Safety Evaluation of Cable Median Barriers in Combination with Rumble Strips on the Inside Shoulder of Divided Roads

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this pooled fund study in 2005 to conduct research on the effectiveness of the safety improvements identified by the *National Cooperative Highway Research Program Report 500* guides as part of implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan. The ELCSI-PFS research provides a crash modification factor and benefit-cost (B/C) economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member States.

This study evaluated application of cable median barriers in combination with rumble strips on the inside shoulder of divided roads. This strategy is intended to reduce the frequency of cross-median crashes, which tend to be very severe. Data were obtained in Illinois, Kentucky, and Missouri. In Illinois and Kentucky, cable median barriers were introduced many years after the inside shoulder rumble strips were installed; therefore, the evaluation determined the safety effect of implementing cable barriers along sections that already had rumble strips. Conversely, in Missouri, the inside shoulder rumble strips and cable barrier were implemented around the same time. The evaluation in Missouri determined the combined safety effect of both strategies. The combined Illinois and Kentucky results indicate an increase in total crashes but a decrease in injury and fatal crashes and head-on plus opposite-direction sideswipe crashes (used as a proxy for cross-median crashes). The results from Missouri for total and injury and fatal crashes were very similar to the combined Illinois and Kentucky results. However, the reduction in cross-median crashes in Missouri was much more dramatic. The economic analysis for B/C ratios shows that this strategy is cost beneficial.

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Research and Development

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16. Abstract
The Development of Crash Modification Factors program conducted the safety evaluation of cable median barriers in combination with rumble strips on the inside shoulder of divided roads for the Evaluation of Low Cost Safety Improvements Pooled Fund Study. This study evaluated safety effectiveness of cable median barriers in combination with rumble strips on the inside shoulders of divided roads. This strategy is intended to reduce the frequency of cross-median crashes, which tend to be very severe. Geometric, traffic, and crash data were obtained for divided roads in Illinois, Kentucky, and Missouri. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before–after analysis was conducted using reference groups of untreated roads with characteristics similar to those of the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. In Illinois and Kentucky, cable median barriers were introduced many years after the inside shoulder rumble strips were installed; therefore, the evaluation determined the safety effect of implementing cable barriers along sections that already had rumble strips. Conversely, in Missouri, the inside shoulder rumble strips and cable barrier were implemented around the same time. Hence, the evaluation in Missouri determined the combined safety effect of inside shoulder rumble strips and cable barriers. The combined Illinois and Kentucky results indicate about a 27-percent increase in total crashes; a 24-percent decrease in fatal, incapacitating, non-incapacitating, and possible injury crashes; a 22-percent decrease in fatal, incapacitating, and non-incapacitating injury crashes; and a 48-percent decrease in head-on plus opposite-direction sideswipe crashes (used as a proxy for cross-median crashes). The results from Missouri for total and injury and fatal crashes were very similar to the combined Illinois and Kentucky results. However, the reduction in cross-median crashes in Missouri was much more dramatic, showing a 96-percent reduction (based on cross-median indicator only) and an 88-percent reduction (based on cross-median indicator plus head-on). The economic analysis for benefit-cost ratios shows that this strategy is cost beneficial.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
B/C	benefit-cost
CMF	crash modification factor
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
GIS	geographic information system
HSIS	Highway Safety Information System
IDOT	Illinois Department of Transportation
KABCO	Scale used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only)
KYTC	Kentucky Transportation Cabinet
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
PDO	property damage only
ROR	run-off-road
SE	standard error
SPF	safety performance function
SVROR	single-vehicle run-off-road
USDOT	U.S. Department of Transportation
VSL	value of a statistical life

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit-cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study, which functions under the DCMF program. This study evaluated the application of cable median barriers in combination with rumble strips on the inside shoulders of divided roads. This strategy is intended to reduce the frequency of crashes by reducing the frequency and severity of cross-median crashes.

The research team obtained geometric, traffic, and crash data at treated multilane divided roads in Illinois, Kentucky, and Missouri. To account for potential selection bias and regression- to-the-mean, the research team conducted an empirical Bayes (EB) before–after analysis using reference groups of untreated multilane lane roads with characteristics similar to those of the treated sites. The analysis of the treatment sites in Missouri required a slightly different approach because Missouri installed cable median barriers and inside shoulder rumble strips on a systemwide basis on certain types of roads. As a result, there was no suitable reference group without the treatment for this road type. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment.

Illinois and Kentucky introduced cable median barriers many years after the inside shoulder rumble strips were installed; therefore, the evaluation determined the safety effect of implementing cable barrier along sections that already had rumble strips. Missouri implemented the inside shoulder rumble strips and cable barriers around the same time; as a result, the Missouri evaluation determined the combined safety effect of inside shoulder rumble strips and cable barriers. The combined Illinois and Kentucky results indicate about a 27-percent increase in total crashes, a 22- to 24-percent decrease in injury and fatal crashes (depending on whether injury crashes were defined as KAB or KABC), and a 48-percent decrease in cross-median crashes (defined as head-on plus opposite-direction sideswipe crashes).[1] The results from Missouri for total and injury and fatal crashes were very similar to the combined Illinois and Kentucky results. However, the reduction in cross-median crashes in Missouri was more dramatic, with a 96-percent reduction (based on cross-median indicator only) and an 88-percent reduction (based on cross-median indicator plus head-on). The research team estimates the B/C

[1]The KABCO Scale is used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only).

ratios to be about 8.28 for the treatment in Illinois and Kentucky and 4.14 for the treatment in Missouri.

CHAPTER 1. INTRODUCTION

This chapter presents background information on the strategy of using cable median barriers and shoulder rumble strips, the goals of the study, and a review of the existing literature on the safety effects of cable median barriers, shoulder rumble strips, and the combination of the two treatments.

BACKGROUND ON STRATEGY

The United States began using cable median barriers in the 1960s as a treatment for preventing cross-median crashes. Initially, the design of the cable barriers was a low-tension type. Later, it became more common for States to use high-tension cable barriers. Villwock et al. reported the primary advantage of high-tension cable barrier as the ability to withstand multiple hits before requiring repair.(1) Many States have begun to use cable median barriers in place of more rigid (e.g., concrete) barriers. They have cited the following reasons:

- Contain vehicles instead of redirecting them into traffic; up to 95 percent of vehicles are contained.
- Are less expensive to install and maintain except for the danger of snow plow damage.
- Eliminate snow accumulation.
- Are environmentally non-intrusive and aesthetically pleasing and blend in with the terrain.

Although there are significant advantages to cable barriers, States have cited some disadvantages, including the following:

- Multiple studies indicate an increase in crash frequency. One study reported an increase in the injury crash rate, although the period for analysis was limited to 16 months.
- Penetrating the barrier is possible by under-riding or over-riding. The identified causes of under-riding include location of the barrier on a slope and having too large an opening between the cable and the ground caused by the presence of a ditch. One of the causes of over-riding is hitting a post.
- There are conflicting results regarding whether a cable barriers can stop a heavy truck.
- Considerable deflection upon impact prohibits the use of cable barrier in narrow medians. This concern is particularly justified on curves, where the deflection can be larger than on straight segments.(1)

The purpose of introducing shoulder rumble strips is to reduce the frequency of run-off-road (ROR) crashes. Although agencies have conducted research into the performance of cable median barriers and shoulder rumble strips (specifically, rumble strips on the outside shoulder) separately, very few studies have looked at the combination of cable median barriers with inside shoulder rumble strips.

BACKGROUND ON STUDY

In 1997, the American Association of State Highway and Transportation Officials Standing Committee on Highway Traffic Safety—with the assistance of FHWA, the National Highway Traffic Safety Administration, and the Transportation Research Board Committee on Transportation Safety Management—met with safety experts in the field of driver, vehicle, and highway issues from various organizations to develop a strategic plan for highway safety. These participants developed 22 key areas that affected highway safety.

The National Cooperative Highway Research Program (NCHRP) then published a series of guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses 1 of the 22 emphasis areas and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Each strategy is designated as proven, tried, or experimental. Many of the strategies discussed in these guides have not been rigorously evaluated; approximately 80 percent of the strategies are considered tried or experimental.

FHWA organized a pooled fund study of 40 States to evaluate low-cost safety strategies as part of this strategic highway safety effort. The purpose of the FHWA Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELSCI-PFS) is to evaluate the safety effectiveness of several tried and experimental, low-cost safety strategies through scientifically rigorous crash-based studies. The ELSCI-PFS selected the use of cable median barriers in combination with rumble strips on the inside shoulder on divided roads as a strategy to evaluate as part of this effort.

LITERATURE REVIEW

This review is summarized in three sections: (1) safety effects of cable median barriers, (2) safety effects of shoulder rumble strips, and (3) safety effects of cable median barriers along with shoulder rumble strips.

Safety Effects of Cable Median Barriers

Villwock, Blond, and Tarko studied the effects of cable barriers on rural interstate highways.[1] They used data from eight States that had installed both low- and high-tension cable median barriers. Their data included 70 mi of treated roadway and 360 mi of control roadway (i.e., sections that did not receive cable barriers). They used a combination of before–after EB analysis with negative binomial and logistic regression to determine the effect on three types of crashes—single-vehicle, multiple-vehicle same-direction, and multiple-vehicle opposite-direction (cross-median or crossover crashes). Their results showed that the cable barriers affected the crash types differently. The overall crash modification factor (CMF) for single-vehicle crashes was 1.83, suggesting an increase in this crash type. The CMF for multiple-vehicle opposite-direction crashes was 0.06, suggesting an effective reduction of this crash type. They did not see a significant effect on multiple-vehicle same-direction crashes.[1]

Cooner et al. evaluated installations of cable median barriers in Texas.(2) Cross-median crashes resulted in a substantial percentage of interstate highway fatalities, which led to widespread installation of cable barriers. This research team had difficulty conducting a rigorous safety evaluation of the cable barrier; owing to a changeover in the management of crash data, the data were unavailable for the years preceding and following the installation. They relied on a simple before–after examination by the Texas Department of Transportation Traffic Operations Division of 407 mi that received cable barriers. This examination, which did not account for the potential effects due to regression-to-the-mean, examined at 1 year before and 1 year after installation at the treated sites only. They observed that head-on fatal crashes decreased from 14 to 1 during the study period.(2)

Chandler reported on the benefits of cable median barriers in Missouri.(3) In 2002, the Missouri Department of Transportation (MoDOT) began to install cable barriers on freeways with median widths of less than 60 ft, focusing on two main interstate highways. From 2002 to 2006, a total of 179 mi of cable barriers were installed, with most of the installations occurring in 2005. From an examination of fatalities on one interstate highway, Chandler concluded that the installation of 179 mi of cable median on freeways nearly eliminated cross-median fatalities. Figure 1 and Figure 2 show a comparison between miles of cable barriers installed and cross-median fatalities. The cross-median fatalities decreased from a high of 24 per year to 2 per year by 2006, a decrease of 92 percent. Chandler concluded that cable median barriers were an effective safety tool in Missouri.(3)

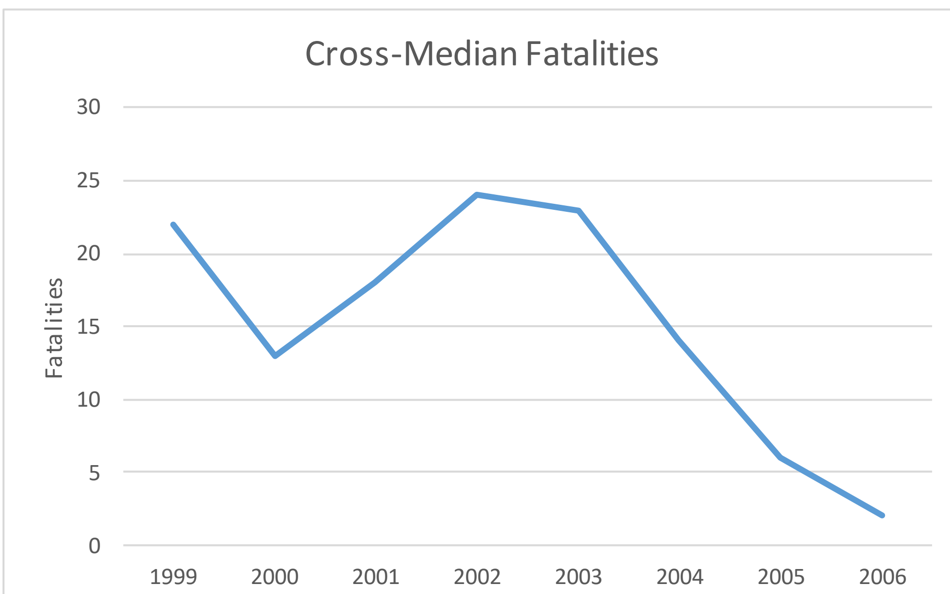

Figure 1. Graph. Cross-median fatalities in Missouri.(3)

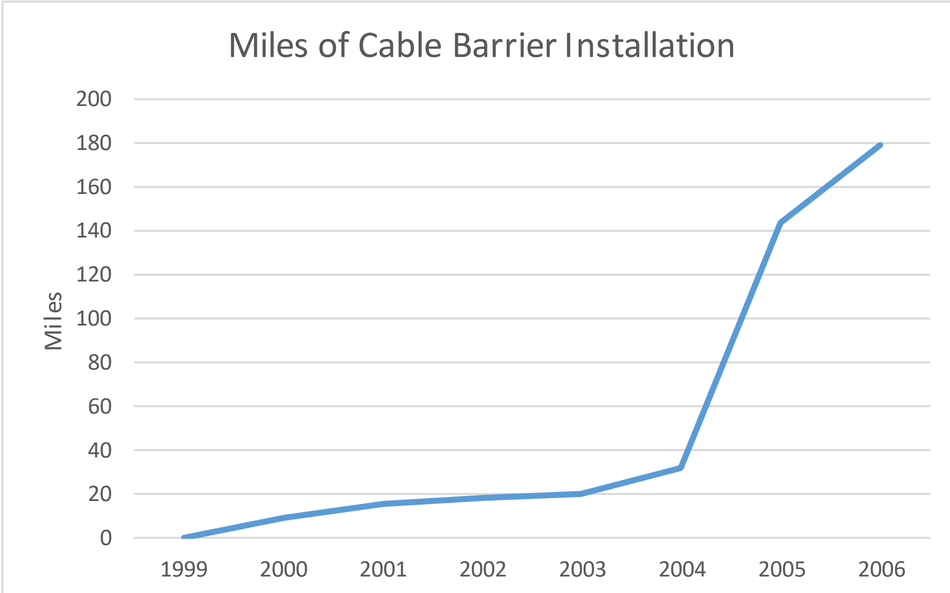

Figure 2. Graph. Miles of cable barrier installation in Missouri.[(3)]

Hunter et al. evaluated the safety of three-strand cable median barriers using data from a section of I-40 outside Raleigh, NC.[(4)] The research team used data from 1990 to 1997 to conduct the analysis. The treatment population was the 8.5-mi section of Interstate 40, and the reference population was identified as the entire North Carolina Interstate System (except for those sections treated with cable median barriers). The research team also identified a secondary reference population to account for discrepancies in traffic volumes between the entire reference population and the treatment segment. They identified this subpopulation as a subset of sites where the annual average daily traffic (AADT) exceeded 50,000 vehicles per day. They developed several regression models, assuming a negative binomial error structure for many of the models, to estimate the effects of the installation of the cable median barriers. The models accounted for year-to-year variations (e.g., AADT and weather conditions).

Results showed that the installation of the three-strand cable median barriers was followed by a reduction in fatal and serious injury crashes. ROR left, hit-fixed-object, and rear-end crashes increased with the installation of the cable median barriers. The models predicted that ROR head-on crashes (i.e., the primary target for the treatment) would decrease with installation of the cable median barriers. However, the research team was not able to confirm this hypothesis because this particular crash type was very rare.[(4)]

Milton and Albin reported on the experience with using cable median barriers in Washington State.[(5)] The authors calculated the total societal benefit of cable barriers as $420,000/mi annually. Their examination of the Washington State Department of Transportation bid history indicated a cost of cable median barriers at $44,000/mi, with an annual maintenance cost of $2,750/mi.[(5)]

Safety Effects of Shoulder Rumble Strips

Griffith studied the safety effects of rumble strips on freeway shoulders in California and Illinois.[(6)] These States installed shoulder rumble strips on the inside and outside shoulders of the highway in both directions. Griffith examined crash data for 280 mi of freeway in Illinois and 120 mi of freeway in California with rumble strip installations. The author conducted a before–after analysis to determine the effect on crashes. Because the author selected the installation sites based on their listing in the resurfacing schedule rather than based on high crash frequency, there was no need to account for regression-to-the-mean bias. Thus, Griffith used a before–after design with a comparison group to account for trends and found that shoulder rumble strips reduced single-vehicle run-off-road (SVROR) crashes by 18.3 percent on all freeways and 21.1 percent on rural freeways. The author did not conduct a separate analysis to determine the effect of installing rumble strips on only the inside shoulder.(6)

Torbic at al. conducted one of the most recent studies on rumble strips under NCHRP Project 17-32.(7) The authors of the report included a review of prior research on the safety impacts of shoulder rumble strips. Table 1 shows an adaptation of table 4 of their report, which summarizes 20 studies that calculated the effect of shoulder rumble strips on crashes (including the study by Griffith previously discussed).(6,7) Although there was no specific breakout of inside versus outside shoulder rumble strip effects, most studies in the list used roadway facility types that were divided (i.e., interstate highways, freeways and other divided highways). Most studies used SVROR crashes as the target crash type. The most common study design was before–after, including naive before–after and before–after with a comparison group.

Table 1. Summarized results of studies that calculated the effect of shoulder rumble strips on crashes (adapted from Torbic et al.).[7]

State	Type of Facility	Type of Collision Targeted	Percent Change in Target Collision Frequency from Application of SRS (Standard Deviation)	Type of Analysis
Arizona	Interstate	SVROR	−80	Cross-sectional comparison
California	Interstate	SVROR	−49	Before–after with comparison sites
California	Interstate	Total	−19	Before–after with comparison sites
Connecticut	Limited-access roadways	SVROR	−32	Before–after with comparison sites
Florida	Not provided	Fixed object	−41	Naive before–after
Florida	Not provided	Ran-into-water	−31	Naive before–after
Illinois and California	Freeways	SVROR (total)	−18 (± 6.8)	Before–after with marked comparison sites and a comparison group
Illinois and California	Freeways	SVROR (injury)	−13 (± 11.7)	Before–after with marked comparison sites and a comparison group
Illinois and California	Rural freeways	SVROR (total)	−21.1 (± 10.2)	Before–after with marked comparison sites and a comparison group
Illinois and California	Rural freeways	SVROR (injury)	−7.3 (±15.5)	Before–after with marked comparison sites and a comparison group
Kansas	Freeways	SVROR	−34	Unknown
Maine	Rural freeways	Total	Inconclusive	Before–after with comparison sites
Massachusetts	Not provided	SVROR	−42	Unknown
Michigan	Not provided	SVROR	−39	Cross-sectional comparison
Minnesota	Rural multilane divided highways	Total	−16	Naive before–after
Minnesota	Rural multilane divided highways	Injury	−17	Naive before–after

State	Type of Facility	Type of Collision Targeted	Percent Change in Target Collision Frequency from Application of SRS (Standard Deviation)	Type of Analysis
Minnesota	Rural multilane divided highways	SVROR (total)	−10	Naive before–after
Minnesota	Rural multilane divided highways	SVROR (injury)	−22	Naive before–after
Minnesota	Rural multilane divided highways	Total	−21	Before–after with comparison sites
Minnesota	Rural multilane divided highways	Injury	−26	Before–after with comparison sites
Minnesota	Rural multilane divided highways	SVROR (total)	−22	Before–after with comparison sites
Minnesota	Rural multilane divided highways	SVROR (injury)	−51	Before–after with comparison sites
Minnesota	Rural two-lane roads	SVROR (total)	−13 (8)	Before–after EB analysis with reference group
Minnesota	Rural two-lane roads	SVROR (injury)	−18 (12)	Before–after EB analysis with reference group
Montana	Interstate and primary highways	SVROR	−14	Before–after with comparison sites
New Jersey	Not provided	SVROR	−34	Unknown
New York	Interstate parkway	SVROR	−65 to 70	Naive before–after
Pennsylvania	Interstate	SVROR	−60	Naive before–after
Tennessee	Interstate	SVROR	−31	Unknown
Utah	Interstate	SVROR	−27	Before–after with comparison sites
Utah	Interstate	Total	−33	Before–after with comparison sites
Virginia	Rural freeways	SVROR	−52	Before–after with comparison sites
Washington	Not provided	Total	−18	Naive before–after
Multiple	Rural freeways	SVROR	−20	Before–after with comparison sites

Note: For information on the original sources, please see Torbic et al.[7]
SRS = Shoulder rumble strips.

Torbic et al. also conducted a survey on the rumble strip installation practices of transportation agencies. The results indicated that 93 percent of agencies installed shoulder rumble strips on both the inside and outside shoulder when installing on a median-divided roadway. Thirty-five percent of agencies indicated that they used different policies for inside shoulders versus outside shoulders. These policies included smaller offsets on the inside (median) shoulder and continuous rumble strips on the inside (median) shoulder compared with intermittent gaps on the outside shoulder.(7)

Torbic et al. conducted an evaluation of the safety effect of shoulder rumble strips according to roadway type, crash severity, placement of the rumble strip (i.e., on edge line versus not on edge line), and offset distance. The analysis did not attempt to separate the effects of inside shoulder versus outside shoulder rumble strips. When developing the dataset, the authors assumed the rumble strips on the inside shoulder were installed at the same time as rumble strips on the outside shoulder. Although SVROR crashes were a target crash type, the analysis of SVROR crashes did not distinguish between those to the left and right of the road.(7)

Torbic et al. conducted the safety evaluation using both the EB before–after study method and a generalized linear modeling cross-sectional approach. Ultimately, they used the EB results because EB was the preferred analysis method in resources such as the *Highway Safety Manual*.(8) They combined the results of their safety evaluation with two other reliable studies to create CMFs for shoulder rumble strips. For rural freeways, the authors estimated that shoulder rumble strips led to an 11-percent reduction in SVROR crashes (standard error (SE) 6) and a 16-percent reduction in SVROR fatal and injury crashes (SE 8). Their analysis did not indicate whether the sites that were treated with shoulder rumble strips had cable median barriers.(7)

Safety Effects of Cable Median Barriers with Shoulder Rumble Strips

Monsere et al. investigated the effects of more than 21.9 mi of continuous three-strand cable median barriers installed on Interstate 5 in Oregon in December 1996 (approximately 7 mi) and April 1998 (approximately 18 mi).(9) In addition, the Oregon Department of Transportation installed milled shoulder rumble strips in fall 1998 in the same area. The crash analysis used two primary datasets: (1) reported crashes (recorded in the State's computerized crash record system) and (2) maintenance logs that documented cable barrier strikes.

For the analysis using State-reported crash data, the authors could identify no suitable reference group, so a simple before–after study was conducted. They used 3 years of before and after data (with the exception of the transition period identified as January 1997 through April 1998). Results showed a decrease in fatal and serious injury cross-median crashes between the before and after time periods—three crashes in the before period and none in the after period and an increase in reported crashes striking a barrier. Although the analysis could not identify left and right side separately, there were 7 crashes in the before period and 60 in the after period. For the analysis using maintenance logs, the authors estimated the effectiveness of the barriers by examining the type of damage the cable median barriers sustained during the crash. Results showed that 105 potential crossovers (of 231 barrier impacts) were contained by the barriers between December 1996 and April 2002.(9)

The authors acknowledged that the State transportation department installed milled shoulder rumble strips around the same time as the second cable median barrier installation, which could have contributed to some of the results from the analysis.[9]

Summary of Literature Review

Overall, the studies seemed to indicate a reduction in cross-median crashes and an increase in crashes involving the striking of a barrier following the installation of cable median barriers. Regarding the effect of shoulder rumble strips, it was evident that they were effective in reducing SVROR crashes. The study by Monsere et al. was the only one that looked at the combination of cable barriers and shoulder rumble strips.[9] However, that study was a simple before–after evaluation and therefore did not account for possible bias due to regression-to-the-mean and the effect of changes in traffic volume. In addition, the sample of crashes was much too small to obtain robust results.[9]

CHAPTER 2. OBJECTIVE

The research for this study examined the safety impacts of cable median barriers with inside shoulder rumble strips in Illinois, Kentucky, and Missouri. The objective of the study was to estimate the safety effectiveness of this strategy as measured by crash frequency. The primary target crash type was cross-median crashes, and the analysis excluded intersection-related and animal crashes.

In addition to cross-median crashes, the research team considered total injury and fatal, median-related, ROR left side, and winter-related crashes. Median-related crashes are those in which the vehicle does not cross the median but ends up in the median after a rollover and/or a collision with an object. Based on the available variables in the crash databases from the States, the research team was not able to determine whether a crash was median-related. Similarly, the research team could not determine run-off-left-side crashes from the crash reports. Consequently, the evaluation did not specifically examine these crash types. The evaluation examined winter-related crashes, but because the sample of crashes was very small, the research team did not report the results here.

It is important to note that the treatment itself was not exactly the same in the three evaluated States. In Illinois and Kentucky, the introduction of cable median barriers came many years after the introduction of rumble strips on inside shoulders. Conversely, Missouri installed cable median barriers and inside shoulder rumble strips about the same time. The before–after conditions in the three States can be summarized as follows:

- Illinois and Kentucky. The before-after conditions were as follows:
  - Before condition: Inside shoulder rumble strips were present, but no cable median barriers were present.
  - After condition: Both inside shoulder rumble strips and cable median barriers were present.
- Missouri. The before-after conditions were as follows:
  - Before condition: No inside shoulder rumble strips or cable median barriers were present.
  - After condition: Both inside shoulder rumble strips and cable median barriers were present.

In addition to determining the overall safety effect of the treatment(s), a further objective was to address the following questions:

- Do effects vary by level of traffic volume?
- Do effects vary by the frequency of crashes before treatment?
- Do effects vary by speed limit?
- Do effects vary by lane width and shoulder width?

The evaluation of overall effectiveness included consideration of the installation costs and crash savings in terms of the B/C ratio.

Meeting these objectives placed some special requirements on the data collection and analysis tasks, including the need to do the following:

- Select a large enough sample size to detect—with statistical significance—what may be small changes in safety for some crash types.
- Identify appropriate untreated reference sites.
- Properly account for changes in safety due to changes in traffic volume and other nontreatment factors.
- Pool data from multiple jurisdictions to improve reliability of the results and facilitate broader applicability of the products of the research.

CHAPTER 3. STUDY DESIGN

When planning a before–after safety evaluation study, it is vital to ensure that enough data are included to detect the expected change in safety with statistical confidence. Even though those designing the study do not know the expected change in safety in the planning stage, it is still possible to make a rough determination of how many sites are required based on the best available information about the expected change in safety. Alternatively, one could estimate the statistically detectable change in safety for the number of available sites. For a detailed explanation of sample size considerations, as well as estimation methods, see chapter 9 of Hauer.(10) The sample size analysis cases presented in this report address (1) how large a sample would be required to statistically detect an expected change in safety and (2) the change in safety that could be detected with available sample sizes.

CASE 1: SAMPLE SIZE REQUIRED TO DETECT AN EXPECTED CHANGE IN SAFETY

For this analysis, the research team assumed that a conventional before–after study with comparison group design would be used because available sample size estimation methods were based on this assumption. The sample size estimates from this method would be conservative in that the EB methodology proposed would likely require fewer sites. To facilitate the analysis, the research team also assumed that the number of comparison sites was equal to the number of treatment sites, which again, was a conservative assumption.

As discussed earlier in the literature review, the crash types that cable median barriers and rumble strips on the inside shoulder would most affect would be cross-median crashes. For the study design, the research team assumed that crashes that were coded as head-on and opposite-direction sideswipe were cross-median. The research team used crash rates from the reference groups for total crashes and injury and fatal crashes; they used crash rates from the treatment group after reducing by 25 percent for cross-median crashes. (The team chose this reduction percentage based on the work by Bahar, which indicated that possible bias due to regression-to-the-mean was not likely to be higher than 25 percent.)(11) Table 2 provides the crash rate assumptions.

Table 2. Before-period crash rate assumptions.

Crash Type	Kentucky (A)	Missouri (B)	Illinois (C)
Total	8.25	1.91	6.95
Injury and fatal	1.90	0.62	1.53
Cross-median	0.27	0.03	0.07

Note: All crash rates are mi/year.

Table 3 provides estimates of the required number of before- and after-period mile-years for statistical significance at both a 90- and 95-percent confidence level for both crash rate assumptions. The minimum sample indicates the level at which a study would seem to be worthwhile; that is, it would be feasible to detect with the desired level of confidence the largest effect that might reasonably be expected based on what was currently known about the strategy. The research team based these sample size calculations on the methodology in Hauer and on specific assumptions regarding the number of crashes per mile and years of available data.[10] Mile-years are the number of miles of highway on which the strategy was implemented multiplied by the number of years of data before or after implementation. For example, if a strategy was implemented at a 10-mi segment and data were available so far for 4 years since implementation, then there would be a total of 40 mi-year of after-period data available for the study.

Table 3. Minimum required before-period mile-years.

Expected Percent Reduction in Crashes	A†	B†	C†	A‡	B‡	C‡
All 10	153*	658*	181*	108*	465*	128*
All 20	32	136	37	22	97	27
All 30	11	49	13	8	34	10
All 40	5	21	6	4	15	4
Injury and Fatal 10	661	2033	825	467	1436	583
Injury and Fatal 20	136*	419*	170*	97*	298*	121*
Injury and Fatal 30	49	150	61	35	106	43
Injury and Fatal40	22	66	27	15	47	19
Cross-median 10	4,666	45,737	18,516	3,296	32,306	13,079
Cross Median 20	963	9,438	3,821	685	6,715	2,719
Cross Median 30	344	3,376	1,367	244	2,396	970
Cross Median 40	152*	1,488*	603*	107*	1,053*	426*
Median-Related 10	1,131	4,875	1,379	799	3,443	974
Median-Related 20	233	1,006	285	166	716	203
Median-Related 30	83	360	102	59	255	72
Median-Related 40	37	159	45	26	112	32

Note: Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
†95-percent confidence level.
‡90-percent confidence level.
*Recommended sample sizes in this study.

The sample size values recommended in this study are indicated with an asterisk in table 3. These values are recommended based on the likeliness of obtaining the estimated sample size as well as the anticipated effects of the treatment. As noted, the sample size estimates provided were conservative in that the state-of-the-art EB methodology proposed for the evaluations would require fewer sites than the less robust conventional before–after study with a comparison group that had to be assumed for the calculations. Estimates can be predicted with greater confidence, or a smaller reduction in crashes would be detectable, if there were more site-years of data available in the after period. The same holds true if the actual data used for the analysis had a higher crash rate for the before period than was assumed.

CASE 2: CHANGE IN SAFETY THAT CAN BE DETECTED WITH AVAILABLE SAMPLE SIZES

The standard deviations of the estimated percent change in safety describe the statistical accuracy attainable for a given sample size. From this, one can estimate *p*-values for various sample sizes and expected change in safety for a given crash history based on the method in Hauer.[10]

For the available data in the three States in this evaluation, the research team estimated the minimum percentage changes in crash frequency that could be statistically detectable at 5- and 10-percent significance levels, as shown in table 4. For these calculations, the research team assumed that data would be available until the end of 2012. The results indicated that the data should be able to detect the recommended crash reduction values from table 3 if such an effect were present. Using these results, the authors made a decision to proceed with the evaluation using the data available at that time.

Table 4. Sample analysis for crash effects.

Crash Type	Mile-Years in Before Period	Mile-Years in After Period	Minimum Percent Reduction Detectable for Crash Rate Assumption* $p = 0.10$	Minimum Percent Reduction Detectable for Crash Rate Assumption* $p = 0.05$
Total	2,512	4,249	3	4
Injury and fatal	2,512	4,249	6	7
Cross-median	2,512	4,249	16	19

Note: Results are to nearest 1 percent.
*Crash rate assumption based on crash rates in table 3.

CHAPTER 4. METHODOLOGY

This evaluation uses the EB methodology for observational before–after studies.[10] This methodology is considered rigorous in that it accounts for regression-to-the-mean using a reference group of similar but untreated sites. In the process, the research team used safety performance functions (SPFs) for the following purposes:

- To overcome the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- To account for time trends.
- To reduce the level of uncertainty in the estimates of safety effects.
- To properly account for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The methodology also provides a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy.

In the EB approach, the change in safety for a given crash type at a site is given by figure 3.

$$\Delta\ Safety = \lambda - \pi$$

Figure 3. Equation. Estimated change in safety.

Where:

λ = Expected number of crashes that would have occurred in the after period without the strategy.
π = Number of reported crashes in the after period.

In estimating λ, the authors used SPFs to explicitly account for the effects of regression-to-the-mean and changes in traffic volume, relating crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (reference sites). They calibrated annual SPF multipliers to account for temporal effects on safety (e.g., variation in weather, demography, and crash reporting).

In the EB procedure, the first step was to use the SPF to estimate the number of crashes that would be predicted in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed (i.e., reference sites). The sum of these annual SPF estimates (*P*) was then combined with the count of crashes (*x*) in the before period at a strategy site to obtain an estimate of the predicted number of crashes (*m*) before strategy. Figure 4 shows this estimate of *m*.

$$m = w(P) + (1 - w)(x)$$

Figure 4. Equation. EB estimate of expected crashes.

Where *w*, the EB weight, is estimated from the mean and variance of the SPF estimate as figure 5 illustrates.

$$w = \frac{1}{1 + kP}$$

Figure 5. Equation. EB weight.

Where *k* is the overdispersion parameter of a negative binomial regression model, which was estimated from the SPF calibration process with the use of a maximum likelihood procedure. *k* could be assumed as a constant or as a function of site characteristics, including segment length. Based on the recommendation from Hauer, *k* was estimated based on segment length and assumed to be $\frac{k_1}{l}$, where k_1 is the overdispersion parameter for a 1-mi segment and *l* is the length of the segment.(12)

A factor was then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor was the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, was an estimate of λ. The procedure also produced an estimate of the variance of λ.

The estimate of λ was then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes observed during the after period in that group (π_{sum}). The variance of λ was also summed over all sites in the strategy group.

The index of effectiveness (θ) is estimated as shown in figure 6.

$$\theta = \frac{\pi_{sum} / \lambda_{sum}}{1 + \left(Var(\lambda_{sum}) / \lambda_{sum}^2 \right)}$$

Figure 6. Equation. Index of effectiveness.

Figure 7 shows how the standard deviation of θ is calculated.

$$StDev(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)^2}}$$

Figure 7. Equation. Standard deviation of index of effectiveness.

The percent change in crashes was calculated as $100(1 - \theta)$; thus, a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

The analysis of the treatment sites in Missouri required a slightly different approach to the methodology. Missouri installed cable median barriers on a systemwide basis for certain road types. As a result, it was virtually impossible to identify comparable roadways without cable barriers for this road type presently or in the near future. For this reason, the research team did not identify a separate reference group of sites without rumble strips.

The research team applied an alternate approach to the standard method of estimating and applying SPFs for the EB before–after methodology. In short, this method used the before-period data at the treatment sites to develop SPFs to control for regression-to-the-mean and traffic volume changes. Because the State applied its policy of installation of cable barriers systemwide, regression-to-the-mean was not as big a concern as it otherwise might have been. The research team used SPFs calibrated from before-period data to account for time trends in the earlier part of the study period, before most of the sites had rumble strips installed. However, after a substantial number of sites had been treated, the number of sites was still too low to develop yearly factors to account for trends. Instead, the research team used time trends from the Missouri data that were used in the rural two-lane centerline plus shoulder rumble strips analysis to calculate the after-period trend when MoDOT had treated most or all of the sites.[13] The research team adjusted the before-period yearly factors based on the ratio of the after-period factors to common years in the rural two-lane data.

To illustrate, consider the fictitious information in table 5. Using the SPFs calibrated for both the before and after periods, annual multipliers were estimated for each year. In 2006, there were no data for the after period, so a multiplier did not exist for that year for the after-period SPF. Similarly, there was no multiplier for 2009–2011 using the before-period data. The average of the multipliers for the common years (2007–2008) was computed. The after-period multipliers post-2007 were adjusted by dividing the values by the 2007–2008 average. Finally, the missing yearly multipliers for the before-period model were adjusted by multiplying the average from 2007–2008 (1.03) by the value of the adjusted after-period multiplier for each year. These were the annual multipliers used in the evaluation.

Table 5. Illustration of alternate approach.

Year	Using After-Period Data	Adjusted After-Period Multipliers	Using Before-Period Data	Adjusted Before-Period Multipliers
2006	N/A	—	0.98	—
2007	1.17	—	1.01	—
2008	0.99	—	1.05	—
Average 2007–2008	1.08	—	1.03	—
2009	1.23	1.14	N/A	1.17
2010	0.84	0.78	N/A	0.80
2011	1.96	1.81	N/A	1.86

— Indicates no adjustment was required.
N/A = Not applicable.

CHAPTER 5. DATA COLLECTION

As mentioned earlier, Illinois, Kentucky, and Missouri provided data for this study. These States also provided data on roadway geometry, traffic volumes, and crashes for both installation and reference sites. They also provided crash injury severities according to the KABCO scale. This chapter summarizes the data assembled for the analysis.

ILLINOIS

This section describes the installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data for Illinois sites used in this evaluation.

Installation Data

The Illinois Department of Transportation (IDOT) provided a list of interstate highway sections where it had installed cable median barriers, along with the date of installation, brand of barrier, and cost of contract. IDOT installed cable median barriers at these locations to reduce cross-median crashes. The agency based its decisions on an examination of 5 years of crash data. Illinois used Fatality Analysis Reporting System (FARS) crashes on interstate highways and looked at head-on and opposite-direction sideswipe crashes. IDOT used this information to develop a warrant chart that could be used for cable median barrier installation. The final set of cable median barrier treatment sites covered approximately 100 mi.

IDOT did not install rumble strips at the same time as the cable median barriers. Thus, the research team wanted to know the exact time period when rumble strips were installed on the treatment sites. To obtain this information, IDOT ran a query of its contracts database to assemble a list of all contracts involving the installation of rumble strips. Owing to a lack of complete data from previous years, the research team was not able to determine a date at which IDOT first installed rumble strips on the treatment sites. However, the query did enable the research team to document any work involving rumble strips that IDOT performed on the treatment sites during the study period. If any record of work appeared for a site, the research team documented it along with the year it was done.

Although IDOT did not know the exact date of rumble strip installation at these sites, the documentation provided an indication of the earliest known year of rumble strip presence based on a visual inspection of 2004 photolog images. This provided the starting point for the analysis period.

Reference Sites

Reference sites for the cable median barrier treatment needed to be segments of road that matched the treatment sites in terms of the type of roadway, the potential for cable median barriers (appropriateness of median), and existence of shoulder rumble strips during the before period of study. The research team identified reference sites for Illinois from an IDOT list of all interstate highway segments in the State known to have shoulder rumble strips based on a visual survey of 2004 photolog images. From this list, the research team selected interstate highway segments if they were on the same route as other segments that had been treated with cable median barriers but that had not received cable median barriers. This ensured that the reference sites would be similar to the treatment sites in terms of driver population, area type, and other factors. The research team selected only segments with a median width of less than 100 ft and no positive barriers. Once the team had assembled this list, they compared it with the query of rumble strip work that IDOT had developed based on a pay item query in its contracts database. The research team documented any work done during the study period involving rumble strips, along with the year the work was done.

This yielded a group of interstate highway segments with rumble strips, medians no wider than 100 ft, and no positive barriers in the median and that were located along the same routes as the treatment sites. The final batch of reference sites comprised approximately 400 mi of road segments.

Roadway Data

The research team obtained roadway data for all treatment and reference sites from the FHWA Highway Safety Information System (HSIS) database. HSIS provided these data on an annual basis for each site from 2001 to 2010. The *HSIS Guidebook for Illinois* provided coding for these variables. [(14)]

The HSIS database yielded the following variables:

- Median Width.
- Total Surface Width.
- Total Number of Lanes.
- Average Lane Width.
- Outside Shoulder Type.
- Outside Shoulder Width.
- Inside Shoulder Type.
- Inside Shoulder Width.
- AADT.
- Functional Class.
- Speed Limit.
- Surface Type.
- Total Inside Shoulder Width.
- Total Outside Shoulder Width.
- Roadway Classification.

Traffic Data

The research team obtained traffic data for all treatment and reference sites as part of the roadway data file from the FHWA HSIS database. HSIS provided an AADT value for each site annually from 2001 to 2010.

Crash Data

The research team obtained crash data for all treatment and reference sites from the FHWA HSIS database. The crash data obtained covered the years 2001 to 2010. The HSIS crash data provided location of crash, date of crash, severity, light condition at time of crash, crash type, and weather. The *HSIS Guidebook for Illinois* provides coding for the crash variables. The crash data can be linked to the treatment and reference sites by county and route (coded as CNTYRTE in HSIS data) and milepost.(14)

Treatment Cost Data

The research team obtained the cost of installing and maintaining cable median barriers and rumble strips from IDOT and summarized these data in table 6.

Table 6. Illinois treatment cost and service life data.

Countermeasure	Initial Installation Cost	Maintenance Cost	Service Life (year)
Cable median barriers	$180,000/mi	$6,000–$12,000/mi per year	15
Rumble strips on new surface	$2,000/mi	No estimate provided	12
Rumble strips on existing surface	$2,000/mi	No estimate provided	8

KENTUCKY

This section describes the installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data for Kentucky sites used in this evaluation.

Installation Data

The Kentucky Transportation Cabinet (KYTC) provided a list of roadway sections where it had installed cable median barriers, along with the date of installation, brand of barrier, and cost of contract. KYTC generally selected sites for cable median barrier installations based on an annual evaluation process that considered crash experience, median width, median slope profile, traffic volume, traffic composition, and speed. From these variables, KYTC prioritized a list of recommended cable barrier projects. KYTC quantified crashes by examining cross-median fatal crashes per mile and total number of cross-median crashes per mile. The initial treatment group added up to 140 mi.

KYTC revealed problems with crash reporting in Jefferson County during the earlier years of the study period. Because the change in the reporting practices could have negatively affected any before–after analysis using Jefferson County crash data, the research team removed these data. Because Jefferson County is one of Kentucky's largest counties and had a significant number of cable barrier installations, omitting it from consideration reduced the sample size to 69 mi.

The State did not install rumble strips at the same time as the cable median barriers, but the prior condition of all treated sites included existing rumble strips on both the outside and inside shoulders. Thus, the research team chose these sites for an analysis of the effect of cable median barrier installation on facilities already equipped with rumble strips.

Reference Sites

KYTC provided a list of interstate highway segments from the entire State. Each segment had an indication of median type and median barrier presence. The research team selected reference sites from this list based on their having a depressed median, no median barriers, and a median width less than or equal to 200 ft. (Very wide medians are at low risk of cross-median crashes even without barriers.) The research team also cross-referenced this list against the cable barrier treatment list to remove treated sections. The final list of reference sites for the cable barrier treatment was approximately 323 mi. KYTC indicated that all reference sites could be assumed to have had median shoulder rumble strips by 2000.

Roadway Data

The authors obtained roadway data in geographic information system (GIS) shapefile format from Kentucky staff. Separate shapefiles, each segmented differently, contained various road characteristics (e.g., shoulder width and traffic volume). The research team obtained GIS files from the KYTC website.(15) The research team obtained characteristics of the treatment and reference sites by matching each study site to the appropriate inventory segment by county, route, and milepost. The team also used the KYTC photolog and Google® aerial and Google Streetview™ imagery to confirm presence, type, and approximate installation dates of rumble strips at cable barrier treatment sites.(16)

Because the sites in Kentucky included freeway sections, and crashes on freeways tend to concentrate near interchanges, the research team requested and obtained data on locations of interchanges from KYTC.

Traffic Data

KYTC maintained traffic volume data in the GIS inventory files, namely the traffic flow (TF) shapefile. The authors obtained traffic data for the treatment and reference sites by matching each study site to the appropriate inventory segment by county, route, and milepost. Specifically, the research team used the TF file from 2010 because it provided two datapoints: current (i.e., 2010) AADT and the prior AADT (with an indication of the year taken). The research team used these volume points to extrapolate yearly AADT for the before period.

Crash Data

KYTC supplied crash data for the routes and counties indicated in the treatment and reference site lists. KYTC also provided a data dictionary that described the fields in the crash data. The crash data contained all crashes for the individual routes and could be linked to the sites with a match based on county, route, and beginning and ending milepost. The field labeled "RDWYIDTXT" was present in both the crash and road files to indicate the route. KYTC indicated that crash location quality improved significantly in 2008. This was because officers used a mapping application, which allowed officers to select the crash location on a screen, which applied latitude/longitude coordinates to the crash record.

Treatment Cost Data

KYTC provided estimates of the costs and services lives of the treatments (see table 7). These data can be used to conduct a B/C analysis of the treatment.

Table 7. Kentucky treatment cost and service life data.

Countermeasure	Initial Installation Cost	Maintenance Cost	Service Life (years)
Cable median barriers	$150,000/mi	Difficult to determine because reporting system did not separate cable barriers from guardrail	20
Edge-line or shoulder rumble strips (installed as part of resurfacing)	$2,500/mi	No additional maintenance cost	12–15 for rumble strip, 2 for stripe

MISSOURI

This section describes the installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data for Missouri sites used in this evaluation.

Installation Data

The State applied cable median barriers with inside shoulder rumble strip treatments statewide on roadways identified as tier 1 or tier 2. (Tier 1 was the highest order of routes followed by tier 2.) MoDOT supplied the list of projects where center-line and shoulder rumble strips or cable median barriers were recently installed or planned to be installed. Among the data the reports provided were the location—including district, State route number, and milepost—and the construction dates. MoDOT reported no other construction activities on these road segments.

The research team identified treatment sites by looking for sites for which both before- and after-period data would be available. The dates of cable median barrier installation did not always match those for one or both sides of the rumble strip installation, but they were close to each other. The team considered before periods to be prior to the installation of both cable barriers and rumble strips and after periods to start after both treatments had been installed.

Reference Sites

Because Missouri had installed cable median barriers on a systemwide basis, it was almost impossible to identify comparable roadways without cable barriers for this road type at the time or in the near future. For this reason, the research team did not identify a separate reference group of sites without rumble strips and applied an alternate approach to the standard method for estimating and applying SPFs in the EB before–after methodology. Chapter 4 of this report describes this approach in more detail.

Roadway Data

The research team obtained roadway data for the treatment sites from MoDOT, and the following variables were included in the data:

- Area type (urban/rural).
- Functional class.
- Divided versus undivided.
- Number of lanes.
- Lane width.
- Shoulder type.
- Shoulder width.
- Surface type.
- Speed limit.

The roadway, traffic, and crash data were stored in a bidirectional manner (i.e., there was a separate record for each direction of travel). MoDOT staff were able to match opposing directions of travel for each site. The research team limited the constructed database to one record per site and the geometric information taken from the primary direction of travel.

Traffic Data

The research team obtained traffic data in the form of AADT from 1999 to 2011 from MoDOT in electronic files for all treatment sites.

Crash Data

The compiled crash data contain many variables related to the location, time, and characteristics of each crash. The crash types of interest included non-intersection- and non-animal-related crashes.

Treatment Cost Data

MoDOT provided estimates of the costs and service lives of the treatments (see table 8).

Table 8. Missouri cost and service life data.

Countermeasure	Initial Installation Cost	Maintenance Cost	Service Life (years)
Cable median barrier	$100,000/mi	Not available	20
Edge-line or center-line rumble strip	$1,000/mi	Not available	7 to 10

DATA CHARACTERISTICS AND SUMMARY

Previous research indicated that cross-median crashes could be identified in many ways. In the crash reports from Kentucky and Missouri, there was a variable to indicate whether the crash was a cross-median crash. Illinois did not have such a variable. Staff from KYTC and the Kentucky Transportation Center indicated that the cross-median indicator in the Kentucky crash report was not reliable and suggested not using that variable. As a result, for Illinois and Kentucky, the research team used head-on plus opposite-direction sideswipe crashes as a proxy for cross-median crashes. The research team removed crashes related to wrong-way driving based on the crash reports. For Missouri, the team used two proxies for cross-median crashes: one based only on the cross-median indicator and the other based on the total number of crashes where either the cross-median indicator was included or the crash was designated as head-on. (Missouri did not indicate whether a sideswipe crash was opposite-direction or same-direction.)

Table 9 and table 10 provide summary information for the data collected for the treatment sites. The information in these tables should not be used to make simple before–after comparisons of crashes per mile-year because they do not account for factors, other than the strategy, that might cause a change in safety between the before and after periods. The research team made such comparisons properly with the EB analysis, as presented in chapter 7. Table 11 provides summary information for the reference site data. As discussed in chapter 4, the team used a different approach in Missouri where they could not find an appropriate reference group.

Table 9. Data summary for treatment sites in Illinois and Kentucky.

Variable	Illinois	Kentucky
Segment length (mi)	100.3	66.39
Mi-yr before	574.59	478.6
Mi-yr after	320.31	160.54
Outside shoulder width minimum (ft)	10	10
Outside shoulder width maximum (ft)	13	11
Outside shoulder width average (ft)	11.35	10.1
Inside shoulder width minimum (ft)	4	3
Inside shoulder width maximum (ft)	12	10
Inside shoulder width average (ft)	7.73	5.95
Median width minimum (ft)	32	40
Median width maximum (ft)	90	54
Median width average (ft)	53.85	47.95
AADT minimum before	14,960	28,148
AADT maximum before	68,283	85,501
AADT average before	35,498	41,684
AADT minimum after	15,300	29,399
AADT maximum after	75,908	73,055
AADT average after	38,213	42,289
Total crashes/mi-yr before	7.98	7.62
Total crashes/mi-yr after	9.61	9.04
Injury crashes (KABC)/mi-yr before	2.07	1.81
Injury crashes (KABC)/mi-yr after	2.27	2.27
Injury crashes (KAB)/mi-yr before	1.6	1.09
Injury crashes (KAB)/mi-yr after	1.37	1.2
Head-on + sideswipe opposite-direction/mi-yr before	0.09	0.21
Head-on + sideswipe opposite-direction/mi-yr after	0.02	0.11

Table 10. Data summary for treatment sites in Missouri.

Variable	Minimum	Maximum	Sum	Mean
Segment length (mi)	0	5.79	288.07	0.28
Mi-yr before	0.01	28.94	1,947.47	1.87
Mi-yr after	0	34.72	817.49	0.79
Outside shoulder width (ft)	4	12	10,072	9.69
Inside shoulder width (ft)	1	10	5,264	5.07
AADT before	6,005	52,059	N/A	24,164
AADT after	5,263	58,530	N/A	24,395
Total crashes/mi-yr before	0	125	3,019.68	2.91
Total crashes/mi-yr after	0	83.33	1,892.68	1.82
Injury crashes (KABC)/mi-yr before	0	66.67	997.51	0.96
Injury crashes (KABC)/mi-yr after	0	34.48	292.88	0.28
Injury crashes (KAB)/mi-yr before	0	20.41	235.78	0.23
Injury crashes (KAB)/mi-yr after	0	10	67.27	0.06
Cross-median crashes/mi-yr before	0	3.86	22.25	0.02
Cross-median crashes/mi-yr after	0	1.28	1.28	0
Cross-median + Head-on/mi-yr before	0	3.86	33.56	0.03
Cross-median + Head-on/mi-yr after	0	1.28	2.06	0

N/A = Not applicable.

Table 11. Data summary for reference sites.

Variable	Illinois	Kentucky
Segment length (mi)	401.02	323.47
Mi-yr	4,010.2	3,558.16
Outside_Shoulder_Width min (ft)	8	10
Outside_Shoulder_Width max (ft)	13	14
Outside_Shoulder_Width avg (ft)	11.09	10.39
Inside_Shoulder_Width (ft)_for_Divide (ft) min	4	2
Inside_Shoulder_Width (ft)_for_Divide (ft) max	10	14
Inside_Shoulder_Width (ft)_for_Divide (ft) avg	7.16	5.45
Median width min	40	30
Median width max	88	200
Median width avg	67.77	66.04
AADT min	9,200.6	12,158.64
AADT max	37,708.5	84,237.64
avg	21,204	35,383
Crashes/mi-yr	2.61	6.18
Injury crashes (KABC)/mi-yr	0.72	1.55
Injury crashes (KAB)/mi-yr	0.61	0.92
Head-On + sideswipe opposite-direction/mi/yr	0.03	0.18

CHAPTER 6. DEVELOPMENT OF SPFS

This chapter presents the SPFs developed for each State. The EB methodology uses SPFs to estimate the safety effectiveness of this strategy.[10] The research team used generalized linear modeling to estimate model coefficients assuming a negative binomial error distribution, which was consistent with the state of research in developing these models. Most previous studies had used the traditional power function as the default for AADT. In this effort, the team used the hoerl function to provide more flexibility in the functional form for AADT.[17] With the hoerl function for AADT, the dependent variable (Y) is related to AADT as shown in figure 8.

$$Y = \exp[a_1 + a_2 AADT + a_3 \ln(AADT)]$$

$$Y = e^{a_1} e^{a_2 AADT} AADT^{a_3}$$

Figure 8. Equation. Functional form for AADT.

Where a_1, a_2, and a_3 are parameters to be estimated. This allows the function for AADT to have a convex/concave shape with inflection points. The other variables were included in a log-linear/exponential form as shown in figure 9:

$$Y = \exp[a_1 + a_2 AADT + a_3 \ln(AADT) + a_4 X_4 + a_5 X_5 + \cdots a_n X_n]$$

Figure 9. Equation. Functional form for SPFs.

Where X_4 through X_n represent the other independent variables and a_4 through a_n are parameters to be estimated. The equation included segment length as an offset. In specifying a negative binomial error structure, the dispersion parameter k was estimated iteratively from the model and the data. For a given dataset, smaller values of k indicate relatively better models. As discussed earlier, k was estimated as a function of the segment length, and k_1 (overdispersion for a 1-mi section) is shown in the tables in the following sections.

ILLINOIS AND KENTUCKY SPFs

The research team calibrated SPFs for each State separately using the reference sites from that State. As discussed in chapter 5, the team developed the Missouri SPFs separately for the before and after periods at the treated sites. Table 12 and table 13 present the SPFs developed for Illinois and Kentucky, respectively.

Table 12. Illinois SPFs.

Parameter	Total Estimate (SE)	KABC Estimate (SE)	KAB Estimate (SE)
Intercept	−15.0452 (2.2366)	−7.9114 (0.7885)	−7.5992 (0.8107)
AADT/1,000	−0.0442 (0.0138)	— (—)	— (—)
In(AADT)	1.8019 (0.2564)	0.8541 (0.0768)	0.8065 (0.0789)
Median width (ft)	−0.0115 (0.0015)	−0.0105 (0.0019)	−0.0106 (0.0019)
Rural	−0.2385 (−0.2385)	−0.2501 (0.0835)	−0.2498 (0.0839)
Urban	0 (0)	0 (0)	0 (0)
k_1	0.8332 (0.0861)	0.8832 (0.1641)	0.7739 (0.1747)

— Indicates that the specific variable was not significant and not included in the model.

Table 13. Kentucky SPFs.

Parameter	Total Estimate (SE)	KABC Estimate (SE)	KAB Estimate (SE)	Cross-Median Estimate (SE)
Intercept	−8.0058 (0.9029)	−9.2966 (1.3347)	−10.9603 (1.6169)	−16.4789 (3.7323)
AADT/1,000	−0.0067 (0.0033)	−0.0096 (0.0046)	−0.0143 (0.0054)	−0.0378 (0.0119)
In(AADT)	1.0624 (0.1)	1.0777 (0.1467)	1.2226 (0.1755)	1.7697 (0.405)
No interchange influence area	−0.3332 (0.0291)	−0.2282 (0.042)	−0.2361 (0.0515)	−0.3142 (0.1161)
Interchange influence area	0 (0)	0 (0)	0 (0)	0 (0)
Rural	−0.1381 (0.04)	−0.2666 (0.0554)	−0.1627 (0.0695)	−0.4636 (0.151)
Urban	0 (0)	0 (0)	0 (0)	0 (0)
Four lanes	−0.6711 (0.0727)	−0.7012 (0.1077)	−0.8153 (0.1281)	−1.4294 (0.3108)
Six lanes	— (0)	0 (0)	0 (0)	0 (0)
Inside shoulder width (ft)	−0.0877 (0.0079)	−0.0953 (0.012)	−0.0926 (0.015)	−0.0757 (0.0367)
Median width (ft)	0.0026 (0.0004)	0.0028 (0.0006)	— (—)	−0.0065 (0.002)
Speed limit lower than 65 mi/h	0.9354 (0.0196)	0.6698 (0.1626)	0.5931 (0.1975)	— (—)
Speed limit greater than 65 mi/h	0 (0)	0 (0)	0 (0)	— (—)
k_1	0.2317 (0.0137)	0.1858 (0.0277)	0.2038 (0.0432)	0.5144 (0.2568)

— Indicates that the specific variable was not significant and not included in the model.

MISSOURI SPFs

As discussed earlier, reference groups were not available in Missouri because the State implemented the treatment systemwide. Therefore, the research team used the before-period data for the treated sites to estimate the SPFs, which are shown in table 14. In Missouri, because the team could not reliably estimate SPFs for cross-median crashes, they based the predictions for cross-median crashes on the product of the SPFs for total crashes with the proportion of cross-median crashes.

Table 14. Missouri before-period SPFs.

Parameter	Total Estimate (SE)	KABC Estimate (SE)	KAB Estimate (SE)
Intercept	−25.4506 (2.4438)	−22.0979 (3.6129)	−9.192 (1.9287)
AADT/1,000	−0.069 (0.0116)	−0.0485 (0.017)	— (—)
In(AADT)	2.7106 (0.2687)	2.2077 (0.3966)	0.6729 (0.2004)
Speed limit lower than 65 mi/h	0.719 (0.1353)	0.6406 (0.2032)	— (—)
Speed limit greater than 65 mi/h	0 (0)	0 (0)	— (—)
Rural	−0.4076 (0.0596)	−0.1754 (0.0898)	— (—)
Urban	0 (0)	0 (0)	— (—)
Full access control	1.0153 (0.1236)	0.9275 (0.1872)	1.0108 (0.2836)
Limited access control	0 (0)	0 (0)	0 (0)
k_1	0.3084 (0.0219)	0.3346 (0.0541)	0.3813 (0.1656)

— Indicates that the specific variable was not significant and not included in the model.

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

This chapter presents the results of the before–after evaluation, including aggregate and disaggregate analysis for Kentucky, Illinois, and Missouri.

AGGREGATE ANALYSIS

Table 15 through table 26 present the resulting CMFs. These tables provide the estimates of predicted crashes in the after period without treatment, the observed crashes in the after period, and the estimated CMF and its SE for all crash types considered. CMFs statistically different from 1.0 at the 95-percent confidence level are indicated with an asterisk. The tables provide separate results for Illinois and Kentucky, the combined results for Illinois and Kentucky, and the results for Missouri. The research team did not combine the results from Missouri with the results from Illinois and Kentucky because the before conditions in Missouri did not include inside shoulder rumble strips, while the before conditions in Illinois and Kentucky included inside shoulder rumble strips.

Table 15. CMFs from 27 urban sites in Illinois.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	1,844.73	2,335	1.265*	0.035
Injury and fatal (KABC)	671.87	455	0.676*	0.040
Injury and fatal (KAB)	493.52	370	0.749*	0.049
Cross-median	19.06	10	0.520*	0.170

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 16. CMFs from 13 rural sites in Illinois.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	323.38	430	1.327*	0.085
Injury and fatal (KABC)	100.87	64	0.631*	0.090
Injury and fatal (KAB)	80.97	59	0.725*	0.108
Cross-median	4.24	2	0.459	0.325

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 17. CMFs from urban and rural sites in Illinois.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	2,168.10	2,765	1.275*	0.033
Injury and fatal (KABC)	772.75	519	0.671*	0.036
Injury and fatal (KAB)	574.49	429	0.746*	0.045
Cross-median	23.30	12	0.512*	0.152

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 18. CMFs from seven urban sites in Kentucky.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	168.79	162	0.957	0.090
Injury and fatal (KABC)	37.29	28	0.744	0.157
Injury and fatal (KAB)	22.57	18	0.787	0.204
Cross-median	4.85	1	0.193*	0.187

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 19. CMFs from 32 rural sites in Kentucky.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	982.48	1,281	1.303*	0.045
Injury and fatal (KABC)	254.18	264	1.037	0.073
Injury and fatal (KAB)	149.37	137	0.916	0.086
Cross-median	31.47	18	0.569*	0.140

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 20. CMFs from urban and rural sites in Kentucky.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	1,151.27	1,443	1.253*	0.041
Injury and fatal (KABC)	291.47	292	1.001	0.067
Injury and fatal (KAB)	171.95	155	0.900	0.080
Cross-median	36.32	19	0.520*	0.125

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 21. CMFs from urban sites in Illinois and Kentucky combined.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	2,013.51	2,497	1.240*	0.033
Injury and fatal (KABC)	709.16	483	0.680*	0.039
Injury and fatal (KAB)	516.09	388	0.751*	0.048
Cross-median	23.91	11	0.456*	0.142

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 22. CMFs from rural sites in Illinois and Kentucky combined.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	1,305.86	1,711	1.310*	0.040
Injury and fatal (KABC)	355.05	328	0.923	0.058
Injury and fatal (KAB)	230.34	196	0.850*	0.068
Cross-median	35.71	20	0.557*	0.130

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 23. CMFs from urban and rural sites in Illinois and Kentucky combined.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	3,319.37	4,208	1.267*	0.026
Injury and fatal (KABC)	1,064.22	811	0.762*	0.033
Injury and fatal (KAB)	746.43	584	0.782*	0.039
Cross-median	59.63	31	0.518*	0.097

Note: Cross-median was defined as head-on plus opposite-direction sideswipe.
*Statistically significant at the 95-percent confidence level.

Table 24. CMFs from 310 urban sites in Missouri.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	345.37	264	0.763*	0.054
Injury and fatal (KABC)	102.33	54	0.526*	0.078
Injury and fatal (KAB)	24.73	9	0.361*	0.124
Cross-median indicator	4.86	0	0.000*	—
Cross-median indicator + head-on	8.48	1	0.117*	0.116

— Indicates could not estimate SE when after-period crashes were 0.
*Statistically significant at the 95-percent confidence level.

Table 25. CMFs from 729 rural sites in Missouri.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	1,435.66	1,957	1.363*	0.041
Injury and fatal (KABC)	486.77	385	0.790*	0.046
Injury and fatal (KAB)	146.24	125	0.853*	0.083
Cross-median indicator	19.49	1	0.051*	0.051
Cross-median indicator + head-on	33.43	4	0.119*	0.060

*Statistically significant at the 95-percent confidence level.

Table 26. CMFs from urban and rural sites in Missouri.

Crash Type	EB Estimate of Crashes Predicted in the After Period Without Strategy	Count of Crashes Observed in the After Period	CMF	SE of CMF
Total	1,781.03	2,221	1.247*	0.034
Injury and fatal (KABC)	589.10	439	0.745*	0.040
Injury and fatal (KAB)	170.96	134	0.783*	0.073
Cross-median indicator	24.35	1	0.041*	0.041
Cross-median indicator + head-on	41.92	5	0.119*	0.053

*Statistically significant at the 95-percent confidence level.

Most of the Kentucky data were from rural roads, whereas most of the Illinois data were from urban roads. Because cross-median crashes are relatively rare, it would be difficult to draw any definitive conclusions unless a relatively large sample of sites were used. As a result, the focus should be on the combined rural and urban results. The combined urban and rural results from Kentucky indicated an increase in total crashes and a reduction in cross-median crashes. The results regarding total and cross-median crashes were similar in Illinois (for rural and urban combined), but the Illinois sites exhibited a reduction in injury and fatal crashes as well. The combined Illinois and Kentucky results (for rural and urban combined) indicate a 27-percent increase in total crashes, 22- to 24-percent decrease in injury and fatal crashes (depending on whether injury crashes were defined as KAB or KABC), and a 48-percent decrease in cross-median crashes. The increase in total crashes—along with a decrease in injury and fatal crashes—reveals an increase in property-damage-only (PDO) crashes. Based on the difference between the EB predicted crashes in the after period for total and injury and fatal crashes, the predicted PDO crashes in the after period (without the cable barrier treatment) were about 2,255.2 (3,319.37 minus 1,064.22), and the actual PDO crashes in the after period were 3,397 (4,208 minus 811). This implies that PDO crashes increased by approximately 51 percent following the implementation of the cable barriers.

The results from Missouri for total and injury and fatal crashes (for rural and urban combined) were very similar to the combined Illinois and Kentucky results. However, the reduction in cross-median crashes in Missouri was much more dramatic, with CMFs of 0.041 (based on cross-median indicator only) and 0.119 (based on cross-median indicator plus head-on).

DISAGGREGATE ANALYSIS

The disaggregate analysis sought to identify those conditions (i.e., before-period EB predicted crash frequency, median width, speed limit, and AADT) under which the treatment was most effective. The research team could discern no patterns, most likely because of the limited sample size for cross-median crashes.

CHAPTER 8. ECONOMIC ANALYSIS

Because it was clear that cable median barriers resulted in an increase in total crashes and a reduction in injury and fatal crashes—thereby implying an increase in PDO crashes—the research team found it necessary to estimate the change in PDO crashes in order to conduct an economic analysis. The team undertook the following steps for the economic analysis:

1. The research team estimated the change in PDO crashes using the EB predicted crashes in the after period and the actual crashes in the after period for total and KABC crashes.

2. Using the number of mile-years in the after period, the research team determined the change in PDO crashes per mile-year and the change in KABC crashes per mile-year. Based on combined data from Illinois and Kentucky, KABC crashes decreased by 0.53 per mi-year, and PDO crashes increased 2.38 per mi-yr. In Missouri, KABC crashes decreased by 0.18/year, and PDO crashes increased by 0.72/mi-yr. The research team discussed the use of KAB crashes per-mile, but used KABC because it was based on a large sample of crashes.

3. The research team used the comprehensive cost estimate for PDO and KABC crashes shown in appendix D (which updated figures from an earlier report by Council et al.) to estimate the annual crash savings in economic terms.[18] The team assumed the cost of a KABC crash was $498,579, and the cost of a PDO crash was $18,877. Using these numbers, the benefit per mile per year was $217,725 in Illinois and Kentucky and $77,917 in Missouri. Appendix D refers to a June 2013 U.S. Department of Transportation (USDOT) memo that prescribes sensitivity analysis based on low and high values of crash costs.[19] Specifically, the USDOT memo suggests that sensitivity analysis should be done by estimating B/C ratios for 0.57 and 1.41 times the 2014 crash costs.[19] Step 5 provides the results based on the sensitivity analysis.

4. The research team estimated the annualized cost of the treatment, as shown in Figure 10.

$$Annual\ Cost = \frac{C * R}{1 - (1 + R)^{-N}}$$

Figure 10. Equation. Determining annual cost.

Where:

C = Treatment cost.
R = Discount rate (as a decimal) and assumed to be 0.07.
N = Expected service life (years).

The annualized treatment cost per mile was $26,286 in Illinois and Kentucky and $18,810 in Missouri.

- **Step 5.** The research team calculated the B/C ratio as the ratio of the annual crash savings to the annualized treatment cost. The resulting B/C ratio for Illinois and Kentucky was 8.28, while the Missouri ratio was 4.14. Based on the sensitivity analysis, the B/C ratio for Illinois and Kentucky could range from 4.72 to 11.68, and the B/C ratio for Missouri could range from 2.36 to 5.84.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness—as measured by crash frequency—of cable median barriers in combination with inside shoulder rumble strips along divided roads. The study used data from three States—Illinois, Kentucky, and Missouri—to examine the effects for specific crash categories, including total, fatal and injury (KAB and KABC), and cross-median crashes. The research team did not include crashes occurring at or related to an intersection and animal-related crashes.

In Illinois and Kentucky, inside shoulder rumble strips were present prior to the implementation of cable barriers; as a result, the evaluation in Illinois and Kentucky determined the safety effect of adding cable barriers on divided roads where inside shoulder rumble strips were already present. On the other hand, Missouri installed inside shoulder rumble strips and cable median barriers at about the same time (or within a few years of each other); therefore, the evaluation in Missouri determined the combined safety effect of cable median barriers and inside shoulder rumble strips. A disaggregate analysis of the results did not reveal any specific patterns, possibly because of the limited sample size for cross-median crashes.

Table 27 presents the recommended CMFs when the before condition included inside shoulder rumble strips. The B/C ratio for this treatment was 8.28. Table 28 provides the recommended CMFs when the before condition had neither inside shoulder rumble strips nor cable median barriers. The associated B/C ratio for this treatment was 4.14.

Table 27. CMFs for the combination of cable median barriers and rumble strips when the before condition included inside shoulder rumble strips.

Crash Type	CMF	SE of CMF
Total	1.267	0.026
Injury and fatal (KABC)	0.762	0.033
Injury and fatal (KAB)	0.782	0.039
Head-on plus opposite-direction sideswipe (proxy for cross-median crashes)	0.518	0.097

Table 28. CMFs for the combination of cable median barriers and rumble strips when the before condition had neither inside shoulder rumble strips nor cable median barrier.

Crash Type	CMF	SE of CMF
Total	1.247	0.034
Injury and fatal (KABC)	0.745	0.040
Injury and fatal (KAB)	0.783	0.073
Cross-median (cross-median indicator plus head-on)	0.119	0.053

The findings of this study indicate that the introduction of cable median barriers resulted in a reduction in head-on, opposite-direction sideswipe, and cross-median crashes. At the same time, the cable median barriers led to an increase in total crashes and a reduction in injury and fatal crashes.

APPENDIX A. ADDITIONAL INSTALLATION DETAILS FROM ILLINOIS

This appendix presents further details about the cable barrier installations from Illinois based on a questionnaire that was sent to the participating States.

Cable Median Barriers and Shoulder Rumble Strip Combination Questions—Illinois

1. What was the "before-period" condition for the treatment sites with respect to rumble strips and cable median barriers?

   - No cable median barriers and no rumble strips.
   - Cable median barriers present but no rumble strips.
   - No cable median barriers but rumble strips present.

   Answer: No cable median barriers but rumble strips present.

2. What type(s) of rumble strips were characteristic of the treatment sites evaluated by this study? (Check all that apply.)

   - Milled.
   - Rolled.
   - Formed.
   - Raised.
   - Other.

   Answer: Milled and rolled.

3. Can you provide specifications and/or standard drawings that address the following characteristics of the rumble strips evaluated by this study?

   - Width.
   - Length.
   - Depth.
   - Spacing.
   - Lateral placement (i.e., in relation to pavement marking).

   Answer:

   Standard 642001-02 → Shoulder rumble strip 16 inches, and

   Standard 642006 → Shoulder rumble strip 8 inches.

   http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Standards/Highway-Standards/HighwaysStandardsRevision215.pdf.

   Specifications → Section 642 Shoulder Rumble Strip (p. 554–555).

   http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Construction/Standard-Specifications/12SpecBook.pdf.

   Bureau of Design and Environment Manual→ CH 34 Section 34-2.02(e) Rumble strip (p. 15–16).

http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Split/Design-And-Environment/BDE-Manual/Chapter%2034%20Cross%20Section%20Elements.pdf

4. Can you provide specifications and/or standard drawings that address the following characteristics of the cable median barrier evaluated by this study?
   - Number of cables.
   - Post spacing.
   - Other important design considerations (i.e., cable pre-stretch, tensioning, slope placement, footing design).

   Answer:

   Bureau of Design and Environment Manual → CH 38-7, Median barriers

   http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Split/Design-And-Environment/BDE-Manual/Chapter%2038%20Roadside%20Safety.pdf

   Supplemental Specification for Section 644 High Tension Cable Median Barriers (p. 58–59)

   http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Construction/Supplemental-Standards-Specifications/2015Supp.pdf

   Approved list of High Tension Cable Median Barriers

   http://idot.illinois.gov/Assets/uploads/files/Doing-Business/Specialty-Lists/Highways/Materials/Materials-&-Physical-Research/Metals/htcmedianbarrier.pdf

5. What were the requirements (e.g., minimum paved shoulder width, minimum median width, number of lanes, etc.) for the installation of rumble strips and cable median barriers at the study sites?

   Answer: Cable median barrier was installed at these locations to reduce cross-median crashes. This was based on an examination of 5 years of crash data. Illinois used FARS crashes on interstates and looked at head on and opposite-direction sideswipe. They used this information to develop a warrant chart [and] a subsequent list of sites for cable median barrier installation. For cable median barrier, the median width had to be no more than 100 ft.

6. What was the lateral offset from the road to the cable median barriers and how was that distance selected?

   Answer: Variable.

7. Please describe any challenges related to the rumble strip and/or cable median barrier installation and how you overcame them.

   Answer: Supervision required for both rumble strip and cable median barrier contractor was pretty extensive. Constant checking for uniformity was required to meet required specification.

8. Please describe any challenges related to the rumble strip and/or cable median barrier maintenance and how you overcame them.

   Answer: Ongoing maintenance is maybe more than originally projected in some Districts due to the number of cable barrier hits. Since cable barrier is doing its job, monthly repairs are not uncommon and should be expected/budgeted.

9. What lessons learned or recommendations would you share with another state interested in the widespread application of cable median barrier and rumble strips?

   Answer: Both low cost safety improvements appear to be a good investment in saving lives on roads.

APPENDIX B. ADDITIONAL INSTALLATION DETAILS FROM KENTUCKY

This appendix presents further details about the cable barrier installations from Kentucky based on a questionnaire that was sent to the participating States.

Cable Median Barriers and Shoulder Rumble Strip Combination Questions—Kentucky

1. What was the "before-period" condition for the treatment sites with respect to rumble strips and cable median barriers?
   - No cable median barriers and no rumble strips.
   - Cable median barriers present but no rumble strips.
   - No cable median barriers but rumble strips present.

   Answer: No cable median barriers but rumble strips present.

2. What type(s) of rumble strips were characteristic of the treatment sites evaluated by this study? (Check all that apply.)
   - Milled.
   - Rolled.
   - Formed.
   - Raised.
   - Other.

   Answer: Milled and rolled.

3. Can you provide specifications and/or standard drawings that address the following characteristics of the rumble strips evaluated by this study?
   - Width.
   - Length.
   - Depth.
   - Spacing.
   - Lateral placement (i.e., in relation to pavement marking).

   Answer:
   http://transportation.ky.gov/Construction/Standard%20amd%20Supplemental%20Specifications/400%20Asphalt%20Pavements%2012.pdf.

   Section 403.03.08

4. Can you provide specifications and/or standard drawings that address the following characteristics of the cable median barriers evaluated by this study?
   - Number of cables.
   - Post spacing.
   - Other important design considerations (i.e., cable pre-stretch, tensioning, slope placement, footing design).

   Answer:

   http://transportation.ky.gov/Construction-Procurement/Proposals/201-CHRISTIAN-MARSHALL-MCCRACKEN-141230.pdf.

5. What were the requirements (e.g., minimum paved shoulder width, minimum median width, number of lanes, etc.) for the installation of rumble strips and cable median barrier at the study sites?

   Answer: Cable installations are generally selected based on an annual evaluation process that considers crash experience, median width, median slope profile, traffic volume, traffic composition, and speed. From these variables, KYTC prioritizes a list of recommended cable barrier projects. Median width had to be narrower than 200 ft.

6. What was the lateral offset from the road to the cable median barriers and how was that distance selected?

   Answer: Approximately 8 ft lateral offset from travel lanes based on deflection on 10 ft post spacing.

7. Please describe any challenges related to the rumble strip and/or cable median barrier installation and how you overcame them.

   Answer: Monitor depth and alignment of rumbles. Ensure proper anchor placement for appropriate median coverage near bridges and coordinate minimum/maximum “gap” spacing for emergency vehicles.

8. Please describe any challenges related to the rumble strip and/or cable median barrier maintenance and how you overcame them.

   Answer: Cable barrier maintenance is handled through contract. No substantial issues with maintenance of rumbles.

9. What lessons learned or recommendations would you share with another state interested in the widespread application of cable median barriers and rumble strips?

   Answer: Have a defendable program to evaluate and select installations.

APPENDIX C. ADDITIONAL INSTALLATION DETAILS FROM MISSOURI

This appendix presents further details about the cable barrier installations from Missouri based on a questionnaire that was sent to the participating States.

Cable Median Barrier and Shoulder Rumble Strip Combination Questions—Missouri

1. What was the “before-period” condition for the treatment sites with respect to rumble strips and cable median barriers?
   - No cable median barriers and no rumble strips.
   - Cable median barriers present but no rumble strips.
   - No cable median barriers but rumble strips present.

   Answer: The median guard cable was not installed in combination with the rumble strips. Both were independent projects, and time of installation will vary. The “before-period” for the locations will not have median guard cable but would have potentially included a 30-inch wide rolled rumble strip (very little value in noise and feel).
2. What type(s) of rumble strips were characteristic of the treatment sites evaluated by this study? (Check all that apply.)
   - Milled.
   - Rolled.
   - Formed.
   - Raised.
   - Other.

   Answer: Missouri uses a milled rumble strip (potential for stamped with concrete pavements). The majority of installed miles to date are milled rumble strips.
3. Can you provide specifications and/or standard drawings that address the following characteristics of the rumble strips evaluated by this study?
   - Width.
   - Length.
   - Depth.
   - Spacing.
   - Lateral placement (i.e., in relation to pavement marking).

   Answer: All of our specifications are in our *Engineering Policy Guide* (EPG), including standard drawings. MoDOT will install this same rumble strip specification for shoulder widths as low as 2 ft. The link below will provide the policy relating to our rumble strip program:

   http://epg.modot.mo.gov/index.php?title=Category:626_Rumble_Strips

4. Can you provide specifications and/or standard drawings that address the following characteristics of the cable median barriers evaluated by this study?
   - Number of cables.
   - Post spacing.
   - Other important design considerations (i.e., cable pre-stretch, tensioning, slope placement, footing design).

   Answer: Our median guard cable program also has policy provided in our EPG. All current specifications and standard drawings are listed in the policy section. Also, please review the document called *MoDOT's Cable Median Barrier Program*, as it provides a lot of good information on our program.

   http://epg.modot.mo.gov/index.php?title=606.2_Guard_Cable

   It is important to note our program began with the low-tension systems, but the majority of miles installed are high-tension.

5. What were the requirements (e.g., minimum paved shoulder width, minimum median width, number of lanes, etc.) for the installation of rumble strips and cable median barriers at the study sites?

   Answer: The cable median barrier program was initially completed on our worst roadways first, and these roads featured very narrow medians (approx. 40 ft) and traffic volumes around 30,000 daily, but we used a systemwide installation method to eliminate the cross-median crash type on the highest need routes. Please see question 4 for more detail, but the treatment has been applied statewide on roadways identified as tier 1 or tier 2.

6. What was the lateral offset from the road to the cable median barriers and how was that distance selected?

   Answer: Historically, our program began with installing the median guard cable in the vertex of the ditch, which was basically in the middle of the median. In 2007, our program changed due to many factors (information on crash dynamics, maintenance issues, and other), and we began installing approximately 8 ft from the stripe. This means it will always be closer to one direction of travel. This information is available in the report identified in question 4 above.

7. Please describe any challenges related to the rumble strip and/or cable median barrier installation and how you overcame them.

   Answer: When MoDOT began the median guard cable program, there was little information available on installation-related issues (location, type, etc.). This ultimately led to a team being formed to determine better policy. I believe the issues with rumble strips relate to both noise and the bicycle community. We initially did not see much pushback from the bicycle community, but we are beginning to see this now as other States have a different specification and standard drawing (more desired by bicycle community). The noise complaints have occurred but have not been a detriment to our program.

8. Please describe any challenges related to the rumble strip and/or cable median barrier maintenance and how you overcame them.

   Answer: With our current specification of the median guard cable location and mow strip, we do not see many maintenance issues (we have an asphalt apron that extends from paved shoulder to approximately 1 ft past cable barrier—this was requested by maintenance). A larger issue related to maintenance of the cable system relates to vehicle crashes. This issue does create a financial issue as our agency is only able to receive about $^{1}/_{3}$ back in claims compared to impacts with the system.

   The rumble strips have not involved a great deal of maintenance issues due to failures. However, where we have seen areas of failures near the joint, we have allowed sections (not longer than 200 ft) to not be re-milled after a pavement repair. Overall, our system has not seen large-scale failures.

9. What lessons learned or recommendations would you share with another state interested in the widespread application of cable median barriers and rumble strips?

   Answer: The implementation needs to be based on a thorough crash type evaluation and involve widespread installations on a system of routes that would share similar characteristics (regardless of current crash information). In other words, when installing the median guard cable, evaluate characteristics of roads that share the cross-median crash type and install over a network of roadways that are similar (median width and roadway AADT could be your criteria). The same application can be applied on installation of rumble strips on improved shoulders. For instance, do roads with a minimum AADT have an over-representation of the roadway departure crash types? If so, all roads that have this minimum AADT threshold should have a rumble strip installed.

   Also, it is critical to create policy on your safety initiatives to allow your programs to succeed. The policy you develop will drive each program.

APPENDIX D. METHODOLOGY FOR CALCULATING CRASH COSTS

This appendix presents the methodology for estimating cost per crash for current year by severity, crash type, and speed limit based on value of a statistical life.[18]

The total cost of a fatal crash is larger than the value of a statistical life since there can be other injuries as well as property damage. The question is: how much larger? That is, how much is the cost of a fatal crash, given the value of a statistical life?

The relationship between value of a statistical life and cost of a crash can be derived by using latest comparable information from two sources involving the same research team. For 2001, the value of a statistical life (VSL) recommended to the National Highway Traffic Safety Administration was $3.8 million, and the mean comprehensive fatal crash cost irrespective of location or speed limit was $4,008,085, giving a ratio of cost per fatal crash to value of a statistical life of 1.055.[19,20]

To update the cost of a fatal crash to 2014, for example, this ratio is applied to the VSL in that year ($9.2 million) as given annually in a USDOT memo to get an updated 2014 cost of a fatal crash of $9.7 million.[21]

For economic analyses in FHWA DCMF evaluations, researchers typically use total crashes (all severities combined), PDO crashes and fatal plus injury crashes combined, sometimes disaggregated for more precision by crash type, site type (e.g., signalized intersections, road segments), and environment (speed limit > 45 and $\geq$ 45 mi/h). These costs are usually derived from the 2005 FHWA crash cost report using the 2001 costs and updating them using the procedure recommended in that report.[20]

It is recommended that researchers continue to use the basic disaggregate cost from the 2005 FHWA report (since that is the latest source of disaggregate crash cost, and disaggregation is desirable) and update it to current year considering the prescribed USDOT VSL number for that year. For example, for 2014:

2014 disaggregate crash cost = (2001 *disaggregate crash cost*/2001 *fatal crash cost*) x (*updated 2014 fatal crash cost derived from 2014 recommended VSL*)

Substituting known values in millions, rounded to one decimal place per the USDOT memo, produces the following result:

2014 Disaggregate crash cost = (2001 *disaggregate crash cost*/4.0) x (9.7)

In other words, the 2001 crash costs are factored up by 9.7/4.0 = 2.425 to update them to 2014.

For example, the fatal and injury crash cost for all locations and speed limits in the FHWA report is $158,177 for 2001, which factors up to $383,579 for 2014.

Continuing the 2014 example, the USDOT memo also prescribes that sensitivity analysis be conducted based on low and high VSLs of $5.2 and $13.0 million for 2014. These translate to

0.57 and 1.41 times the $9.2 million VSL recommended for use. By inference, sensitivity analysis should also be done for DCMF evaluations by estimating B/C ratios for 0.57 and 1.41 times the 2014 crash costs derived using the method above. For example, for the fatal and injury crashes, B/C ratios would be estimated based on costs of $218,640 and $540,846.

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