Safety Evaluation of Edge-Line Rumble Stripes on Rural Two-Lane Horizontal Curves

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS 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 the implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan. The ELCSI-PFS studies provide 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 edge-line rumble stripes (ELRSs) on rural two-lane horizontal curves. ELRSs are a variation of common shoulder rumble strips used to alert drowsy or distracted drivers when they are leaving the travel lane to the right. ELRSs are installed with the edge-line pavement marking placed directly over the rumble strip. Data were obtained at treated rural two-lane horizontal curves in Kentucky and Ohio. The results for Kentucky indicate statistically significant reductions for total, injury, run-off-road (ROR), and nighttime crashes. The results for Ohio indicate statistically significant reductions for all crash types (i.e., total, injury, ROR, nighttime, and nighttime ROR). The B/C analysis results suggest that this treatment can be highly cost-effective. This report is intended for State departments of transportation, transportation agencies, academics, researchers, and other practitioners.

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Acting Director, Office of Safety
Research and Development

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16. Abstract The Development of Crash Modification Factors (DCMF) program conducted safety evaluations of edge-line rumble stripes (ELRSs) on rural two-lane horizontal curves for the Evaluation of Low-Cost Safety Improvements Pooled Fund Study. This study evaluated the application of ELRSs on rural two-lane horizontal curves. ELRSs are a variation of common shoulder rumble strips used to alert drowsy or distracted drivers when they are leaving the travel lane to the right. ELRSs are installed with the edge-line pavement marking placed directly over the rumble strip. Geometric, traffic, and crash data were obtained at treated rural two-lane horizontal curves in Kentucky and Ohio. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before–after analysis was conducted using reference groups of untreated rural horizontal curves with similar characteristics to the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. Owing to a small sample for the reference group in Kentucky and a simultaneous statewide curve warning sign upgrade program in Ohio, alternative reference sites were used to account for annual trends. The results for Kentucky indicated statistically significant reductions for total, injury, run-off-road (ROR), and nighttime crashes, with crash modification factors (CMFs) of 0.75, 0.64, 0.74, and 0.63, respectively. The results for Ohio indicated statistically significant reductions for all crash types, with total, injury, ROR, nighttime, and nighttime ROR CMFs of 0.79, 0.79, 0.78, 0.75, and 0.71, respectively. The two States' results could not be combined because of the statewide curve signing program in Ohio. It is important to note that all crash types considered in this research excluded intersection-related and animal crashes. Benefit–cost (B/C) ratios were estimated to be 331:1 for Kentucky and 477:1 for Ohio. If ELRSs were used as a curve-specific treatment, the B/C ratio would likely be much smaller because of the higher installation cost; however, these results suggest that the treatment can be highly cost effective.			
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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	average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
B/C	benefit–cost
C-G	comparison group
CLRS	center-line rumble strip
CMF	crash modification factor
DCMF	Development of Crash Modification Factors (program)
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
ELRS	edge-line rumble stripe
FHWA	Federal Highway Administration
FTM	flat thermoplastic edge marking
GIS	geographic information system
HPMS	Highway Performance Monitoring System
HSIS	Highway Safety Information System
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, O is property damage only)
KYTC	Kentucky Transportation Cabinet
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
ODOT	Ohio Department of Transportation
PFS	pooled fund study
ROR	run-off-road
SE	standard error
SPF	safety performance function
SRS	shoulder rumble strip
SVROR	single-vehicle run-off-road

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 new strategies for statewide safety improvements. Forty State transportation departments have provided technical feedback on safety improvements to the DCMF program and have implemented 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 edge-line rumble stripes (ELRSs) on rural two-lane horizontal curves. ELRSs are a variation of common shoulder rumble strips (SRSs) used to alert drowsy or distracted drivers when they leave the travel lane to the right. ELRSs are installed where edge-line pavement markings would normally be placed, and the pavement marking is installed directly over the rumble strip. In this way, the ELRSs are installed closer to the travel lane than common SRSs. In addition, the vertical faces that are created within the milled rumble strip to which pavement markings are applied have the effect of enhancing the visibility of the edge line during nighttime and wet-weather conditions.

The project team obtained geometric, traffic, and crash data at treated rural horizontal curve locations in Kentucky and Ohio. To account for potential selection bias and regression-to-the-mean, the project team conducted an empirical Bayes (EB) before–after analysis using reference groups of untreated rural horizontal curves with similar characteristics to the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. While the analysis focused on the safety effectiveness on horizontal curves, the treatment applications were not limited only to horizontal curves. The treatment was a corridor treatment applied to segments consisting of both tangents and curves; however, the analysis removed horizontal tangents and only considered the effectiveness on curves.

The results for Kentucky indicated statistically significant reductions for total, injury, run-off-road (ROR), and nighttime crashes at the 95-percent confidence level. Nighttime crashes had the smallest crash modification factor (CMF), or the greatest reduction, with a value of 0.63. Total, injury, and ROR crashes had CMFs of 0.75, 0.64, and 0.74, respectively. The CMF for nighttime ROR crashes was 0.75 and was consistent with the same CMF from Ohio; however, it was significant only at the 80-percent level, suggesting that sample size was the reason for the lack of statistical significance at the 95-percent level. The results for Ohio indicated statistically significant reductions for all crash types. Nighttime ROR crashes had the smallest CMF of 0.71. Total, injury, ROR, and nighttime crashes had CMFs of 0.79, 0.79, 0.78, and 0.75, respectively. The resulting Ohio installation CMFs reflected the installation of ELRSs on horizontal curves as well as the impact of the statewide signing program. It is also important to note that all crash types considered in this research excluded intersection-related and animal crashes.

A disaggregate analysis of the results indicated larger safety benefits for horizontal curves with average annual daily traffic (AADT) greater than 4,000 for all crash types; however, the differences by AADT were not statistically significant at the 95-percent confidence level. The disaggregate analysis further indicated larger safety benefits for horizontal curves with a higher before-period expected crash frequency. The results suggested no benefit for curves with low before-period expected crash frequencies for all crash types. The difference in CMFs between low before-period expected crash frequency and high before-period expected crash frequency was statistically significant for total and ROR crashes. Due to correlation between variables, caution should be used in interpreting and applying these disaggregate results; however, the disaggregate analysis CMFs may be used to inform the process of prioritizing treatment sites for ELRSs.

Estimated B/C ratios range from 189:1 to 467:1 for Kentucky and from 272:1 to 672:1 for Ohio. On first inspection, the B/C ratios were larger than expected for an installation of this type. However, the installations took place on corridors, while the analysis only looked at the safety effects on horizontal curves. Horizontal curves have higher crash rates than overall corridors, and the cost per mile of installation would not be representative for installations only on horizontal curves. As a curve-specific treatment, the B/C ratio would likely be reduced owing to the higher deployment cost for spot-specific installations. Regardless, these results suggest that the treatment, even in its most expensive variation, can be highly cost effective.

CHAPTER 1. INTRODUCTION

This chapter presents background information on the strategy of using edge-line rumble stripes (ELRSs), the goals of the study reported here, and a review of the existing literature on the use of rumble strips.

BACKGROUND ON STRATEGY

ELRSs are a variation of the common shoulder rumble strips (SRSs) used to alert drowsy or distracted drivers when they leave the travel lane to the right. SRSs and ELRSs both target run-off-road (ROR) crashes. Key distinctions between SRSs and ELRSs are provided in the following points:

- SRSs are provided on the shoulder between the pavement marking and the outside edge of the pavement and can be defined by their offset from the edge-line pavement marking.
- ELRSs are installed where the edge-line pavement marking would normally be placed, and the pavement marking is installed directly over the rumble strip. In this way, the rumble stripes are installed closer to the travel lane than common SRSs. In addition, vertical faces are created within the milled rumble strip to which pavement markings are applied, thereby enhancing the visibility of the edge line during nighttime and wet-weather conditions.

Application of ELRSs varies among States depending on climate and roadway surface type. In colder areas, rumble strips are milled into the surface of the roadway, allowing them to be snowplowable. In areas that do not receive snowfall, profiled thermoplastic pavement markings can be used. In addition, profiled thermoplastic pavement markings have been used as an alternative to milled ELRSs for roadways with a chip seal surface. The research in this study focused on the safety effectiveness of milled ELRSs.

Several research studies have examined the use of SRSs; however, research into the performance of ELRSs has been rare and has not been rigorously evaluated. In addition, milled rumble strips have been installed on roadway segments consisting of both horizontal tangents and horizontal curves. Installations on only horizontal curves have been uncommon, and therefore, safety effectiveness evaluations have not focused on their effectiveness on horizontal curves specifically. This study focused on the safety effectiveness of ELRSs on rural two-lane horizontal curves taken from rumble strip installations that were not specific to horizontal curves.

Additional details concerning current practice with rumble strips can be found on the Federal Highway Administration (FHWA) *Rumble Strip Community of Practice* Web page.[1] This site provides a description of the three major types of rumble strips (milled, rolled (or formed), and raised), detailed construction drawings, effectiveness estimates, interviews with users and other experts, and other important material.

BACKGROUND ON STUDY

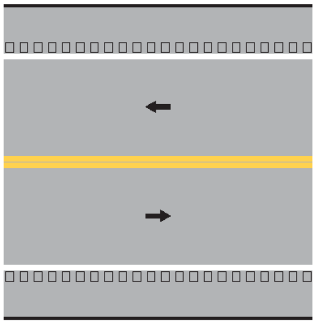
In 1997, the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Highway Traffic Safety, with the assistance of FHWA, the National Highway Traffic Safety Administration, and the Transportation Research Board Committee on Transportation Safety Management, 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 emphasis areas that affect highway safety. The 22 emphasis areas were published in the *AASHTO Strategic Highway Safety Plan*.(2)

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 one of the key emphasis areas and includes an introduction to the problem, a list of objectives for improving safety, 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; about 80 percent of the strategies are considered tried or experimental.

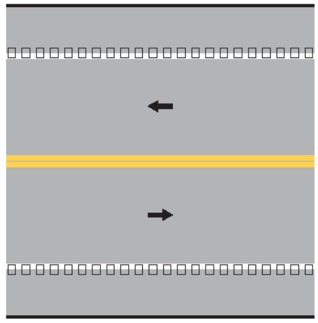
In 2005, to support the implementation of the guides, FHWA organized a pooled fund study (PFS) to evaluate low-cost safety strategies as part of this strategic highway safety effort. Over time, the pooled fund has grown in size and, at the time of this study, included 40 States. The PFS evaluates the safety effectiveness of several tried and experimental, low-cost safety strategies through scientifically rigorous crash-based studies. FHWA selected the use of ELRSs as a strategy to be evaluated as part of this effort.

LITERATURE REVIEW

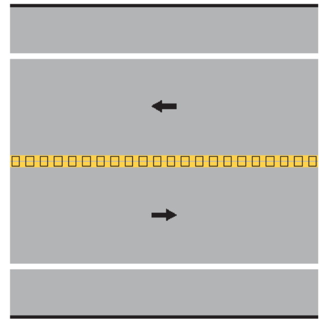
The *Manual on Uniform Traffic Control Devices* (MUTCD) defines rumble strips as either slightly raised or depressed road surfaces with a rough texture designed to provide a haptic alert for inattentive drivers leaving the travel lane.(3) As shown in figure 1, rumble strips may be installed either on the shoulders or center line on rural two-lane highways, and the edge line may be adjacent to the rumble strip or overlapping with it, creating a rumble stripe.



A. Edge line not on rumble strip.



B. Edge line on rumble strip.



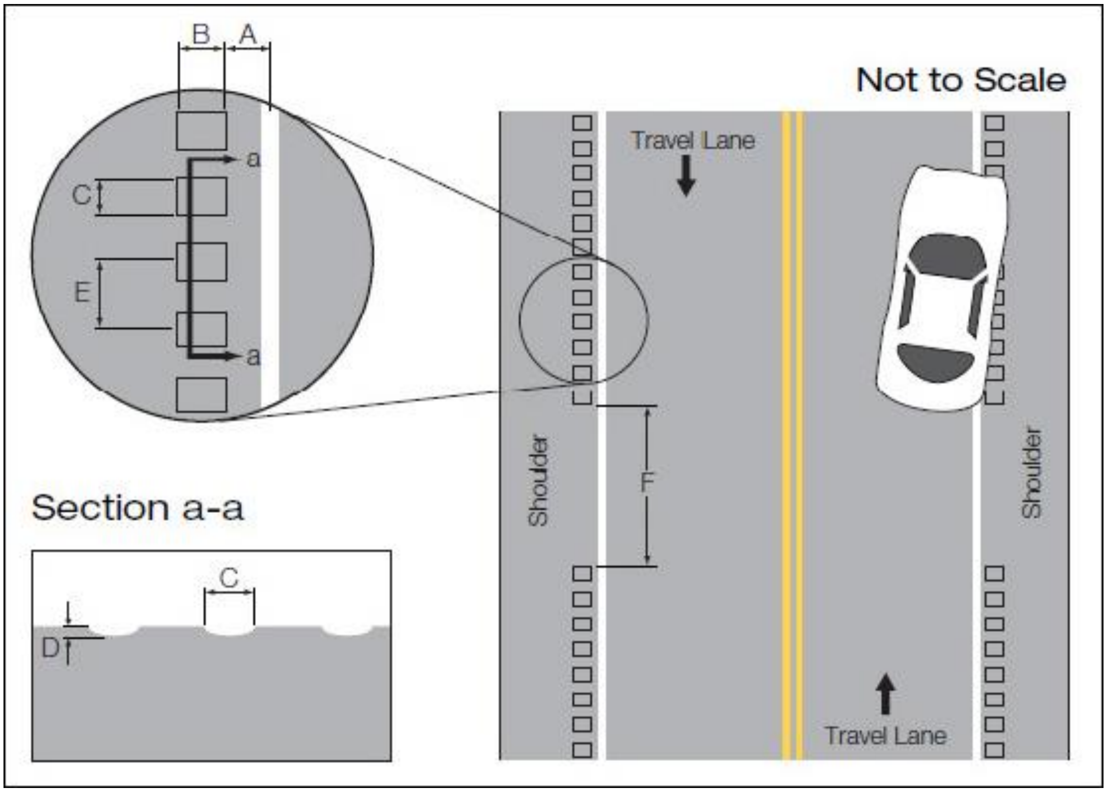
C. Center line on rumble strip.

Source: FHWA.
Note: (A) Edge lines may be located alongside the rumble strip, (B) on the rumble strip, or (C) the center line markings may also be located on a center line rumble strip. Arrows indicate direction of travel. Empty squares indicate rumble strip.

Figure 1. Illustration. Examples of longitudinal rumble strip markings.[3]

Figure 2 provides an illustration of rumble strip dimensions, which are explained as follows:[4]

- **A—Offset**: Distance from the pavement marking (delineating the edge of the traveled way) to the inside edge of the rumble strip.
- **B—Length**: Dimension of the strip that is perpendicular to the travel directions of the roadway. This is often referred to as the transverse width of the rumble strip.
- **C—Width**: Dimension of the strip that is parallel to the travel direction of the roadway.
- **D—Depth**: Maximum distance from the surface of the roadway to the bottom of the rumble strip.
- **E—Spacing**: Distance between adjacent rumble strips. It is most often measured from the center of the strip to the center of the adjacent strip.
- **F—Gap**: Distance from the edge of the rumble strip to edge of rumble strip when there is a break in the pattern. Gaps are commonly used to allow bicycles to cross the rumble strip pattern, to allow passing vehicles to cross center-line rumble strips (CLRSs), and to allow for turning movements at intersections and driveways.



Source: FHWA.

Figure 2. Illustration. Overview of rumble strip dimensions.[(4)]

The University Transportation Center for Alabama conducted an evaluation of ELRS markings in terms of service life, lifecycle cost, and wet and dry visibility in comparison with flat thermoplastic edge markings (FTMs).[(5)] The authors measured nighttime dry and wet retroreflectivity at 16 1-mi FTM segments and 5 2-mi ELRS segments. They found that initial dry retroreflectivity was similar between the two groups; however, ELRSs lost visibility at a lower rate due to cumulative traffic passes. ELRSs were found to provide a higher dry retroreflectivity and longer service life than FTMs under similar traffic conditions. For wet retroreflectivity, the ELRSs had a higher initial value than FTMs, but the degradation could not be compared between the two because of a lack of data for FTMs. The cost per mile for ELRSs was $2,424 for a 5-year marking service life and an 8-year lifecycle.

A study by Miles et al. used video data to examine the impacts of CLRSs and ELRSs on passing operations and lateral position on Texas highways.[(6)] After application of milled CLRSs on no-passing and passing zones, the authors found no change in passing opportunities or the percentage of vehicles that passed. However, center-line crossing time increased significantly, and gap distance decreased significantly, irrespective of the speed of the data-recording vehicle. For lateral position, vehicle placement shifted farther from the center line after implementation of CLRSs. After implementation of ELRSs, researchers noted a decrease of about 50 percent in shoulder encroachments as well as a significant reduction in other encroachments, including inadvertent contact with the edge line.

Carlson et al. examined wet-night visibility of pavement markings using experimental drivers on a closed rain tunnel.(7,8) The study tested nine different treatments in random orders and measured perception distance for each sample location. The driver alerted the researcher when he or she observed a marking and when the type could be determined. This research included testing rumble stripes. The findings suggested there was little difference in detection distance between flat thermoplastic lines and rumble strip lines at low rainfall rates. However, the detection distance was 13 to 38 percent greater for rumble strip lines for medium and heavy rainfall rates.

The Mississippi Department of Transportation installed ELRSs on a portion of Interstate 59 with generally encouraging results.(9) Preliminary data indicated that the strategy provided an excellent audible alert, increased visual awareness of the travel lane, increased reflectivity, and provided results similar to those for inverted profile striping, and Mississippi residents welcomed the installation. However, some concerns associated with the rumble stripes arose, including noise pollution and the potential for an increase in over-correcting and head-on crashes.

Torbic et al. summarized numerous studies on SRSs.(10) Table 1 summarizes their results of many States' studies (negative percentages indicate a decrease in crashes), and their NCHRP report outlines several key findings.(10) The report notes that SRSs installed along freeways made up the majority of the safety effectiveness evaluations and that only a small percentage of the studies evaluated the safety effectiveness of nonfreeway installations. While the evaluations generally focused on crash types most directly affected by rumble strip presence, such as single-vehicle ROR (SVROR) crashes, several studies looked at the safety effect on total crashes. Rumble strip application showed an average reduction of 36 percent in SVROR-type crashes, with a range of 10 to 80 percent. The reduction of total crashes ranged from 13 to 33 percent, with an average reduction of 21 percent.(10)

Table 1. Summary of studies on changes in target collision frequency from application of SRSs.[10]

State	Type of Facility	Type of Collision Targeted	Percent Change in Target Collision Frequency (Standard Deviation)	Type of Analysis
Arizona[11]	Interstate	SVROR	−80	Cross-sectional comparison
California[12]	Interstate	SVROR	−49	Before–after with comparison sites
California[12]	Interstate	Total	−19	Before–after with comparison sites
Connecticut[13]	Limited-access roadways	SVROR	−32	Before–after with comparison sites
Florida[11]	—	Fixed object	−41	Naive before–after
Florida[11]	—	Ran-into-water	−31	Naive before–after
Illinois and California[14]	Freeways	SVROR (total)	−18 (± 6.8)	Before–after with marked comparison sites and a comparison group
Illinois and California[14]	Freeways	SVROR (injury)	−13 (±11.7)	Before–after with marked comparison sites and a comparison group
Illinois and California[14]	Rural freeways	SVROR (total)	−21.1 (±10.2)	Before–after with marked comparison sites and a comparison group
Illinois and California[14]	Rural freeways	SVROR (injury)	−7.3 (±15.5)	Before–after with marked comparison sites and a comparison group
Kansas (unpublished, cited in Stutts[15])	Freeways	SVROR	−34	Unknown
Maine [16]	Rural freeways	Total	Inconclusive	Before–after with comparison sites
Massachusetts (unpublished, cited in Stutts[15])	—	SVROR	−42	Unknown
Michigan[17]	—	SVROR	−39	Cross-sectional comparison

State	Type of Facility	Type of Collision Targeted	Percent Change in Target Collision Frequency (Standard Deviation)	Type of Analysis
Minnesota[(18)]	Rural multilane divided highways	Total	−16	Naive before–after
Minnesota[(18)]	Rural multilane divided highways	Injury	−17	Naive before–after
Minnesota[(18)]	Rural multilane divided highways	SVROR (total)	−10	Naive before–after
Minnesota[(18)]	Rural multilane divided highways	SVROR (injury)	−22	Naive before–after
Minnesota[(18)]	Rural multilane divided highways	Total	−21	Before–after with comparison sites
Minnesota[(18)]	Rural multilane divided highways	Injury	−26	Before–after with comparison sites
Minnesota[(18)]	Rural multilane divided highways	SVROR (total)	−22	Before–after with comparison sites
Minnesota[(18)]	Rural multilane divided highways	SVROR (injury)	−51	Before–after with comparison sites
Minnesota[(19)]	Rural two-lane roads	SVROR (total)	−13 (8)	Before–after EB analysis with reference group
Minnesota[(19)]	Rural two-lane roads	SVROR (injury)	−18 (12)	Before–after EB analysis with reference group
Montana[(20)]	Interstate and primary highways	SVROR	−14	Before–after with comparison sites
New Jersey (unpublished, cited in Stutts[(15)])	—	SVROR	−34	Unknown
New York[(21)]	Interstate parkway	SVROR	−65 to 70	Naive before–after
Pennsylvania[(22)]	Interstate	SVROR	−60	Naive before–after
Tennessee[(23)]	Interstate	SVROR	−31	Unknown
Utah[(24)]	Interstate	SVROR	−27	Before–after with comparison sites

State	Type of Facility	Type of Collision Targeted	Percent Change in Target Collision Frequency (Standard Deviation)	Type of Analysis
Utah[24]	Interstate	Total	−33	Before–after with comparison sites
Virginia[25]	Rural freeways	SVROR	−52	Before–after with comparison sites
Washington[26]	—	Total	−18	Naive before–after
Multistate[11]	Rural freeways	SVROR	−20	Before–after with comparison sites

Note: This table is adapted from table 4 in Torbic et al. (2009).[10]
—Information was not available.

Of all the rumble strip crash reduction studies reviewed by Torbic et al., only one (Patel et al.) specifically addresses rural two-lane roads.(19) That study focused on roads in Minnesota and used the EB analysis approach, which is generally more accurate than alternative before–after analysis types. Therefore, from among the listed sources, the Minnesota study appeared to provide the most relevant and reliable indications of the potential safety effects of ELRSs. It estimated a crash reduction of 13 percent (standard error (SE) = 8) for all SVROR crashes and 18 percent (SE = 12) for SVROR injury crashes. It should be noted, however, that these crash reduction factors only applied to rural two-lane roads with an AADT greater than 4,000.(27)

Torbic et al. examined the safety effectiveness of SRSs on rural two-lane highways.(10) The EB before–after results indicated no change in crashes after application of SRSs for total crashes and fatal and injury crashes for combined data from Minnesota, Missouri, and Pennsylvania. The results indicated a significant 16-percent decrease in SVROR crashes and a significant 36-percent decrease in SVROR fatal and injury crashes at combined sites. Additional analyses indicated that Pennsylvania had a significant 24-percent reduction in total crashes, 44-percent decrease in SVROR crashes, and 37-percent decrease in SVROR fatal and injury crashes. In consideration of all analytical methods employed, Torbic et al. recommended the following CMFs for SRSs on rural two-lane roads based on their research:(10)

- 0.84 for SVROR crashes.
- 0.64 for SVROR fatal and injury crashes.

In addition, Torbic et al. quantified the impact of SRS placement on safety, focusing on SVROR fatal and injury crashes. Placement was defined as edge line and non-edge line, which were compared with no rumble strips. ELRSs were defined as rumble strips with an offset distance of 0 to 8 inches, and non-ELRSs were defined as having an offset of 9 inches or more. For two-lane rural roadways, there was no significant or practical difference between ELRSs and non-ELRSs. Also, there was no evidence that suggested SRSs resulted in a reduction of SVROR crashes involving heavy vehicles.(10)

Khan et al. evaluated the safety benefits of SRSs on rural two-lane highways in Idaho.(28) The authors conducted an EB before–after analysis using data from 178.63 mi of data from treatment sites. The results indicated a 14-percent reduction in ROR crashes. Further analysis indicated a 33-percent reduction in ROR crashes for sections with an AADT less than 1,000. In addition, SRSs were most effective on horizontal tangents and horizontal curves with moderate curvature. The study found that SRSs were most effective for paved shoulder widths of 3 ft or more.(28)

Potts et al. evaluated the safety impacts of wider pavement markings with both CLRSs and ELRSs with resurfacing on rural two-lane highways in Missouri.(29) The EB analysis indicated a significant 47.4-percent reduction in fatal and disabling injury crashes and a significant 38.3-percent reduction in fatal and all injury crashes. A benefit–cost (B/C) evaluation indicated a B/C ratio of 35.6 for wide markings and both CLRSs and ELRSs with resurfacing on rural two-lane roadways.(29)

Lyon et al. evaluated the safety impacts of combined SRSs and CLRSs using data from Kentucky, Missouri, and Pennsylvania.(30) Kentucky data included SRSs and ELRSs, and the final data included sites where SRSs/ELRSs and CLRSs were installed concurrently as part of a resurfacing effort or where CLRSs had been installed as retrofits. Table 2 provides the dimensions of the rumble strips implemented in each of the three States. Note that Pennsylvania had two typical applications for CLRSs and an alternative design for bicycle-tolerable rumble strips.

Table 2. Rumble strip dimensions from Lyon et al.[30]

Location	Type	Width (inches)	Length (inches)	Depth (inches)	Spacing (inches)
Kentucky	CLRS	7–7.5	12	${}^{1}/_{2}$–${}^{5}/_{8}$	24
Kentucky	SRS	$7 \pm {}^{1}/_{2}$	16	${}^{1}/_{2} \pm {}^{1}/_{8}$	12 ± 1
Missouri	CLRS	$7 \pm {}^{1}/_{2}$	12	${}^{7}/_{16} \pm {}^{1}/_{16}$	12 and 24
Missouri	SRS	$7 \pm {}^{1}/_{2}$	12	${}^{7}/_{16} \pm {}^{1}/_{16}$	12
Pennsylvania	CLRS 1	$7 \pm {}^{1}/_{2}$	16	${}^{1}/_{2} \pm {}^{1}/_{16}$	24 and 48
Pennsylvania	CLRS 2	$7 \pm {}^{1}/_{2}$	14–18	${}^{1}/_{2} \pm {}^{1}/_{16}$	24
Pennsylvania	ELRS	$5 \pm {}^{1}/_{2}$	6	${}^{1}/_{2} \pm {}^{1}/_{16}$	7
Pennsylvania	Bike-tolerable SRS[1]	$5 \pm {}^{1}/_{2}$	16	${}^{3}/_{8} \pm {}^{1}/_{16}$	7
Pennsylvania	Bike-tolerable SRS[2]	$5 \pm {}^{1}/_{2}$	16	${}^{3}/_{8} \pm {}^{1}/_{16}$	6

[1]Roadway's posted speed limit was greater than or equal to 55 mi/h.
[2]Roadway's posted speed limit was less than 55 mi/h.

The EB analysis indicated the following significant CMFs for combined States:[30]

- 0.80 for total crashes (excluding intersection-related and animal crashes).
- 0.77 for fatal and injury crashes.
- 0.74 for ROR crashes.
- 0.63 for head-on crashes.
- 0.77 for sideswipe-opposite-direction crashes.
- 0.70 for head-on and sideswipe-opposite-direction crashes.
- 0.73 for ROR, head-on, and sideswipe-opposite-direction crashes.

Further disaggregate analyses by Lyon et al. indicated significant reductions in Kentucky and Missouri but not in Pennsylvania.[30] The authors surmised that earlier installations (which were used by Torbic et al.) were higher-crash locations, while more recently treated sites did not have a high target crash issue (and therefore no safety benefit).[10] Additional analysis by Lyon et al. indicated the following:[30]

- Larger reductions in ROR crashes for higher traffic volumes (greater than 3,200 AADT).
- Larger reductions in head-on and sideswipe-opposite-direction crashes for lower traffic volumes (less than 9,200 AADT).

A B/C analysis found an estimated B/C ratio between 20.2 and 54.7 based on estimated service lives of 7 to 12 years and estimated annual costs of \$557 to \$1,511/mi.[30]

Sayed et al. evaluated the safety effectiveness of CLRSs and SRSs alone and combined on rural two-lane and four-lane divided highways in British Columbia using an EB before–after study design.[31] The combined application on rural two-lane highways resulted in a 21.4-percent reduction in off-road right, off-road left, and head-on collisions combined. For rural two-lane highways, SRS applications resulted in a 26.1-percent reduction in off-road right collisions, and CLRS applications resulted in a 29.3-percent reduction in off-road left and head-on collisions.(31)

Torbic et al. evaluated the effect of combined CLRSs and SRSs using data from approximately 80 mi of treated roadways in Mississippi.(32) The target crash types evaluated included SVROR crashes left or right, sideswipe-opposite-direction crashes, and head-on crashes. Crash severities evaluated individually included total crashes, fatal and injury crashes, and fatal and serious injury crashes. The results of the EB before–after analysis indicated a significant 35-percent reduction in total target crashes, significant 40-percent reduction in fatal and injury target crashes, and an insignificant 12-percent increase in fatal and serious injury target crashes.(32)

Kay et al. evaluated the safety impacts of CLRSs and combined CLRSs and SRSs on rural two-lane highways in Michigan.(33) The EB before–after analysis examined approximately 3,000 mi of CLRS applications and 1,075 mi of combined CLRS and ELRS applications. The results for CLRSs indicated the following significant reductions (K, A, B, C, and O refer to the KABCO scale used to represent injury severity in crash reporting where K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only):(33)

- 15.8 percent for total crashes.
- 27.3 percent for target crashes.
- 52.9 percent for target-wet pavement crashes.
- 1.4 percent for target-wintry pavement crashes.
- 42.8 percent for target-passing crashes.
- 28.8 percent for target-impaired driving crashes.
- 44.2 percent for target-K injury crashes.
- 32.0 percent for target-A injury crashes.
- 39.3 percent for target-B injury crashes.
- 27.9 percent for target-C injury crashes.
- 16.2 percent for target-O crashes.

The results for combined CLRSs and SRSs indicated the following significant reductions:(33)

- 17.2 percent for total crashes.
- 32.8 percent for target crashes.
- 55.6 percent for target-wet pavement crashes.
- 4.6 percent for target-wintry pavement crashes.
- 35.7 percent for target-passing crashes.
- 39.9 percent for target-impaired driving crashes.
- 51.4 percent for target-K injury crashes.
- 32.5 percent for target-A injury crashes.
- 53.7 percent for target-B injury crashes.
- 35.2 percent for target-C injury crashes.
- 28.5 percent for target-O crashes.

Target crashes were identified manually as crashes involving a vehicle crossing the center line of the roadway.

Olson et al. conducted a before–after evaluation of combined CLRSs and SRSs on rural two-lane highways in Washington.[(34)] The analyses compared simultaneous installations, installations where CLRSs were later added to sections with SRSs, and installations where SRSs were later added to sections with CLRSs. In addition, the authors analyzed composite conditions where there were no rumble strips in the before period and conditions with both CLRSs and SRSs, disregarding when they were installed.

For simultaneous installations, the application resulted in a 63.3-percent reduction in lane departure crashes, a 65.4-percent reduction in crossover crashes, and a 61.4-percent reduction in ROR right crashes. Installations were noted to be more effective at higher speeds and for sections with shoulders greater than 4 ft.[(34)]

For sections where CLRSs were added to SRSs, the application resulted in a 64.7-percent reduction in crossover crashes and an 8.5-percent increase in ROR right crashes, resulting in a combined 44.6-percent reduction in lane-departure crashes. For sections where SRSs were added to CLRSs, the application resulted in a 47-percent reduction in ROR right crashes and a 6.8-percent reduction in crossover crashes, resulting in a 37.2-percent reduction in lane-departure crashes.[(34)]

The composite analysis indicated a 66-percent reduction in lane-departure crashes and a 56-percent reduction in fatal and serious injury crashes. The combined application was noted to be slightly more effective for 11-ft lane widths than 12-ft lane widths.

Kubas et al. evaluated the safety effectiveness of CLRSs and SRSs and SRSs only on rural two-lane highways in North Dakota.[(35)] The authors compared before- and after-crash rates to estimate the effectiveness of rumble strip applications for various crash types. The installation of CLRSs and SRSs resulted in a 2-percent decrease in total crashes, 45-percent decrease in fatal crashes, 21-percent increase in injury crashes, 5-percent decrease in property damage only crashes, and 29-percent decrease in ROR crashes based on a limited sample. The installation of SRSs resulted in a 15-percent decrease in total crashes, 22-percent decrease in property damage only crashes, and 97-percent increase in ROR crashes based on a limited sample. It should be noted that no CMFs from this study received more than a two-star rating in the CMF Clearinghouse.[(35)]

CHAPTER 2. OBJECTIVE

The research described in this report examined the safety impacts of ELRSs on rural horizontal curves in Kentucky and Ohio with the objective to estimate the safety effectiveness of this strategy as measured by crash frequency. Excluding intersection-related and animal crashes, the study included the following crash types:

- Total (all types and severities combined).
- Injury (K, A, B, and C injuries on the KABCO scale).
- ROR (all severities combined).
- Nighttime (including dusk and dawn; all severities combined).
- Nighttime ROR (including dusk and dawn; all severities combined).

A further objective was to address questions of interest including the following:

- Do effects vary by level of traffic volumes?
- Do effects vary by posted speed limit?
- Do effects vary by paved shoulder width?

Other questions included the following:

- Are crash migration effects evident?
- Are spillover effects evident?

The evaluation of overall effectiveness included the 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

The study design involved a sample size analysis and prescription of needed data elements. The sample size analysis assessed the size of sample required to statistically detect an expected change in safety and also determined what changes in safety could be detected with likely available sample sizes.

Sample size estimations required assumptions of the expected treatment effect and the average crash rate at treatment sites prior to treatment. The project team calculated minimum and desired sample sizes assuming a conventional before–after with comparison group (C-G) study design, as described in Hauer, and a literature review of likely safety effects.(36) The sample size analysis undertaken for this study addressed the size of sample required to statistically detect an expected change in safety. The sample size estimates were conservative because the more robust EB methodology was actually used in the before–after analysis rather than the C-G methodology.

Sample sizes were estimated for various assumptions of the likely annual crash rate in the before period and likely safety effects of the strategy. Annual crash rates were assumed for five crash types (i.e., total, injury, ROR, nighttime, and nighttime ROR) as shown in table 3. Intersection-related and animal crashes were not included in these crash rates.

The horizontal curve site crash rates for the all and injury crash types were obtained directly from Torbic et al. (rates A and B) and before-period data from Kentucky (rate C) and Ohio (rate D).(10) The crash rates for Washington (rate A) and Minnesota (rate B) were selected in particular because they represented the general upper and lower range of national crash rates. For instance, estimated crash rates for sites in Pennsylvania and Missouri from the same NCHRP report were 1.75 total crashes per mi/yr and 2.11 total crashes per mi/yr, respectively, which were both within that range. The before-period crash rates for Washington and Minnesota were used for planning purposes during the development of the study design, and the rates for Kentucky and Ohio were provided to show the actual rates. The before-period rates for Kentucky and Ohio were greater than those assumed during the planning stages, indicating that sufficient sample sizes were more achievable.

The Washington and Minnesota crash rates for the ROR crash type were estimated by multiplying the total crash rate by the ratio of ROR crashes to total crashes based on data from Washington between 2001 and 2005. The nighttime crash rates were estimated by multiplying the total crash rate by the ratio of nighttime collisions to total collisions based on 2008 Kentucky crash data. The nighttime ROR crash rates were estimated by multiplying the nighttime crash rate by the same ROR crashes ratio.

Table 3. Before-period crash rate assumptions.

Crash Type	Rate A (Washington) (crashes/mi/yr) Average Site Length 0.164 mi	Rate B (Minnesota) (crashes/mi/yr) Average Site Length 0.142 mi	Rate C (Kentucky) (crashes/mi/yr) Average Site Length 0.068 mi	Rate D (Ohio) (crashes/mi/yr) Average Site Length 0.073 mi
Total	3.37	0.84	3.37	4.12
Injury	1.52	0.31	1.25	1.69
ROR	0.94	0.23	2.04	3.15
Nighttime	1.15	0.29	0.97	1.54
Nighttime ROR	0.32	0.08	0.67	1.30

Table 4 through table 8 provide estimates of the required number of before- and after-period mile-years for both the 90- and 95-percent confidence levels on horizontal curve sites by crash type. The minimum sample indicated the level for which a study seemed worthwhile (i.e., it was feasible to detect with the level of confidence the largest effect that might reasonably be expected based on what was currently known about the strategy). These sample size calculations were based on specific assumptions regarding the number of crashes per mile and years of available data. Mile-years is the number of miles where 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 9-mi segment and data were available for the 3 years since implementation, then a total of 27 mi-years of after-period data would be available for the study.

The sample size values recommended in this study are highlighted with an asterisk in table 4 through table 8. These were selected 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 are 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 C-G that was 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 had been assumed.

Table 4. Minimum required before-period mile-years for treated sites—total crashes.

Expected Percent Reduction in Crashes[1]	Rate A (Washington)[2]	Rate B (Minnesota)[2]	Rate C (Kentucky)[2]	Rate D (Ohio)[2]	Rate A (Washington)[3]	Rate B (Minnesota)[3]	Rate C (Kentucky)[3]	Rate D (Ohio)[3]
10	550	2,208	550	451	342	1,373	342	280
20	83*	332*	83*	68*	57*	230*	57*	47*
30	28	113	28	23	20	80	20	17
40	12	49	12	9	9	35	9	7

[1]Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
[2]95-percent confidence level.
[3]90-percent confidence level.
*Sample size values recommended in this study.

Table 5. Minimum required before-period mile-years for treated sites—injury crashes.

Expected Percent Reduction in Crashes[1]	Rate A (Washington)[2]	Rate B (Minnesota)[2]	Rate C (Kentucky)[2]	Rate D (Ohio)[2]	Rate A (Washington)[3]	Rate B (Minnesota)[3]	Rate C (Kentucky)[3]	Rate D (Ohio)[3]
10	1,220	5,984	1,485	1,100	759	3,719	923	683
20	184*	900*	223*	165*	127*	623*	154*	114*
30	63	306	76	56	44	216	53	40
40	27	132	33	25	19	94	23	17

[1]Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
[2]95-percent confidence level.
[3]90-percent confidence level.
*Sample size values recommended in this study.

Table 6. Minimum required before-period mile-years for treated sites—ROR crashes.

Expected Percent Reduction in Crashes[1]	Rate A (Washington)[2]	Rate B (Minnesota)[2]	Rate C (Kentucky)[2]	Rate D (Ohio)[2]	Rate A (Washington)[3]	Rate B (Minnesota)[3]	Rate C (Kentucky)[3]	Rate D (Ohio)[3]
10	1,973	8,065	910	589	1,227	5,013	565	366
20	297*	1,213*	137*	89*	205*	839*	95*	62*
30	101	413	47	31	71	291	33	22
40	44	178	20	13	31	126	15	10

[1]Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
[2]95-percent confidence level.
[3]90-percent confidence level.
*Sample size values recommended in this study.

Table 7. Minimum required before-period mile-years for treated sites—nighttime crashes.

Expected Percent Reduction in Crashes[1]	Rate A (Washington)[2]	Rate B (Minnesota)[2]	Rate C (Kentucky)[2]	Rate D (Ohio)[2]	Rate A (Washington)[3]	Rate B (Minnesota)[3]	Rate C (Kentucky)[3]	Rate D (Ohio)[3]
10	1,613	6,397	1,912	1,207	1,003	3,976	1,190	750
20	243*	962*	287*	181*	168*	666*	199*	125*
30	83	328	98	62	58	231	69	43
40	36	141	42	27	25	100	30	19

[1]Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
[2]95-percent confidence level.
[3]90-percent confidence level.
*Sample size values recommended in this study.

Table 8. Minimum required before-period mile-years for treated sites—nighttime ROR crashes.

Expected Percent Reduction in Crashes[1]	Rate A (Washington)[2]	Rate B (Minnesota)[2]	Rate C (Kentucky)[2]	Rate D (Ohio)[2]	Rate A (Washington)[3]	Rate B (Minnesota)[3]	Rate C (Kentucky)[3]	Rate D (Ohio)[3]
10	5,797	23,188	2,775	1,427	3,603	14,413	1,724	888
20	872	3,488	416	214	603	2,413	287	148
30	297*	1,188*	142*	73*	209*	838*	99*	51*
40	128	513	61	32	91	363	43	22

[1]Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
[2]95-percent confidence level.
[3]90-percent confidence level.
*Sample size values recommended in this study.

Following the data collection for both the before and after periods, the total mile-years of data available was 90.38 for the before period and 34.36 for the after period in Kentucky. Ohio had 217.01 mi-yr for the before period and 120.99 mi-yr for the after period. The States are reported separately because Ohio had additional statewide safety treatments (e.g., in-curve and advance horizontal curve warning signage) applied at the same time as the ELRS installation. The statistical accuracy attainable for a given sample size is described by the standard deviations of the estimated percent change in safety. From this, one can estimate *P*-values for various sample sizes and the expected change in safety for a given crash history. A set of such calculations is shown in table 9 for Kentucky and table 10 for Ohio. The calculations were based on methodology in Hauer.[36]

For the available data, the minimum percentage changes in crash frequency that could be statistically detectable at 5- and 10-percent significance levels were estimated using the same crash rates in table 3. The results indicate that the data should allow detection of the anticipated crash reduction effects highlighted in table 4 through table 8 (i.e., 20-percent reductions for all crash types except for nighttime ROR) in Ohio, if such an effect were present. It might be more difficult to use the Kentucky data to detect the crash reduction effects highlighted in table 4 through table 8. However, as noted previously, the values were conservative because the EB methodology requires fewer sites than a conventional before–after with C-G methodology. Using these results, a decision was made to proceed with the evaluation using the data available at the time.

Table 9. Analysis for crash effects in Kentucky.

Crash Type	90-Percent Confidence Level[1]	95-Percent Confidence Level[1]
Total	20	25
Injury	30	35
ROR	25	30
Nighttime	35	40
Nighttime ROR	40	45

[1]Minimum percent reduction detectable for crash rate assumption. Minimum percent reduction is rounded to nearest 5 percent.
Note: Mile-years in before period = 90.38; mile-years in after period = 34.36.

Table 10. Analysis for crash effects in Ohio.

Crash Type	90-Percent Confidence Level[1]	95-Percent Confidence Level[1]
Total	15	15
Injury	20	20
ROR	15	15
Nighttime	20	20
Nighttime ROR	20	25

[1]Minimum percent reduction detectable for crash rate assumption. Minimum percent reduction is rounded to nearest 5 percent.
Note: Mile-years in before period = 217.01; mile-years in after period = 120.99.

CHAPTER 4. METHODOLOGY

The EB methodology for observational before–after studies was used for the evaluation conducted in this study. 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, safety performance functions (SPFs) were used, which did the following:

- Overcame the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Accounted for time trends.
- Reduced the level of uncertainty in the estimates of safety effect.
- Properly accounted for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.
- Provided 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 in 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 effects of regression-to-the-mean and changes in traffic volume were explicitly accounted for using SPFs, relating crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (reference sites). Annual SPF multipliers were calibrated to account for temporal effects on safety (e.g., variation in weather, demography, and crash reporting).

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with characteristics similar to the one being analyzed (i.e., traffic volume and reference sites). The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the expected number of crashes (m) before installation, as shown in figure 4.

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

Figure 4. Equation. EB estimate of expected crashes.

Where w is estimated from the mean and variance of the SPF estimate, which is shown in figure 5.

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

Figure 5. Equation. EB weight.

Where k is constant for a given model.

k is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In that process, a negative binomial distributed error structure is assumed, with k being the overdispersion parameter of this distribution.

A factor is 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 is 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, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is 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 is also summed over all sites in the strategy group.

Figure 6 illustrates the estimate of the index of effectiveness (θ).

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

Figure 6. Equation. Index of effectiveness.

Figure 7 illustrates the standard deviation of θ.

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

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

The percent change in crashes is 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.

CHAPTER 5. DATA COLLECTION

Kentucky and Ohio provided data containing locations and dates of the installation of ELRSs. These States also provided roadway geometry, traffic volumes, and crash data for both installation and reference sites. This chapter summarizes the data assembled for the analysis. Additional details about the design, installation, and maintenance of ELRSs, as well as lessons learned, can be found in the appendix of this report.

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 ELRSs were installed as part of resurfacing projects. The treatment consisted of adding the new pavement surface, installing milled rumble strips, and painting the edge line on top of the strip. KYTC resurfaced shoulders along with the travel lanes but did not widen shoulders as part of this effort. KYTC installed the milled rumble strips with a standard 12-inch width and 1-inch depth. Installations took place on corridors consisting of both tangents and horizontal curves. Kentucky staff identified specific curves for treatment sites for this study using the geographic information system (GIS) roadway curve inventory to select moderately to very sharp curves (i.e., Highway Performance Monitoring System (HPMS) classes D, E, and F) within these treated corridors. The final list of treated sites comprised 229 horizontal curves (15.6 mi) where KYTC installed ELRSs.

Reference Sites

The treatment applied by KYTC had the potential for crash migration or spillover effects. Crash migration occurs when there is “a transfer of crashes resulting from an improvement rather than a reduction” (p. 4).[37] Spillover occurs when the safety benefits of a treatment extend to untreated sites downstream of the treated site.

To detect crash migration and spillover effects, the project team used a two-stage approach involving two reference groups. In the first stage, the project team selected one reference group from a large sample of untreated sites less than 5 mi downstream of treated sites and a second group from a limited sample of untreated sites located greater than 5 mi downstream of treated sites. Two reference groups were selected in this way to observe potential crash migration or spillover effects in the first reference group. According to a simulator study involving drowsy drivers and rumble strips, signs of drowsiness return to drivers approximately 5 min after hitting a rumble strip.[38] Assuming a 5-min drowsiness-relapse time and vehicle speed equal to or less than 60 mi/h, the project team observed crash migration and spillover effects within 5 mi of a treated site. By comparing the crash data of these two reference groups, the existence and magnitude of the crash migration and spillover could be detected. If no crash migration or spillover effects were detected, then the two reference groups were pooled together to form the reference group for the EB method.

Roadway Data

Roadway data provided by Kentucky staff were in GIS shapefile format. The various road characteristics (e.g., shoulder width) were contained in separate shapefiles, each segmented differently. GIS files were obtained from the Kentucky Roadway Information and Data website. The most useful file segmented the Kentucky road network into curve and tangent sections, likely for HPMS purposes. Each curve was denoted along with its degree of curvature and HPMS curve classification (A–F). Spatial joining was used to glean the available roadway characteristic information: shoulder type and width, traffic volume, and degree of curvature. To obtain many other roadway characteristics, such as area type, number of lanes, illumination, rumble strip presence, and roadside hazard rating, the data collectors used Google® Maps™ and Google® Street View™ imagery. To locate and view the curve in Google® Maps™, the coordinates of the curve were extracted from the GIS map, imported to Microsoft® Excel, and concatenated into a hyperlink that could be used to quickly find that location in Google® Maps™.

Traffic Data

KYTC maintains traffic volume data in the GIS inventory files, specifically the Traffic Flow (TF) shapefile. The project team obtained traffic data for the treatment and reference sites by spatially joining the TF layer to the site layer to obtain the current and past years' AADT values.

Crash Data

Crash data for Kentucky are publicly available on the Kentucky State Police's crash data website.(39) The project team used the following specifications for crash queries for each route:

- Crash query dates were from 1/1/2004 to 12/31/2012.
- A crash study area was defined for each horizontal curve, which consisted of up to 0.05 mi on each approach of the horizontal curve. If two curves were closer than 0.10 mi, then the study area was defined as the midpoint between the curves.
- Separate files for collisions, units, and individuals were obtained for each site.

Treatment Cost Data

KYTC provided estimates of the costs and service lives of the treatments for use in conducting a B/C analysis of the treatment (table 11).

Table 11. Kentucky treatment cost and service life data.

Countermeasure	Initial Installation Cost	Maintenance Cost	Service Life
Edge-line or shoulder rumble strips (installed as part of resurfacing)	$2,500/mi for rumble strip, $305/mi for stripe	No additional maintenance cost	12–15 years for rumble strip, 2 years for stripe

OHIO

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

Installation Data

The Ohio Department of Transportation (ODOT) provided a list of roadway sections where ELRSs were installed on nonfreeway highways. The Highway Safety Information System (HSIS) provided data identifying rural two-lane segments, and extents of horizontal curves. The project team verified installations using ODOT's video logs as well as Google® Streetview™. Most installations were confirmed but several treatment sites were noted to have not received the ELRS installation. The final list of treated sites comprised 579 horizontal curves (42.3 mi) where ELRSs were installed.

Reference Sites

As with the Kentucky data, the project team used two reference groups in Ohio to account for spillover or crash migration effects. The project team selected both reference groups (within 5 mi of treatment sites and more than 5 mi downstream of treated sites) from the list of installation sites that were not actually treated and were upstream/downstream of installation sites on the same corridors. The final list of reference sites comprised 428 horizontal curves (26.1 mi).

Roadway Data

Roadway data were obtained from the HSIS for each study year. Requisite roadway data for identifying study sites included functional classification, number of lanes, and extents of horizontal curvature. Additional data included degree of curvature, posted speed limit, and shoulder width. The project team used route, beginning milepost, and ending milepost to merge roadway data with traffic data and crash data.

Traffic Data

The project team obtained traffic data from the HSIS for each study year. Traffic data were obtained for the treatment and reference sites to obtain current and past years' AADT values. While data have not been collected every year, HSIS data included AADT information for each year in the study.

Crash Data

The project team obtained Ohio crash data from the HSIS for each study year. The project team used the following specifications for crash queries for each route:

- Crash query dates were from 1/1/2005 to 12/31/2013.
- A crash study area was defined for each horizontal curve, which consisted of up to 0.05 mi on each approach of the horizontal curve. If two curves were closer than 0.10 mi, then the study area was defined as the midpoint between the curves.

Treatment Cost Data

ODOT provided estimates of the costs and service lives of the treatment for use in conducting a B/C analysis of the treatment (table 12).

Table 12. Ohio treatment cost data.

Countermeasure	Initial Installation Cost	Maintenance Cost	Service Life
Edge-line or shoulder rumble strips (installed as part of resurfacing)	$850/mi for one side of roadway	No additional maintenance cost	Time until next resurfacing

DATA CHARACTERISTICS AND SUMMARY

Table 13 defines the crash types used by each State. The project team attempted to make the crash type definitions consistent. In all States, intersection-related and animal-related crashes were excluded.

Table 13. Definitions of crash types.

Crash Types	Kentucky	Ohio
Total	Identified as non-intersection and non-ramp and excluding those where "Event Collision With" indicated an animal or deer involvement	Identified as non-intersection and non-animal related
Injury	Resulted in an injury or possible injury	Resulted in a fatal injury, incapacitating injury, non-incapacitating injury, or possible injury
ROR	"Event Collision With" indicates an object off roadway was struck, and "Pre-Collision Action" is "avoiding object in roadway," "going straight ahead," or "slowing or stopped"	"Accident Type" described as other non-vehicle, fixed object, other object, other non-collision
Night	Identified including "Dusk," "Dawn," "Dark" (light), or "Dark (no light)"	Identified including "Dusk," "Dawn," "Dark-No-Lights," or "Dark-Lighted."
Nighttime ROR	Identified as being nighttime and ROR	Identified as being nighttime and ROR

Table 14 provides summary information for the data collected for the treatment sites. The information in table 14 should not be used to make simple before–after comparisons of crashes per mile-year because it does not account for factors (other than the strategy) that might cause a change in safety between the before and after periods. Such comparisons were properly done with the EB analysis, as presented later. Table 15 and table 16 provide summary information for the reference site data for Kentucky and Ohio, respectively. As discussed previously, separate reference groups were established to identify potential spillover and crash migration effects.

Table 14. Data summary for treatment sites.

Variable	Kentucky	Ohio
Number of miles	15.59	42.25
Mile-years before	90.38	217.01
Mile-years after	34.36	120.99
Total crashes/mile/year before	3.37	4.12
Total crashes/mile/year after	2.50	3.35
Injury crashes/mile/year before	1.25	1.69
Injury crashes/mile/year after	0.76	1.36
ROR crashes/mile/year before	2.04	3.15
ROR crashes/mile/year after	1.46	2.52
Nighttime crashes/mile/year before	0.97	1.54
Nighttime crashes/mile/year after	0.61	1.19
Nighttime ROR crashes/mile/year before	0.67	1.30
Nighttime ROR crashes/mile/year after	0.49	0.94
AADT before	Average 1,589 Minimum 412 Maximum 4,268	Average 2,784 Minimum 240 Maximum 15,670
AADT after	Average 1,500 Minimum 400 Maximum 4,443	Average 2,659 Minimum 240 Maximum 14,660
Average paved shoulder width (ft)	Average 1.36 Minimum 0.00 Maximum 2.00	Average 3.46 Minimum 0.00 Maximum 10.00
Average degree of curve	Average 23.38 Minimum 8.50 Maximum 221.50	Average 10.03 Minimum 3.00 Maximum 58.00

Table 15. Data summary for Kentucky reference sites.

Variable	<5 mi	>5 mi
Number of miles	2.69	5.47
Mile-years	24.19	49.27
Total crashes/mile/year	5.13	1.12
Injury crashes/mile/year	1.53	0.43
ROR crashes/mile/year	2.94	0.57
Nighttime crashes/mile/year	1.24	0.28
Nighttime ROR crashes/mile/year	0.87	0.24
AADT	Average 1,475 Minimum 224 Maximum 7,960	Average 403 Minimum 101 Maximum 2,450
Average paved shoulder width (ft)	Average 1.46 Minimum 0.00 Maximum 4.00	Average 1.11 Minimum 0.00 Maximum 2.00
Average degree of curve	Average 22.47 Minimum 8.50 Maximum 173.62	Average 21.80 Minimum 8.70 Maximum 124.4

Table 16. Data summary for Ohio reference sites.

Variable	Ohio	
	<5 mi	>5 mi
Number of miles	8.45	17.67
Mile-years	76.05	159.03
Total crashes/mile/year	6.14	4.42
Injury crashes/mile/year	2.41	1.97
ROR crashes/mile/year	4.21	3.56
Nighttime crashes/mile/year	2.25	1.65
Nighttime ROR crashes/mile/year	1.66	1.44
AADT	Average 3,383 Minimum 240 Maximum 15,670	Average 2,819 Minimum 250 Maximum 11,460
Average paved shoulder width (ft)	Average 2.23 Minimum 0.00 Maximum 10.00	Average 3.09 Minimum 0.00 Maximum 10.00
Average degree of curve	Average 9.57 Minimum 3.00 Maximum 23.00	Average 10.20 Minimum 3.00 Maximum 27.00

CHAPTER 6. DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This chapter presents the SPFs developed for each crash type. The SPFs were used in the EB methodology to estimate the safety effectiveness of this strategy.[36] Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. 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.

CRASH SPILLOVER AND MIGRATION

Before developing SPFs, the project team analyzed the separate reference groups to identify potential crash migration and spillover effects. An SPF was developed using data from both reference groups in order to develop yearly multipliers for each group. The form of the SPF is provided in figure 8, with parameter estimates presented in table 17.

$$Crashes/mile/year = e^{a} * AADT^{b} * L^{c} * e^{(invradius\ *d + right\_shoulder\ *e)}$$

Figure 8. Equation. SPF model form for crash migration or spillover effects.

Where:

AADT = annual average daily traffic volume.
L = segment length (mi).
invradius = inverse of the horizontal curve radius (ft).
right_shoulder = right shoulder width (ft).
a, b, c, d, e = parameters estimated in the SPF calibration process.
k = overdispersion parameter of the model.

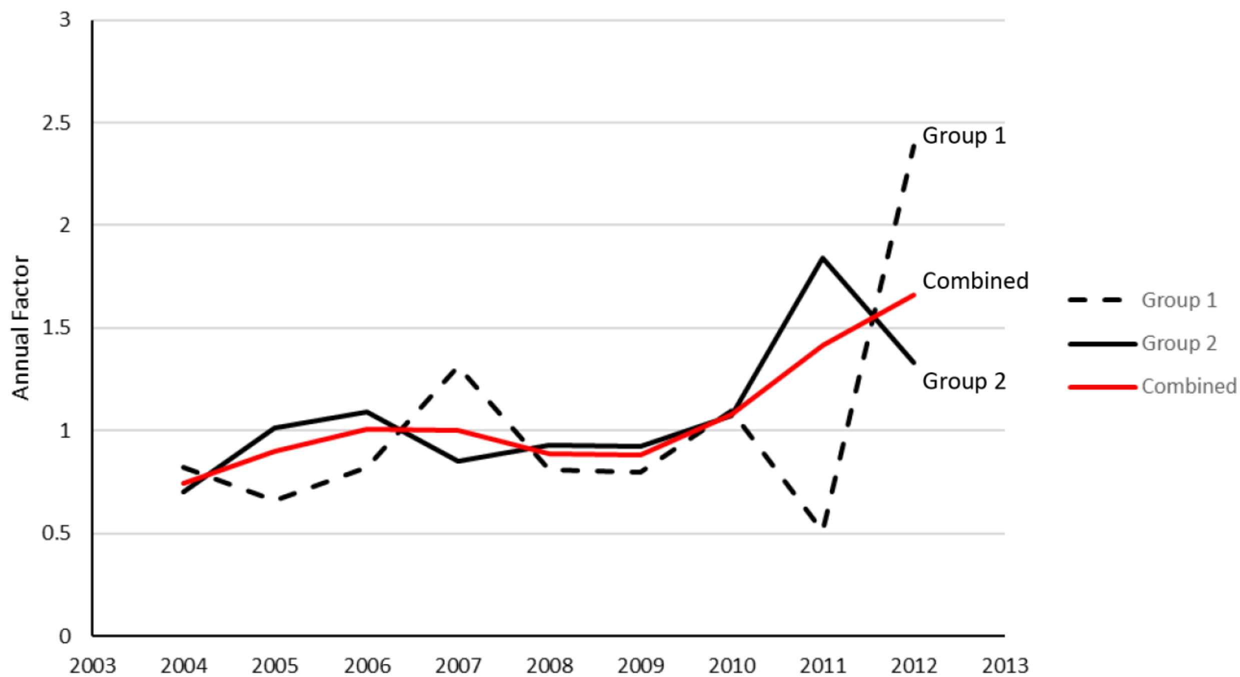
Table 17. Reference group SPF for total crashes—parameter estimates.

State	***a*** (SE)	***b*** (SE)	***c*** (SE)	***d*** (SE)	***e*** (SE)	***k***
Kentucky	−9.063 (0.843)	1.288 (0.111)	0.391 (0.219)	27.738 (37.716)	−0.298 (0.159)	2.183
Ohio	−5.226 (0.442)	0.634 (0.046)	0.390 (0.057)	206.883 (47.521)	−0.069 (0.019)	1.022

Table 18 presents the observed crashes versus predicted crashes for each of the two reference groups in Kentucky. Group 1 was the reference group more than 5 mi downstream, and group 2 was the reference group immediately downstream of the treatment sites. Group 1 also included reference sites that were on different roadways than the treatment sites. The yearly factors were the ratio of observed crashes to predicted crashes for the given group within the given year. Spillover and crash migration effects would be apparent if the yearly factors became drastically different between group 1 and group 2 after treatment application (2010 for most sites). These effects would also become apparent if the yearly factor for group 2 increased or decreased markedly after treatment application. However, neither of these scenarios appeared to be the case. Figure 9 provides a graphical representation of the yearly factors from table 18.

Table 18. Observed and predicted crashes for reference groups in Kentucky.

Year	Group 1 Observed	Group 2 Observed	Group 1 Predicted	Group 2 Predicted	Group 1 Factor	Group 2 Factor
2004	5	9	6.072	12.806	0.823	0.703
2005	4	13	6.074	12.817	0.659	1.014
2006	5	14	6.077	12.827	0.823	1.091
2007	8	11	6.103	12.875	1.311	0.854
2008	5	12	6.166	12.928	0.811	0.928
2009	5	12	6.265	13.001	0.798	0.923
2010	7	14	6.368	13.065	1.099	1.072
2011	3	23	5.875	12.515	0.511	1.838
2012	13	16	5.446	12.007	2.387	1.333



Source: FHWA.

Figure 9. Graph. Yearly multiplier by year for reference groups in Kentucky.

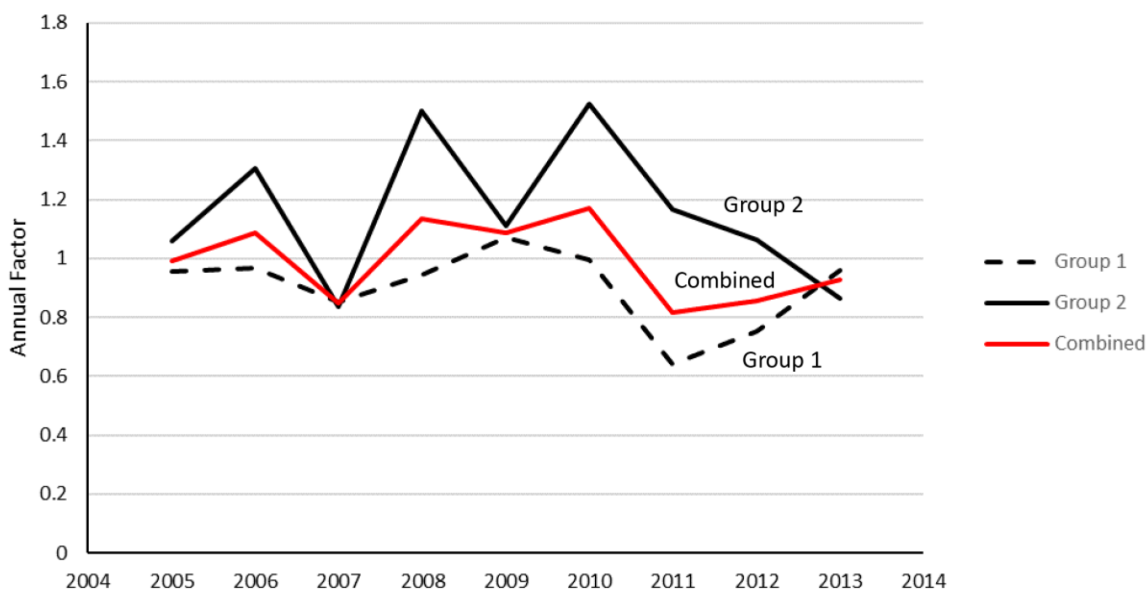
The sample sizes for reference sites were too small to make a statistical observation of difference between the groups (i.e., fewer than 20 crashes per year were observed). However, both groups experienced an abnormally large number of total crashes in 2011 or 2012, and group 1 observed an abnormally low number of crashes in 2011. Therefore, data for 2011 and 2012 were removed for the reference sites for SPF development. Before-period data from treatment sites were combined with reference-site data to bolster sample size, and the project team estimated an interaction term for the pretreatment site indicator and AADT to determine whether there was a difference in the effect of traffic volume at treatment sites in the before period versus at the references sites. The results indicated that the reference data and pretreatment data could be combined for SPF estimation.

In addition, because of the lack of data at the reference curves in this dataset, the project team sought an alternative reference group for developing annual factors. The Kentucky reference data from Lyon et al. provided a robust dataset for estimating annual factors for the before and after periods from combined horizontal curves and tangents.[30] This reference set included sections that were eligible for resurfacing but had not yet received resurfacing and had texturing; this was consistent with the treatment group. The reference set also included those identified by Lyon et al. to be "resurfacing effort" sites but excluded sites that had SRSs in the prior condition.[30] In total, the reference group consisted of 401.21 roadway mi. The project team used the reference segments to develop predicted crashes, which were compared with observed crashes to develop annual factors. The after-period factor was 1.034 for 2009 installations, 0.993 for 2010 installations, and 0.982 for 2011 installations. Table 19 presents the observed crashes versus predicted crashes for each of the two reference groups in Ohio. As with Kentucky, group 1 represents the reference group more than 5 mi downstream, and group 2 represents the reference group immediately downstream of the treatment sites. Figure 10 provides a graphical representation of the yearly factors from table 19. The annual factors show that the reference sites, particularly those not adjacent to treatment sites, observed a substantial reduction, beginning in 2011, relative to the before period. This possibility was expected for group 2 but not for group 1.

The project team explored this finding further with statewide data for rural two-lane roadways and for horizontal curves on rural two-lane highways. Consistently, the trends showed an approximate 10- to 15-percent reduction in crashes beginning in 2011. The project team contacted ODOT to gain further insight into this finding to determine why this systematic reduction was observed statewide. ODOT noted that in 2010, the systemic program focused on upgrading signage for horizontal curves statewide. This included upgrading hundreds of curves. The upgraded signage included chevrons, curve ahead signs, and speed advisory signs, among others. Therefore, the project team considered using horizontal tangent sections as a potential reference group for developing annual factors to mitigate the impact of signage upgrades on the overall findings. Spillover effects were observed for short tangents; the annual multipliers for short tangents (i.e., tangents less than 0.5 mi in length) were found to match those of horizontal curves within 1.0 percent for each installation year. Tangents longer than 1.0 mi were used as a reference group for developing annual factors because no spillover effects were observed. The reference segments were used to develop predicted crashes, which were compared with observed crashes to develop annual factors. The after-period factor was 1.040 for 2010 installations, 1.043 for 2011 installations, and 1.038 for 2012 installations.

Table 19. Observed and predicted crashes for reference groups in Ohio.

Year	Group 1 Observed	Group 2 Observed	Group 1 Predicted	Group 2 Predicted	Group 1 Factor	Group 2 Factor
2005	81	49	84.82	46.24	0.954963	1.059689
2006	83	60	85.75	45.87	0.96793	1.308044
2007	72	38	84.47	45.37	0.852374	0.837558
2008	79	66	83.64	43.95	0.944524	1.501706
2009	87	49	81.15	44.11	1.072089	1.110859
2010	90	68	90.33	44.56	0.996347	1.526032
2011	58	52	90.33	44.61	0.64209	1.165658
2012	67	47	88.88	44.13	0.753825	1.065035
2013	86	38	89.71	43.88	0.958645	0.865998



Source: FHWA.

Figure 10. Graph. Yearly multiplier by year for reference groups in Ohio.

SAFETY PERFORMANCE FUNCTIONS

Figure 11 shows the form of the SPFs for combined reference groups, which are presented in table 20.

$$Crashes/mile/year = e^{a} * AADT^{b} * L^{c} * e^{(invradius * d + right\_shoulder * e + posted * f)}$$

Figure 11. Equation. SPF model form for Kentucky and Ohio.

Where:

posted = posted speed.

f = parameter estimated in the SPF calibration process.

The Kentucky SPF was estimated using treatment site before period data and 2004 to 2010 reference site data. The Ohio SPFs were estimated using reference site data from 2005 to 2010.

Table 20. SPFs by crash type.

Parameters	Kentucky Total (SE)	Ohio Total (SE)	Ohio ROR (SE)
a	−10.338 (0.573)	−6.962 (0.813)	−6.443 (0.927)
b	1.249 (0.072)	0.697 (0.060)	0.553 (0.066)
c	0.128 (0.100)	0.365 (0.069)	0.433 (0.078)
d	N/A	236.022 (58.139)	282.222 (63.957)
e	N/A	−0.063 (0.024)	−0.099 (0.028)
f	N/A	0.021 (0.011)	0.0319 (0.013)
k	0.738	1.083	1.289

N/A = not applicable.

In addition, the project team considered crash sample size for reference sites in the development of SPFs. In Kentucky, total crashes per year ranged from 65 to 77. Other crash types had smaller sample sizes. The *Highway Safety Manual* recommends a minimum of 100 crashes per year to produce reliable SPFs.(40) Therefore, an SPF was developed for total crashes, and proportion factors relating other crash types to total crashes were used in place of separate SPFs. In Ohio, total crashes ranged from 110 to 158. There were sufficient crashes to develop separate SPFs for total crashes and ROR crashes. To relate other crash types to total crashes, proportion factors were used in place of separate SPFs. The prediction from the SPF was multiplied by the proportion factor to determine the number of predicted crashes of each specific crash type. The following is a list of crash type proportions for Kentucky:

- Fatal and injury crashes = 0.370.
- ROR crashes = 0.603.
- Nighttime crashes = 0.289.
- Nighttime ROR crashes = 0.200.

The following is a list of crash type proportions for Ohio:

- Fatal and injury crashes = 0.403.
- Nighttime crashes = 0.373.
- Nighttime ROR crashes = 0.314.

In addition, observed crashes and predicted crashes were used to develop annual factors for time-based trends at reference sites. Factors were used as multipliers for predicted crashes at treatment sites in the after period. Factors greater than 1.00 indicate an increase in crashes at reference sites, and factors less than 1.00 indicate a decrease in crashes at reference sites. Table 21 provides the annual factors based on total crashes in Kentucky and Ohio for each installation year.

Table 21. Time trend factors for predicted crashes.

Year	Kentucky Total	Ohio Total
2009	1.034	N/A
2010	0.993	1.040
2011	0.982	1.043
2012	N/A	1.038

N/A = not applicable.

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

This chapter presents the results of the before–after evaluation, including aggregate analysis for both Kentucky and Ohio and disaggregate analysis of the Ohio data. Disaggregate analysis of the Kentucky data was not conducted because the sample size was too small.

AGGREGATE ANALYSIS

Table 22 provides the estimates of expected 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 in Kentucky. Table 23 presents the results for Ohio.

Table 22. Aggregate analysis results for Kentucky.

Statistic	Total	Injury	ROR	Nighttime	Nighttime ROR
EB estimate of crashes expected in the after period without strategy	113.9	40.8	67.6	33.1	22.5
Count of crashes observed in the after period	86	26	50	21	17
Estimate of CMF	0.75*	0.64*	0.74*	0.63*	0.75
SE of estimate of CMF	0.09	0.14	0.11	0.14	0.19

*Statistically significant results at the 95-percent confidence level.

Table 23. Aggregate analysis results for Ohio.

Statistic	Total	Injury	ROR	Nighttime	Nighttime ROR
EB estimate of crashes expected in the after period without strategy	514.2	208.6	392.7	191.6	160.1
Count of crashes observed in the after period	405	165	305	144	114
Estimate of CMF	0.79*	0.79*	0.78*	0.75*	0.71*
SE of estimate of CMF	0.04	0.07	0.05	0.07	0.07

*Statistically significant results at the 95-percent confidence level.

The results for Kentucky indicated statistically significant reductions for all crash types except nighttime ROR crashes at the 95-percent confidence level. Nighttime crashes had the smallest CMF (which translates to the greatest reduction) with a value of 0.63. Total, injury, and ROR crashes had CMFs of 0.75, 0.64, and 0.74, respectively. The CMF for nighttime ROR crashes was 0.75 and was consistent with the same CMF from Ohio; however, it was significant only at the 80-percent level, suggesting that sample size was the reason for the lack of statistical significance at the 95-percent confidence level. The CMFs were smaller than—but consistent with—those found in the most comprehensive and reliable study of SRSs to date.(10) Based on a before–after EB analysis, the project team found that milled SRSs had a crash reduction of

16 percent (SE = 8) for all SVROR crashes and 36 percent (SE = 10) for SVROR injury crashes.[10] However, the analysis results for SRSs in Torbic et al. considered segments with both horizontal tangents and curves; therefore, a direct comparison of results cannot be made.[10] It is also important to remember that all crash types considered in this research excluded intersection-related and animal crashes.

The results for Ohio indicated statistically significant reductions for all crash types. Nighttime ROR crashes had the smallest CMF with a value of 0.71. Total, injury, ROR, and nighttime crashes had CMFs of 0.79, 0.79, 0.78, and 0.75, respectively. As with the Kentucky results, the CMFs were smaller than but consistent with those found in Torbic et al.[10] The resulting Ohio installation CMFs reflected the installation of ELRSs on horizontal curves as well as the impact of the statewide signing program.

A subset of both treatment and reference curves received sign upgrades, including chevrons, curve ahead signs, and speed advisory signs, all of which target crash types (i.e., nighttime and ROR) similar to those targeted by ELRSs but through a different mechanism (i.e., rumble strips target distracted or drowsy drivers through a haptic alert). The initial set of reference sites accounted for the impact of the signing upgrades. Additional analyses of the reference sites indicated a spillover effect of the horizontal curve signing program on curves that did not receive treatments as well as shorter tangents; therefore, longer tangent segments were used to determine the expected trend in the after period had no treatment (i.e., the signing program or ELRS installation) occurred. Owing to the spillover effects of the signing program, further analyses involving curves that specifically received new or additional signs were not fruitful (i.e., the resulting CMFs could not separate the effects of the signing program from those resulting from ELRS installation).

DISAGGREGATE ANALYSIS OF OHIO DATA

The disaggregate analysis sought to identify those conditions under which the treatment was most effective. Because ROR, nighttime, and nighttime ROR crashes were the focus of this treatment, the project team focused on these crash types for the disaggregate analysis. In addition, disaggregate results are presented for total crashes and fatal and injury crashes. The data sample for Kentucky was too small to perform disaggregate analyses; therefore, disaggregate analyses focused only on Ohio data.

Several variables were identified as being of interest and available for both States, including degree of curve, posted speed limit, paved shoulder width, lane width, AADT, and before-period expected crash frequency. Disaggregate results are provided by AADT in table 24 and before-period expected crash frequency in table 25. The number of crashes in the after period is presented for each CMF to indicate the sample size available. Several of the estimated CMFs rely on small samples, especially for nighttime crashes and nighttime ROR crashes.

Table 24. Ohio results by AADT.

Crash Type	<4,000 Observed	<4,000 CMF (SE)	4,000+ Observed	4,000+ CMF (SE)
Total	289	0.82* (0.06)	116	0.72* (0.08)
Injury	118	0.82* (0.08)	47	0.72* (0.12)
ROR	239	0.82* (0.06)	66	0.64* (0.09)
Nighttime	105	0.79* (0.08)	39	0.66* (0.12)
Nighttime ROR	88	0.78* (0.09)	26	0.54* (0.11)

*Statistically significant results at the 95-percent confidence level.

Table 25. Ohio results by before-period expected crash frequency.

Crash Type	Expected Crash Frequency	Less Than Value—Observed	Less Than Value—CMF (SE)	Greater Than or Equal to Value—Observed	Greater Than or Equal to Value—CMF (SE)
Total	0.25	136	1.09 (0.11)	269	0.69* (0.05)
Injury	0.10	63	1.00 (0.14)	102	0.70* (0.08)
ROR	0.20	111	1.13 (0.12)	194	0.66* (0.05)
Nighttime	0.15	85	0.93 (0.11)	59	0.59* (0.08)
Nighttime ROR	0.075	38	0.85 (0.15)	76	0.66* (0.08)

*Statistically significant results at the 95-percent confidence level.

As shown in table 24, smaller CMFs (i.e., larger safety benefits) were found for all crash types for sites with an AADT of 4,000 or more vehicles per day; however, the 95-percent confidence intervals overlap for each crash type. At AADTs lower than 4,000 vehicles per day, for example, an ROR crash CMF of 0.82 was estimated versus a CMF estimate of 0.64 for AADTs of 4,000 vehicles per day or greater. A similar difference was found for all other crash types. The 4,000 vehicles per day AADT cutoff is consistent with previous research by Patel et al. and Lyon et al.(19,30)

For the before-period expected crash frequency, as shown in table 25, the project team found larger safety benefits for all crash types for higher before-period expected crash frequency. The 95-percent confidence intervals did not overlap for total crashes and ROR crashes. Owing to the differences in the frequencies of different crash types, the before-period expected crash frequency cutoff varied for each crash type. For example, an ROR crash CMF of 1.13 was estimated for horizontal curves with an ROR before-period expected crash frequency of less than 0.20 crashes/yr. This can be compared with a CMF of 0.66 for horizontal curves with 0.20 or more before-period expected crashes/year. Note that the CMF of 1.13 for an ROR before-period expected crash rate less than 0.20 is not statistically significant. Similar results were found for all other crash types.

Caution should be used in interpreting and applying these disaggregate CMF results because of correlation among variables and because they were not robust enough to develop crash modification functions. A crash modification function is a formula used to compute the CMF for a specific site as a function of its site-specific characteristics. For example, crash modification functions would allow the estimation of CMFs for different levels of AADT and before-period crash frequency. In addition, the disaggregate analysis results used the EB analysis data, which include the effects of the statewide horizontal curve signing program. However, the disaggregate analysis CMF results can be used to inform the process of prioritizing treatment sites for ELRSs. For example, sites with a high proportion of ROR crashes and high AADTs could have high priority for receiving this treatment because those are the sites likely to benefit the most.

CHAPTER 8. ECONOMIC ANALYSIS

The project team conducted an economic analysis to estimate the B/C ratio for this strategy on rural two-lane horizontal curves. For the purposes of the economic analysis, the assumed treatment was the application of ELRSs. The project team used the recommended CMFs of 0.75 for Kentucky and 0.79 for Ohio to estimate the benefit of this treatment strategy. The Ohio results likely included the impact of additional sign upgrades, which were not provided or considered in this analysis. In addition, the cost of pavement markings was not considered in the study because these markings were already present on the roadway and the ELRSs did not affect the lifespan of edge-line pavement markings. Treatment costs ranged from $1,700/mi for Ohio to $2,500/mi for Kentucky. For Kentucky, service life was estimated as 12 to 15 years. For Ohio, ODOT noted that the service life was as long as the pavement life, which was assumed as 7 to 10 years. A conservative value of 12 years was assumed for Kentucky and 7 years for Ohio.

The FHWA Office of Safety Research and Development suggested using the Office of Management and Budget's *Circular A-4* to determine the conservative real discount rate of 7 percent.(41) This value was applied to calculate the annual cost of the treatment for 12- and 7-year service lives in Kentucky and Ohio, respectively. With this information, the capital recovery factor was computed to be 7.94 for a 12-year service life and 5.39 for a 7-year service life.

At the time of this report, the most recent FHWA mean comprehensive crash costs disaggregated by crash severity, location type, and speed limit were based on 2001 dollar values.(42) The 2001 unit costs for property damage only and fatal and injury crashes from the FHWA report ($7,428 and $158,177, respectively) were multiplied by the ratio of the 2014 (when the analysis was performed) value of a statistical life of $9.2 million to the 2001 value of a $3.8 million.(43,44) The project team applied this ratio of 2.42 to the unit costs for property damage only and fatal and injury crashes. The results were weighed by the frequencies of these two crash types in the after period to obtain aggregate 2014 unit costs for total crashes for Kentucky and Ohio. The resulting values were $128,268 and $166,603, respectively.

The total crash reduction was calculated by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The number of crashes saved per mile-year was 0.812 in Kentucky and 0.913 in Ohio. These numbers were obtained by dividing the total crash reduction by the number of after period mile-years per site.

The annual benefit (i.e., crash savings) of $104,165 in Kentucky and $150,368 in Ohio was the product of the crash reduction per mile-year and the aggregate cost of a crash (all severities combined). The B/C ratio was calculated as the ratio of the annual benefit per mile to the annual cost per mile. The B/C ratio was estimated as 331:1 in Kentucky and 477:1 in Ohio. USDOT recommended a sensitivity analysis be conducted by assuming values of a statistical life of 0.57 and 1.41 times the recommended 2014 values.(43) These factors were applied directly to the estimate B/C ratios to obtain a range of 189:1 to 467:1 for Kentucky and 272:1 to 672:1 for Ohio. On first inspection, the B/C ratios were larger than would reasonably be expected for an installation of this type. However, the installations took place on corridors, while the analysis only examined the safety effects on horizontal curves. Horizontal curves have higher crash rates than overall corridors, and the cost per mile of installation would not be representative for installations only on horizontal curves. As a curve-specific treatment, the B/C ratio would likely be reduced owing to the higher installation cost; however, these results suggest that the treatment can be highly cost effective.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The objective of this study was to perform a rigorous before–after evaluation of the safety effectiveness, as measured by crash frequency, of ELRSs applied on rural two-lane horizontal curves. The study used data from Kentucky and Ohio to examine the effects for specific crash types, including total, fatal and injury, ROR, nighttime, and nighttime ROR crashes. Crashes occurring at or related to intersections, as well as animal-related crashes, were not included. Based on the aggregate results, table 26 and table 27 show the recommended CMFs for the various crash types. Note that the results for Kentucky were based on smaller sample sizes and that the results for Ohio included the effects of a statewide horizontal curve warning sign upgrade program.

Table 26. Recommended CMFs for ELRSs based on Kentucky data.

Statistic	Total	Injury	ROR	Nighttime	Nighttime ROR
Estimate of CMF	0.75*	0.64*	0.74*	0.63*	0.75
SE error of estimate of CMF	0.09	0.14	0.11	0.14	0.19

*Statistically significant results at the 95-percent confidence.

Table 27. Recommended CMFs for ELRSs and curve signage based on Ohio data.

Statistic	Total	Injury	ROR	Nighttime	Nighttime ROR
Estimate of CMF	0.79*	0.79*	0.78*	0.75*	0.71*
SE of estimate of CMF	0.04	0.07	0.05	0.07	0.07

*Statistically significant results at the 95-percent confidence.

To date, the most comprehensive and reliable study of SRSs was published by Torbic et al.[10] Compared with the results of that study for ELRSs, the results of the current study suggest that greater reductions in all crash types may be found by placing rumble strips on or near the edge line for horizontal curves.

A disaggregate analysis of the results of the current study indicated that larger safety benefits were found for horizontal curves with AADT greater than 4,000 for all crash types; however, the differences by AADT were not statistically significant at the 95-percent confidence level. The disaggregate analysis further indicated larger safety benefits for horizontal curves with a higher before-period expected crash frequency. The results suggested no benefit for curves with low before-period expected crash frequencies for all crash types. The difference in CMFs that were dependent on before-period expected crash frequency were statistically significant for total and ROR crashes. Caution should be used in interpreting and applying these disaggregate results; however, the disaggregate analysis CMFs may be used in prioritizing treatment sites.

Estimated B/C ratios range from 189:1 to 467:1 for Kentucky and from 272:1 to 672:1 for Ohio. On first inspection, the B/C ratios were larger than would reasonably be expected for an installation of this type. However, the installations took place on corridors, while the analysis only looked at the safety effects on horizontal curves. Horizontal curves have higher crash rates than overall corridors, and the cost per mile of installation would not be representative for installations only on horizontal curves. For a curve-specific treatment, the B/C ratio would likely be reduced owing to the higher deployment cost for spot-specific installations. Regardless, these results suggest that the treatment, even in its most expensive variation, can be highly cost effective.

APPENDIX: ADDITIONAL INSTALLATION DETAILS

The following appendix presents additional details provided by Kentucky and Ohio. The States were asked to provide responses to the following questions:

1. What was the "before-period" condition for the treatment sites with respect to center-line and edge-line rumble strips? (No rumble strips? Center-line rumble strips only? Edge-line rumble strips only? Or some combination of these?)

2. Do you know whether the treatment sites analyzed by this study were installed as a RETROFIT, through RESURFACING, or by a combination of these?

3. The installation dates for the treatment sites on our list range from 2009 to 2011. What type of rumble strip was installed at these treatment sites? (If there is more than one, please indicate all that apply.)

    a. Milled.
    b. Rolled.
    c. Formed.
    d. Raised.
    e. Other.

4. We would like to provide a summary of the rumble strip characteristics below. Would you have any standard drawings—dated 2009/2010—that applied to all of the treatment sites considered in this study? If not, would you be able to identify the following characteristics for the edge-line rumble strips at the study sites?

    a. Width.
    b. Length.
    c. Depth.
    d. Spacing.
    e. Pavement marking type.
    f. Pavement marking width.

5. Were there any other requirements (e.g., minimum paved shoulder width, pavement structure, etc.) for the installation of rumble strips at the study sites?

6. Were any other safety countermeasures (besides RESURFACING, if that was your answer to no. 2 above) installed in conjunction with the rumble stripes at the treatment sites evaluated by this study?

7. Please describe any notable challenges related to the rumble stripe installation and how you overcame them.

8. Please describe any notable challenges related to the rumble stripe maintenance and how you overcame them.

9. What lessons learned or recommendations would you share with another States interested in the widespread application of edge-line rumble stripes?

RESPONSES FROM KENTUCKY

Kentucky staff responded to all questions. Their responses are listed in numeric order.

1. The "before condition" had no rumble strips.

2. The treatment sites analyzed by this study were a combination of RETROFIT and RESURFACING.

3. The installations were all milled rumble strips.

4. The following dimensions were used for the ELRS based on the pavement cross section in the ELRS Standard Drawings provided by Kentucky:

    a. Width: 7 inches to 7.5 inches.
    b. Length: 6, 8, and 12 inches, based on pavement width.
    c. Depth: 0.5 to 0.625 inches.
    d. Spacing: 12 inches center-to-center.

5. The pavement width was required to be at least 20 ft minimum (lanes and shoulders), and the speed limit was 50 mi/h and greater.

6. No (that I am aware of). There may be sites that received updated signs but not in conjunction with this treatment.

7. Communication with the field personnel through meetings to alleviate any misconceptions and trepidation.

8. Minor issues with rumbles installed at the edge of the mat may cause accelerated pavement edge degradation.

9. Communicate the intentions. Initially target overrepresented crash routes to convey safety improvements. Provide experience from other public agencies as testimony. Leave room for flexibility in design and implementation. Track crash statistics of comparative routes that do not have rumbles to indicate missed opportunities for crash reductions.

RESPONSES FROM OHIO

Ohio staff responded to all questions. Their responses are listed in numeric order.

1. The "before condition" had no rumble strips.

2. They were installed on routes meeting the minimum requirements (i.e., shoulder width, acceptable PCR….and not just resurfacing). They may have been added to district

pavement marking contracts as well as resurfacing in the year or two when they were installed through the systematic program.

3. The installations were all milled rumble strips.

4. The following dimensions were used for the ELRS based on the pavement cross section in the ELRS Standard Drawings provided by Kentucky:

    a. Width: 5 inches ± 0.5 inches.
    b. Length: 6, 10, and 16 inches, based on shoulder width.
    c. Depth: 0.375 inches.
    d. Spacing: 12 inches center-to-center.

5. The treatment sites were installed as a combination of adequate shoulder (2 ft or greater), acceptable pavement condition (PCR rating of 80 or higher), minimum lane widths (11 ft), two-lane routes outside of urban areas and locations where the speed limit is 45 mi/h or greater.

6. No. Sites were gathered if they met the criteria shown in question 5.

7. After surveying a few of the ODOT Districts, no notable challenges were encountered upon installation.

8. After surveying a few of the ODOT Districts, no notable challenges were mentioned in regard to the maintenance of the rumble stripes.

9. The recommendation would be to have some sort of policy set that governs where they will/can be installed. We all know that they provide a safety benefit; however, we are still selective of where they can be placed depending on shoulder width and pavement condition. The goal is to uphold the condition of the roadway system as best we can while continuing to improve safety.

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REFERENCES

1. Federal Highway Administration. (2017). *Rumble Strips Community of Practice*, Federal Highway Administration, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/, last accessed May 12, 2017.

2. American Association of State Highway and Transportation Officials. (2005). *AASHTO Strategic Highway Safety Plan*, American Association of State Highway Transportation Officials, Washington, DC.

3. Federal Highway Administration. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*, Federal Highway Administration, Washington, DC.

4. Federal Highway Administration. (2015). *Rumble Strips and Rumble Stripes*, Federal Highway Administration, Washington, DC. Available online: http://safety.fhwa.dot.gov/roadway_dept/ pavement/rumble_strips/design-and-construction.cfm, last accessed December 23, 2015.

5. Lindly, J. and Narci, A. (2006). *Evaluation of Rumble Stripe Markings*, UTCA Report 04405, University Transportation Center for Alabama, University of Alabama, Tuscaloosa, AL.

6. Miles, J.D., Carlson, P.J., Pratt, M.P., and Thompson, T.D. (2005). *Traffic Operational Impacts of Transverse, Centerline, and Edgeline Rumble Strips*, Report No. FHWA/TX-05/0-4472-2, Texas Department of Transportation, Austin, TX.

7. Carlson, P.J., Miles, J.D., Pratt, M.P., and Pike, A.M. (2005). *Evaluation of Wet-Weather Pavement Markings: First Year Report*, Report No. FHWA/TX-06/0-5008-1, Texas Department of Transportation, Austin, TX.

8. Carlson, P.J., Miles, J.D., Pike, A.M., and Park, E.S. (2007) *Evaluation of Wet-Weather and Contrast Pavement Marking Applications: Final Report*, Report No. FHWA/TX-07/0-5008-2, Texas Department of Transportation, Austin, Texas.

9. Willis, J. and Dean, W. (2004). *Mississippi's Rumble Stripe Experience*, 83rd Annual Meeting of the Transportation Research Board, Washington, DC.

10. Torbic, D., Hutton, J., Bokenkroger, C., Bauer, K., Harwood, D., Gilmore, D., Dunn, J., Ronchetto, J., Donnell, E., Sommer III, H., Garvey, P., Persaud, B., and Lyon, C. (2009). *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, National Cooperative Highway Research Board Report 641, Transportation Research Board, Washington, DC.

11. Ligon, C.M., Carter, E.C., Joost, D.B., and Wolman, W.F. (1985). *Effects of Shoulder Textured Treatments on Safety*, Report No. FHWA/RD-85/027, Federal Highway Administration, Washington, DC.

12. Chaudoin, J.H. and Nelson, G. (1985). *Interstate Routes 15 and 40 Shoulder Rumble Strips*, Report No. Caltrans-08-85-1, California Department of Transportation, Sacramento, CA.

13. Annino, J.M. (2003). *Rumble Strips in Connecticut: A Before/After Analysis of Safety Benefits*, Connecticut Department of Transportation, Newington, CT.

14. Griffith, M.S. (1999). "Safety Evaluation of Rolled-in Continuous Shoulder Rumble Strips Installed on Freeways," *Transportation Research Record*, *1665*, pp. 28–34, Transportation Research Board, Washington, DC.

15. Stutts, J.C. (2000). *NCHRP Synthesis of Highway Practice 287: Sleep Deprivation Countermeasures for Motorists Safety*, Transportation Research Board, Washington, DC.

16. Gårder, P. and Alexander, J. (1995). *Continued Research on Continuous Rumble Strips: Final Report*, Technical Report 94-4, Maine Department of Transportation, Augusta, ME.

17. Morena, D.A. (2003). *The Nature and Severity of Drift-Off Road Crashes on Michigan Freeways, and the Effectiveness of Various Shoulder Rumble Strip Designs*, 82nd Annual Meeting of the Transportation Research Board, Washington, DC.

18. Carrasco, O., McFadden, J., Chandhok, P., and Patel, R. (2004). *Evaluation of the Effectiveness of Shoulder Rumble Strips on Rural Multi-Lane Divided Highways in Minnesota*, 83rd Annual Meeting of the Transportation Research Board, Washington, DC.

19. Patel, R.B., Council, F.M., and Griffith, M.S. (2007). *Estimating the Safety Benefits of Shoulder Rumble Strips on Two-Lane Rural Highways in Minnesota: An Empirical Bayes Observational Before–After Study*, 86th Annual Meeting of the Transportation Research Board, Washington, DC.

20. Marvin, R.R. and Clark, D.J. (2003). *An Evaluation of Shoulder Rumble Strips in Montana*, Montana Department of Transportation, Helena, MT.

21. Perrillo, K. (1998). *The Effectiveness and Use of Continuous Shoulder Rumble Strips*, Federal Highway Administration, Albany, NY. Available online: https://safety.fhwa.dot.gov/roadway_dept/research/conts_rumble/conts_rumble.pdf, last accessed May 12, 2017.

22. Hickey, Jr., J.J. (1997). "Shoulder Rumble Strip Effectiveness, Drift-Off-Road Accident Reductions on the Pennsylvania Turnpike," *Transportation Research Record*, *1573*, pp. 105–109, Transportation Research Board, Washington, DC.

23. Tennessee Department of Transportation. (2005). *Statewide Installation of Shoulder Rumble Strips on Tennessee's Interstates*, Tennessee Department of Transportation, Nashville, TN.

24. Cheng, E.Y.C., Gonzalez, E., and Christensen, M.O. (1994). "*Application and Evaluation of Rumble Strips on Highways*," Utah Department of Transportation, Compendium of Technical Papers, 64th ITE Annual Meeting, Dallas, TX.

25. Chen, C., Darko, E.O., and Richardson, T.N. (2003) "Optimal Continuous Shoulder Rumble Strips and the Effects on Highway Safety and the Economy," *ITE Journal*, *73*(5), Institute of Transportation Engineers, Washington, DC.

26. Harwood, D.W. (1993). *NCHRP Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety*, Transportation Research Board, Washington, DC.

27. Bahar, G., Masliah, M., Wolff, R., and Park, P. (2008). *Desktop Reference for Crash Reduction Factors*, Report No. FHWA-SA-08-011, Federal Highway Administration, Washington, DC.

28. Khan, M., Abdel-Rahim, A., and Williams, C. (2014). "*Potential Crash Reduction Benefits of Shoulder Rumble Strips in Two-Lane Rural Highways*," 93rd Annual Meeting of the Transportation Research Board, Washington, DC.

29. Potts, I.B., Harwood, D.W., Bokenkroger, C.D., and Knoshaug, M.M. (2011). *Benefit/Cost Evaluation of MoDOT's Total Striping and Delineation Program: Phase II*, Report No. CM 12-002, Missouri Department of Transportation, Jefferson City, MO.

30. Lyon, C., Persaud, B., and Eccles, K. (2015). *Safety Evaluation of Centerline Plus Shoulder Rumble Strips*, Report No. FHWA-HRT-15-048, Federal Highway Administration, Washington, DC.

31. Sayed, T., DeLeur, P., and Pump, J. (2010). *Impact of Rumble Strips on Collision Reduction on Highways in British Columbia, Canada: Comprehensive Before-and-After Safety Study. Transportation Research Record*, *2148*, pp. 9–15, Transportation Research Board, Washington, DC.

32. Torbic, D., Bauer, K., Hutton, J., and Campbell, J. (2014). *Delta Region Transportation Development Program: Rural Safety Innovation Program Evaluation*, Report No. FHWA-SA-14-029, Federal Highway Administration, Washington, DC.

33. Kay, J., Savolainen, P.T., Gates, T.J., Datta, T.K., Finkelman, J., and Hamadeh, B. (2015). *Safety Impacts of a Statewide Centerline Rumble Strip Installation Program*, Paper No. 15-0179, 94th Annual Meeting of the Transportation Research Board, Washington, DC.

34. Olson, D., Sujka, M., and Manchas, B. (2013). *Performance Analysis of Centerline and Shoulder Rumble Strips Installed in Combination in Washington State*, Report No. WA-RD 799.1, Office of Research and Library Services, Washington State Department of Transportation, Olympia, WA.

35. Kubas, A., Kayabas, P., Vachal, K., and Berwick, M. (2013). *Rumble Strips in North Dakota: A Comparison of Road Segments, Safety, and Crash Patterns*, prepared for North Dakota Department of Transportation and Federal Highway Administration, North Dakota State University, Fargo, ND.

36. Hauer, E. (1997). *Observational Before–After Studies in Road Safety—Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*, Elsevier Science, Incorporated, Amsterdam, Netherlands.

37. Bonneson, J. and Lord, D. (2005). *Role and Application of Accident Modification Factors in the Highway Design Process*, Report No. FHWA/TX-05/0-4703-2, Texas Department of Transportation, Austin, TX.

38. Anund, A., Kecklund, G., Vadeby, A., Hjälmdahl, M., and Akerstedt, T. (2008). "The Alerting Effect of Hitting a Rumble Strip—A Simulator Study with Sleepy Drivers," *Accident Analysis and Prevention, 40*, pp. 1,970–1,976, Elsevier Science, Incorporated, Amsterdam, Netherlands.

39. Kentucky State Police. (2017). *Kentucky Collision Analysis for the Public*, Kentucky State Police, Frankford, KY. Available at http://crashinformationky.org. Last accessed February 1, 2017.

40. American Association of State Highway and Transportation Officials. (2010). *Highway Safety Manual*, American Association of State Highway and Transportation Officials, Washington, DC.

41. Office of Management and Budget. (2003). *Circular A-4: Regulatory Analysis*, Office of Management and Budget, Washington, DC.

42. Council, F., Zaloshnja, E., Miller, T., and Persaud, B. (2005). *Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries*, Report No. FHWA-HRT-05-051, Federal Highway Administration, Washington, DC.

43. U.S. Department of Transportation. (2014). *Guidance on Treatment of the Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2014 Adjustment*, Memo dated June 13, 2014. Available online: http://www.dot.gov/sites/dot.gov/files/docs/VSL_Guidance_ 2014.pdf, last accessed November 12, 2014.

44. Zaloshnja, E., Miller, T., Council, F., and Persaud, B. (2006). "Crash Costs in the United States by Crash Geometry," *Accident Analysis and Prevention, 38*(4), pp. 644–651, Elsevier Science, Incorporated, Amsterdam, Netherlands.

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