Safety Evaluation of Centerline Plus Shoulder Rumble Strips

PUBLICATION NO. FHWA-HRT-15-048 JUNE 2015

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI–PFS). The FHWA established this pooled fund study in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program Report 500 Guides as part of 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 (CMF) and benefit-cost (B/C) economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member states.

The combined application of centerline and shoulder rumble strips evaluated under this pooled fund study is intended to reduce the frequency of crashes by alerting drivers that they are about to leave the travelled lane. Geometric, traffic, and crash data were obtained at treated two-lane rural road locations in Kentucky, Missouri, and Pennsylvania. The results of this evaluation show that head-on, run-off-road, and sideswipe-opposite-direction crashes were significantly reduced, and application of centerline and shoulder rumble strips also has potential to reduce crash severity for all types of crashes.

Monique R. Evans, P.E.
Director, Office of Safety
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-15-048	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Safety Evaluation of Centerline Plus Shoulder Rumble Strips		5. Report Date June 2015
		6. Performing Organization Code
7. Author(s) Lyon, Craig; Bhagwant Persaud; and Kimberly Eccles.		8. Performing Organization Report No.
9. Performing Organization Name and Address Vanessa Hangen Brustlin, Inc (VHB) Persaud Lyon, Inc 8300 Boone Blvd., Ste. 700 87 Elmcrest Road Vienna, VA 22182-2626 Toronto, Ontario M9C 3R7		10. Work Unit No.
		11. Contract or Grant No. DTFH61-13-D-00001
12. Sponsoring Agency Name and Address Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Safety Evaluation
		14. Sponsoring Agency Code: FHWA

15. Supplementary Notes. The Federal Highway Administration (Office of Safety Research and Development) managed this study. The project team members were Craig Lyon, Dr. Bhagwant Persaud, Kimberly Eccles, and Jonathan Soika. The FHWA Office of Safety Research and Development Contract Task Order Manager was Roya Amjadi.

16. Abstract

The Federal Highway Administration organized a pooled fund study of 38 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. One of the strategies selected for evaluation was the combined application of centerline and shoulder rumble strips. This strategy is intended to reduce the frequency of crashes by alerting drivers that they are about to leave the travelled lane. Geometric, traffic, and crash data were obtained at treated two-lane rural road locations in Kentucky, Missouri, and Pennsylvania. To account for potential selection bias and regression-to-the-mean, an Empirical Bayes before-after analysis was conducted, using reference groups of untreated two-lane rural roads with similar characteristics to the treated sites. The analysis also controls for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. The combined results for all States indicate statistically significant crash reductions for all crash types analyzed. The crash type with the smallest crash modification factor (CMF) (i.e., the greatest crash reduction) is head-on, with a CMF of 0.632. Run-off-road and sideswipe-opposite-direction crashes have estimated CMFs of 0.742 and 0.767, respectively. For run-off-road, head-on, and sideswipe-opposite-direction crashes combined (i.e., lane departure crashes), the estimated CMF is 0.733. For all crash types combined, CMFs of 0.800 for all severities and 0.771 for fatal+injury were estimated. Intersection-related and animal crashes were excluded from the evaluation. Benefit-cost ratios were estimated to range from 20.2 to 54.7, depending on the treatment cost and service life assumption, which varied by State. These results are based on conservative service life assumptions.

17. Key Words: Rumble strips, low-cost, safety improvements, safety evaluations, Empirical Bayesian.		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages: 59	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed pages authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AADT	Average annual daily traffic
B/C	Benefit-cost
C-G	Comparison group
CLRS	Centerline rumble strips
CMF	Crash modification factor
EB	Empirical Bayes
FI	Fatal+injury
FHWA	Federal Highway Administration
GIS	Geographic information system
KYTC	Kentucky Transportation Cabinet
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
PennDOT	Pennsylvania Department of Transportation
SPF	Safety performance functions
SRS	Shoulder rumble strip
SVROR	Single-vehicle run-off-road

LIST OF SYMBOLS

Δ	Greek letter delta
λ	Greek letter lamda
π	Greek letter pi
θ	Greek letter theta

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) organized a pooled fund study of 38 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. The purpose of the FHWA Low-Cost Safety Improvements Pooled Fund Study is to evaluate the safety effectiveness of several low-cost safety strategies through scientifically rigorous crash-based studies. One of the strategies selected for evaluation for this study was the application of shoulder rumble strips (SRS) and centerline rumble strips (CLRS) in combination. This strategy is intended to reduce the frequency of crashes by alerting drivers that they are about to leave the travelled lane. While research has been published on the safety effectiveness of SRS or CLRS used in isolation, the effectiveness of the combined treatment has not been shown.

Geometric, traffic, and crash data were obtained at treated two-lane rural road locations in Kentucky, Missouri and Pennsylvania. To account for potential selection bias and regression-to-the-mean, an Empirical Bayes (EB) before-after analysis was conducted using reference groups of untreated two-lane rural roads with similar characteristics to the treated sites. A slightly different approach was required for the analysis of the treatment sites in Missouri, which is installing rumble strips on two-lane rural roads whenever a resurfacing project is undertaken. As a result, a suitable reference group with no rumble strips for this road type presently or in the near future did not exist. The analysis also controls for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment.

The combined results for all States indicate reductions in crashes for all crash types analyzed that are statistically significant at the 95-percent confidence level (i.e., 5-percent significance level). The crash type with the smallest crash modification factor (CMF) (i.e., the great crash reduction) is head-on, with a CMF of 0.632. Run-off-road and sideswipe-opposite-direction crashes have estimated CMFs of 0.742 and 0.767, respectively. For run-off-road, head-on, and sideswipe-opposite-direction crashes combined (i.e., lane departure crashes), the estimated CMF is 0.733. For all crash types combined, CMFs of 0.800 for all severities and 0.771 for fatal+injury (FI) were estimated. It is important to remember that all crash types considered exclude intersection-related and animal crashes.

The disaggregate analysis sought to identify those conditions under which the treatment is most effective. Run-off-road, head-on, and sideswipe-opposite-direction crashes were the focus of this analysis because they are the focus of this treatment. The analysis found no clear trend between the CMF and values for posted speed, lane width, or shoulder width. Larger percentage crash reductions were found for run-off-road crashes at higher average annual daily traffic (AADT). For head-on+sideswipe-opposite-direction crashes, the trend is reversed with smaller percentage crash reductions at higher AADTs.

For the expected crash frequency, larger percentage crash reductions were found for run-off-road crashes for higher crash frequencies. For head-on+sideswipe-opposite-direction crashes, the trend is reversed with smaller percentage crash reductions at higher crash rates. Because expected crashes increase with volume as seen in the Safety Performance Functions (SPF) developed, the trend of lower percentage crash reductions at higher crash rates for head-on+sideswipe-opposite-direction crashes would be expected given the results for AADT.

Benefit-cost (B/C) ratios are estimated to range from 20.2 for a higher cost/higher service life assumption (based on Kentucky information) to 54.7 for a lower cost/lower service life assumption (based on information from Missouri). These results, which are based on conservative service life assumptions, suggest that the treatment, even in its most expensive variations, can be highly cost effective.

CHAPTER 1. INTRODUCTION

BACKGROUND ON STRATEGY

This strategy involves the application of CLRS and SRS in combination. SRS may be placed on the edge line or offset some distance into a paved shoulder.

As described in volume 6 and volume 4 of the National Cooperative Highway Research Program (NCHRP) 500 Series Reports, SRS are crosswise grooves in the road shoulder, generally 0.5 inches deep, spaced about 7 inches apart, and cut in groups of 4 or 5.(1,2) States have developed various designs and methods of installation, including rolling the rumble strips into hot asphalt or concrete as it is laid, or milled in later. The rumble strips produce a vibrotactile or auditory warning in the form of a sudden rumbling sound or vibration to inattentive, drowsy, or sleeping drivers that encroach on the shoulder. SRS are used extensively in the United States on all types of roadways.

CLRS are similar to SRS but are placed on the center line and typically extend into the travel lane by 5 inches to 1.5 ft. They may be placed continuously or with periodic gaps.

SRS and CLRS are compatible with other measures taken to reduce crashes (e.g., curve flattening) and may be included in existing construction plans with minimal extra cost.

While research into the performance of SRS and CLRS has been conducted, the combination of SRS and CLRS is still relatively rare and has not been previously evaluated.

Additional details concerning current practice with rumble strips can be found on FHWA's Office of Safety Rumble Strip Web site at the following URL: http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/. This site provides technical advisories regarding SRS and CLRS along with other information of interest.

BACKGROUND ON STUDY

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

NCHRP published a series of guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses one of the 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 to evaluate low-cost safety strategies as part of this strategic highway safety effort. Over the years the pooled fund has grown in size and now includes 38 States. The purpose of the pooled fund study is to evaluate the safety effectiveness of several tried and experimental, low-cost safety strategies through scientifically rigorous crash-based studies. The use of CLRS in combination with SRS was selected as a strategy to be evaluated as part of this effort.

LITERATURE REVIEW

A recent and comprehensive study of SRS and CLRS is documented in *NCHRP Report 641—Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*.[3] This report includes a thorough literature review, which is summarized herein. A list of the critical references from the NCHRP report is included at the end of this document, after the references for this report.

SRS

A summary of previous research is shown in table 1, which is a reproduction of table 4 from *NCHRP Report 641*. This table shows the location of the evaluation, facility type, collision types analyzed, estimated effects, and the methodology applied. Most of the evaluations at that time had focused on freeways, with a limited number looking at non-freeway facilities. Collision types included single-vehicle run-off-road (SVROR) and in some cases total collisions. Effects for run-off-road collisions ranged from a 10 to 80 percent reduction, with an average of 36 percent. Effects for total crashes ranged from a 13 to 33 percent reduction, with an average of 21 percent.

Table 1. Information on safety effects of SRS in table 4 of *NCHRP Report 641*.[(3)]

State/Location	Type of Facility	Type of collisions targeted	Percent decrease (-) or percent increase (+) in target collision frequency from application of shoulder rumble strips (standard deviation)	Type of analysis
Arizona (16)	Interstate	SVROR	-80 percent	Cross-sectional comparison
California (17)	Interstate	SVROR	-49 percent	Before-after with comparison sites
		Total	-19 percent	
Connecticut (18)	Limited-access roadways	SVROR	-32 percent	Before-after with comparison sites
Florida (16)		Fixed object	-41 percent	Naïve before-after
		Ran-into-water	-31 percent	
Illinois and California (1)	Freeways	SVROR (total)	-18 percent (±6.8 percent)	Before-after with marked comparison sites and a comparison group
		SVROR (injury)	-13 percent (±11.7 percent)	
	Rural freeways	SVROR (total)	-21.1 percent (±10.2 percent)	
		SVROR (injury)	-7.3 percent (±15.5 percent)	
Kansas (unpublished; cited in Stutts (19))	Freeways	SVROR	-34 percent	Unknown
Maine (20)	Rural freeways	Total	Inconclusive	Before-after with comparison sites
Massachusetts (unpublished; cited in Stutts (19))		SVROR	-42 percent	Unknown
Michigan (21)		SVROR	-39 percent	Cross-sectional comparison

State/Location	Type of Facility	Type of collisions targeted	Percent decrease (-) or percent increase (+) in target collision frequency from application of shoulder rumble strips (standard deviation)	Type of analysis
Minnesota (3)	Rural multilane divided highways	Total	-16 percent	Naïve before-after
		Injury	-17 percent	
		SVROR (total)	-10 percent	
		SVROR (injury)	-22 percent	
		Total	-21 percent	Before-after with comparison sites
		Injury	-26 percent	
		SVROR (total)	-22 percent	
		SVROR (injury)	-51 percent	
Minnesota (2)	Rural two-lane roads	SVROR (total)	-13 percent (8 percent)	Before-after EB analysis with a reference group
		SVROR (injury)	-18 percent (12 percent)	
Montana (22)	Interstate and primary highways	SVROR	-14 percent	Before-after with comparison sites
New Jersey (unpublished; cited in Stutts (19))		SVROR	-34 percent	Unknown
New York (23)	Interstate Parkway	SVROR	-65 percent to 70 percent	Naïve before-after
Pennsylvania (24)	Interstate	SVROR	-60 percent	Naïve before-after
Tennessee (25)	Interstate	SVROR	-31 percent	Unknown
Utah (26)	Interstate	SVROR	-27 percent	Before-after with comparison sites
		Total	-33 percent	
Virginia (27)	Rural freeways	SVROR	-52 percent	Before-after with comparison sites
Washington (15)		Total	-18 percent	Naïve before-after
Multistate (16)	Rural freeways	SVROR	-20 percent	Before-after with comparison sites

Note: The follow reference callouts are numbered and presented in the same manner as in the original reference.

1. Griffith, M. S., Safety Evaluation of Rolled-in Continuous Shoulder Rumble Strips Installed on Freeways, In *Transportation Research Record*, No. 1665, TRB, National Research Council, Washington, D.C., 1999.

2. Patel, R. B., F. M. Council, and M. S. Griffith, *Estimating the Safety Benefits of Shoulder Rumble Strips on Two Lane Rural Highways in Minnesota: An Empirical Bayes Observational Before-After Study*, Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., January 2007.
3. Carrasco, O., J. McFadden, P. Chandhok, and R. Patel, *Evaluation of the Effectiveness of Shoulder Rumble Strips on Rural Multi- lane Divided Highways in Minnesota*, Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., January 2004.
15. Harwood, D. W., *NCHRP Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety*, TRB, National Research Council, Washington, D.C., 1993.
16. Ligon, C. M., E. C. Carter, D. B. Joost, and W. F. Wolman, *Effects of Shoulder Textured Treatments on Safety*, Report No. FHWA/RD-85/027, FHWA, U.S. Department of Transportation, 1985.
17. Chaudoin, J. H., and G. Nelson, *Interstate Routes 15 and 40 Shoulder Rumble Strips,* Report Caltrans-08-85-1. California Department of Transportation, August 1985.
18. Annino, J.M., *Rumble Strips In Connecticut: A Before/After Analysis of Safety Benefits,* Connecticut Department of Transportation, 2003.
19. Stutts, J. C., *NCHRP Synthesis of Highway Practice 287: Sleep Deprivation Countermeasures for Motorists Safety,* TRB, National Research Council, Washington, D.C., 2000.
20. Gårder, P., and J. Alexander, *Continued Research on Continuous Rumble Strips. Final Report*, Technical Report 94-4. Maine Department of Transportation, December 1995.
21. Morena, D.A., *The Nature and Severity of Drift-Off Road Crashes On Michigan Freeways, and the Effectiveness of Various Shoulder Rumble Strip Designs*. Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.
22. Marvin, R.R., and D.J. Clark, *An Evaluation of Shoulder Rumble Strips In Montana*, Montana Department of Transportation, 2003.
23. Perrillo, K., *The Effectiveness and Use of Continuous Shoulder Rumble Strips*, Federal Highway Administration, Albany, NY, 1998.
24. Hickey, J.J., Jr., "Shoulder Rumble Strip Effectiveness, Drift-Off-Road Accident Reductions on the Pennsylvania Turnpike." In *Transportation Research Record* 1573. TRB, National Research Council, Washington, D.C., 1997, pp. 105–109.
25. Tennessee Department of Transportation, *Statewide Installation of Shoulder Rumble Strips on Tennessee's Interstates.* http://www.tdot.state.tn.us/rumble/release.htm. Accessed September 2005.
26. Cheng, E. Y. C., E. Gonzalez, and M. O. Christensen, *Application and Evaluation of Rumble Strips on Highways*, Utah Department of Transportation, Compendium of Technical Papers, 64th ITE Annual Meeting, Dallas, Texas, 1994.
27. Chen, C., E. O. Darko, and T. N. Richardson, Optimal Continuous Shoulder Rumble Strips and the Effects on Highway Safety and the Economy, *ITE Journal*, Vol. 73, No. 5, May 2003.

The original research documented in *NCHRP Report 641* focused on total, FI, SVROR, and SVROR FI collisions. Site types included urban freeways, rural freeways, rural multi-lane divided roads, and rural two-lane roads from Pennsylvania, Missouri, and Minnesota. The authors recommend that the following effects of SRS for rural freeways and rural two-lane roads be considered based on their research and previous credible studies:

Rural Freeways:

- 11 percent reduction in SVROR crashes.
- 16 percent reduction in SVROR FI crashes.

Rural Two-Lane Roads:

- 15 percent reduction in SVROR crashes.
- 29 percent reduction in SVROR FI crashes.

For urban freeway and rural multi-lane divided roads, the results were deemed to be insignificant and unreliable, so there was no recommendation.

Subsequent disaggregate analyses indicated the following:

- On rural freeways, SRS placed closer to the edge line (i.e., edgeline rumble strips) are more effective in reducing SVROR FI crashes than those placed further from the edge line (i.e., non-edgeline rumble strips).
- On rural two-lane roads, there is no difference in the safety effect of SRS placed closer to the edge line (i.e., edgeline rumble strips) as compared with rumble strips placed further from the edge line (i.e., non-edgeline rumble strips).
- On rural freeways, SRS resulted in an estimated reduction of SVROR crashes involving heavy vehicles by approximately 40 percent.
- On rural two-lane roads, there is no evidence that suggests SRS may result in a reduction of SVROR crashes involving heavy vehicles.
- SRS appear to provide a positive safety benefit during low-lighting conditions.

CLRS

A summary of previous research is shown in table 2, a reproduced version of table 5 from *NCHRP Report 641*. This table shows the location of the evaluation, facility type, collision types analyzed, estimated effects, and the methodology applied. Although most of the previous studies used poor study methods, they are quite consistent in observing collision reductions for total and specific collisions related to a vehicle crossing the center line. All but one study looked at two-lane rural roads. The one remaining study did consider rural multi-lane roads. Effects for head-on crashes ranged from 34 to 95 percent, with an average of 65 percent. It should be noted that the *Highway Safety Manual, First Edition* only recommends the results for one of the studies (reference 4 in table 2) concerning rural two-lane roads. The methodologies applied for the other studies are suspect, and therefore, those results are not recommended.

Table 2. Information on safety effects of CLRS in table 5 of *NCHRP Report 641*.[3]

State/Location	Type of facility	Type of collisions targeted	Percent decrease (-) or percent increase (+) in the target collision frequency from application of centerline rumble strips (95-percent confidence interval)	Type of analysis
California (29)	Rural two-lane	Head-on (total)	-42 percent	Naïve before-after
		Head-on (fatal)	-90 percent	
Colorado (30)	Rural two-lane road	Head-on	-34 percent	Naïve before-after
		Sideswipe	-36.5 percent	
Delaware (31)	Rural two-lane road	Head-on	-95 percent	Naïve before-after
		Drove left of center	-60 percent	
		PDO	+13 percent	
		Injury	+4 percent	
		Fatal	N/A	
		Total	-8 percent	
Massachusetts (32)	Rural two-lane	Head-on	Inconclusive	Before-after with comparison group
		Opposite-direction angle		
		Opposite-direction sideswipe		
		SVROR with centerline encounters		
Minnesota (33)	Rural two-lane roads	Total	-42 percent	Cross-sectional comparison
		Total (fatal and severe injury)	-73 percent	
		Head-on/opposite-direction/ sideswipe/ SVROR-to-the-left (all severities)	-43 percent	
		Head-on/opposite-direction sideswipe/SVROR-to-the-left (fatal and severe injury	13 percent	

State/Location	Type of facility	Type of collisions targeted	Percent decrease (-) or percent increase (+) in the target collision frequency from application of centerline rumble strips (95-percent confidence interval)	Type of analysis
Missouri (34)	Rural two-lane roads	Total	-60 percent	Naïve before-after
Nebraska (35)	Rural two-lane roads	Cross-over crashes	-64 percent	Naïve before-after
Oregon (36)	Rural two- and four-lane highways	Cross-over crashes	-69.5 percent -79.6 percent	Naïve before-after Before-after with comparison group
Multistate (4)	Rural two-lane roads	Total	-14 percent (8–20 percent)	Empirical Bayes before-after
		Injury	-15 percent (5–25 percent)	
		Frontal/opposite-direction sideswipe (total)	-21 percent (5–37 percent)	
		Frontal/opposite-direction sideswipe (injury)	-25 percent (5–45 percent)	

Note: The follow reference callouts are numbered and presented in the same manner as in the original reference.

4. Persaud, B. N., R. A. Retting, and C. A. Lyon, Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-lane Roads. Insurance Institute for Highway Safety, Arlington, VA, September 2003. http://www.dot.state.mn.us/trafficeng/safety/rumble/IIHS_report.pdf. Accessed November 2005.

29. Fitzpatrick, K., K. Balke, D. W. Harwood, and I. B. Anderson, *NCHRP Report 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways*, Transportation Research Board, National Research Council, Washington, D.C., 2000.

30. Outcalt, W., *Centerline Rumble Strips*, Report No. CDOT-DTD- R-2001-8. Colorado Department of Transportation, August 2001.

31. Delaware Department of Transportation (DelDOT). *CRS: The Delaware Experience*. http://www.deldot.net/static/projects/rumblestrip/handout.pdf. Accessed November 2005.

32. Noyce, D. A., and V. V. Elango, Safety Evaluation of Centerline Rumble Strips: A Crash and Driver Behavior Analysis, *In Transportation Research Record*, No. 1862, TRB, National Research Council, Washington, D.C., 2004.

33. Briese, M., *Safety Effects of Centerline Rumble Strips in Minnesota*, Capstone Project for Infrastructure Systems Engineering Program, University of Minnesota, December 2006.

34. Missouri Department of Transportation, unpublished results provided to the research team.

35. Nebraska Department of Roads, unpublished results provided to the research team.

36. Russell, E. R., and M. J. Rys, *NCHRP Synthesis 339: Centerline Rumble Strips*. TRB, National Research Council, Washington, D.C., 2005.

The original research documented in *NCHRP Report 641* focused on total, FI, target, and target FI collisions. Target collisions included head-on and sideswipe-opposite-direction. Site types included urban two-lane roads and rural two-lane roads from Pennsylvania, Minnesota, and Washington. The authors recommend that the following effects for CLRS be considered based on their research and previous credible studies:

Urban Two-Lane Roads:

- 40 percent reduction in total target crashes.
- 64 percent reduction in FI target crashes.

Rural Two-Lane Roads:

- 9 percent reduction in total crashes.
- 12 percent reduction in FI crashes.
- 30 percent reduction in total target crashes (head-on and sideswipe-opposite-direction).
- 44 percent reduction in FI target crashes (head-on and sideswipe-opposite-direction).

A disaggregate analysis indicated no difference in effectiveness between horizontal curves and tangent segments for total target collisions. There were some limited mileage installations of shoulder and CLRS in combination but not enough to allow a formal evaluation.

Additional Research

Sayed et al. evaluated the safety impacts of applying CLRS and SRS alone and in combination on two-lane rural and four-lane divided rural highways in British Columbia, Canada.(4) The EB before-after study approach was applied. Results for the combined application on two-lane roads indicated a reduction of 21.4 percent in off-road right, off-road left, and head-on collisions combined. SRS on their own indicated a reduction of off-road right collisions of 26.1 percent on two-lane roads and 18.4 percent on four-lane divided roads. CLRS on their own on two-lane roads indicated a reduction of 29.3 percent in off-road left and head-on collisions combined. It is of interest that the estimated reduction for the combined application on two-lane roads is smaller than the reduction of target crashes for single applications of either CLRS or SRS. It is possible that the locations subject to the dual application had lower target crash rates or were otherwise different from locations with single applications, prior to application. The paper does not provide enough details to assess if this is true.

Torbic et al. evaluated the safety impacts of applying CLRS and SRS in combination using data for 80 mi of rural two-lane roads in Mississippi by applying the EB before-after approach.(5) Target collisions were defined as the sum of head-on, sideswipe-opposite-direction, and SVROR. The results showed a 35 percent reduction in target collisions of all severities and a 39.6 percent reduction in FI target collisions.

CHAPTER 2. OBJECTIVE

This research examined the safety impacts of the combined application of CLRS and SRS in Kentucky, Missouri, and Pennsylvania. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Intersection-related and animal crashes were excluded. Excluding these crash types, target crash types included the following:

- Total crashes (all types and severities combined).
- Injury crashes (K (fatal), A (incapacitating), B (non-incapacitating), and C (possible) injuries on KABCO scale).
- Run-off-road crashes (all severities combined).
- Head-on crashes (all severities combined).
- Sideswipe-opposite-direction crashes (all severities combined).

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

- Do effects vary by level of traffic volumes?
- Do effects vary by the frequency of crashes before treatment?
- Do effects vary by vehicle speeds?
- Do effects vary by lane width and shoulder width?
- What is the difference between the combined effects of CLRS and SRS and effects of either in isolation?

The evaluation of overall effectiveness included the consideration of the installation costs and crash savings in the form of 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 non-treatment 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 a sample required to statistically detect an expected change in safety and also determined what changes in safety can be detected with likely available sample sizes.

SAMPLE SIZE ESTIMATION OVERVIEW

Sample size estimations require assumptions of the expected treatment effect and the average crash rate at treatment sites prior to treatment. Minimum and desired sample sizes were calculated assuming a conventional before-after with comparison group (C-G) study design, as described in Hauer and a literature review of likely safety effects.[(6)] 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 are conservative because the more robust EB methodology is 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, run-off-road, head-on plus sideswipe-opposite-direction, and all target crashes (run-off-road plus head-on plus sideswipe-opposite-direction)), as shown in table 3. Intersection-related and animal crashes are not included in these crash rates. These crash rates, which were obtained from preliminary data for the untreated reference group data collected for the EB analysis, represent a range of mean crash rates. Only crash rates from Pennsylvania and Kentucky were used at the time of the sample size analysis. The study design assumed that the number of comparison sites would be equal to the number of treatment sites for a C-G study.

Table 3. Before period crash rate assumptions.

Crash Type	Pennsylvania (Crashes/Mi/Year)	Kentucky (Crashes/Mi/Year)
All	0.96	1.21
Injury[1]	0.51	0.38
Run-Off-Road	0.15	0.19
Head-On+Sideswipe-Opposite-Direction	0.06	0.08
All Target Crashes	0.21	0.27

[1]Non-injury crash type proportions assumed to be same as Pennsylvania for run-off-road, head-on, and sideswipe-opposite-direction.

Table 4 provides estimates of the required number of before and after period mile-years for statistical significance at both a 90- and 95-percent confidence level for both crash rate assumptions. The minimum sample indicates the level for which a study seems worthwhile; that is, it is feasible to detect with the level of confidence the largest effect that may reasonably be expected based on what is 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 are 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 are available so far for 3 years since implementation, then there are a total of 27 mi-year of after period data available for the study.

Table 4. Minimum required before period mile-years for treated sites.[1,2]

Expected Percent Reduction in Crashes		95-Percent Confidence Level		90-Percent Confidence Level	
		PA Rate	KY Rate	PA Rate	KY Rate
Total	5	1,057	444	740	311
	10	**216**	**91**	**151**	**64**
	20	77	32	54	23
	30	33	14	23	10
Injury	10	2,508	3,366	1,756	2,357
	20	**512**	**687**	**359**	**481**
	30	182	244	127	171
	40	79	106	55	74
Run-Off-Road	10	8,528	6,733	5,971	4,714
	20	**1,742**	**1,375**	**1,219**	**963**
	30	618	488	432	341
	40	269	212	188	149
Head-On+Sideswipe-Opposite-Direction	10	21,321	15,991	14,927	11,195
	20	**4,354**	**3,265**	**3,048**	**2,286**
	30	1,544	1,158	1,081	811
	40	672	504	471	353
All Target Crashes	10	6,092	4,738	4,265	3,317
	20	1244	968	871	677
	30	**441**	**343**	**309**	**240**
	40	192	149	134	105

[1]Assumes equal number of mile-years for treatment and comparison sites and equal length of before and after periods.
[2]Bold indicates sample size values recommended in this study.

The sample size values recommended in this study are highlighted in bold in table 4. These values are recommended based on the likeliness of obtaining the estimated sample size as well as the anticipated effects of the treatment. As noted, the sample size estimates provided 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 comparison group that had to be assumed for the calculations. Estimates may be predicted with greater confidence or a smaller reduction in crashes will be detectable if there are more site-years of data available in the after period. The same holds true if the actual data used for the analysis had a higher crash rate for the before period than was assumed.

Following the data collection for both the before and after periods, the total mile-years of data available was 6,392 for the before period and 2,623 for the after period. For the available data, the minimum percentage change in crash frequency that could be statistically detectable at 95- and 90-percent confidence levels was estimated using the same crash rates found in table 3. The calculations are based on methodology in Hauer.(6) The results, which are shown in table 5, indicate that the data should be able to detect the recommended crash reduction values from table 4, if such an effect were present. Using these results, a decision was made to proceed with the evaluation using the data available at the time.

Table 5. Analysis for crash effects detectable with available sample size.

Crash Type	Mile-Years in Before Period	Mile-Years in After Period	90-Percent Confidence Level[1]	95-Percent Confidence Level[1]
Total	6,392	2,623	5.0	7.5
Injury			7.5	10.0
Run-Off-Road			10.0	12.5
Head-On+Sideswipe-Opposite-Direction			17.5	20.0
All Target Crashes			7.5	10.0

[1]Minimum percent reduction detectable for crash rate assumption. Minimum percent reduction is rounded to nearest 2.5 percent.

CHAPTER 4. METHODOLOGY

The EB methodology for observational before-after studies was used for the evaluation.(6) 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, SPFs are used for the following reasons:

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

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

In the EB approach, the change in safety for a given crash type at a site is given in figure 1:

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

Figure 1. 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 traffic volumes and other characteristics similar to the one being analyzed (i.e., 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 strategy. This estimate of *m* is seen in figure 2:

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

Figure 2. Equation. EB estimate of expected crashes.

W is estimated from the mean and variance of the SPF estimate as seen in figure 3:

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

Figure 3. Equation. EB weight.

Where:

k = constant for a given model and 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.

The index of effectiveness (θ) is estimated as seen in figure 4:

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

Figure 4. Equation. Index of effectiveness.

The standard deviation of θ is in figure 5:

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

Figure 5. 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.

A slightly different approach to the methodology was required for the analysis of the treatment sites in Missouri, which is installing rumble strips on two-lane rural roads whenever a resurfacing project is undertaken. As a result, it would be very difficult to identify comparable roadways with no rumble strips for this road type presently or in the near future. For this reason, a separate reference group of sites without rumble strips was not identified.

An alternate approach to the standard EB before-after methodology was applied. In short, this method makes use of the before period data at the treatment sites to develop SPFs to control for regression-to-the-mean and traffic volume changes. Because the installation of rumble strips is a policy for all resurfacing projects, regression-to-the-mean is not as high a concern as it otherwise may be. The SPFs calibrated from before period data are also used to account for time trends in the earlier part of the study period, before most of the sites have had rumble strips installed. However, after a substantial number of sites have been treated, the number of sites is low for developing yearly factors and is not possible after all have been treated. For these later years, the after period data are used to develop SPFs for calculating yearly factors for the after period. The before period yearly factors are extrapolated based on the ratio of the after period factors to a common year.

To illustrate, consider the fictional information in table 6. Using the SPFs calibrated for both the before and after periods, annual multipliers were estimated for each year. In 2006, there was no data for the after period, so a multiplier does not exist for that year for the after period SPF. Similarly, there is no multiplier for 2009–2011 using the before period data. The average of the multipliers for the common years (2007–2008) is computed. The after period multipliers post-2007 are adjusted by dividing the values by the 2007–2008 average. Finally, the missing yearly multipliers for the before period model are adjusted by multiplying the average from 2007–2008 (1.03) by the value of the adjusted after period multiplier for each year. These are the annual multipliers used in the evaluation.

Table 6. Illustration of alternate approach.

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

N/A = Not applicable.
Blank cell = No adjustment is required.

CHAPTER 5. DATA COLLECTION

Kentucky, Missouri, and Pennsylvania provided data containing locations and dates of the installation of CLRS and SRS. In Missouri, SRS are placed on the edge line; in Kentucky and Pennsylvania, they are both installed on the edge line and placed further into the shoulder. Throughout the report, the abbreviation SRS will be used to refer to both installation types. These States also provided roadway geometry, traffic volumes, and crash data for both installation and reference sites. This section provides a summary of the data assembled for the analysis.

KENTUCKY

Installation Data

The Kentucky Transportation Cabinet (KYTC) provided a list of roadway sections where CLRS had been installed, along with an indication of whether SRS or edgeline rumble stripes were installed concurrently. As stated previously, the report will refer to both as SRS in abbreviated form. In cases where the rumble strip is placed on the edge line, these are referred to as rumble stripes because the lane striping is applied on top. Both edgeline and shoulder applications have been applied in Kentucky. The final list of treated sites used for analysis comprises 12 sections (42 mi) where CLRS and SRS were installed at the same time as part of a resurfacing effort, and 15 sections (122 mi) where CLRS had been installed as retrofits. All roadways previously had SRS installed, so the results will strictly pertain to the incremental effects of adding CLRS to roadways that have SRS. Thus, the estimated benefits could be considered as conservative in that even greater crash reductions would be expected for run-off-road crashes if SRS had not previously existed. It should be noted, however, that for the resurfaced sites, it is possible that the rumble strips had exceeded their service life, although this could not be determined.

The two types of treatment groups are described as follows:

- Retrofit treatment sites are sections of road where CLRS were milled into the existing asphalt. These sites were selected as roadways that were wide enough to apply CLRS and had a history of crashes over a certain threshold (3 head-on, sideswipe, or opposite-direction crashes in the 2004–2008 period). The KYTC safety office funded and applied the installations. All sites had a prior condition of rolled SRS.
- Resurfacing treatment sites are sections of road where CLRS and new edgeline rumble stripes were installed simultaneously as part of a resurfacing effort. The KYTC safety office, working in conjunction with the roadway maintenance and pavement office, identified the locations. A contractor performed a field inspection to verify installation date and type. KYTC indicates that these sites were selected as part of the regular resurfacing schedule with no specific consideration of crash history in their selection. Almost all resurfacing sites were rural locations. All sites had a prior condition of SRS or texturing and no CLRS.

Reference Sites

As described above, one set of treated sites was selected for treatment under a retrofit program that installed CLRS on sites that were selected on the basis of high target crashes (i.e., head-on and sideswipe-opposite-direction). To match these retrofit treated sites, the KYTC identified sites that were selected to receive CLRS (with a projected installation date of summer 2012) but had not yet received the treatment. This retrofit reference group comprises 133 mi of road.

The other set of treatment sites was selected as part of the resurfacing effort (and not on the basis of crashes). To match these resurfacing treatment sites, the research team desired to identify a reference group that would match the characteristics of the resurfaced sites and would be eligible to receive resurfacing but would not yet have received resurfacing. The reference group was identified initially by considering all statewide mileage that was undivided (as noted by a median width of 0 ft), had two lanes, had an 11-ft or greater lane width, and had a 50 mi/h or greater speed limit (and was thus eligible to receive CLRS in any resurfacing effort). These locations were cross-referenced against several lists to remove sites that were identified in the State's Roadway Departure plan as having high target crashes (head-on and sideswipe-opposite-direction) and to remove sites that already received CLRS through past construction activities. This resurfacing reference group comprises 1,588 mi of road.

Roadway Data

KYTC staff provided roadway data in geographic information system (GIS) shapefile formats. The various road characteristics (e.g., shoulder width) were contained in separate shapefiles for each segment. GIS files were obtained from the Kentucky Roadway Information and Data Web site. Characteristics of the treatment and reference sites were obtained by matching each study site to the appropriate inventory segment by county, route, and milepost.

Traffic Data

Traffic volume data are maintained by KYTC in the GIS inventory files. Traffic data were obtained for the treatment and reference sites by matching each study site to the appropriate inventory segment by county, route, and milepost. Specifically, the inventory file from year 2010 was used because it provided two data points—a current (2010) AADT and the prior AADT (with an indication of the year taken). These volume points can be used as needed to extrapolate yearly AADT for the before period. Subsequently, a similar file was obtained with 2012 traffic counts. The multiple traffic counts were used to develop annual trends, but these estimates were determined to be unreliable because extrapolating over a significant number of years often resulted in unreasonable values (e.g., negative AADT counts). As such, the average AADT using actual counts was used in both the before and after periods.

Crash Data

KYTC provided crash data for the routes and counties indicated in the treatment and reference site lists for 2002–2012 and a data dictionary for interpreting the fields in the crash data. The crash data can be linked to the sites based on county, route, and begin and end mileposts. The field labeled "RDWYIDTXT" is present in both the crash and road files to indicate the route. Of note, KYTC indicated that crash location quality improved significantly in 2008. This improvement is the result of law enforcement using the Map It application, which the officers could use to select the crash location on a screen, which would apply latitude/longitude coordinates to the crash record.

Treatment Cost Data

KYTC provided estimates of the costs and services lives of the treatments for use in conducting a benefit-cost analysis of the treatment (table 7).

Table 7. Kentucky treatment cost and service life data.

Countermeasure	Initial Installation Cost	Maintenance Cost	Service Life[1]
Edgeline strips or SRS (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
CLRS (retrofit, milled into asphalt)	$4,000/mi for rumble strip $350/mi for stripe	No additional maintenance cost	12–15 years for rumble strip, 2 years for stripe

[1]Stripes were used in cases when the rumble strip was placed directly on the edge line.
CLRS = Centerline rumble strips.
SRS = Shoulder rumble strips.

MISSOURI

Installation Data

The Missouri Department of Transportation (MoDOT) provided a list of projects where CLRS and edgeline rumble strips were recently installed or planned to be installed. The total length of roadway with CLRS and SRS installations was 460 mi. Among the data provided by the reports were the location (including district, State route number, and mileposts) and the construction dates. MoDOT reported that some locations also had 6-inch striping, bigger and brighter signs, and delineation on guardrails.

Reference Sites

Missouri now installs rumble strips on two-lane rural roads whenever a resurfacing project is undertaken. As a result, it would be very difficult to identify roadways with no rumble strips for this road type presently or in the near future. For this reason, a separate reference group of sites without rumble strips has not been identified. An alternate approach to the standard EB before-after methodology was applied, which is further described in the section on study design. In short, this method used before period data at the treatment sites to develop SPFs to control for regression-to-the-mean and traffic volume changes. Because the installation of rumble strips is a policy for all resurfacing projects, regression-to-the-mean was not as high a concern as it otherwise may be. Time trends were accounted for using both early installations and later installations.

Roadway Data

MoDOT provided roadway data for the treatment sites and included the following variables:

- Area type (urban/rural).
- Functional class.

- Divided versus undivided.
- Number of lanes.
- Lane width.
- Shoulder type.
- Shoulder width.
- Surface type.
- Speed limit.

The roadway data are stored in a bidirectional manner, meaning there is a separate record for each direction of travel. MoDOT staff matched opposing directions of travel for each site. The constructed database is limited to one record per site and the geometric information taken from the primary direction of travel.

Traffic Data

MoDOT provided traffic data in the form of AADT from 1999 to 2011 in electronic files for all treatment sites.

Crash Data

MoDOT provided crash data from 1999 to 2011, including many variables related to the location, time, and characteristics of each crash.

Treatment Cost Data

MoDOT provided approximate installation costs of $1,000/mi for either edgeline or centerline. MoDOT estimates that the service lives of rumble strips is 7 to 10 year.

PENNSYLVANIA

Installation Data

The Pennsylvania Department of Transportation (PennDOT) provided a list of projects where both CLRS and SRS were recently installed or planned to be installed. The sites used for analysis totaled 218 mi. These data included information on the location (including PennDOT district, county, State route number, and Segment/Offset, which is PennDOT's milepost system) and the project number of the installations. The project number is used for tracking project progress. The project team obtained construction start and end dates from a PennDOT Web site with this number.

PennDOT reported that some locations may have had shoulders widened to accommodate the SRS.

Reference Sites

The project team derived a preliminary list of reference sites by matching PennDOT's rumble strip inventory to the inventory of all rural two-lane roads. Roads having neither CLRS nor SRS were retained for reference sites. PennDOT confirmed that rumble strips have not been applied to any of the reference sites. The list was further reduced by including only those sites whose characteristics matched the range of treatment sites as follows:

- ACC_CODE=3 (no access control).
- Divisor in 0,1,2,3 (none, painted divided, man-made barrier, earth divided).
- DIV_WDT = 0 (divided width equal to 0 ft.).
- Speed Limit 20–55 mi/h.
- Number of lanes = 2.
- AADT between 650 and 26,570.

The sum of reference site miles was 17,931 mi.

Roadway Data

The project team obtained roadway data for the treatment and reference sites from the PennDOT Roadway Management System and included the following variables:

- Surface type.
- Pavement width.
- Speed limit.
- Number of lanes.
- Year of resurfacing.
- Shoulder type.
- Shoulder width.
- Area type (urban/rural).

Traffic Data

The project team obtained traffic data in the form of AADT from PennDOT from 2003 to 2011 in electronic files for all treatment and reference sites. The percentage of trucks in the traffic stream was also provided.

Crash Data

The PennDOT Crash Database is maintained by the Bureau of Highway Safety and Traffic Engineering's Crash Information Systems & Analysis Division. The compiled crash data contain many variables related to the location, time, and characteristics of each crash. Data from 2003 to 2012 were obtained.

Treatment Cost Data

Table 8 provides a breakdown of installation costs/ft provided by PennDOT. This average has steadily decreased over the last decade. In the early 2000s, the average cost was $0.77/ft. Note that these costs are associated with a single "row" or "line" of rumble strips. That cost is for a two-lane roadway with CLRS and SRS; the costs in table 8 should be multiplied by three.

Table 8. Pennsylvania treatment cost data, 2009–2011.

District	Average Cost/ft	Average Quantity Installed (ft)
1	$0.1136	111,135
2	$0.3568	14,655
3	$0.4532	12,795
4	$0.1866	533,779
5	$0.2071	65,161
6	$0.3017	37,553
8	$0.2309	23,353
9	$0.1391	93,192
10	$0.1778	45,805
11	$0.2070	63,525
12	$0.2504	129,780
State Average	$0.2386	102,794

The costs are per ft. Taking into consideration consistent driveway, intersection, and other types of breaks, PennDOT provided an average cost of $1,267/mi for a single line of rumble strips. Therefore, the average cost for CLRS and SRS along a two-lane roadway would be approximately $3,800/mi. These costs assume there are no maintenance costs. PennDOT assumes a life cycle of 7 year for the rumble strips.

Data Characteristics and Summary

Table 9 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 9. Definitions of crash types.

State	Total	Injury	Run-Off-Road	Head-On	Sideswipe-Opposite-Direction
Kentucky	Identified as non-intersection and non-ramp and excludes those where Event Collision With indicated an animal or deer involvement.	Resulted in an injury or possible injury.	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."	Manner of Collision is "head-on," and Event Collision With is "other motor vehicle."	Manner of Collision is "sideswipe-opposite-direction," and Event Collision With is "other motor vehicle."
Missouri	Identified as non-intersection and non-animal related.	Resulted in a fatal, disabling, or minor injury.	Accident Type described as "ran-off-road," "ran-off road-fixed-object," "ran-off-road-overturning," "ran-off-road-parked-motor-vehicle," or "ran-off-road-other."	Accident Type described as "head-on."	Accident Type described as "sideswipe." Note that the data do not indicate whether a sideswipe crash was opposite or same direction.
Pennsylvania	Identified as a midblock crash and not "deer" or "other animal."	If number of fatal or injured persons is greater than zero.	Relation To Road indicates the crash occurred outside the trafficway in an area not intended for vehicles.	Collision Type is "head-on."	Collision Type is "sideswipe-opposite-direction."

Table 10 provides summary information for the data collected for the treatment sites. The information in table 10 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 may cause a change in safety between the before and after periods. Such comparisons are properly done with the EB analysis as presented later. Table 11 provides summary information for the reference site data. As discussed previously, a different approach was used in Missouri where an appropriate reference group could not be found.

Table 10. Data summary for treatment sites.

Variable	Kentucky	Missouri	Pennsylvania
Number of miles	164	460	218
Mile-years before	604	4,238	1,407
Mile-years after	764	1,286	512
Crashes/mile/year before	1.61	0.74	1.13
Crashes/mile/year after	0.94	0.49	1.13
Injury crashes/mile/year before	0.50	0.32	0.62
Injury crashes/mile/year after	0.27	0.18	0.62
Run-off-road crashes/mile/year before	0.62	0.30	0.16
Run-off-road crashes/mile/year after	0.20	0.21	0.18
Head-on crashes/mile/year before	0.06	0.04	0.05
Head-on crashes/mile/year after	0.02	0.02	0.05
Sideswipe-opposite-direction crashes/mile/year before	0.10	0.05	0.03
Sideswipe-opposite-direction crashes/mile/year after	0.04	0.02	0.03
AADT before	Average: 6,101 Minimum: 1,282 Maximum: 20,433	Average: 5,290 Minimum: 154 Maximum: 15,848	Average: 4,990 Minimum: 782 Maximum: 25,796
AADT after	Average: 6,101 Minimum: 1,282 Maximum: 20,433	Average: 5,106 Minimum: 155 Maximum: 13,522	Average: 4,657 Minimum: 562 Maximum: 26,118
Average paved shoulder width (ft)	Average: 8.19 Minimum: 2.00 Maximum: 12.00	Average: 7.21 Minimum: 0.00 Maximum: 12.00	Average: 4.60 Minimum: 0.00 Maximum: 10.00

AADT = Annual average daily traffic.

Table 11. Data summary for reference sites.

Variable	Kentucky	Pennsylvania
Number of miles	1,532	17,931
Mile-years	16,852	161,377
Crashes/mile/year	1.07	1.23
Injury crashes/mile/year	0.34	0.64
Run-off-road crashes/mile/year	0.38	0.22
Head-on crashes/mile/year	0.03	0.05
Sideswipe-opposite-direction crashes/mile/year	0.05	0.03
AADT	Average: 2,702 Minimum: 10 Maximum: 17,701	Average: 4,350 Minimum: 473 Maximum: 25,067
Average paved shoulder width (ft)	Average: 6.16 Minimum: 0.00 Maximum: 14.00	Average: 2.18 Minimum: 0.00 Maximum: 16.00

AADT = Average annual daily traffic.

CHAPTER 6. DEVELOPMENT OF SPFS

This section presents the SPFs developed for each State. The SPFs are used in the EB methodology to estimate the safety effectiveness of this strategy.[6] 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.

SPFs were calibrated separately for Kentucky and Pennsylvania using the corresponding reference sites from each State. As discussed in the methodology section, the Missouri SPFs were developed separately for the before and after periods at the treated sites. The SPFs developed are presented by State in the following sections. The parameter estimates are presented by State with the standard error of the estimates.

KENTUCKY SPFS

The form of the SPFs for Kentucky, which are presented in table 12, is seen in figure 6:

$$\text{Crashes/mile/year} = \exp^{(a)} \text{AADT}^{b} \exp^{(\text{reftype}*c)}$$

Figure 6. Equation. SPF model form for Kentucky.

Where:

AADT = Average annual daily traffic volume.
reftype = 1 if a resurfacing reference site; 0 if a retrofit reference site.
a, *b*, *c* = Parameters estimated in the SPF calibration process.
k = The overdispersion parameter of the model.

Table 12. Kentucky SPFs.

	Parameter Estimates (Standard Error)			
Crash Type	**a**	**b**	**c**	**k**
Total	-5.8124 (0.3410)	0.6304 (0.0355)	1.1548 (0.1859)	0.8803
Injury	-6.3308 (0.3641)	0.5520 (0.0385)	1.0702 (0.1839)	0.6981
Run-Off-Road	-5.0019 (0.3974)	0.3933 (0.0418)	1.1128 (0.2046)	0.9091
Head-On	-9.3272 (0.6967)	0.6610 (0.0751)	0.7647 (0.2791)	0.8055
Sideswipe-Opposite-Direction	-7.0892 (0.5705)	0.4372 (0.0612)	0.8975 (0.2597)	0.8536

MISSOURI SPFS

As discussed in the methodology section, the analysis of the Missouri data required that SPFs be developed for both the before and after periods. The before period SPFs are shown in table 13. For the after period, the time trend is only based on total crashes because of the low numbers of other crash types. Thus, only total crashes were modeled, as indicated in n/a = not applicable.

table 14.

The form of the SPFs for Missouri is seen in figure 7:

$$\text{Crashes/mile/year} = \exp^{(a)}\text{AADT}^{b}\exp^{(shldwid*c+urbrur*d)}$$

Figure 7. Equation. SPF model form for Missouri.

Where:

AADT = Average annual daily traffic volume.
shldwid = Average shoulder width in ft.
urbrur = 1 if rural; 0 if urban.
a, *b*, *c*, *d* = Parameters estimated in the SPF calibration process.
k = The overdispersion parameter of the model.

Table 13. Missouri before period SPFs.

	Parameter Estimates (Standard Error)				
Crash Type	**a**	**b**	**c**	**d**	**k**
Total	-7.8094 (0.6409)	1.0091 (0.0747)	-0.0691 (0.0144)	-0.4479 (0.1205)	0.8958
Injury	-8.7627 (0.7731)	0.9958 (0.0892)	-0.0581 (0.0166)	-0.3273 (0.1503)	0.8644
Run-Off-Road	-5.3832 (0.7745)	0.6168 (0.0906)	-0.1116 (0.0179)	-0.2298 (0.1652)	0.9827
Head-On	-12.5421 (1.5038)	1.1047 (0.1751)	N/A	N/A	0.8202
Sideswipe-Opposite-Direction	-11.5757 (1.3814)	1.0508 (0.1662)	-0.0553 (0.0284)	N/A	0.5565

N/A = Not applicable.

Table 14. Missouri after period SPFs.

	Parameter Estimates (Standard Error)				
Crash Type	**a**	**b**	**c**	**d**	**k**
Total	-6.7214 (1.0431)	0.8107 (0.1193)	-0.0440 (0.0202)	-0.6187 (0.1828)	0.8154

PENNSYLVANIA SPFS

The form of the Pennsylvania SPFs, which are provided in table 15, is seen in figure 8:

$$\text{Crashes/mile/year} = \exp^{(a)} AADT^{b} \exp^{(shldwid*c+width*d)}$$

Figure 8. Equation. SPF model form for Pennsylvania.

Where,

AADT = Average annual daily traffic volume.
shldwid = Average shoulder width in ft.
width = Pavement width in ft.
a, *b*, *c*, *d* = Parameters estimated in the SPF calibration process.
k = The overdispersion parameter of the model.

Table 15. Pennsylvania SPFs.

	Parameter Estimates (Standard Error)				
Crash Type	**a**	**b**	**c**	**d**	**k**
Total	-5.9379 (0.0402)	0.7603 (0.0050)	-0.0471 (0.0019)	N/A	0.4519
Injury	-6.7027 (0.0461)	0.7703 (0.0057)	-0.0371 (0.0021)	N/A	0.4493
Run-Off-Road	-5.8811 (0.0728)	0.6254 (0.0106)	-0.0793 (0.0036)	-0.0233 (0.0016)	0.9507
Head-On	-10.3415 (0.1232)	0.9024 (0.0146)	-0.0325 (0.0051)	N/A	0.7623
Sideswipe-Opposite-Direction	-10.0866 (0.1496)	0.8161 (0.0178)	-0.0452 (0.0064)	N/A	0.7521

N/A = Not applicable.

CHAPTER 7. BEFORE-AFTER EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 16 through table 19 provide the estimates of expected crashes in the after period without treatment, the observed crashes in the after period, and the estimated CMF and its standard error for all crash types considered. Results are provided separately for each State as well as all States combined.

The results for Kentucky in table 16 indicate reductions for all crash types that are statistically significant at the 95-percent confidence level. All treatment sites in Kentucky had SRS or edgeline rumble stripes prior to treatment, so the results indicate that CLRS further reduce run-off-road crashes.

Table 16. Results for Kentucky.

	Total	Injury	Run-Off-Road	Head-On	Sideswipe-Opposite-Direction
EB estimate of crashes expected in the after period without strategy	851.54	256.91	241.30	30.48	33.92
Count of crashes observed in the after period	719	210	149	15	31
Estimate of CMF	**0.842**	**0.812**	**0.613**	**0.480**	0.891
Standard error of estimate of CMF	**0.054**	**0.088**	**0.073**	**0.142**	0.210

Bold indicates CMF estimates that are statistically significant at the 95-percent confidence level.
CMF = Crash modification factor.
EB = Empirical Bayes.

The results for Missouri in table 17 also indicate reductions for all crash types that are statistically significant at the 95-percent confidence level. Prior to treatment, rumble strips were not present. It is logical that the CMF for total crashes is smaller than that for Kentucky, for which the CMF pertains to the addition of CLRS on roadways that previously had SRS or stripes. That the CMF for run-off-road crashes in Missouri is larger than in Kentucky, where SRS previously existed, is not intuitive, but such comparisons for specific crash types can be influenced by how crash types are defined in different jurisdictions and the extent of the overrepresentation of specific crash types prior to treatment.

Table 17. Results for Missouri.

	Total	Injury	Run-Off-Road	Head-On	Sideswipe-Opposite-Direction
EB estimate of crashes expected in the after period without strategy	965.83	418.82	360.04	47.35	50.94
Count of crashes observed in the after period	631	234	273	24	32
Estimate of CMF	**0.653**	**0.558**	**0.758**	**0.506**	**0.628**
Standard error of estimate of CMF	**0.029**	**0.039**	**0.050**	**0.105**	**0.113**

Bold indicates CMF estimates that are statistically significant at the 95-percent confidence level.
CMF = Crash modification factor.
EB = Empirical Bayes.

The results for Pennsylvania, where rumble strips were not present prior to treatment, are shown in table 18. These results indicate reductions in total, run-off-road, and sideswipe-opposite-direction crashes, and increases in injury and head-on crashes. However, none of these results are statistically significant. Nevertheless, these results are still of interest because they could be used to increase the significance of a combined CMF based on the results of all three States. More discussion of the Pennsylvania results is provided in the next section on disaggregate analysis, while the combined results for the three States are presented next.

Table 18. Results for Pennsylvania.

	Total	Injury	Run-Off-Road	Head-On	Sideswipe-Opposite-Direction
EB estimate of crashes expected in the after period without strategy	591.63	310.91	99.82	24.43	15.41
Count of crashes observed in the after period	577	317	92	25	14
Estimate of CMF[1]	0.975	1.019	0.920	1.021	0.907
Standard error of estimate of CMF	0.046	0.063	0.103	0.210	0.246

[1]None of the CMF estimates are statistically significant at the 95-percent confidence level.
CMF = Crash modification factor.
EB = Empirical Bayes.

The combined results in table 19 indicate reductions for all crash types analyzed that are statistically significant at the 95-percent confidence level. It should be noted that combining the results of the three States produces a more robust CMF because the standard error of the combined CMF estimate (relative to the CMF) is smaller than that from any State or from the combination of the two States with the most significant results (Kentucky and Missouri). The crash type with the smallest CMF (which translates to the greatest reduction) is head-on with a CMF of 0.632. Run-off-road and sideswipe-opposite-direction crashes have estimated CMFs of 0.742 and 0.767, respectively. For all crash types combined, CMFs of 0.800 for all severities and

0.771 for FI were estimated. For run-off-road, head-on, and sideswipe-opposite-direction crashes combined (i.e., lane departure crashes), the estimated CMF is 0.733. It is important to remember that all crash types considered exclude intersection-related and animal crashes.

As discussed in the literature review, the most comprehensive and reliable study to date of both SRS and CLRS is published in *NCHRP Report 641*. This report does not include recommended findings for the combination of SRS and CLRS but does recommend CMFs for these treatments separately. A comparison of the results for the combined treatment with the recommended CMFs is encouraging.

In *NCHRP Report 641*, for SRS, a CMF of 0.85 is recommended for SVROR crashes. The results for other crash types were not statistically significant and so were not recommended. These results included a 6-percent reduction in total crashes and an 8-percent increase in FI crashes. In comparison with the new results, it appears that the effect of combining CLRS and SRS further reduces run-off-road crashes with a CMF of 0.742 for dual application versus 0.85 for SRS alone.

In *NCHRP Report 641*, CMFs of 0.91 for total crashes, 0.88 for FI crashes, and 0.70 for head-on plus sideswipe-opposite-direction crashes were recommended for CLRS. The new results, which estimated CMFs of 0.800 for all severities and 0.771 for FI for dual application, indicate that SRS further reduce these crashes. However, the CMF of 0.70 for head-on plus sideswipe-opposite-direction crashes suggests that dual application does not further reduce crashes of this type, which is intuitive.

Table 19. Results for combined States.

	Total	Injury	ROR	HO	S-OD	HO+S-OD	ROR+HO+ S-OD
EB estimate of crashes expected in the after period without strategy	2409.00	986.63	712.11	102.64	101.41	204.05	916.15
Count of crashes observed in the after period	1,927	761	529	65	78	143	672
Estimate of CMF[1]	**0.800**	**0.771**	**0.742**	**0.632**	**0.767**	**0.700**	**0.733**
Standard error of estimate of CMF	**0.025**	**0.034**	**0.041**	**0.085**	**0.097**	**0.064**	**0.035**

Bold indicates CMF estimates that are statistically significant at the 95-percent confidence level.
CMF = Crash modification factor.
EB = Empirical Bayes.
HO = Head-on.
ROR = Run-off-road.
S-OD = Sideswipe-opposite-direction.

DISAGGREGATE ANALYSIS

While the combined results for all States provide results that meet expectations and are statistically significant, the results are not consistent amongst the three States. The results for Kentucky and Missouri show statistically significant crash reductions for all crash types, with the exception of sideswipe-opposite-direction crashes in Kentucky, for which the CMF of 0.891 is not statistically significant.

For Pennsylvania, the results are much different. The CMFs estimated for Pennsylvania are all very close to 1.0, ranging from 0.920 to 1.021—none of which are statistically significant. These results are initially surprising. They differ from the findings for Kentucky and Missouri, and results in *NCHRP Report 641* for two-lane roads in Pennsylvania indicated large crash reductions for some crash types. For SRS, the *NCHRP Report 641* reports CMFs of 0.76 for total crashes and 0.56 for SVROR crashes, which were both statistically significant at the 95-percent confidence level. For CLRS, a non-significant CMF of 0.74 was estimated for head-on plus sideswipe-opposite-direction crashes. Anecdotally, this may be explained by the fact that Pennsylvania has been installing rumble strips on two-lane roads for many years with a goal of blanket coverage of their two-lane rural road system. Given this fact, it is likely that most higher-crash locations have already been prioritized and treated and that the sites that were evaluated in the current study did not have a high target crash issue and so logically will not have exhibited a large safety benefit compared with those that did and were evaluated for *NCHRP Report 641*. PennDOT indicated that sites are selected to prioritize high-volume locations and those with a high run-off-road or head-on crash frequency. A comparison of the summary statistics for the Pennsylvania data in *NCHRP Report 641* and the current study support this hypothesis. Table 20 shows the crash rates per mile-year before treatment and the proportion of total crashes for both the current and previous study. For run-off-road crashes, the crash rate of 0.87 in *NCHRP Report 641* is much higher in than the rate of 0.16 for data used in the current study. Similarly the *NCHRP Report 641* crash rate of 0.31 for head-on plus sideswipe-opposite-direction is much higher than the rate of 0.08 (0.05 for head-on and 0.03 for sideswipe-opposite-direction) for data used in the current study.

Table 20. Comparison of Pennsylvania crash rates.

Study	Crash Type	Crash Rate Before (Per Mile-Year)	Crash Proportion Before
Current Study	Run-Off-Road	0.16	0.38
	Head-On	0.05	0.03
	Sideswipe-Opposite-Direction	0.03	0.06
NCHRP 641	Run-Off-Road	0.87	0.69
	Head-On+Sideswipe-Opposite-Direction	0.31	0.14

The different results in the present study for Pennsylvania compared with Missouri and Kentucky illustrate how the extent of the target crash problem at a location will affect the crash reduction benefits that can be expected. The before period crash rates in table 10 show that run-off-road and sideswipe-opposite-direction crash rates were higher in Missouri and Kentucky than in Pennsylvania, and the head-on crash rate in Kentucky was higher than in Pennsylvania.

The disaggregate analysis sought to identify those conditions under which the treatment is most effective. Since run-off-road, head-on, and sideswipe-opposite-direction crashes are the focus of this treatment, these crash types are the focus of the disaggregate analysis. Several variables were identified as being of interest and available for all three States, including speed limit, shoulder width, lane width, AADT, and the expected crash frequency per mile prior to treatment.

The analysis found no clear trend between the CMF and values for posted speed, lane width, or shoulder width.

For AADT, as shown in table 21, larger percentage crash reductions were found for run-off-road crashes for higher AADTs with some stability reached at an AADT of approximately 3,200. At AADTs above 3,200, the estimated CMF does not change significantly. At AADTs lower than 3,200, a run-off-road crash CMF of 0.851 is estimated versus 0.702 for AADTs at 3,200 or greater. For head-on+sideswipe-opposite-direction crashes, the stability in the CMF is reached at an AADT of approximately 9,200, and the trend is reversed with a CMF of 0.679 at AADTs under 9,200 and 0.817 for AADTs over 9,200. A possible explanation for a larger CMF value for head-on+sideswipe-opposite-direction crashes is that at higher AADTs, there are fewer passing opportunities, and not all head-on or sideswipe-opposite-direction crashes are due to vehicles drifting out of their lane.

For the expected crash frequency per mile-year without treatment as shown in table 21, larger percentage crash reductions were found for run-off-road crashes for higher crash frequencies with some stability reached at a crash rate of approximately 0.500/mi-year. At rates lower than 0.500, a run-off-road crash CMF of 0.840 is estimated versus 0.621 for rates at 0.500 or greater. For head-on+sideswipe-opposite-direction crashes, the stability in the CMF is reached at approximately a rate of 0.065, and the trend is reversed with a CMF of 0.608 at rates under 0.065 and 0.715 for rates over 0.065. Since expected crashes increase with volume as seen in the SPFs developed, the trend of a larger CMF at higher crash rate for head-on+sideswipe-opposite-direction crashes would be expected, given the results for AADT.

Caution should be used in interpreting and applying these disaggregate results because they are not robust enough to develop CMFunctions. A CMFunction is an equation that would allow the estimation of CMFs for different levels of AADT and expected crash frequency. However, they may be used in prioritizing treatment sites. For example, sites with a high proportion of run-off-road crashes and high AADTs will have higher priority than sites with high AADTs and a high proportion of head-on+sideswipe-opposite-direction crashes.

Table 21. Results disaggregated by ranges of AADT and expected crash frequency.

	AADT		**Expected Crashes/Mile-Year Without Treatment**	
Crash Type	**Range**	**CMF (Standard Error)**	**Range**	**CMF (Standard Error)**
Run-off-road	< 3200	0.851 (0.089)	< 0.500	0.840 (0.058)
	≥ 3200	0.702 (0.045)	≥ 0.500	0.621 (0.055)
Head-on+sideswipe-opposite-direction	< 9200	0.679 (0.069)	< 0.065	0.608 (0.147)
	≥ 9200	0.817 (0.172)	≥ 0.065	0.715 (0.071)

AADT = Average annual daily traffic.
CMF = Crash modification factor.

CHAPTER 8. ECONOMIC ANALYSIS

For the purposes of the economic analysis, the assumed treatment is, conservatively, the dual application of CLRS and SRS for which the combined CMF of 0.800 for total crashes (table 8) is recommended. Treatment costs used range from $3,000/mi for Missouri to $12,000/mi in Kentucky. Service lives are 7–10 and 12–15 years, respectively. Results are presented for these two extremities.

The FHWA Office of Safety R&D suggests that the Office of Management and Budget Circular A-4 be used to determine the conservative real discount rate of 7 percent that was applied to calculate the annual cost of the treatment for 7- and 12-year service lives, respectively. Applying the lower ends of the service life ranges conservatively gives annual costs of $557 and $1,511/mi for the two cost/service life extremes.

The most recent FHWA mean comprehensive crash costs disaggregated by crash severity, location type, and speed limit are based on 2001 dollar values.(8) The 2001 unit costs for property damage only (PDO) and FI crashes from the FHWA report ($7,428 and $158,177) were multiplied by the ratio of the 2014 value of a statistical life of $9.2 million to the 2001 value of $3.8 million.(7,8) Applying this ratio of 2.42 to the unit costs for PDO and FI crashes, and then weighting by the frequencies of these two crash types in the after period, an aggregate 2014 unit cost for total crashes of $162,045 was obtained. Fatal crashes were not considered on their own because of the very low numbers of such crashes in the data, which would skew the results.

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 0.1881, which was obtained by dividing the total crash reduction (482.0) by the number of after period mile-years per site (2,562).

The annual benefit (i.e., crash savings) of $30,481 is the product of the crash reduction per mile-year (0.1881) and the aggregate cost of a crash (all severities combined) ($162,045). The B/C ratio is calculated as the ratio of the annual benefit per mile to the annual cost per mile. The B/C ratios are estimated to be 20.2 for the higher cost/higher service life assumption and 54.7 for the lower cost/lower service life assumption. These results suggest that the treatment, even in its most expensive variation, can be highly cost effective.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before-after evaluation of the safety effectiveness, as measured by crash frequency, of SRS and CLRS applied in combination on two-lane rural roads. The study used data from three States (Kentucky, Missouri, and Pennsylvania) to examine the effects for specific crash types, including total, FI, run-off-road, head-on, and sideswipe-opposite-direction crashes. Crashes occurring at or related to an intersection and animal-related crashes were not included. Based on the combined results, the CMFs shown in table 22 are recommended for the various crash types. The benefits indicated by these CMFs may be regarded as conservative for two reasons. First, the sites in Kentucky already had SRS, although those at the retrofit sites had already exceeded their useful lives. Second, the results include Pennsylvania sites, which experienced fewer benefits (likely because they were lower priority sites for the strategy).

Table 22. Recommended CMFs.

	Total	Injury	ROR	HO	S-OD	HO + S-OD	ROR+HO+S-OD
CMF	0.800	0.771	0.742	0.632	0.767	0.700	0.733
Standard error of estimate of CMF	0.025	0.034	0.041	0.085	0.097	0.064	0.035

CMF = Crash modification factor.
HO = Head-on.
ROR = Run-off-road.
S-OD = Sideswipe-opposite-direction.

To date, the most comprehensive and reliable study of both SRS and CLRS individually applied is published in *NCHRP Report 641—Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*. When compared with the recommended CMFs from that study, the results suggest that the effect of combining CLRS and SRS further reduces run-off-road crashes versus applying SRS alone. It also appears that SRS do not further reduce head-on plus sideswipe-opposite-direction crashes further than applying CLRS in isolation.

A disaggregate analysis of the results indicated that larger percentage crash reductions were found for run-off-road crashes for sites with higher AADTs. For head-on+sideswipe-opposite-direction crashes, smaller percentage crash reductions were found for higher AADTs. For the expected crash frequency per mile-year without treatment, larger percentage crash reductions were found for run-off-road crashes for higher crash frequencies. For head-on+sideswipe-opposite-direction crashes, smaller percentage crash reductions were seen at higher crash frequencies. Caution should be used in interpreting and applying these disaggregate results because they are not robust enough to develop CMFunctions that would allow the estimation of CMFs for different levels of AADT and expected crash frequency. However, they may be used in prioritizing treatment sites.

B/C ratios are estimated to range from 20.2 for a higher cost/higher service life assumption based on Kentucky information to 54.7 for a lower cost/lower service life assumption based on information from Missouri. These results, which are based on conservative service life assumptions, suggest that the treatment, even in its most expensive variations, can be highly cost effective.

APPENDIX: ADDITIONAL INSTALLATION DETAILS FROM STATES

The following appendix presents additional details provided by the three participating States regarding the installation of the subject strategies in their State.

DETAILS OF THE KENTUCKY SITES

Kentucky provided the rumble strip specifications seen in table 23:

Table 23. Installation details for Kentucky.

Dimensions	Centerline Rumble Strips	Shoulder Rumble Strips
Width	7 inches minimum $7^{1}/_{2}$ inches maximum	7 inches ± $^{1}/_{2}$ inch
Length	12 inches	16 inches
Depth	$^{1}/_{2}$ inch minimum $^{5}/_{8}$ inch maximum	$^{1}/_{2}$ ± $^{1}/_{8}$
Spacing	24 inches	12 inches ± 1 inch
Lateral Placement	Center of roadway, perpendicular to centerline pavement markings	Place 1 ft out from the mainline pavement

Kentucky was also asked to provide some additional insight on their experience with the strategy. Their responses to several topics are presented below. The following responses are provided from the perspective of the State and are phrased informally:

- **Types of Rumble Strips Evaluated**: All new rumble strips were milled.
- **Before-Period Rumble Strip Condition**: No CLRS were present, but all sites had a preexisting condition of rolled SRS.
- **Retrofit or Resurfacing Projects?**: Both; the retrofit sites had rolled SRS in place, and CLRS were milled in as the treatment. In the resurfacing projects, milled rumble strips were installed.
- **Installation Requirements**: For CLRS through resurfacing, lane widths had to be 11 ft or wider and the speed limit 50 mi/h or greater. For retrofit routes, we performed visual analysis on pavement condition.
- **Installation Challenges**: Finding a good contractor with appropriate equipment is difficult. One contractor had a pull-behind unit on a tractor that had difficulty with maintaining the offsets and alignments.
- **Installation Mechanism**: Rumble strips were installed by both retrofit- and resurfacing-type projects.

- **Additional Installed Countermeasures**: No other safety countermeasures were installed with the rumble strips at the treatment sites.

- **Lessons Learned**: Do not wait for unanimous support; instead, plan your implementation and move forward.

- **Maintenance Challenges**: When the centerline joint starts to fail, rumbles make it look worse. However, it does not appear that it expedites the deterioration of the joint. We have not seen the CLRS joints deteriorating any quicker than the non-CLRS joints. Most challenges are overcome through information exchange and documented analysis and review of the benefits and pavement concerns.

DETAILS OF THE MISSOURI INSTALLATIONS

Missouri provided the rumble strip specifications seen in table 24:

Table 24. Installation details for Missouri.

Dimensions	Centerline Rumble Strips (Typical Drawing Detail #1)	Shoulder Rumble Strips
Width	7 inches ± $^{1}/_{2}$ inch	7 inches ± $^{1}/_{2}$ inch
Length	12 inches	12 inches
Depth	$^{7}/_{16}$ inch ± $^{1}/_{16}$ inch	$^{7}/_{16}$ inch ± $^{1}/_{16}$ inch
Spacing	12 inches and 24 inches (alternating pattern)	12 inches
Lateral Placement	Centered on the centerline of the roadway	Placed on the outside edge of the edge line

Missouri was also asked to provide some additional insight on their experience with the strategy. Their responses to several topics are presented below. As with Kentucky, the following responses are provided from the perspective of the State and are phrased informally:

- **Types of Rumble Strips Evaluated**: All new rumble strips were milled.

- **Before-Period Rumble Strip Condition**: No rumble strips. (Some locations potentially had the 30-inch wide rolled rumble strip, which is not at all aggressive.)

- **Retrofit or Resurfacing Projects?**: Resurfacing with paved shoulders.

- **Installation Requirements**: We do encourage a new pavement depth of at least 1¾ inch.

- **Installation Challenges**: We are now beginning to hear more from the bicycle community, but we have over 10,000 line mi now milled. As we continue to do more, we do look at the road users.

- **Additional Installed Countermeasures**: We did much of this effort with the combination of wider stripes (6 inches), bigger and brighter signs, and delineation (tabs at 50 ft on guardrails and cables).

- **Lessons Learned**: Determine a system of roadways that will benefit the most and then just do them. Yes, you need to work with your partners, but you need to develop a plan of action and go forth.

- **Maintenance Challenges**: Many locations have gone through several winters (freeze/thaw) and for the most part are in pretty good shape. When locations do fail, we have allowed gaps up to 200 ft to exist (in anticipation of repair).

DETAILS OF THE PENNSYLVANIA INSTALLATIONS

Pennsylvania provided the rumble strip specifications seen in table 25 and table 26:

Table 25. Installation details for Pennsylvania.

Dimensions	Centerline Rumble Strips (Typical Drawing Detail #1)	Centerline Rumble Strips (Typical Drawing Detail #2)	Edge Line Rumble Strips
Width	7 inches ± $^{1}/_{2}$ inch	7 inches ± $^{1}/_{2}$ inch	5 inches ± $^{1}/_{2}$ inch
Length	16 inches	14–18 inches	6 inches
Depth	$^{1}/_{2}$ inch ± $^{1}/_{16}$ inch	$^{1}/_{2}$ inch ± $^{1}/_{16}$ inch	$^{1}/_{2}$ inch ± $^{1}/_{16}$ inch
Spacing	2 ft and 4 ft (alternating pattern)	2 ft	7 inches
Lateral Placement	Placed on both sides of the centerline, from inner edge of double yellow line marking and extending 16 inches into lane	Center of roadway, perpendicular to centerline pavement markings	Centered over 4-inch edge line and edge line placed 4–6 ft from outside edge of shoulder

Table 26. Installation details for bicycle tolerable rumble strips for Pennsylvania.

Dimensions	Bicycle Tolerable Shoulder Rumble Strip (55 mi/h or more)	Bicycle Tolerable Shoulder Rumble Strip (less than 55 mi/h)
Width	5 inches ± $^{1}/_{2}$ inch	5 inches ± $^{1}/_{2}$ inch
Length	16 inches	16 inches
Depth	$^{3}/_{8}$ inch ± $^{1}/_{16}$ inch	$^{3}/_{8}$ inch ± $^{1}/_{16}$ inch
Spacing	7 inches	6 inches
Lateral Placement	6 inches from edge of travel lane and 4 ft minimum from outside edge of shoulder	6 inches from edge of travel lane and 4 ft minimum from outside edge of shoulder

Pennsylvania was also asked to provide some additional insight on their experience with the strategy. Their responses to several topics are presented below. As with Kentucky and Missouri, the following responses are provided from the perspective of the State and are phrased informally:

- **Types of Rumble Strips Evaluated**: All new rumble strips were milled.
- **Installation Challenges**: Again, minimum shoulder width needs to be installed for SRS to accommodate the bicycle community. Edgeline rumble strips should be omitted on the inside of moderate to sharp curves, which encompass dwellings. Drivers tend to use the shoulder area more in these situations, increasing the noise level. We have seen cases of pavement cracking when installing rumble strips in older pavement. We recommend only installing rumble strips where pavement is less than 3 years old. (Less than 1 year is ideal pavement age.)
- **Additional Installed Countermeasures**: Treatment sites must have a minimum paved shoulder width of 6 ft to install SRS and 4 ft to install edgeline rumble strips. Other than paved shoulders, no other safety countermeasures were installed.
- **Lessons Learned**: While the combination of CLRS and SRS does create tight travel lanes for the driver, our data does not show an increase in crashes at these locations. To the best of our knowledge, there has not been any issues or complaints with this application. As long as lane width is at least 11 ft and minimum shoulder width requirements are met, we will continue to deploy this application throughout Pennsylvania. Our Roadway Departure Implementation Plan has also identified sites recommended for both CLRS and SRS.
- **Maintenance Challenges**: Our biggest challenge with maintenance has been rumble strips being filled in by thin overlays and not being re-installed. We have collected locations from our Districts where this is happening and information on their experiences with preserving, filling in, and re-cutting rumbles on two-lane rural highways. We are currently developing a synthesis of best practices (estimated completion June 2014) to provide guidance related to rumble strips and thin overlays.

ACKNOWLEDGEMENTS

This report was prepared by Vanasse Hangen Brustlin, Inc (VHB) for the Federal Highway Administration Office of Safety under Contract DTFH61-13-D-00001. The FHWA Contracting Officer's Technical Manager for this project was Roya Amjadi. Kimberly Eccles, P.E, of VHB was the study principal investigator. Dr. Bhagwant Persaud and Craig Lyon, subcontractors to VHB, developed the study design, conducted the analysis of the strategy, and are the primary authors of the report.

The project team gratefully acknowledges the participation of the following organizations and individuals for their assistance in this study:

Mr. Tracy Allen Lovell, PE
Kentucky Transportation Cabinet
Division of Traffic Operations

Ms. Ashley Reinkemeyer, P.E.
Missouri Department of Transportation
Traffic and Highway Safety

Mr. John Miller, P.E.
Missouri Department of Transportation
Traffic and Highway Safety

Mr. Girish Modi, P.E.
Pennsylvania Department of Transportation
Bureau of Highway Safety & Traffic Engineering

Mr. Jeffrey Roecker
Pennsylvania Department of Transportation
Bureau of Highway Safety & Traffic Engineering

Mr. Steven Fink
Pennsylvania Department of Transportation
Bureau of Highway Safety and Traffic Engineering

REFERENCES

1. Neuman, T.R. et al., *Volume 6: A Guide for Addressing Run-Off-Road Collisions*, Transportation Research Board, Washington, DC, 2003a.

2. Neuman, T.R. et al., *Volume 4: A Guide for Addressing Head-On Collisions*, Transportation Research Board, Washington, DC, 2003b.

3. Torbic, D. et al., *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

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

5. Torbic, D., Bauer, K., Hutton, J., and Campbell, J., *Delta Region Transportation Development Program: Rural Safety Innovation Program Evaluation*, Draft Final Report, Federal Highway Administration, McLean, VA, 2013.

6. Hauer, E., *Observational Before-After Studies in Road Safety—Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*, Elsevier Science, Incorporated, 1997.

7. U.S. Department of Transportation, *Guidance on Treatment of the Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2014 Adjustment*, Memo, June 13, 2014, last accessed on November 12, 2014, http://www.dot.gov/sites/dot.gov/files/docs/VSL_Guidance_2014.pdf.

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

Recycled
Recyclable

HRDS-20/06-15(200)E