of lower initial cost, forgiving nature, suitability in moderate slopes, lateral drainage capability, and aesthetic appearance [8]. One of the major advantages of CMB is that the installation cost is significantly lower than that of a

W-beam guardrail and precast concrete barrier. Another advantage of CMB is that it significantly reduces the injury severity of crashes. As cable barrier allows more deflection, it absorbs energy from the collusion, making it more forgiving in nature compared to the other types of barriers [9], [10]. While CMB are known to reduce the frequency of fatal, serious injury, and cross-median crashes, most of the studies found that CMB are responsible for increase in the number of single-vehicle, fixed object, and total crashes [11]–[13]. Higher numbers of CMB hits also induce higher maintenance costs and repair efforts. The CMB installed on the freeways of different states conform to either NCHRP Report 350 Testing Level-3 or Testing Level-4 [14]. That means they are mainly designed to stop the passenger cars, pickup trucks, or at most, the single unit trucks [4]. Heavy vehicles such as tractor trailers (36,000 lb.) may not be stopped by the CMB, which poses a significant risk of cross-median crashes. It is crucial to address all these issues while evaluating the effectiveness of CMB.

The goal of the Louisiana Strategic Highway Safety Plan (SHSP) Infrastructure and Operations Emphasis Area Team is to continue reducing roadway departure, intersection, and non-motorized user fatalities and severe injuries by 50% by 2030 compared with 2010. To reach the goal of Destination Zero Deaths [15] and reduce roadway departure crashes, DOTD started to implement cable barriers on freeways and expressways in 2008. As of February 2022, Louisiana has approximately 623 miles of CMB throughout the state, and the goal is to install nearly 731 miles by the end of 2023. Figure 1 shows the spatial distribution of installed cable median barriers in Louisiana. Therefore, evaluating the effectiveness of these CMB countermeasures is essential for the Louisiana Highway Safety Improvement Program.

Figure 1. Spatial distribution of CMB segments in Louisiana



The primary objective of this research was to investigate the safety effectiveness of CMB installed on Louisiana highways. To evaluate the safety effectiveness, this study conducted an observational before-after analysis of the targeted crashes as well as total crashes. In addition to the observational crash analysis, crash modification factors (CMFs) for all crash severities were estimated using the improved prediction model proposed by E. Hauer [16]. Finally, the benefit-cost ratios for the CMB segments were estimated to evaluate their cost effectiveness.

Literature Review

This chapter provides a summary of the information learned from existing studies regarding the safety effectiveness and benefit-cost analysis of CMB. First, the methods adopted by different studies for evaluating safety and their key findings are presented. Next, the limited information found regarding CMB installation and maintenance practices, as well as the costs reported by different states are summarized. Finally, the research team reviewed the existing benefit-cost analysis studies and guidelines to document the key information such as crash unit costs, discount rates, monetary value conversion, and estimated ranges of benefit-cost ratio.

Safety Effectiveness of Cable Median Barriers

In this section, the previous CMB studies conducted by various states were examined in order to obtain information on the evaluation of CMB's safety effectiveness.

Types of Analysis

A sizeable number of studies have been conducted to evaluate the safety effectiveness of CMB on freeways. Some of the studies performed the observational before-after analysis using either observed crash frequencies or observed crash rates, while other studies implemented the empirical bayes (EB) model. The Texas Department of Transportation Traffic Safety Division study [11] conducted safety evaluation of CMB using only one-year-before and one-year-after crash frequencies. Crash frequencies of at least three years before and after periods were considered by Kansas and Kentucky studies while conducting the simple before-after analysis [17], [18]. More reliable observational before-after analysis using crash rates instead of crash frequencies were done in several states including Florida, Wisconsin, and Washington [19]–[21]. The Michigan study [22] used the EB method for three crash severity levels: (1) fatal and serious injury crashes, (2) moderate injury crashes, and (3) complaint and property damage only (PDO) crashes. The study also conducted a before-after analysis using observed crashes and concluded that the analysis using observed crash rates overestimates the effectiveness of CMB. Chimba et al. [23] developed SPF for rural multilane highway using a negative binomial model and applied the EB model to perform the before-after analysis.

The EB method is the most comprehensive way of observational before-and-after analysis in road safety since it accounts for the regression to the mean phenomenon. However, while an SPF is required for EB analysis, the improved prediction method can be employed in the absence of SPFs to estimate the unbiased crash changes. The improved prediction method by E. Hauer [16] is a statistical approach to predict road safety that accounts for the change in traffic flow from the before to the after period. In a 2019 Louisiana before-and-after study [24] that evaluated the effectiveness of lane conversion, Sun and Rahman utilized the improved prediction model for estimating the CMF for combined (segment + intersection) crashes.

Targeted Crashes

A crucial part of evaluating CMB safety effectiveness is to identify the targeted crashes since CMB have no impact on some types of crashes, such as single vehicle run off roadway to the right crash. In a Florida state report, Alluri et al. [19] defined several types of targeted crashes such as median-related (when errant vehicles leave the designated travel lane to the left), CMB-related (when vehicles hit the CMB), and median-crossover crashes (when the errant vehicles traverse the opposite travel lane). For identifying the targeted crashes, most of the previous studies took the approach of manually reviewing all the crash reports [17], [19], [22], [25], [26]. In a 2018 report [26], Savolainen et al. used both crash code logic function and manual review of crash narratives in separate trials. They found that crashes identified by manually reviewing the crash narratives are significantly more accurate than those identified using crash database. Though the identified targeted crashes have very high accuracy, it can be strenuous and often not feasible to manually review a significant amount of crash reports. Another study [18] performed in Kentucky solely relied on a flowchart to query cross-median crashes that identifies the targeted crashes with 83% accuracy.

Crash Reduction Reported by Different States

Based on the previous literature, the effectiveness of CMB can be categorized into four major areas based on cable barrier's performance in preventing: (1) Cross-median crashes, (2) cable barrier penetrations, (3) fatal and incapacitating injury crashes, and (4) PDO and total crashes.

Cross-median crashes (also known as median crossover crashes) are the crashes where an errant vehicle runs off the roadway to the left, crosses the median, and traverses the opposite travel lanes [19], [26]. Most states reported a reduction of 65% to 96% cross-median crashes after installing CMB [14], [19], [21], [22], [27], [28]. Placing a greater emphasis on fatalities, majority of the studies showed that the installation of CMB decreased the fatal cross-median crash rates by more than 90% [12], [27], [29], [30].

Another important criterion for evaluating CMB effectiveness is the cable barrier's ability to capture a vehicle and preventing barrier penetration. A study in Rhode Island [31] reported 100% prevention of barrier penetration when vehicles collided with CMB. However, the study only included very few numbers of CMB collisions. In other states, CMB was found to be at least 90% effective in stopping the vehicles from going through the cable barrier [22], [28], [30], [32]–[35].

Almost all the previous studies established CMB to be highly effective in reducing fatal and incapacitating injury crashes. Findings from the research conducted in Florida, Iowa, Washington and Michigan [19], [21], [22], [26] showed that the number of fatal and severe injury crashes decreased by 30-70% and 20-60%, respectively.

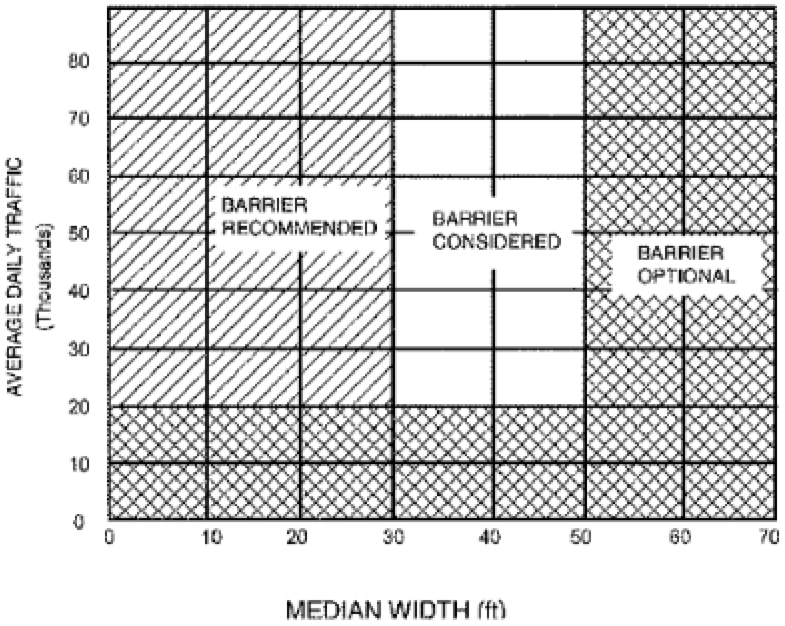
However, CMB are found responsible for radically increasing the number of total and PDO crashes. Synthesizing the findings from different studies [19], [26] on cable barrier effectiveness, PDO crash rates were found to increase by 88-95%, consequently increasing the crash rate for total crashes by 38-76%.

Installation Guidelines and Cost

CMB installation guidelines are intended to provide the departments of transportation with instructions pertaining to installation, barrier placement, design, testing level, and other factors that indicate whether or not CMB is warranted at a specific location.

Based on the Roadside Design Guide by AASHTO [4], median barriers are warranted in fully controlled-access highways where the median width is 30 ft. or less, and the AADT is greater than 20,000 vehicles per day. For medians' width of 30-50 ft., whether median barriers are warranted have to be determined by the analysis of cost effectiveness. Installation of median barriers is considered optional for median widths that are greater than 50 ft. The roadside design guide by AASHTO recommends the following chart in Figure 2 [4] for installing any median barrier (including CMB).

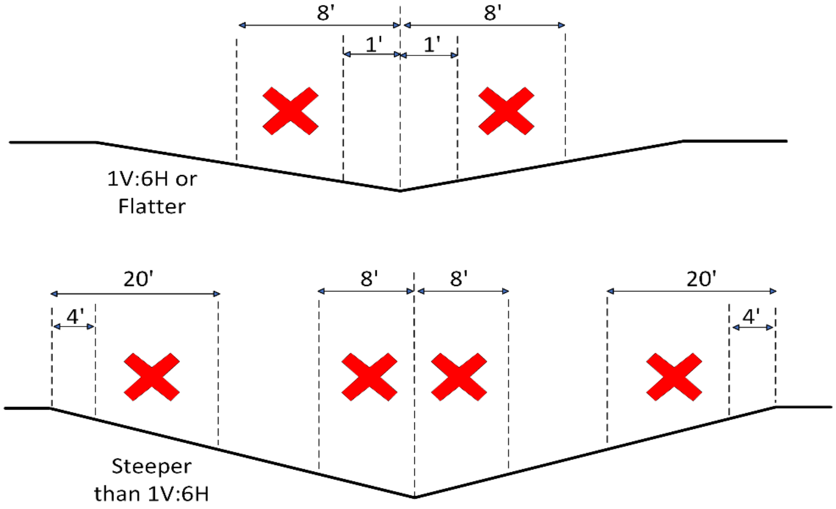
Figure 2. AASHTO median barrier guidance



The AASHTO Roadside Design Guide recommends the utilization of CMB that comply with NCHRP Report 350 [36] testing levels 3 and 4. CMB should be situated on slopes with a ratio of 1V:6H or less, but they may be employed on slopes of up to 1V:4H to a limited extent. When CMB are positioned on slopes with a ratio of 1V:4H, they should be located no more than 4 ft. from the beginning of the slope and at least 9 ft. away from the bottom of the ditch.

According to NCHRP Report 711 [37], the warrant criteria for installing CMB recommended by AASHTO and individual state guidelines were found to be appropriate. The report also aligns with AASHTO guidelines, stating that CMB should not be placed on slopes steeper than 1V:4H. In medians with both V-shaped and flat bottoms and slopes that are 1V:6H or flatter, CMB should not be positioned between 1 to 8 ft. from the ditch center or flat-bottom breakpoint. If the slope is steeper than 1V:6H, CMB should not be placed near 8 ft. of the ditch bottom, and the area between 4 to 20 ft. from the median's edge should be avoided. For ease of understanding, the CMB placement guidelines mentioned by NCHRP 711 are illustrated in Figure 3.

Figure 3. CMB placement guidelines adopted from NCHRP report 711



Several states have developed their own CMB installation guidelines. For instance, Minnesota has detailed placement guidelines in place for installing CMB. Similar to AASHTO guidelines, the Minnesota Design Guidelines [38] for high tension CMB forbids the installation of CMB in slopes steeper than 1V:4H. For placement along the median, the Minnesota guideline exactly follows the recommendation developed by NCHRP Report 711 [Figure 3]. However, the guideline adds that, if CMB needs to be placed on the sides, it should be installed on the side where the fore-slope is flatter, and the roadway elevation is higher than the other side. According to the guidelines, CMB systems conforming to TL-4 require slopes with a gradient of 1:6 or flatter; whereas, for slopes that have a gradient ranging between 1:6 to 1:4, TL-3 systems are recommended. Cable barriers should consist of four prestressed cables and either steel or concrete may be used to build the socket foundation. The guideline also suggests considering installing two cable barriers at places where the median is narrow. Moreover, in Minnesota, several risk factors such as median width, traffic volume, and severe and non-severe crash history were analyzed to prioritize locations for CMB deployment [39].

In Washington, Washington DOT design manual's chapter 1610 [40] provides guidelines for installing CMB. For CMB to be warranted, at least 30 ft. wide median is needed. Deflection characteristics, slopes, and environmental issues also need to be considered when selecting cable barrier. Slopes of 1V:6H is recommended for CMB, with special considerations for placement in 1V:4H slopes. Similar to the NCHRP Report 711 and the Minnesota guidelines, cable barrier should be avoided from 1 to 8 ft. offset from the low point in the median. The guidelines further added that CMB should be placed minimum 8 ft. away from the edge of travel way, and in the case of horizontal curves, CMB should be placed along the inside of the curve. The design manual recommends four strand high tension cable barriers with a minimum height of 35 in. for the top cable and a maximum height of 19 in. for the bottom cable.

The 2009 Texas CMB guidelines [41] provide detailed information for CMB placement in Texas. In general, the report recommends the use of any median barrier when median width is less than 30 ft., regardless of traffic volume. For median widths between 30 to 60 ft., barriers should be installed if the average daily traffic exceeds 30,000 vehicles per day. For all other cases, the guidance recommends that a project engineer assess the cost-effectiveness and necessity of implementing a continuous barrier to decrease cross-median crashes. However, for CMB, median width must be at least 25 ft. or wider. Although the previous literature showed CMB placement is allowed on median steeper than 1V:6H, the guideline only advocates slopes of 1V:6H or flatter for CMB installation in Texas. The guideline further adds that a minimum distance of 12 ft. should be maintained between CMB and the edge of travel lane. Both TL-3 and TL-4 are recommended similar to other states. Some other recommendations by this guideline are mentioned below:

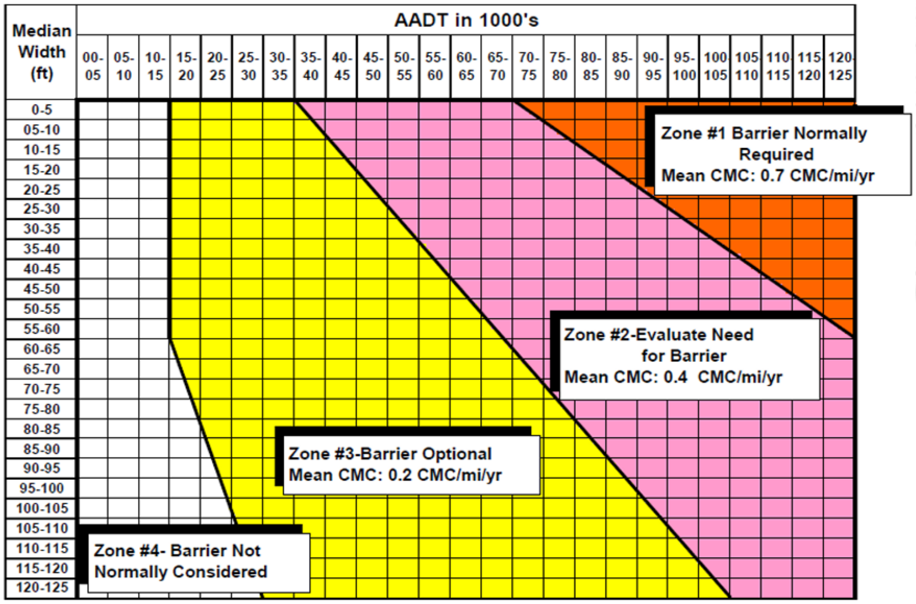
- Cable median barriers should have a length ranging from at least 1,000 ft. to a maximum of 10,000 ft..
- CMB should not be placed within 1 to 8 ft. of the center of a V-ditch.
- At horizontal curves, the post spacing should be smaller.
- CMB should be placed near the convex side of horizontal curves.

The CMB installation guidelines in the Texas *Cable Median Barrier Maintenance Manual* [10] recommend careful consideration of temperature effect on cable tension. It is also encouraged to use mow strips with CMB. While installation of CMB, soil conditions must be addressed, and cable height needs to be checked. According to the Texas DOT specifications item 543 [42], TL-3 or TL-4 CMB can be used with a maximum deflection of 8 ft.. Barrier delineators should be located at a maximum spacing of 100 ft.. Other CMB details and dimensions should follow the manufacturer's recommendations.

According to New York State DOT *Highway Design Manual* [43], cable barriers are used on median wider than 22 ft.. They should be placed a minimum of 12 ft. away from the edge of travel lanes and may be placed on slopes up to 1V:6H. The New York state guideline recommends the installation of any median barriers at the middle of V-shaped median (avoiding the ditch bottom) if the slope is 1V:10H or flatter. For steeper slopes, barriers should be placed at the sides of the median maintaining appropriate clear zone. Following the CMB design revision by the New York State DOT in 2008, the CMB in New York have four cables with 6 in. of space among them, and the lowest cable being 10 in. above the ground to prevent vehicle under-riding.

Colorado cable barrier guide [44] recommends the use of either TL-3 or TL-4 high-tension cable barriers based on site conditions, traffic volume, truck percentage, and installation costs. CMB should be used on 1:6 slopes or flatter. Slopes steeper than 1:6 should be re-graded before CMB installation. If re-grading is not feasible, some cable barrier systems may be used on slopes up to 1:4. A minimum clear distance of 10 ft. should be maintained between the cable barrier and the travel lanes or any other roadside objects. For placement on a V-shaped median, the guideline is similar to the one recommended by NCHRP Report 711. CMB should not be placed at 1 to 8 ft. from the ditch bottom, and with slopes steeper than 1V:6H, CMB position should not be further than 4 ft. from the start of the slope (slope breakpoint). Additionally, guideline states CMB should be placed on the concave side of horizontal curves, and on the side of the higher roadway if there is a difference in elevation. The maximum post spacing is 20 ft., which should be lowered while placing CMB on horizontal curves. The chart based on AADT, median width and cross-median crash (CMC) rates shown in Figure 4 [44] is used to justify the installation of CMB in several states including Colorado.

Figure 4. Guidelines for installing median barriers in Colorado



When installing CMB in Louisiana, CMB should be considered for medians that are 10 to 100 ft. wide. The cable system should consist of four prestressed high-tension cables, and the maximum post spacing should be 16 ft.. The placement and testing level of CMB are determined based on the median slope. For slopes that are 1V:6H or flatter, TL-4 CMB should be installed and placed near the center of the median, while maintaining a minimum distance of 8 ft. away from the toe of the slope. On the other hand, for 1V:4H slope, TL-3 CMB should be installed on one side of the median and positioned within 4 ft. of the slope breakpoint. Additionally, CMB should sit on a concrete strip to provide better stability and support.

This study also reviewed literature to obtain information on the installation cost of CMB in other states. Obtaining data on the cost of installing CMB is essential to gain insight into the affordability of these barriers and to compare them to other types of barriers for effective capital investment. One of the reasons for the widespread use of CMB is its low installation cost compared to other types of median barriers. In a Washington state cable median barrier study [25], McClanahan et al. found that the installation cost per mile for CMB was approximately one-half that of W-beam guardrail and one-third that of precast concrete barrier. This study extracted information on CMB installation cost from different publications available online. The collected information showed that the installation cost of CMB usually ranges from around $80,000 to $240,000 per mile in different states, as presented in Table 1.

Table 1. Cable median barrier installation cost in different states

State	CMB Implementation Starting Year	Installation cost per mile	Source
Texas	2000	$110,000	[11]
Iowa	2003	$80,803	[26]
Minnesota	2004	$125,000-$150,000	[45]
Washington	1995	$242,880	[21]
Missouri	1980s	$100,000-$120,000	[46]
Michigan	2008	$155,621	[22]
Illinois	2005	$163,000	[47]

Cable Median Barriers Maintenance Guidelines and Repair Cost

To ensure optimal performance, it is crucial to maintain the CMB system. Proper maintenance of CMB involves more than just repairs after a crash or collision. It also requires regular and ongoing maintenance, such as cable re-tensioning, mowing, and monitoring the system for signs of wear and tear. Proper guidelines for CMB repair and maintenance are necessary since neglecting routine maintenance can lead to decreased effectiveness of the barrier and potentially even compromise its ability to mitigate the severity of a crash.

As part of this literature review, the research team explored different state DOT guidelines available online to obtain valuable information regarding the maintenance and repair guidelines for CMB. CMB maintenance and repair policies adopted by various states, as well as the associated costs are reported in this section. First, the standard practice and guidelines, including authorities accountable for repair, repair response time, cable tension inspection, and other miscellaneous maintenance tasks are presented, followed by the annual maintenance expenses and per-collision repair costs.

In most states, CMB maintenance is either performed by the in-house maintenance crews (DOT personnel) or contractors. Usually, when the magnitude of the repair work is very high or if the in-house forces are preoccupied, the maintenance and repair works are awarded to contractors [10], [39]. The NCHRP Synthesis 493 summarizes the practice adopted by different states regarding the responsible authority for CMB repairs, which is presented in Table 2 [48].

Table 2. CMB repair and maintenance- work distribution in different states

States	In-house Repair	Contracted Repair
Alabama	75%	25%
Delaware	95%	5%
Florida	10%	90%
Iowa	20%	80%
Indiana	90%	10%
Kentucky	0%	100%
Louisiana	5%	95%
Michigan	94%	6%
Ohio	20%	80%
Oklahoma	70%	30%
Texas	40%	60%

States	In-house Repair	Contracted Repair
West Virginia	30%	70%

Among the available literature, Texas's CMB maintenance and repair policies provide the most detailed information. The key takeaways from the *Texas Cable Median Barrier Maintenance Manual* [10] are summarized below:

1. When scheduling CMB repair and maintenance activities, ensuring the safety of the crews and minimizing traffic delays must be the primary concern.
2. The repair works must be started within 72 hours of notification.
3. A standard maintenance and repair log should be maintained.
4. Coordination with law enforcement agencies should be done to recover repair costs from the responsible parties.

In addition to repairs after hits, CMB requires several other routine maintenance activities such as mowing and re-tensioning. For example, in Minnesota, the necessity of mowing around the CMB is reported [39]. For mowing and miscellaneous maintenance, the following equipment are recommended by the report: a “spider” mower ($45,000), a Laforge Hitch ($14,000), a pressure washer ($10,000) and a swaging machine ($28,000). Moreover, regular inspections of cable barrier heights and cable tension are required for optimal functioning. Texas maintenance policy [10] recommends that the cable tension should be checked at least once per year for pre-stretched cables. In the case of standard cable system, the cable tension should be checked a minimum of twice per year. More information about CMB maintenance and repair cost in other states is summarized in the NCHRP Synthesis 493 [48].

Crash-related damages account for a significant proportion of CMB maintenance costs. Because of the reduction of available clear zone for vehicles and the weak nature of cable barrier, frequent maintenance, and repairs of CMB are needed. Maintenance and repair costs reported by several states are presented in Table 3.

Table 3. Cable median barrier maintenance and repair cost in different states

State	Maintenance cost per mile per year	Source
Texas	$4,000-$4,500	[11]
Minnesota	$3,600	[45]
Washington	$2,636	[21]
Missouri	$6,000-$10,000	[12]
Illinois	$10,000	[47]

It is also important to find out the average repair cost associated with each cable barrier hit since the total yearly repair cost can be estimated from the repair cost per collision data, considering that the total annual number of CMB hits is available. Table 4 presents the CMB repair cost per impact reported by different states.

Table 4. Cable median barrier repair cost per collision in different states

State	Repair cost per collision	Source
Texas	$635	[11]
Iowa	$733	[26]
Minnesota	$1,435	[39]
Washington	$1,025	[21]
Ohio	$631	[49]
Colorado	$1,000	[49]
Indiana	$312	[49]

Because cable barriers are more forgiving, vehicles frequently drive away after a collision, leaving it hard to collect the repair costs from the insurance company. According to data reported by Texas and Washington, slightly more than half of the CMB repair reports can be matched with reported crashes and can be recovered from the responsible motorists.

Cable Median Barriers Funding Sources

As the effectiveness of CMB as a countermeasure for preventing cross-median crashes has been proven, many states have started implementing it widely to improve road safety. However, since most states use safety funds for implementing CMB, it is crucial to explore other funding opportunities that could be used to supplement safety programs.

This can help ensure that the necessary funds are available for the installation and maintenance of CMB. The research team searched and documented information on the funds utilized by different states for the CMB installation. However, limited information regarding CMB funds could be retrieved from online sources.

In Texas, safety bond money was used in the cable barrier projects. As of 2009, Texas DOT used approximately $157 million of safety bond money to fund 94 projects to install 738 miles of CMB [11].

As of 2015, Iowa DOT had installed 251 miles of CMB along the interstates, which represents an investment of $20,281,553. The fund came from different sources- Additional FFY 2010 federal aid ($60 million), Carryover highway funds from FY 2010 ($30.5 million), Iowa DOT operations budget reversion, resulting from an effort by the department to reduce operational spending ($8 million) [50].

In Minnesota, CMB projects were funded through the Highway Safety Improvement Program funds. Other state and federal funds were also used [39].

In Washington, there was no dedicated funding source for implementing the CMB program when it was initiated in 2001. From 2003 to 2005, set aside safety improvement dollars were used to target median barrier installations. Revenue from the 5-cent gas tax increase (2003) and the 9.5-cent gas tax increase (2005) were also used. Dedicated fund for cable barriers were used for projects that were completed in 2011 [21].

Benefit-Cost Analysis

Benefit-cost analysis is a methodical approach for estimating and comparing the benefits and costs associated with a particular project. In the context of highway safety, benefit-cost analysis is used to aid transportation agencies in making well-informed and consistent decisions when evaluating the economic value of safety countermeasures. It accounts for all the societal benefits of a highway safety project and the expenses associated with achieving those benefits, regardless of which party incurs the costs or receives the benefits [51]. This study reviewed the FHWA benefit-cost analysis guidelines and other existing CMB benefit-cost studies to gain a comprehensive understanding of the analysis process, including the identification of sources of benefits and costs, the use of discount rates, service years, dollar worth conversion, and crash unit costs.

FHWA Highway Safety Benefit-Cost analysis (BCA) Guide [51] suggests using the present value at time zero for the benefit-cost analysis. According to the BCA guideline, the discount rate typically varies between 3% to 7%. The FHWA crash cost for highway safety analysis guide [52] recommends using the comprehensive crash costs instead of the economic crash costs. Economic costs represent the monetary effects of collisions, which include products and services associated to crash response, property damage, and medical expenses. In other words, it refers to the costs that can be quantified in monetary terms, such as medical expenses and lost wages. On the other hand, the comprehensive crash costs account for not only the economic costs but also the intangible repercussions of crashes, such as the physical and mental distress of crash victims and their families. The intangible effects are generally quantified in terms of quality-adjusted life years (QALY). The national crash unit costs recommended by FHWA Highway Safety BCA Guide and Tool is presented in Table 5 [52]. However, these costs should be updated for the current year and adjusted for individual states.

Table 5. FHWA comprehensive crash unit cost (2016 dollars)

Crash Severity	Economic Crash Unit Costs	QALY Crash Unit Costs	Comprehensive Crash Unit Cost
Fatal	$1,722,991	$9,572,411	$11,295,400
Severe Injury	$130,068	$524,899	$655,000
Moderate Injury	$53,700	$144,792	$198,500
Possible Injury	$42,536	$83,026	$125,600
PDO	$11,906	$0	$11,900

Many states conducted benefit-cost analyses for CMB, but the methods used for these analyses vary among states. For instance, in the Iowa CMB study [26], the ratio between the total crash cost saving to the total cost of installation and maintenance was calculated. All the benefits and costs were converted to annual monetary value utilizing a discount rate of four percent and a service life of 20 years. Iowa-specific crash costs were used to estimate the benefits of crash reduction and a benefit-cost ratio of 16.08 was achieved. In the 2002 Washington study [53], CMB was found to have the highest benefit-cost ratio compared to guardrail and concrete barrier. This study used the present worth of money for calculating the ratio. The estimated benefit-cost ratios for different median width groups are presented in the Table 6 [53].

Table 6. Benefit-cost ratio for different barrier types in Washington

Median Width Group	Under 30’	30’-40’	41’-50’	51’-60’	61’-70’	71’-80’	Over 80’
CMB	2.7	5.5	4.7	3.2	0.6	0.8	2.3
Guardrail	1.9	3.9	3.3	2.3	0.4	0.6	1.6
Concrete Barrier	1.1	2.3	2.0	1.4	0.3	0.4	1.0

Another Washington study in 2003 [25] estimated an annual crash saving of $10.26 million after the installation of CMB. However, the study did not compare this benefit with the installation and maintenance costs, thus a benefit-cost ratio was not reported. The Kentucky study [18] estimated benefit-cost ratios for median cross-over crashes using both the economic crash costs and the comprehensive crash costs. However, as the severity distribution for the median cross-over crashes was not available, the study calculated the average unit cost of KABCO crashes and used that average value to monetize the crash reductions (Here, K, A, B, C and O stand for fatal, incapacitating injury, non-incapacitating injury, possible injury and PDO crashes, respectively). All the installation and maintenance costs were converted to present year dollars. Using the economic crash costs, the study obtained benefit-cost ratios of 7.92 and 22.15 for 3-year and 5-year analysis periods, respectively. The benefit-cost ratios for the 3-year and 5-year analysis periods, when using comprehensive crash unit costs, were 55.27 and 154.66, respectively.

Table 7 summarizes different crash costs utilized in different studies mentioned in this section.

Table 7. Unit crash costs used in previous studies to estimate benefit

Crash Type	**Washington** [53] ***(2002)***	**Washington** [25] ***(2003)***	**Kentucky** [18] ***(2017)***	**Iowa** [26] ***(2018)***
Fatal	$800,000	$3,760,000	$1,500,000	$5,382,353
Severe Injury	$800,000	$315,000	$88,500	$402,510
Moderate Injury	$62,000	$70,000	$25,600	$86,141
Possible Injury	$33,000	$35,000	$21,000	$43,476
PDO	$5,800	$6,500	$4,200	$7,400
			Average: $327,860	

Objective

The goal of this project was to evaluate the effectiveness of CMB installed on Louisiana highways. Specifically, the objectives were to:

1. Investigate safety effectiveness of CMB; and

2. Estimate the benefit-cost ratio of CMB.

Scope

This project focused on Louisiana freeways and expressways that have had cable median barriers in operation for three years or more. Therefore, based on the availability of crash data, 23 existing CMB segments throughout the state consisting of 275 miles were used in this study.

Methodology

This section discusses the data processing, verification, details of the crash data analysis scheme and the benefit-cost analysis methodology. The data processing and verification consisted of collecting CMB project information from Louisiana DOTD, verification of the CMB construction years and collecting other key element data for the selected sections. After CMB project data processing, the corresponding crash data collection and data cleaning steps were carried out. A crash analysis scheme was developed, and a comprehensive flow chart was created to identify the targeted crashes. Lastly, benefit-cost analysis for the CMB segments was carried out to evaluate the cost-effectiveness of CMB.

Data Collection and Preparation

CMB Project Data

As of February 2022, Louisiana has already installed approximately 623 miles of cable barriers throughout the state [54]. The information on the existing CMB projects in Louisiana was collected from Louisiana DOTD. The data provided by the DOTD included the let date, notice to proceed date and acceptance date for the CMB projects. The geographical location, length, and the final project bid amount of all the CMB segments were also included.

Utilizing the notice to proceed date and the final acceptance date along with the confirmation from Google Earth historical imagery, the construction years of each CMB project were accurately identified. Following that, the three years before and after the construction of CMB were assigned to each segment for the analysis.

For the before-and-after analysis, crash data for the three years before and the three years after CMB implementation is needed. Consequently, based on the availability of crash data, 23 CMB segments were selected in this study consisting of 275 miles.

Following the selection of the 23 freeway segments, various geometric characteristics of these segments were obtained such as median width and CMB testing level. The number of interchanges in each segment was also identified, which provided us the opportunity to investigate and eliminate intersection crashes surrounding the interchanges. The CMB testing level-3 (TL-3) or testing level-4 (TL-4) was identified based on its position in the median. CMB placed close to the middle of the median conforms to TL-4 while TL-3 cable barriers were placed close to any of the sides of the median. Table 8 shows the selected 23 CMB segments and their characteristics identified by the research team.

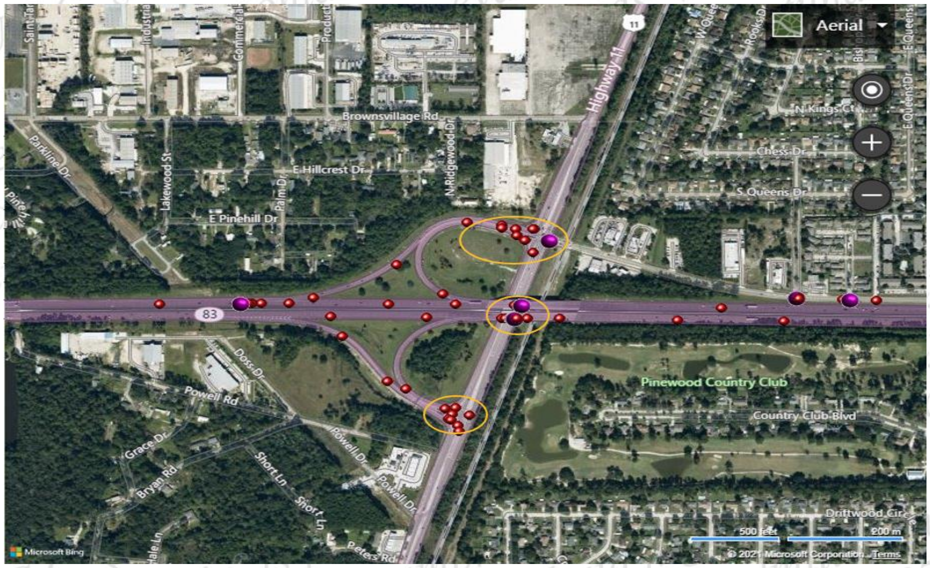
Table 8. CMB segments selected for analysis

Segment	Location	Construction year	Before period	After Period	Length (miles)	Median Width (ft.)	Testing Level	No. of inter-changes
1	I-10 (St. James)	2008, 2009	2005-2007	2010-2012	6.87	64	TL-4	1
2	I-12 (St. Tammany)	2008, 2009	2005-2007	2010-2012	30.21	64	TL-3	10
3	I-12 CMB	2010, 2011	2007-2009	2012-2014	0.51	60	TL-3	0
4	I-12 CMB	2010, 2011	2007-2009	2012-2014	17.82	64	TL-3	5
5	I-10 (Dist. 61,62,02)	2011, 2012	2008-2010	2013-2015	2.69	64	TL-4	0
6	I-10 (Dist. 61,62,02)	2011, 2012	2008-2010	2013-2015	2.54	64	TL-4	0
7	I-10 (Dist. 61,62,02)	2011, 2012	2008-2010	2013-2015	6.87	64	TL-4	1
8	I-10 (Dist. 61,62,02)	2011, 2012	2008-2010	2013-2015	11.80	60	TL-4	1
9	I-10 (Dist. 61,62,02)	2011, 2012	2008-2010	2013-2015	1.89	64	TL-3	1
10	I-10 (Dist. 61,62,02)	2011, 2012	2008-2010	2013-2015	1.15	64	TL-4	1
11	I-10/610 (Dist. 02)	2012, 2013	2009-2011	2014-2016	0.44	64	TL-4	0
12	I-10/610 (Dist. 02)	2012, 2013	2009-2011	2014-2016	0.27	44	TL-4	0
13	LA 8 Vernon Parish	2013, 2014	2010-2012	2015-2017	0.20	40	TL-4	0
14	I-20 (Bienville/Caddo)	2013, 2014	2010-2012	2015-2017	13.48	64, 40	TL-3	5
15	I-20 (Bienville/Caddo)	2013, 2014	2010-2012	2015-2017	17.36	64	TL-3	4
16	I-20 (Bossier/Webster)	2013, 2014	2010-2012	2015-2017	5.96	56	TL-3	1
17	I-20 (Bossier/Webster)	2013, 2014	2010-2012	2015-2017	0.32	56	TL-3	0
18	I-20 (Bossier/Webster)	2013, 2014	2010-2012	2015-2017	2.80	56	TL-3	1
19	I-20 (Bossier/Webster)	2013, 2014	2010-2012	2015-2017	17.68	56	TL-3	5
20	I-20 (Madison/Richland)	2014, 2015	2011-2013	2016-2018	60.28	56	TL-3	11
21	I-10 (Orleans Parish)	2014, 2015	2011-2013	2016-2018	7.65	56	TL-3	2
22	I-20 (Lincoln/Ouachita)	2015, 2016	2012-2014	2017-2019	56.00	64	TL-3	22
23	LA 3132 CG:I-20to E of LA 523	2016, 2017	2013-2015	2018-2020	10.21	64	TL-4	8
	Total				274.99 miles			

Crash Data

Crash data for the before and after years was collected from DOTD Access Crash Database. Although the accuracy of crash data has greatly improved in Louisiana over the years, it is still not 100% accurate. After collecting the crash data for the 23 selected freeway segments, many “intersection” coded crashes were found by the research team. Since freeway segments do not have intersections, there are two possible scenarios that might have happened. First, these crashes mostly occurred at the intersections of local roadways and ramps within the interchange areas (Figure 5). In this case, these crashes should be removed from the dataset. Secondly, these “intersection” coded crashes might have occurred on the freeway segments but were incorrectly coded as “intersection” in the police report. If that’s the case, these crashes should be included as freeway crashes for our study. Because of this complexity, additional investigation of crash reports was performed to determine whether to include the “intersection” coded crashes or remove them from analysis.

Figure 5. Coded intersection crashes on a service interchange



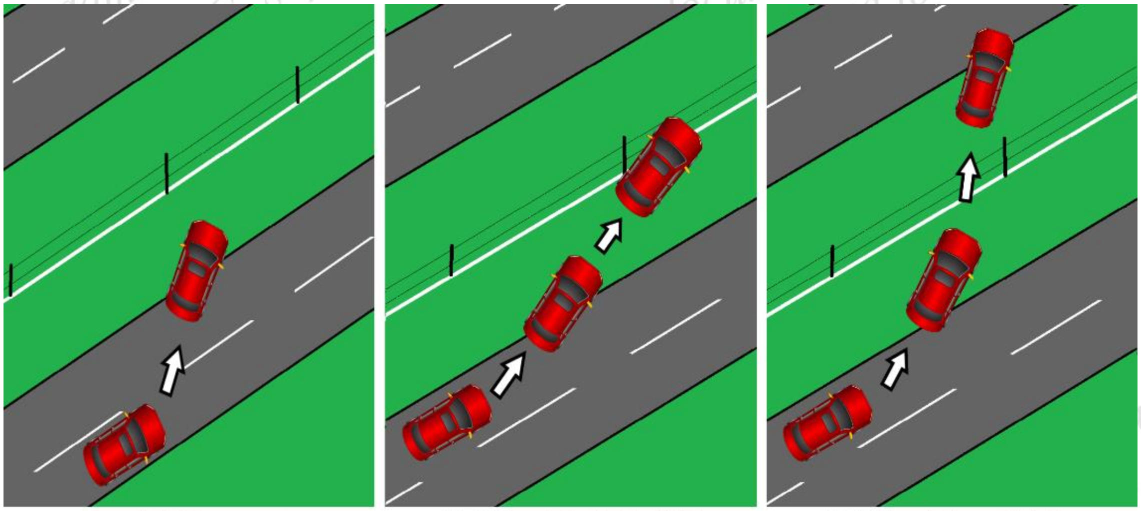
Crash Analysis Scheme

Identifying the Targeted Crashes

To investigate the CMB effectiveness, it is critical to know the changes in median-related crashes and cross-median crashes beyond just the total crashes between the three years before-and-after CMB project. Total crashes are all crashes for the selected study segments and durations. The median-related crashes occur when vehicles run off roadway to the left (also known as Run to the left or RTL crashes) and enter median with the following three possible scenarios as shown in Figure 6:

1. vehicle stops on median
2. vehicle maneuvers back to the original travel direction from the median and possible hits other vehicles/objects
3. vehicle crosses the median and crash into other vehicles traveling on the opposite direction, or crash into fixed objects (cross-median crashes)

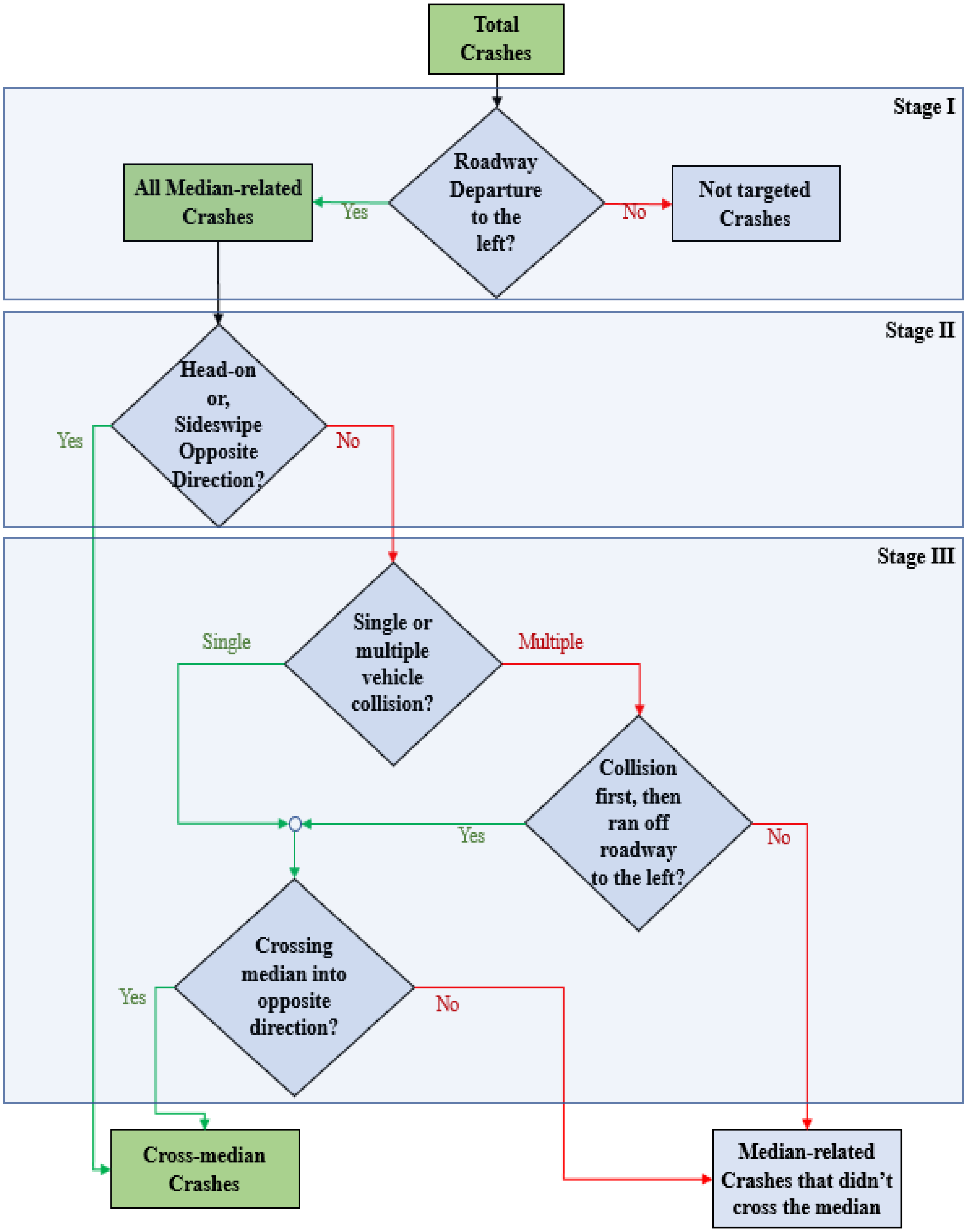
Figure 6. Illustration of median-related crash



(a) RTL (b) RTL and Crash into CMB (c) RTL and Crossed Median

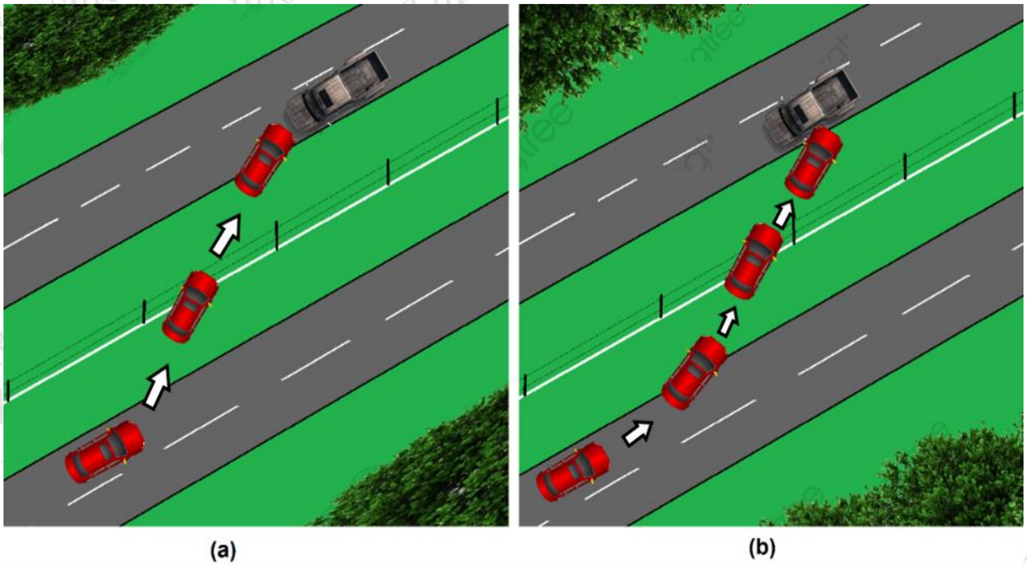
However, the median-related crashes including cross-median crashes are not directly recorded in the original crash report, thus unavailable for query from the current crash database. The median-related crashes are identified based on the harmful events. If the first or second or third or most harmful event of a crash is either run of roadway to the left or cross the median or collision with other traffic barrier, then that crash is considered a median-related crash. In other words, all median-related crashes are roadway departures to the left. The targeted crash identification process is illustrated in Figure 7. In this study, total crashes, all median-related crashes, and cross-median crashes were included in the before-and-after analysis (indicated in the figure by the green boxes).

Figure 7. Flow chart of identifying targeted crashes



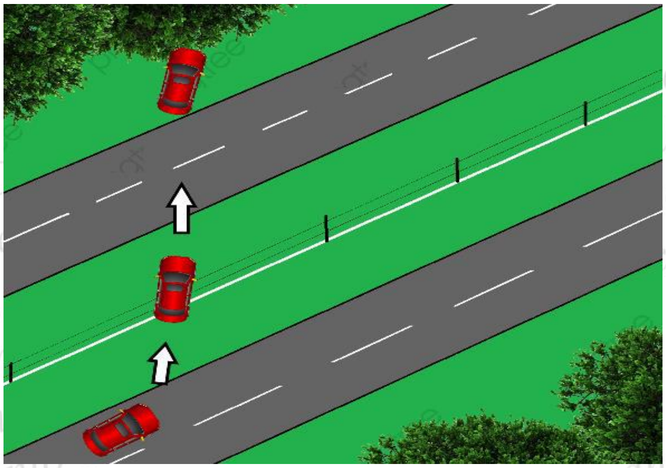
After finding out all median-related crashes, the CMB related cross-median crashes were identified based on the manner of collision and prior movement of crashes following the flowchart in Figure 7. To filter out the cross-median crashes that involved colliding with vehicles traveling in the opposite direction, the collision type of each median-related crash was examined. All median-related crashes with manner of collision either head-on or sideswipe opposite direction are considered as cross-median crashes. All other median-related crashes with manner of collision expect head-on and sideswipe opposite direction are again combined with their prior movements to identify the targeted cross-median crashes. The identified head-on crashes were further evaluated by reading the original police crash reports to make sure they are not caused by wrong-way operations. Figure 8 illustrates the possible outcomes (manners of collision) for cross-median crashes.

Figure 8. Cross-median crashes — manner of collision (a) head-on, (b) sideswipe opposite direction



A run of roadway to the left vehicle could happen in two ways: running to the left first and then colliding with a vehicle traveling in the opposite direction (as head-on or sideswipe opposite direction), or collision with vehicle traveling on the same direction first and then running or "pushed" into median. As shown in Figure 7, there are several steps in identifying the cross-median crashes for both cases in addition to head-on and sideswipe opposite direction crashes. The single vehicle crashes with prior movement as crossed median are grouped to cross-median crashes (Figure 9). Median-related crashes involving in single vehicle collision with all manner of collision expect head-on and sideswipe opposite direction combine with prior movements crossed median or centerline into opposite direction crashes are identified as cross-median crashes.

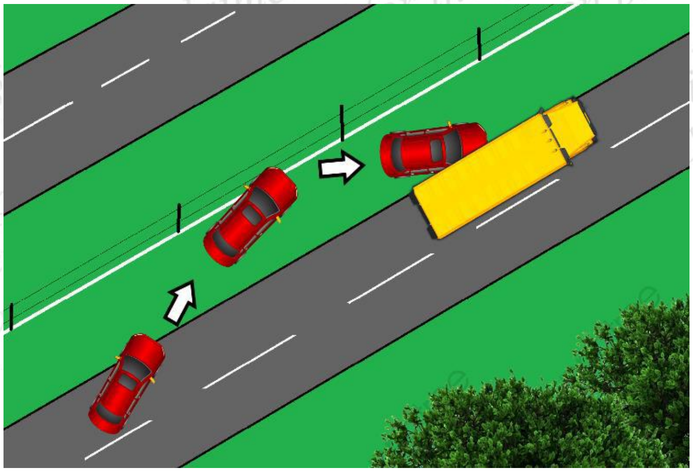
Figure 9. Single vehicle cross-median crashes



Multiple vehicle collisions occurred first and then RTL or “pushed” to crossed median are also grouped as cross-median crashes. Multiple vehicle crashes, if the collision occurred first, then the vehicle ran off the roadway to the left with the same manner of collision and prior movement stated above, similar as a single vehicle, are also identified as cross-median crashes.

Although rare, it is also possible that a vehicle runs off the roadway to the left, hits the cable barrier, then comes back to the previous travel lane and collides with another vehicle. In such cases, the movement prior to crash would be “entering traffic from median,” and the manner of collision should be either “rear-end” or “sideswipe same direction” as shown in Figure 10, which is still grouped as a median-related crash. Only two such crashes were identified in this study.

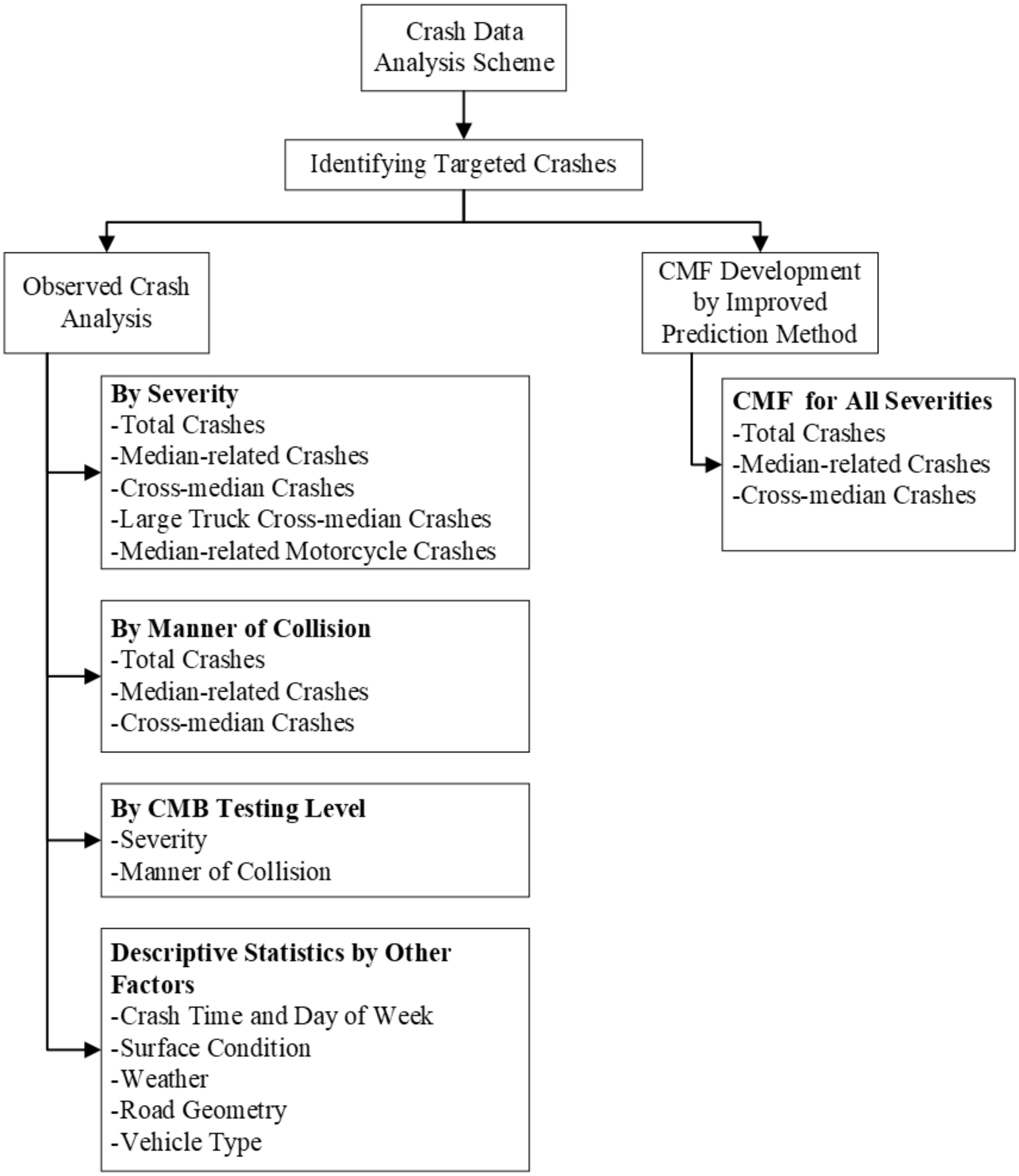
Figure 10. A special case for median-related but not cross-median crashes



Crash Data Analysis Scheme

The crash data analysis scheme is summarized in Figure 11.

Figure 11. Crash data analysis scheme



CMF Development Using Improved Prediction Method

Because of the changes in AADT and potential other design elements, such as pavement surface friction improvement, shoulder ramble strips and shoulder width, between the before and after periods, the observed crash statistics do not accurately estimate impact of CMB. The Empirical Bayes model recommended by the first edition of Highway Safety Manual is the best model in roadway safety evaluation, because it yields the most reliable and accurate results. However, due to the unavailable safety performance functions for freeway, this research used the *Improved Prediction Method* developed by Hauer [16] . The four steps of the improved prediction method application are presented below.

Step 1:

The expected number of crashes if CMB was not installed in the after period ($\hat{\pi}$) and the expected number of crashes in the after period with CMB implementation ($\hat{\lambda}$) are estimated.

$$\hat{\lambda} = N \tag{1}$$

$$\hat{\pi} = \hat{r}_{tf} * K \tag{2}$$

Here,

$\hat{\lambda} =$ Estimated expected number of crashes in the after period with CMB implementation

$N =$ Observed number of crashes in the after period with CMB implementation

$\hat{\pi} =$ Estimated expected number of crashes in the after period if CMB was not implemented

$K =$ Observed number of crashes in the before period without CMB implementation

$\hat{r}_{tf} = \frac{\hat{A}_{avg}}{\hat{B}_{avg}} =$ traffic flow correction factor

$\hat{A}_{avg} =$ Average traffic flow during the after period

$\hat{B}_{avg} =$ Average traffic flow during the before period

Step 2:

The variances of $\hat{\lambda}$ and $\hat{\pi}$ are estimated.

$$\widehat{var}\{\hat{\lambda}\} = \hat{\lambda} \tag{3}$$

$$\widehat{var}\{\hat{r}_{tf}\} = (\hat{r}_{tf})^2 \left(v^2\{\hat{A}_{avg}\} + v^2\{\hat{B}_{avg}\}\right) \tag{4}$$

$$\widehat{var}\{\hat{\pi}\} = (\hat{r}_d)^2[(\hat{r}_{tf})^2K + K^2\widehat{var}\{\hat{r}_{tf}\}] \tag{5}$$

Here,

$\widehat{var}\{\hat{\lambda}\}$ = Estimated variance of $\hat{\lambda}$

$\widehat{var}\{\hat{\pi}\}$ = Estimated variance of $\hat{\pi}$

v = percent coefficient of AADT estimates

$$v = \left(1 + \frac{7.7}{number\ of\ count - days} + \frac{1650}{AADT^{0.82}}\right) * 0.01 \tag{6}$$

Step 3:

The crash difference ($\hat{\delta}$) and the ratio ($\hat{\theta}$) are calculated.

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{7}$$

$$\hat{\theta} = \frac{\frac{\hat{\lambda}}{\hat{\pi}}}{\left[1 + \frac{\widehat{var}\{\hat{\pi}\}}{\hat{\pi}^2}\right]} \tag{8}$$

Here,

$\hat{\delta}$ = Estimated safety impact of CMB installation

$\hat{\theta}$ = Estimated unbiased expected crash modification factor (CMF)

Step 4:

The standard deviation of $\hat{\delta}$ and $\hat{\theta}$ are estimated.

$$\hat{\sigma}(\hat{\delta}) = \sqrt{\widehat{var}\{\hat{\lambda}\} + \widehat{var}\{\hat{\pi}\}} \tag{9}$$

$$\hat{\sigma}(\hat{\theta}) = \frac{\hat{\theta} * \sqrt{\frac{\widehat{var}\{\hat{\lambda}\}}{\hat{\lambda}^2} + \frac{\widehat{var}\{\hat{\pi}\}}{\hat{\pi}^2}}}{1 + \frac{\widehat{var}\{\hat{\pi}\}}{\hat{\pi}^2}} \tag{10}$$

Finally, using the estimated standard deviation of the CMFs, the 95% confidence intervals for the CMF estimation were calculated.

Benefit-Cost Analysis Method

A benefit-cost study was done to determine the cost-effectiveness of cable median barriers segments selected for this study. In this section, the steps of the benefit-cost analysis are presented in detail.

Estimation of Benefit

Crash cost savings are the source of CMB's benefits. Reducing the incidence of fatal, severe injury, and moderate injury crashes is the primary source of benefits, whereas some costs are induced by the increased number of PDO and complaint injury crashes. The costs associated with these crash increments are deducted from the total benefit to calculate the net benefit of each CMB segment.

First, the estimated annual crash reduction is calculated using the CMFs generated by the improved prediction method.

$$\delta Y_i = \bar{Y}_i - \left(\bar{Y}_i * \hat{\theta}_i\right) \tag{11}$$

Here,

$\delta Y_i =$ *Estimated annual crash reduction*

$\bar{Y}_i =$ *Avg. no. of crashes per year in the before years*

$\hat{\theta}_i =$ *Estimated CMF*

$i =$ *Fatal, serious injury, moderate injury, complaint, PDO crashes*

This estimated reduction of crashes was converted to monetary value by multiplying with the crash unit cost for each severity.

$$B' = \sum_i (\delta Y_i * C_i) \tag{12}$$

Here,

$B' =$ Estimated annual benefit

$C_i =$ Average crash unit costs

The 2021 Louisiana-specific crash unit costs provided by the Center for Analytics and Research in Transportation Safety (CARTS) were used in this study. Benefits were calculated separately using the economic unit crash costs and the comprehensive unit crash costs (include quality of life cost as well as economic cost). The 2021 Louisiana-specific crash unit costs are presented in Table 9.

Table 9. Louisiana-specific unit crash costs for estimating benefits

Severity	Economic crash unit costs-2021	Comprehensive crash unit costs-2021
Fatal	\$2,036,913	\$12,237,896
Severe Injury	\$582,241	\$2,274,578
Moderate Injury	\$198,021	\$701,251
Possible Injury	\$66,461	\$105,267
PDO	\$28,363	\$28,363

The annual benefits were estimated using both unit costs presented in Table 9. Lastly, the total benefit for each CMB segment was calculated by multiplying the annual benefit with the number of years that CMB segment is in operation.

$$B = B' * n \tag{16}$$

Here,

B = *Benefit in present year (2021) monetary value*

n = *Number of years in service*

The above steps were repeated for calculating the benefit for total crashes, median-related crashes, and cross-median crashes.

Estimation of Costs

The total cost of implementing CMB comprises of the initial installation costs and the maintenance/repair costs associated with CMB.

The initial installation cost for each CMB segment was calculated from the actual bid amount for that respective CMB segment. These installation costs were then converted to 2021 monetary values.

$$C_I = C'_I * (1 + r)^n \tag{17}$$

Here,

C_I = *Installation cost in 2021 monetary value*

C'_I = *Installation cost at the construction year*

The estimation of the maintenance/repair cost was a complex step as multiple authorities are involved in CMB repair works. In Louisiana, each district in-house personnel do the cable barrier repair tasks when the scope of the repair is small. However, whenever the scope of the repair is large, i.e., 10 or more cable barrier posts need replacing, the repair works are given to contractors. In this study, the contracted repair cost was calculated from the data provided by the DOTD Section 42; whereas, the in-house repair cost was estimated based on the information provided by individual districts.

$$R_{total} = R_{In-house} + R_{Contract} \tag{18}$$

R_{total} = Estimated total repair cost per mile per year

$R_{In-house}$ = Estimated inhouse repair cost per mile per year

$R_{Contract}$ = Estimated contracted repair cost per mile per year

Utilizing the estimated total repair cost/mile/year (in 2021 dollars), annual repair costs for each of the 23 CMB segments were calculated.

$$C'_R = R_{total} * L \tag{19}$$

Here,

C'_R = *Annual repair cost for each segment*

L = *Length of each segment*

The annual repair costs were then converted to total repair cost by multiplying with number of years (n).

$$C_R = C'_R * n \tag{20}$$

Here,

C_R = *Total Repair cost for each segment in 2021 monetary value*

Benefit-Cost Ratio

Following the estimation of the CMB benefits and costs, the benefit-cost (B/C) ratio was calculated for total crashes, median-related crashes, and cross-median crashes. The B/C ratios were reported for different discount rates ranging from 3% to 7% based on the FHWA *Highway Safety Benefit-Cost analysis (BCA) Guide*.

$$B/C\ ratio = \frac{\sum_i^N B_i}{\sum_i^N (C_{I_i} + C_{R_i})} \tag{21}$$

Here,

N = Number of CMB segments = 23

Results and Discussion

The objective of the study was to assess the safety and cost-effectiveness of CMB. To do this, 23 CMB segments were chosen for a three-year before-and-after crash analysis, with 2005 as the earliest and 2020 as the latest year, depending on the segments' construction years. For evaluating safety, an observed crash analysis and an improved prediction method were employed, followed by a benefit-cost analysis to evaluate the implementation of CMB from an economic standpoint. The findings of the analysis are presented and discussed in this chapter. Even though the analysis of total crashes is included in this chapter, more attention should be given to median-related and cross-median crashes since they directly reflect the effect of CMB implementation; whereas, the total crashes can be affected by other factors unrelated to CMB.

Changes by Crash Severity

For a better understanding of the effect of CMB on different types of crashes, crash analysis was done for total, median-related, and cross-median crashes. The observed crash frequencies before and after CMB installation are shown in Table 10.

Table 10. Observed crashes by severity

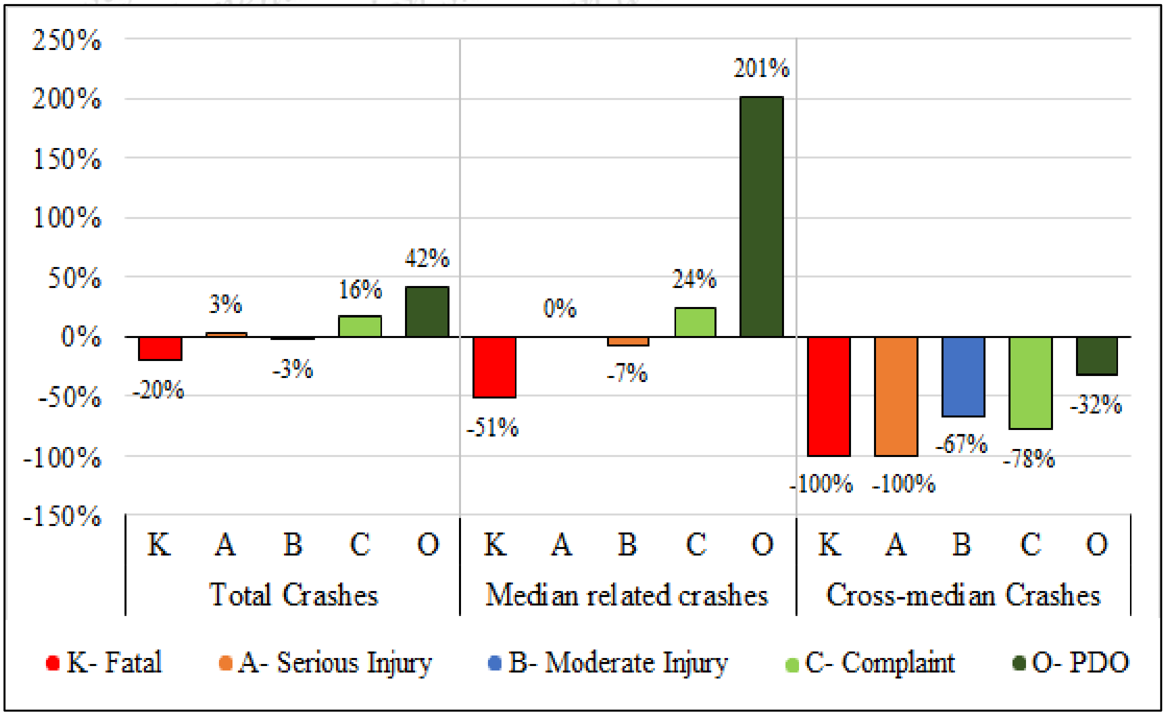
Crash by Severity	**Crash Frequency**		**% Change**
	Before	**After**	
Total Crashes			
• Fatal	92	74	**-20%**
• Serious Injury	63	65	3%
• Moderate Injury	451	439	**-3%**
• Complaint/possible injury	1610	1875	16%
• PDO	4795	6826	42%
Total Crashes	7011	9279	32%
Median-related Crashes			
• Fatal	45	22	**-51%**
• Serious Injury	14	14	0%
• Moderate Injury	99	92	**-7%**
• Complaint/possible injury	301	373	24%

• PDO	563	1697	201%
Total Median-related Crashes	1022	2198	115%
<u>Cross-median Crashes</u>			
• Fatal	12	0	**-100%**
• Serious Injury	3	0	**-100%**
• Moderate Injury	12	4	**-67%**
• Complaint/possible injury	27	6	**-78%**
• PDO	37	25	**-32%**
Total Cross-median Crashes	91	35	**-62%**

Utilizing the crash identification flowchart, a total of 7011 crashes were identified during the before period, 1022 of which were median-related and 91 cross-median. After CMB implementation, the number of total and median-related collisions increased (9,279 and 2,198, respectively); whereas, cross-median collisions decreased to 35. The increase in total and median-related crashes can be attributed to the rise in PDO collisions.

The observed changes in total, median-related, and cross-median crashes by severity are shown in Figure 12.

Figure 12. Percent change in observed crashes by severity



The total fatal and moderate injury crashes were reduced by 20% and 3%, respectively. The serious injury crashes were almost unchanged, and PDO crashes increased by 42% after the implementation of CMB.

The median-related crashes reflect the impact of CMB more precisely. The reductions in median-related fatal and moderate injury crashes are 51% and 7%, respectively. The reductions in fatal and injury crashes are much higher than that of the total crashes. However, an increase in complaint (24%) and PDO (201%) crashes was observed after CMB installation. It is reasonable to say that the increase in PDO crash is attributed to CMB. Before the CMB installation, some of run off roadway to the left vehicles might possibly regain control and drive away. After median barrier installation (leading to smaller clear zone), such run-off roadway to the left vehicles crashed into CMB with minor damages, thus increasing the number of PDO crashes. This trade-off between crash severities (fatal and injury vs. PDO crashes) is, we believe, not only economically justified but also in consent with the safety objective of reducing severe crashes.

It is important to know how many cross-median crashes are prevented by CMB, which is the most direct measurement of CMB effectiveness. The 100% reduction in fatal and serious injuries for cross-median crashes is very impressive. The reduction in cross-median crashes of moderate injury, possible injuries, and PDO is also impressive at 67%, 78%, and 32%, respectively, which is much higher than that from total and median-related crashes.

Since TL-3 and TL-4 median barriers are not designated by MASH to stop large trucks, it is important to investigate CMB's performance in stopping the run-off roadway large trucks. The literature review has also highlighted an additional concern that must be addressed, which pertains to determining whether CMB are contributing to the rise in fatalities of motorcyclists. To address these issues, a comparison of observed cross-median crashes involving large trucks and observed median-related crashes involving motorcycles were carried out. The observed change in large truck cross-median and median-related motorcycle crashes are presented in Table 11.

Table 11. Large truck and motorcycle crashes by severity

Crashes by Severity	Crash Frequency		% Change
	Before	After	
Large Truck in Cross-Median Crashes			
• Fatal	0	0	0%
• Serious Injury	0	0	0%
• Moderate Injury	0	0	0%
• Complaint/possible injury	0	0	0%
• PDO	3	0	**-100%**
Total Large Truck in Cross-Median Crashes	3	0	**-100%**
Motorcycles in Median-related Crashes			
• Fatal	2	1	**-50%**
• Serious Injury	3	0	**-100%**
• Moderate Injury	5	7	40%
• Complaint/possible injury	5	5	0%
• PDO	5	1	**-80%**
Total Motorcycle in Median-Related Crashes	20	14	**-30%**

Before the implementation of CMB, three large truck cross-median crashes were found, all of which were PDO. This number was reduced to zero following the installation of CMB, indicating that CMB performed well in stopping large vehicles from crossing the median. However, this finding may not represent the actual scenario since the number of cross-median crashes found in this study was very small. In the case of median-related motorcycle crashes, the fatal, serious injury, and PDO collisions reduced by 50%, 100%, and 80%, respectively, after the implementation of CMB, while only the moderate injury crashes increased by 40%. These findings do not show CMB to be particularly more hazardous to motorcyclists.

Changes in Total and Targeted Crashes by Targeted Manner of Collision

The head-on, sideswipe opposite direction, and single vehicle ran-off crashes are the targeted manner of collisions that are closely related to CMB effectiveness evaluation. As shown in Table 12, the reductions in head on crashes are 37%, 88%, and 88% for total crashes, median-related crashes, and cross-median crashes, respectively. The crash reports for cross-median head-on crashes were analyzed thoroughly to make sure that they were not incorrectly coded. It was revealed from the crash reports that none of the cross-median head-on collisions after CMB installation resulted from the wrong way operation or by vehicles backing into the front of other vehicles. Because the median-related crashes include cross-median crashes as defined earlier, the crash reduction in head-on collisions for the median-related entirely came from cross-median crashes.

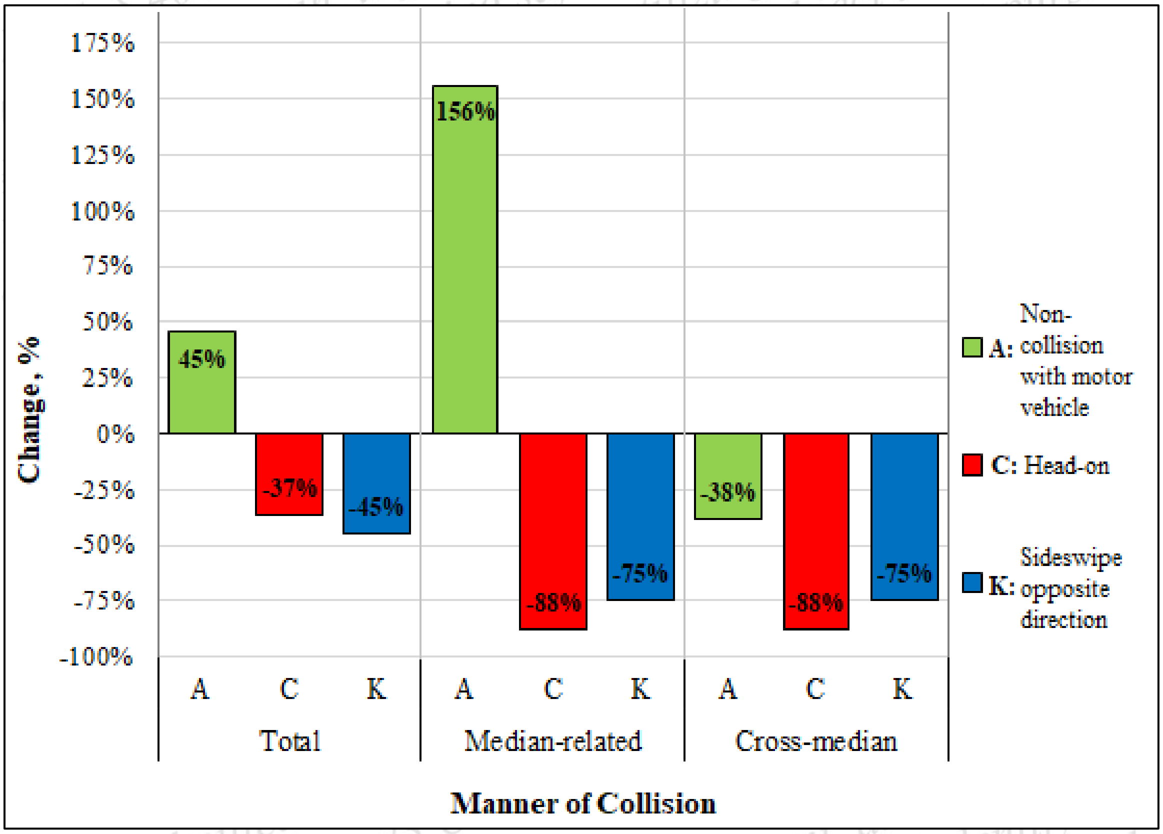
The reductions in sideswipe collisions (between vehicles in opposite direction) are 45%, 75%, and 75% for total crashes, median-related crashes, and cross-median crashes, respectively. The single vehicle ran-off-roadway (non-collision with motor vehicles) for total and median-related crashes increased by 45% and 156%, respectively, but most importantly, for cross-median and large truck in cross-median crashes, decreased by 38% and 100%, respectively. Both before and after the installation of CMB, there were no incidents of cross-median head-on or sideswipe collisions involving large trucks. Consequently, it was not possible to draw any conclusion regarding the effectiveness of CMB in preventing large truck head-on or sideswipe crashes.

Table 12. Observed crashes by manner of collision

Crash Types	Crash Frequency		% Change
	Before	After	
Total Crashes			
Non-collision With Motor Vehicle	2,364	3,437	45%
Head-on	60	38	**-37%**
Sideswipe Opposite Direction	31	17	**-45%**
Median-related Crashes			
Non-collision With Motor Vehicle	608	1,558	156%
Head-on	24	3	**-88%**
Sideswipe Opposite Direction	16	4	**-75%**
Cross-median Crashes			
Non-collision With Motor Vehicle	34	21	**-38%**
Head-on	24	3	**-88%**
Sideswipe Opposite Direction	16	4	**-75%**
Large Truck in Cross-median Crashes			
Non-collision With Motor Vehicle	3	0	**-100%**
Head-on	0	0	0%
Sideswipe Opposite Direction	0	0	0%

Figure 13 presents the percentage reduction of head-on, sideswipe opposite direction, and single vehicle crashes (non-collision with motor vehicles), showing impressive reductions in both head-on and sideswipe opposite direction crashes.

Figure 13. Percent change of observed crashes by manner of collision



Changes in Crash Severity and Manner of Collision by Testing Level

An analysis of crashes classified by both median width and CMB testing level was carried out to investigate whether the effectiveness of CMB differs based on these factors. However, the assessment of median width did not produce reliable results due to the substantial variation in segment lengths across different median widths. In addition, the total lengths of freeway segments with medians measuring 40, 44, and 60 ft. were significantly small, with lengths of only 0.20, 0.27, and 12.31 miles, respectively, making the crash data analysis for these segments less dependable. As a result, the analysis of observed crashes by median width was not included in this report.

Crash analysis by CMB testing level was carried out to see if there were significant differences between the performance of TL-3 and TL-4 CMB. In Louisiana, TL-3 CMB is installed by the side of median or close to the freeway left-shoulder while TL-4 CMB is placed close to the middle of median. Table 13 lists the changes in crash severity by CMB testing level.

Table 13. Changes in crash severities by CMB testing level

Crashes severity		**TL-3 (233.1 miles)** **CMB Position: side of median** **Median Fore slope: between 1:4 & 1:6**			**TL-4 (42 miles)** **CMB Position: middle of median** **Median Fore Slope: At or flatter than 1:6**		
		Before	**After**	**% Change**	**Before**	**After**	**% Change**
Weighted Average AADT		38,259	44,018	15%	40,079	46,847	17%
Total Crashes	Fatal	71	58	-18%	21	16	-24%
	Serious Injury	50	49	-2%	13	16	23%
	Moderate Injury	340	342	1%	111	97	-13%
	Complaint/possible injury	1133	1328	17%	477	547	15%
	PDO	3649	5142	41%	1146	1684	47%
	Total Crashes	5243	6919	32%	1768	2360	33%
Median-related Crashes	Fatal	34	19	-44%	11	3	-73%
	Serious Injury	9	9	0%	5	5	0%
	Moderate Injury	68	73	7%	31	19	-39%
	Complaint/possible injury	225	272	21%	76	101	33%
	PDO	476	1340	182%	87	357	310%
	Total Median-related Crashes	812	1713	111%	210	485	131%
Cross-median Crashes	Fatal	8	0	-100%	4	0	-100%
	Serious Injury	1	0	-100%	2	0	-100%
	Moderate Injury	8	3	-63%	4	1	-75%
	Complaint/possible injury	19	5	-74%	8	1	-88%
	PDO	30	19	-37%	7	6	-14%

Crashes severity		**TL-3 (233.1 miles) CMB Position: side of median Median Fore slope: between 1:4 & 1:6**			**TL-4 (42 miles) CMB Position: middle of median Median Fore Slope: At or flatter than 1:6**		
		Before	**After**	**% Change**	**Before**	**After**	**% Change**
	Total Cross-median Crashes	66	27	-59%	25	8	-68%
Large Truck in Cross-median Crashes	Fatal	0	0	0%	0	0	0%
	Serious Injury	0	0	0%	0	0	0%
	Moderate Injury	0	0	0%	0	0	0%
	Complaint/possible injury	0	0	0%	0	0	0%
	PDO	2	0	-100%	1	0	-100%
	Total Large Truck Cross-median Crashes	2	0	-100%	1	0	-100%

Because of its placement away from the roadway, TL-4 CMB offers clearer zone space than TL-3. In that respect, TL-4 CMB should generally perform better than that of TL-3. However, such a conclusion cannot be drawn from the findings of this study. As shown in Table 13, TL-4 and TL-3 CMB perform almost similarly in the case of total crashes (33% and 32% increase, respectively). Cross-median crash reduction rate is higher for TL-4 (68% reduction) than that of TL-3 (59% reduction). On the contrary, after CMB installation, frequency of median-related crashes increased more on the segments with TL-4 CMB (131% increase) compared to that of TL-3 (111% increase). In terms of crash severity, TL-4 CMB performed better in preventing fatal crashes; whereas, TL-3 CMB was better in the case of PDO crashes.

Similarly, Table 14 lists the crash changes in the manner of collision by CMB testing level. For total head on crashes, the reductions are 63% for the TL-4 and 24% for TL-3, and for both median-related head on crashes and cross-median head on crashes, the reductions are 88% for TL-4 and TL-3.

Table 14. Manner of collision crashes by CMB testing level

Manner of Collision		TL-3 (233.1 miles) CMB Position: side of median Median Fore slope: between 1:4 & 1:6			TL-4 (42 miles) CMB Position: middle of median Median Fore Slope: At or flatter than 1:6		
		Before	**After**	**% Change**	**Before**	**After**	**% Change**
Total Crashes	Non-collision with Motor Vehicle	1782	2584	45%	583	852	46%
	Head-on	41	31	-24%	19	7	-63%
	Sideswipe Opposite Direction	23	11	-52%	8	6	-25%
Median-related Crashes	Non-collision with Motor Vehicle	476	1190	150%	134	367	174%
	Head-on	16	2	-88%	8	1	-88%
	Sideswipe Opposite Direction	11	3	-73%	5	1	-80%
Cross-median Crashes	Non-collision with Motor Vehicle	25	16	-36%	9	5	-44%
	Head-on	16	2	-88%	8	1	-88%
	Sideswipe Opposite Direction	11	3	-73%	5	1	-80%

Crash Distribution by Vehicle Types and Crash Environment

This study examined the distribution of crashes by vehicle type and environmental conditions in order to better comprehend crash patterns and contributing factors. Although these descriptive statistics do not offer a definitive analysis of the effectiveness of CMB, they do provide useful insight about the factors that could potentially lead to median-related and cross-median crashes. Table 15 shows the distribution of total, median-related, and cross-median crashes by several factors such as crash time, day of week, surface condition, weather, road geometry, and vehicle type.

Table 15. Distribution of crash by vehicle types and environmental factors

	Total Crashes				**Median-related Crashes**				**Cross-median Crashes**			
	Before		**After**		**Before**		**After**		**Before**		**After**	
Total	**7011**		**9279**		**1022**		**2198**		**91**		**35**	
	Freq.	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
Crash Time and Day												
• ***Weekday***	**5224**		**6872**		**715**		**1534**		**64**		**22**	
12:00am-2:59am	220	4.2%	292	4.2%	40	5.6%	110	7.2%	2	3.1%	0	0.0%
3:00am-5:59am	240	4.6%	369	5.4%	46	6.4%	96	6.3%	3	4.7%	0	0.0%
6:00am-8:59am	987	18.9%	1254	18.2%	125	17.5%	245	16.0%	11	17.2%	5	22.7%
9:00am-11:59am	618	11.8%	832	12.1%	93	13.0%	207	13.5%	13	20.3%	2	9.1%
12:00pm-2:59pm	874	16.7%	1086	15.8%	123	17.2%	268	17.5%	10	15.6%	4	18.2%
3:00pm-5:59pm	1215	23.3%	1643	23.9%	149	20.8%	289	18.8%	15	23.4%	5	22.7%
6:00pm-8:59pm	664	12.7%	914	13.3%	77	10.8%	190	12.4%	5	7.8%	4	18.2%
9:00pm-11:59pm	406	7.8%	482	7.0%	62	8.7%	129	8.4%	5	7.8%	2	9.1%
• ***Weekend***	**1787**		**2407**		**307**		**664**		**27**		**13**	
12:00am-2:59am	186	10.4%	192	8.0%	39	12.7%	55	8.3%	5	18.5%	0	0.0%
3:00am-5:59am	171	9.6%	251	10.4%	31	10.1%	83	12.5%	0	0.0%	4	30.8%
6:00am-8:59am	165	9.2%	238	9.9%	35	11.4%	82	12.3%	4	14.8%	2	15.4%
9:00am-11:59am	197	11.0%	303	12.6%	37	12.1%	91	13.7%	5	18.5%	2	15.4%
12:00pm-2:59pm	317	17.7%	416	17.3%	52	16.9%	91	13.7%	3	11.1%	1	7.7%
3:00pm-5:59pm	330	18.5%	459	19.1%	56	18.2%	123	18.5%	5	18.5%	2	15.4%
6:00pm-8:59pm	239	13.4%	328	13.6%	28	9.1%	85	12.8%	4	14.8%	2	15.4%
9:00pm-11:59pm	182	10.2%	220	9.1%	29	9.4%	54	8.1%	1	3.7%	0	0.0%

	Total Crashes				Median-related Crashes				Cross-median Crashes			
	Before		After		Before		After		Before		After	
Total	**7011**		**9279**		**1022**		**2198**		**91**		**35**	
	Freq.	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
Surface Condition												
Dry	5497	78.4%	6833	73.6%	755	73.9%	1320	60.1%	66	72.5%	24	68.6%
Wet	1394	19.9%	2313	24.9%	245	24.0%	829	37.7%	22	24.2%	11	31.4%
Ice/Snow/Slush	102	1.5%	112	1.2%	21	2.1%	47	2.1%	3	3.3%	0	0.0%
Other	18	0.3%	21	0.2%	1	0.1%	2	0.1%	0	0.0%	0	0.0%
Weather												
Clear	4718	67.3%	6046	65.2%	651	63.7%	1157	52.6%	58	63.7%	21	60.0%
Cloudy	1004	14.3%	1134	12.2%	135	13.2%	256	11.6%	11	12.1%	7	20.0%
Rain	1151	16.4%	1945	21.0%	211	20.6%	727	33.1%	21	23.1%	7	20.0%
Fog/Smoke	48	0.7%	37	0.4%	5	0.5%	10	0.5%	0	0.0%	0	0.0%
Snow/Sleet/Hail	60	0.9%	94	1.0%	17	1.7%	45	2.0%	1	1.1%	0	0.0%
Other	30	0.4%	23	0.2%	3	0.3%	3	0.1%	0	0.0%	0	0.0%
Road Geometry												
Straight	6390	91.1%	8655	93.3%	921	90.1%	2083	94.8%	89	97.8%	33	94.3%
Curve	607	8.7%	615	6.6%	101	9.9%	113	5.1%	2	2.2%	2	5.7%
Other	14	0.2%	9	0.1%	0	0.0%	2	0.1%	0	0.0%	0	0.0%
Vehicle Type												
Passenger Car	3048	43.5%	4236	45.7%	466	45.6%	1102	50.1%	38	41.8%	12	34.3%
Pickup truck, Van, SUV	2911	41.5%	3762	40.5%	437	42.8%	888	40.4%	46	50.5%	19	54.3%
Motorcycle	59	0.8%	71	0.8%	20	2.0%	14	0.6%	0	0.0%	0	0.0%

	Total Crashes				**Median-related Crashes**				**Cross-median Crashes**			
	Before		**After**		**Before**		**After**		**Before**		**After**	
Total	**7011**		**9279**		**1022**		**2198**		**91**		**35**	
	Freq.	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**	**Freq.**	**%**
Single unit truck	138	2.0%	128	1.4%	12	1.2%	20	0.9%	0	0.0%	1	2.9%
Large Truck	590	8.4%	834	9.0%	61	6.0%	135	6.1%	3	3.3%	0	0.0%
Other	265	3.8%	248	2.7%	26	2.5%	39	1.8%	4	4.4%	3	8.6%

The descriptive statistics are discussed below:

- ***Crash Time and Day of Week:*** During the weekdays (Monday-Friday), the highest percentage of crashes in both the pre-CMB and post-CMB periods occurred at 6:00 a.m.-8:59 a.m. and 3:00 p.m.-5:59 p.m. This trend was observed in both total and targeted crashes and can be attributed to the fact that these time intervals partially coincide with the morning and evening peak hours. In addition to that, for cross median crashes, a high percentage of crashes (20.3%) was observed during the time interval 9:00 a.m.-11:59 a.m. in the before period. On weekends (Saturday and Sunday), the interval of 12:00 p.m. to 5:59 p.m. experienced the highest percentages of total and median-related crashes. For total and median-related crashes, no significant difference in crash percentage was found for before and after CMB implementation.
- ***Surface Condition:*** The data shows that on average 22.4% (19.9% before and 24.9% after CMB) of total crashes occurred in wet conditions. However, median-related and cross-median crashes had a higher average occurrence rate of 30.85% (24.0% before, 37.7% after) and 27.8% (24.2% before, 31.4% after) in wet conditions, respectively, suggesting that wet pavement may be a contributing factor to these types of crashes.
- ***Weather:*** The observed crash analysis already showed that after CMB implementation, the median-related crashes increased significantly, almost one-third of which happened during rainy weather conditions. In contrast, the percentage of total crashes that happened during rain was only 18.7% on average (16.4% before, 21.0% after).
- ***Road Geometry:*** To investigate whether or not median-related and cross-median crashes were more frequent on horizontal curves, the distribution of crashes by road geometry was calculated. However, no direct relationship between road geometry and the targeted crashes were found for the observed data in this study.
- ***Vehicle Types:*** For this analysis, vehicles were grouped into several categories. Passenger cars and pickup trucks/vans/SUVs were grouped into separate categories because of the difference in size. Based on the MASH testing criteria, single unit trucks were separated from large trucks as the single unit trucks are tested to be stopped by TL-4 CMB. Even though a greater number of median-related crashes after the installation of CMB involved passenger cars (50.1%) compared to pickup trucks/vans/SUVs (40.4%), the percentage of these run-off roadway trucks/vans/SUVs crossing the median (54.3%) was higher than that of

passenger cars (34.3%). This suggests that trucks/vans/SUVs are more susceptible to cross-median collisions than passenger cars possibly because of their larger size and weight.

Improved Prediction Method

CMFs for total, median-related, and cross-median crashes were estimated using the improved prediction method, as explained in the Methodology section. The results are listed in Table 16, which includes not only the estimated CMF but also the standard deviation of the CMF as well as the range of the estimated CMF at 95% confidence.

Table 16. Estimated CMF for crashes using improved prediction method

	Severity	Before, $\hat{\pi}$	After, $\hat{\lambda}$	% Change	CMF, $\hat{\theta}$	Std. (CMF), $\hat{\sigma}(\hat{\theta})$	Range of CMF with 95% Confidence
Total Crashes	Fatal	106	74	-30%	0.688	0.112	(0.464, 0.912)
	Serious Injury	73	65	-11%	0.878	0.159	(0.56, 1.196)
	Moderate Injury	520	439	-16%	0.840	0.072	(0.696, 0.984)
	Complaint/possible injury	1857	1875	1%	1.006	0.064	(0.878, 1.134)
	PDO	5531	6826	23%	1.230	0.070	(1.089, 1.371)
	Total	8087	9279	15%	1.144	0.064	(1.015, 1.273)
Median-related Crashes	Fatal	52	22	-58%	0.414	0.107	(0.199, 0.628)
	Serious Injury	16	14	-13%	0.807	0.287	(0.234, 1.381)
	Moderate Injury	114	92	-19%	0.795	0.121	(0.553, 1.038)
	Complaint/possible injury	347	373	7%	1.068	0.100	(0.867, 1.268)
	PDO	649	1697	161%	2.601	0.188	(2.224, 2.978)
	Total	1179	2198	87%	1.857	0.122	(1.613, 2.102)
Cross-median Crashes	Fatal	14	0	-100%	0.000	0.000	(0, 0)
	Serious Injury	3	0	-100%	0.000	0.000	(0, 0)
	Moderate Injury	14	4	-71%	0.266	0.142	(0, 0.55)
	Complaint/possible injury	31	6	-81%	0.185	0.081	(0.023, 0.347)
	PDO	43	25	-41%	0.569	0.146	(0.277, 0.861)
	Total	105	35	-67%	0.329	0.067	(0.195, 0.463)

While the crash reduction trends are similar to the observed crash analysis, the estimated CMF by the improved safety model reflects a bigger decline in fatal and injury crashes than that from the observed crashes. The results from the improved safety model clearly indicate that CMB can reduce the cross-median crashes at all severity levels because the upper boundaries of the estimated CMFs are less than one. At 95% confidence, the upper bound of estimated CMF for PDO is 0.861, and the rest is less than or equal to 0.55. These impressive numbers validate the CMB effectiveness. The higher than one CMF for total median-related crashes and the highest CMF, 2.601 for the median-related PDO crashes again indicate that CMB can induce more non-injury crashes while reducing the severe crashes. Figure 14 graphically summarizes the estimated CMF and CMF's upper and lower bounds by crash severity for the total crashes and the two targeted crashes.

Figure 14. CMF by crash severity for total and two targeted crashes

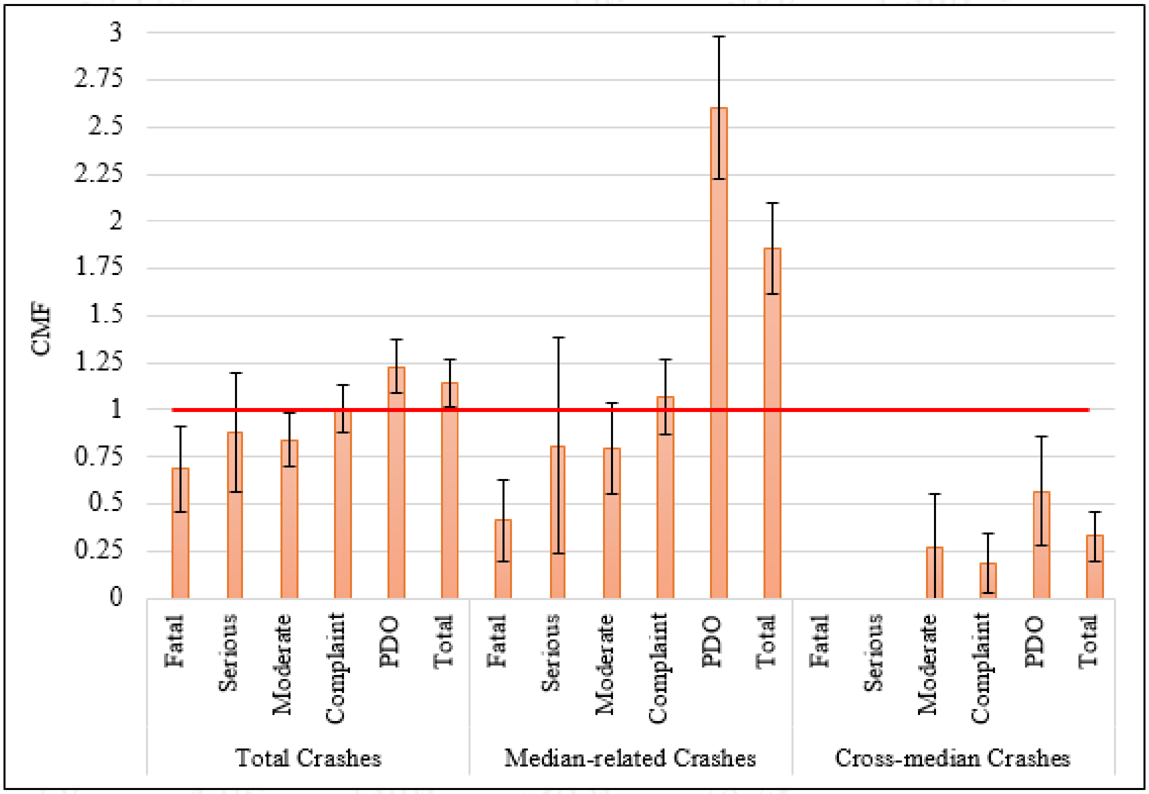


Table 17 presents the summary of results compared between the observed crashes and estimated crashes using the improved prediction model. The results from the improved prediction model are not only reliable but also give the distribution of the CMF based on the estimated standard deviation.

Table 17. Summary of observed and estimated crashes

	Observed Crash Analysis				Improved Prediction Model					
	Crash by Severity	Before	After	% Change	Before, $\hat{\pi}$	After, $\hat{\lambda}$	% Change	CMF, $\hat{\theta}$	Std.(CMF), $\hat{\sigma}(\hat{\theta})$	Range of CMF with 95% Confidence
Total Crashes	Fatal	92	74	-20%	106	74	-30%	0.688	0.112	(0.464, 0.912)
	Serious Injury	63	65	3%	73	65	-11%	0.878	0.159	(0.56, 1.196)
	Moderate Injury	451	439	-3%	520	439	-16%	0.840	0.072	(0.696, 0.984)
	Complaint/possible injury	1610	1875	16%	1857	1875	1%	1.006	0.064	(0.878, 1.134)
	PDO	4795	6826	42%	5531	6826	23%	1.230	0.070	(1.089, 1.371)
	Total	7011	9279	32%	8087	9279	15%	1.144	0.064	(1.015, 1.273)
Median-related Crashes	Fatal	45	22	-51%	52	22	-58%	0.414	0.107	(0.199, 0.628)
	Serious Injury	14	14	0%	16	14	-13%	0.807	0.287	(0.234, 1.381)
	Moderate Injury	99	92	-7%	114	92	-19%	0.795	0.121	(0.553, 1.038)
	Complaint/possible injury	301	373	24%	347	373	7%	1.068	0.100	(0.867, 1.268)
	PDO	563	1697	201%	649	1697	161%	2.601	0.188	(2.224, 2.978)
	Total	1022	2198	115%	1179	2198	86%	1.857	0.122	(1.613, 2.102)
Cross-median Crashes	Fatal	12	0	-100%	14	0	-100%	0.000	0.000	(0, 0)
	Serious Injury	3	0	-100%	3	0	-100%	0.000	0.000	(0, 0)
	Moderate Injury	12	4	-67%	14	4	-71%	0.266	0.142	(0, 0.55)
	Complaint/possible injury	27	6	-78%	31	6	-81%	0.185	0.081	(0.023, 0.347)
	PDO	37	25	-32%	43	25	-41%	0.569	0.146	(0.277, 0.861)
	Total	91	35	-62%	105	35	-67%	0.329	0.067	(0.195, 0.463)

CMB Maintenance and Repair Information

This section provides information on the maintenance/repair costs associated with CMB and repair practices adopted in Louisiana.

When a cable barrier is damaged due to traffic crashes in any of the districts, the repair is done either by in-house crews of that district or by contractors. However, the criteria for determining whether to employ in-house workers or contractors vary across districts. Based on the limited information provided by several DOTD districts, CMB repairs are assigned to contractors whenever more than 10 to 14 posts are damaged and whenever cable re-tensioning or end treatment is required. Generally, in-house workers perform the repairs only if the extent of the repair is small. This is because the utilization of district crews for large-scale CMB repairs necessitates the devotion of time, funds, and labor.

For in-house CMB repairs, the district budget is utilized, while the contracted repairs are funded by the DOTD Section 42. As a result, the cost for in-house and contracted repairs had to be estimated based on the data from two separate sources. In this study, the repair data for the contracted repairs was collected from the DOTD Section 42 and the in-house repair information was provided by several individual districts. Based on the information from 2015 to 2021, the annual contracted repair cost per mile was estimated to be $4,206. It should be noted that despite the fact that this estimate is made for all DOTD districts, not all districts have repair cost information dating back to 2015 because they began installing cable barriers at a later date. The estimated in-house annual repair cost was $1,278. This estimation is based on the information provided by three DOTD districts for 2015-2021. When combined, the total annual repair cost, which includes both contracted and in-house repairs, was calculated to be $5,414 per mile.

Findings from Benefit-Cost Analysis

This section presents the findings of the benefit-cost analysis for the CMB segments. The estimated benefits and the estimated costs are presented first, followed by the calculation of B/C ratio using different discount rates.

Estimated Benefits

As the construction years for CMB segments used in this study differ, the number of years in operation varies; therefore, the benefit for each segment was estimated individually. In addition, benefits from reducing total, median-related, and cross-median crashes were calculated separately. For all monetary conversions in this section, a discount rate of 3% was used. Table 18 presents the estimated benefit for all segments for total crashes. The methodology section includes more details on how these values were estimated.

Table 18. Estimation of benefit for total crashes using economic unit crash costs

Segment	Years in Operation (up to the end of 2021)	Total Crashes	
		Annual Monetary Value of Crash Reduction	Total Benefit (2021-dollar)
1	12	$1,508,988.20	$18,107,858
2	12	$3,535,586.27	$42,427,035
3	10	$199,990.50	$1,999,905
4	10	$1,413,716.98	$14,137,170
5	9	$70,302.15	$632,719
6	9	$328,650.00	$2,957,850
7	9	$786,914.41	$7,082,230
8	9	$702,148.00	$6,319,332
9	9	$28,766.42	$258,898
10	9	-$375,066.47	-$3,375,598
11	8	-$61,817.77	-$494,542
12	8	-$47,259.49	-$378,076
13	7	-$2,174.50	-$15,221
14	7	$437,669.99	$3,063,690
15	7	$766,189.52	$5,363,327
16	7	$751,430.65	$5,260,015
17	7	$5,946.28	$41,624
18	7	-$65,988.32	-$461,918
19	7	$1,102,552.03	$7,717,864
20	6	$474,524.23	$2,847,145
21	6	$466,461.37	$2,798,768
22	5	$2,613,051.55	$13,065,258
23	4	$462,652.21	$1,850,609
		Total Benefit	**$131,205,941**

This study also included the estimation of benefits associated with the targeted crashes. Economic benefits from saving median-related crashes and cross-median crashes are presented in Table 19.

Table 19. Estimation of benefit for targeted crashes using economic unit crash costs

Segment	Years in Operation (up to the end of 2021)	Annual Monetary Value of Crash Reduction (Annual Benefit)		Total benefits (2021-dollars)	
		Median-related	Cross-median	Median-related	Cross-median
1	12	$1,153,603.41	$739,644.59	$13,843,241	$8,875,735
2	12	$3,937,204.11	$2,429,880.06	$47,246,449	$29,158,561
3	10	$364,591.33	$0.00	$3,645,913	$0
4	10	-$97,242.21	$99,102.92	-$972,422	$991,029
5	9	$238,337.86	$198,155.15	$2,145,041	$1,783,396
6	9	$677,301.68	$18,055.24	$6,095,715	$162,497
7	9	$639,745.68	$781,471.64	$5,757,711	$7,033,245
8	9	$543,219.24	$811,979.75	$4,888,973	$7,307,818
9	9	-$14,075.96	$0.00	-$126,684	$0
10	9	-$65,707.93	$242,529.47	-$591,371	$2,182,765
11	8	$0.00	$0.00	$0	$0
12	8	$0.00	$0.00	$0	$0
13	7	-$15,136.39	$0.00	-$105,955	$0
14	7	$135,913.96	$4,074.82	$951,398	$28,524
15	7	-$244,153.91	$62,315.35	-$1,709,077	$436,207
16	7	$624,189.88	$216,210.39	$4,369,329	$1,513,473
17	7	-$16,642.84	$0.00	-$116,500	$0
18	7	-$103,066.93	$48,449.14	-$721,468	$339,144
19	7	-$95,405.42	$775,755.07	-$667,838	$5,430,285
20	6	$313,509.25	$767,605.43	$1,881,056	$4,605,633
21	6	$366,097.78	$678,971.00	$2,196,587	$4,073,826
22	5	$2,070,282.64	$1,396,371.33	$10,351,413	$6,981,857
23	4	$380,689.64	$678,971.00	$1,522,759	$2,715,884
			Total Benefit	**$99,884,269**	**$83,619,879**

In addition to the economic unit crash costs, the comprehensive crash costs were also utilized for monetizing the benefits of CMB. Table 20 shows the benefits for total and targeted crashes that are estimated using the comprehensive unit crash costs.

Table 20. Estimation of benefit for total and targeted crashes using comprehensive unit crash costs

Segment	Years in Operation (up to the end of 2021)	Total Benefits		
		Total Crashes	Median-related Crashes	Cross-median Crashes
1	12	$115,078,173	$88,793,300	$51,157,150
2	12	$359,897,673	$366,170,538	$158,618,858
3	10	$12,873,436	$23,554,241	$0
4	10	$121,689,144	$63,434,738	$2,327,688
5	9	$12,943,454	$21,931,276	$6,860,407
6	9	$23,616,636	$43,156,724	$257,378
7	9	$48,381,337	$42,156,260	$38,110,597
8	9	$52,075,703	$45,219,754	$40,316,753
9	9	$15,732,444	$1,138,917	$0
10	9	-$8,257	$1,277,369	$8,367,889

Segment	Years in Operation (up to the end of 2021)	Total Benefits		
		Total Crashes	Median-related Crashes	Cross-median Crashes
11	8	$355,611	$0	$0
12	8	-$385,527	$0	$0
13	7	-$15,221	-$105,955	$0
14	7	$33,568,619	$15,313,236	$28,524
15	7	$37,858,426	$13,264,066	$657,596
16	7	$33,769,652	$33,472,213	$5,536,055
17	7	$228,410	-$122,657	$0
18	7	$93,550	-$276,988	$1,201,009
19	7	$52,752,514	$16,820,132	$30,242,037
20	6	$27,582,761	$27,805,230	$25,872,848
21	6	$17,474,309	$14,146,861	$24,475,792
22	5	$121,084,425	$102,839,768	$41,037,845
23	4	$18,727,698	$10,189,647	$16,317,195
	Total Benefit	**$1,105,374,971**	**$930,178,669**	**$451,385,620**

One of the primary concerns regarding CMB is that it may increase the number of less severe and PDO crashes, resulting in increased crash costs. This effect is illustrated by the negative benefit values for some of the segments in the preceding tables. Even though several of the 23 segments had negative benefits, the overall benefit was determined to be positive.

Estimated Costs

The installation cost and the annual repair cost for each segment were estimated and then converted to 2021-monetary value using a discount rate of 3%. The estimated costs are shown in Table 21.

Table 21. Estimation of costs for the cable median barrier segments

Segment	Length (miles)	Years in Operation (up to the end of 2021)	Estimated Installation Cost	Installation cost converted to 2021-dollars	Annual repair cost	Total repair cost in 2021-dollars
1	6.87	12	$1,000,000	$1,425,761	$37,687	$452,244
2	30.21	12	$5,380,362	$7,671,110	$165,660	$1,987,914
3	0.51	10	$66,368	$89,194	$2,802	$28,024
4	17.82	10	$2,313,805	$3,109,560	$97,700	$977,000
5	2.69	9	$272,517	$355,573	$14,758	$132,820
6	2.54	9	$256,921	$335,224	$13,913	$125,219
7	6.87	9	$695,622	$907,629	$37,671	$339,035
8	11.80	9	$1,195,287	$1,559,579	$64,729	$582,564
9	1.89	9	$191,501	$249,866	$10,371	$93,335
10	1.15	9	$116,865	$152,483	$6,329	$56,958
11	0.44	8	$113,368	$143,612	$2,413	$19,304

Segment	Length (miles)	Years in Operation (up to the end of 2021)	Estimated Installation Cost	Installation cost converted to 2021-dollars	Annual repair cost	Total repair cost in 2021-dollars
12	0.27	8	$69,567	$88,125	$1,481	$11,846
13	0.20	7	$169,644	$208,641	$1,080	$7,563
14	13.48	7	$1,607,003	$1,976,411	$73,943	$517,599
15	17.36	7	$2,068,735	$2,544,283	$95,188	$666,318
16	5.96	7	$1,008,754	$1,240,640	$32,696	$228,875
17	0.32	7	$54,481	$67,005	$1,766	$12,361
18	2.80	7	$473,075	$581,823	$15,334	$107,336
19	17.68	7	$2,991,914	$3,679,676	$96,976	$678,833
20	60.28	6	$7,758,938	$9,264,578	$330,573	$1,983,439
21	7.65	6	$1,235,312	$1,475,027	$41,932	$251,591
22	56.00	5	$9,204,415	$10,670,440	$307,101	$1,535,505
23	10.21	4	$1,644,838	$1,851,280	$55,993	$223,972
Total				$49,647,519		$11,019,657
				Total Cost		**$60,667,176**

Estimated Benefit-Cost Ratio

Following the estimation of benefits and costs, the B/C ratio for the CMB segments was calculated by taking the ratio of the total benefit to the total cost. Separate B/C ratios were calculated for total crashes, median-related crashes, and cross-median crashes. The estimated B/C ratios are shown in Table 22.

Table 22. Estimation of benefit-cost ratios for economic unit crash costs

	Estimated Total Benefit (Using economic crash costs)	Estimated Total Cost	Estimated B/C Ratio
Total Crashes	$131,205,941	$60,667,176	2.163
Median-related Crashes	$99,884,269		1.646
Cross-median Crashes	$83,619,879		1.378

The B/C ratio was found to be higher than 2 for total and higher than 1.5 for median-related crashes (2.163 and 1.646, respectively), demonstrating the remarkable cost-effectiveness of CMB. Taking into account only the reduction in cross-median crashes, the predicted B/C ratio (1.378) was still more than one, indicating that the benefits exceeded the cost. As cross-median crashes were much less frequent in the before years, the cross-median crash reduction in terms of crash frequency was similarly smaller, resulting in a lower B/C ratio than that of the other categories of crashes.

The B/C ratios were also estimated utilizing the Louisiana-specific comprehensive crash costs and compared to the ratios calculated using the economic crash costs. Table 23 shows the B/C ratios estimated using the comprehensive unit crash costs.

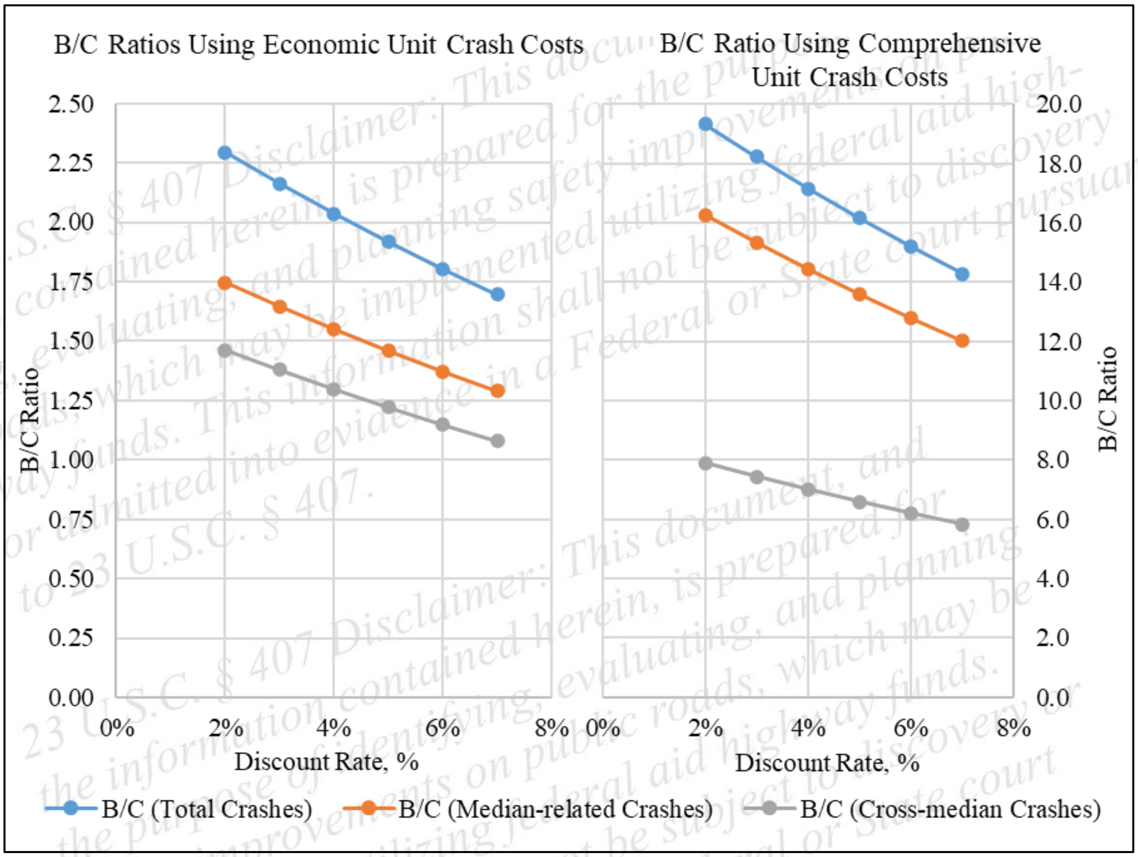
Table 23. Estimation of benefit-cost ratios for comprehensive unit crash costs

	Estimated Total Benefit (Using comprehensive crash costs)	Estimated Total Cost	Estimated B/C Ratio
Total Crashes	$1,105,374,971	$60,667,176	18.220
Median-related Crashes	$930,178,669		15.332
Cross-median Crashes	$451,385,620		7.440

Using the comprehensive crash unit costs, the B/C ratios for total, median-related, and cross-median collisions were found to be 18.220, 15.332, and 7.440, respectively, which is a significant improvement from the estimates derived using the economic crash costs. Because the comprehensive crash cost takes into account the monetary value of the lost quality of life due to death or injury, using it increases the unit cost of fatal and injury collisions. However, the unit cost of PDO crashes remains the same as they are not linked to any casualties or injuries. As a result, the benefit estimates from reducing fatality and injury crashes are much larger than the cost estimates from increased PDO crashes, yielding significantly higher B/C ratios.

As the estimation of benefit and cost included conversion to 2021-monetary values, the value of B/C ratio depends on the discounting rate. The discount rate normally ranges from 3% to 7% according to the BCA guidelines. The B/C ratios for different discount rates are presented in Figure 15.

Figure 15. Benefit-cost ratio for different discount rates



In this study, discount rates were used to calculate the present value of money that was earned or spent in the past. The present value represents the equivalent value of that historical benefit or cost in today's dollars (2021-dollars). With an increase in the discount rate, the initial installation cost incurred in the past is amplified when converted to present worth. However, since the annual benefits were estimated using present-year unit costs and did not need any conversion, they were not affected by the discount rate. As a consequence, the benefit-to-cost ratio decreased as the discount rate increased.

Conclusions

With a carefully designed data analysis scheme and improved safety prediction model, this research investigated the CMB effectiveness and developed the CMFs by crash severity and three types of crashes, namely total, median-related, and cross-median crashes. The analysis results demonstrate that CMB can effectively improve freeway safety in the following cases:

- Reducing all fatal and serious injury crashes involving cross-median vehicles (100% reduction)
- Significantly reducing moderate-injury, possible-injury, and PDO crashes (71%, 81%, and 41%) for cross-median vehicles
- Significantly reducing median-related fatal, serious injury, and moderate injury crashes (58%, 13%, and 19%)
- Reducing 88% of head-on crashes involving cross-median vehicles

The estimated impressive crash modification factors for the targeted crashes and their corresponding standard deviation indicate the assurance of crash reductions after the implementation of CMB. At 95% confidence, the upper bound of estimated CMF for all severity levels of cross-median crashes was less than one, which demonstrates a notably impressive performance of CMB.

The comparison between TL-4 and TL-3 CMB showed that TL-4 CMB performed slightly better in preventing cross-median crashes as well as median-related fatalities and more severe injuries. The descriptive statistics showed that rainy weather and wet pavement contributed to the increase in median-related crashes. Additionally, pickup trucks/van/SUVs were found to be more susceptible to cross-median crashes compared to passenger cars.

Contrary to the remarkable reductions in cross-median crashes, there is a 201% rise in observed median-related PDO crashes, which translates to an estimated CMF of 2.601, within an upper and lower bound of 2.224 and 2.978. The increased PDO crashes are a result of reduced clear zone, particularly at CMB locations close to the shoulder. It was necessary to investigate whether or not this trade-off between eliminating high severity crashes and increasing non-injury crashes is acceptable from both safety and economic point of view, which leads to the benefit-cost analysis of the CMB segments. The benefit-cost analysis for economic crash costs yielded B/C ratios of 2.163, 1.646, and 1.378 for total, median-related, and cross-median crashes, respectively. When using the comprehensive crash unit costs, the B/C ratios for total, median-related, and cross-median collisions were found to be 18.220, 15.332, and 7.440, respectively.

The B/C ratio values were found to be greater than one, demonstrating that CMB are not only lifesaving but also cost-effective countermeasures.

The report also documented information regarding CMB effectiveness in some other states. The findings from this research are almost analogous to the results published in these previous studies. Last of all, installation, maintenance, and repair guidelines and costs associated with CMB in different states are also documented in the literature review.

Recommendations

Based on the comprehensive analysis of CMB on Louisiana freeways, this project has revealed that CMB is an effective and economically justified crash countermeasure. Thus, DOTD should continue implementation of CMB along the state's rural interstate systems where feasible. Additionally, as this study encountered difficulties in collecting repair and maintenance data from districts, DOTD should consider developing standard operating procedures and timelines for the repair and maintenance of CMB. All districts need to provide similar performance and achieve comparable results in the repair and maintenance of this roadside safety feature.

Acronyms, Abbreviations, and Symbols

Term	Description
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BCA	Benefit-Cost Analysis
CARTS	Center for Analytics & Research in Transportation Safety
CMB	Cable Median Barriers
CMC	Cross-Median Crash
CMF	Crash Modification Factor
DOT	Department of Transportation
DOTD	Department of Transportation and Development
EB	Empirical Bayes
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FFY	Federal Fiscal Year
FY	Fiscal Year
HSIP	Highway Safety Improvement Program
LTRC	Louisiana Transportation Research Center
MASH	Manual for Assessing Safety Hardware
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
QALY	Quality-Adjusted Life Years
RTM	Regression to the Mean
RTL	Run to the Left
SHSP	Strategic Highway Safety Plan
SPF	Safety Performance Function
TL	Testing Level

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