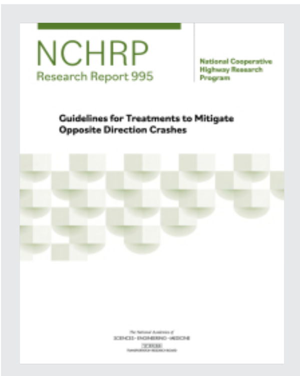

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 995

Guidelines for Treatments to Mitigate Opposite Direction Crashes

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2022

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Christopher T. McKenney
Senior Program Officer
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This research report provides state departments of transportation (DOTs) practitioners and other transportation professionals with comprehensive guidelines for the selection of cost effective countermeasures to address opposite direction crashes. These guidelines should be of immediate use to experienced practitioners working to reduce crashes and improve safety on the surface transportation system.

According to the NHTSA Fatality Analysis Reporting System (FARS), from 2016 through 2018, there were more than 19,200 vehicles involved in opposite direction crashes that resulted in a fatality. Approximately 68 percent of these crashes occurred on two-lane roadways. Countermeasures, such as rumble strips or stripes, delineators, and barriers have proven to reduce total crashes and serious injuries; however, there is limited guidance on the specific performance for many of these treatments as they directly relate to opposite direction crashes. Improved guidance was needed on when and what type of countermeasure is appropriate, and what roadway factors may lead to higher opposite direction crash frequency rates. For purposes of this study, an opposite direction crash occurs between two or more vehicles traveling in opposing directions before the crash and not attempting to execute a turning maneuver at the time of the crash.

Under NCHRP Project 17-66, "Selection of Appropriate Countermeasures for Opposite Direction Crashes," Texas A&M Transportation Institute (TTI) was asked to develop guidelines for the identification, prioritization, and selection of effective countermeasures to reduce or eliminate opposite direction crashes. TTI accomplished this objective by identifying existing databases that could be subjected to additional analysis. The analysis is therefore bounded by the available data compiled by other researchers.

The research identified the rare and random nature of opposite direction crashes creates challenges when statistically assessing the influence of a safety treatment on the reduction in opposite direction crashes. The results will be considered by the AASHTO Technical Committee on Roadside Safety for inclusion in the AASHTO *Roadside Design Guide*.

In addition to the published guidelines, the research agency's report that documents the entire research effort can be found on www.nap.edu by searching for *NCHRP Research Report 995: Guidelines for Treatments to Mitigate Opposite Direction Crashes*.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.nap.edu) retains the color versions.

CHAPTER 1

Introduction

Crashes between vehicles traveling in opposing directions often result in severe injuries or fatalities. According to the National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting System (FARS), from 2014 through 2018 there were more than 16,500 fatal head-on collisions that occurred as a result of opposite direction crashes. Several safety treatments may be considered to help reduce the number of opposite direction crashes or to minimize the crash severity if a crash occurs. There is a need to better understand what factors will influence opposite direction crashes, which countermeasures are best suited for specific locations, and what adverse impacts may occur because of implementation of these safety treatments.

Definition of Opposite Direction Crash

For the purposes of these guidelines, an opposite direction crash is defined as: a crash that occurs between two or more vehicles traveling in opposing directions prior to the crash and where the drivers were not attempting to execute a turning maneuver at the time of the crash.

This definition helps to isolate crashes that are due to maneuvers common to head-on or opposite direction sideswipe crashes by excluding driveway or intersection related turning maneuver crashes. An associated type of crash may be a run-off-the-road crash. In some cases, a vehicle may exit the road, re-enter the active travel lanes, and then impact an approaching vehicle. This type of crash is included in the definition of opposite direction crashes, but if a vehicle is not present in the opposing lane of travel, the crash may simply be designated a single-vehicle run-off-the-road crash.

Purpose of Guidelines

There is a need to better understand how and when to apply safety treatments that target opposite direction crashes. In many cases, past research efforts have estimated the reduction in total crashes that can be attributed to unique countermeasures; however, the associated safety performance of many of these individual countermeasures, as applied to opposite direction crashes, is not always known. This document identifies countermeasures with known safety effects for reducing opposite direction crashes and provides supporting information for identification and application of these treatments. As defined, the opposite direction crash involves two or more vehicles; however, it is possible that a near-crash could occur between opposing vehicles and this event would not be captured in a crash database.

These guidelines target opposite direction crashes with the understanding that applicable countermeasures also may reduce other crashes such as single-vehicle collisions and near-crash events. The identified countermeasures are primarily treatments that can be applied to an existing roadway with minimal infrastructure construction or reconstruction and treatments for which opposite direction crashes or crashes related to opposite direction collisions have known safety performance values. Improvements, such as adding entire lanes or substantially widening existing lanes, can be expected to be associated with fewer opposite direction crashes, but their specific influence on crash reductions is difficult to isolate since this type of infrastructure improvement usually includes many other roadway elements that also could affect crash reductions.

Guideline Target Audience

Transportation professionals responsible for identifying when and where to deploy roadway treatments will benefit from this guideline document. The content of this guide will help these decision makers identify the most promising safety treatment options for locations associated with their facilities where opposite direction crashes occur.

How to Navigate This Guideline Document

This guide identifies countermeasures known to help reduce opposite direction crashes. Chapter 2 reviews target crashes, identifies potential contributing factors that may be targeted by the treatments, and provides an overview of the countermeasures included in the subsequent chapters. As part of this overview, Chapter 2 includes a summary table of the individual countermeasures identified in the guideline document so anyone using this document can quickly identify and locate information relative to a treatment or crash condition.

Chapters 3, 4, and 5 provide information specific to the candidate countermeasures. This content is consistently structured to help address the questions of what, why, and where to consider applying the treatment. Each countermeasure summary begins with a header like the example shown in Figure 1. The header identifies the treatment, the general project cost (separated into low, moderate, and high categories), the target crash type, and recommended facility characteristics.

The cost of a treatment can fluctuate depending on geographic location, type of project, and quantity of countermeasures. For the purposes of this guide, the cost categories shown in each countermeasure header are defined as follows:

- Low cost – Assumes signage, pavement marking, and/or rumble strip applications. Though the initial cost may be low, these treatments may have a short service life and require ongoing maintenance costs.
- Moderate cost – Based on countermeasures that require some modest infrastructure improvements but do not require the purchase of additional right-of-way (ROW).
- High cost – Treatments require more extensive infrastructure improvements than those listed as moderate and, in many cases, will also require the purchase of additional ROW.

Treatment/Countermeasure: Install SafetyEdge[SM] treatment			
Project Type/Cost:	**Low**	**Moderate**	**High**
Crash Type: Head-on, opposite direction sideswipe, and single-vehicle run-off-road			
Facility Type/Characteristics: Two-lane highways, multilane highways, and freeways			

Figure 1. Example countermeasure summary sheet header.

Chapters 3, 4, and 5 are organized in order of priority. For example, the countermeasures identified in Chapter 3 will help a vehicle stay in the lane (the preferred option). In the event vehicles inadvertently exit their lanes, deploying the countermeasures summarized in Chapter 4 will help to reduce the likelihood of a crash between opposing directions. Chapter 5 then identifies another treatment that will help reduce the potential for crashes or reduce the crash severity if a roadway or lane departure crash should occur.

References identifies the references cited throughout the document.

CHAPTER 2

Crash Conditions and Selecting Countermeasures

Each potential safety treatment is expected to help reduce the number of crashes and/or minimize severity if a crash occurs; however, issues associated with treatment cost, suitability, and effectiveness are key factors to consider when selecting these recommended safety treatments. This chapter first identifies the primary crash types targeted by these guidelines. In some cases, a countermeasure may help to eliminate or reduce more than one type of crash. These supplemental crash types are noted where applicable. Next, this chapter identifies a list of candidate countermeasure options to consider for a recurring crash type and then identifies how the user of the guidelines can narrow this list down to treatments suitable for a given location.

Target Crash Characteristics

Opposite direction crashes often result in serious injuries or fatalities. For this reason, these guidelines primarily target treatments expected to help reduce the frequency and/or severity of opposite direction crashes. The two most common crash types are head-on and opposite direction sideswipe crashes. In some cases, the countermeasure may also help to reduce the number of run-off-road (ROR), nighttime crashes, or same direction sideswipe crashes. Information about these supplemental crash types has been included for comparison purposes in the guideline, but is not intended to be the focus of this document. In some cases, researchers broadly defined ROR crashes to include opposite direction crashes.

In addition to the crash type, effective countermeasures should minimize the number of fatal or injury crashes. Because fatal and severe injury crashes occur infrequently, most of the countermeasure crash analysis has focused on total crashes, fatal injury and serious injury (KA) crashes, or total injury crashes (KABC). In some studies, property damage only (PDO) crash information has been developed and is shown where practical.

Crash Severity Scale
KABCO, KABC, KA, ABC
K = crash with at least one fatal injury A = crash with incapacitating injury B = crash with non-incapacitating injury C = crash with possible injury O = property damage only crash

Identifying List of Candidate Countermeasures for the Crash Type

Table 1 provides a summary of candidate countermeasures and their applicable road type or location that should be considered for a specific crash type. This information can be used as a starting point to identify candidate countermeasure options. Though some of the countermeasures may be located on a variety of roadway types, the effectiveness of a treatment may have only been tested for a specific roadway configuration. Consequently, the road type information shown in the table represents the basis for the current state-of-practice knowledge related to the specific treatment.

Following identification of candidate countermeasures, the guideline user can then explore the best options for the specific site by inspecting Table 2.While all countermeasure options should be considered, the countermeasures listed in this table are categorized by priority for reducing risk. The preferred treatment would prevent an opposite direction crash from occurring by reducing the opportunity for vehicles to inadvertently leave their directional lane of travel. This group of countermeasures is identified as the “Keep Vehicles in Lane” category. Where vehicles leave their lane despite one or more of these preferred treatments, the “Reduce Likelihood of Head-On Crash” option can be expected to also help minimize the risk by providing a better opportunity for the driver to recover without a head-on crash. The final countermeasure category also addresses instances when a vehicle does leave the lane or road, but this countermeasure is common for a broader range of crash types than head-on collisions. This countermeasure is included in the “Reduce Severity of Crash” treatment list.

Table 2 also includes information about the project cost level, crash type, and facility type.

Table 1. Identifying candidate countermeasures for crash type.

Crash Type	Road Type / Location	Candidate Countermeasures
Head-on and opposite direction sideswipe crash	Two-lane highway	• Centerline rumble strips • Widen edge line • Centerline buffer area • Install alternating/periodic passing lanes • Shoulder rumble strips • Widen or pave shoulders • Improve pavement friction • Enhance horizontal curve delineation (e.g., edgeline, chevrons, advance warning signs)
	Divided highway and/or freeway	• Widen median • Install median barrier • Shoulder rumble strips • Widen or pave shoulders • Improve pavement friction • Install SafetyEdge^{SM} treatment
Single-vehicle run-off-road	All	• Widen edge line • Shoulder rumble strips • Widen or pave shoulders • Improve pavement friction • Install SafetyEdge^{SM} treatment • Enhance horizontal curve delineation
Nighttime-only crashes	All	Install lighting
Same direction sideswipe	Two-lane highway	Install alternating/periodic passing lanes

Table 2. Summary of countermeasures.

Countermeasure	Project Cost	Crash Type	Facility Type
Keep Vehicles in Lane			
Centerline rumble strips	Low	Head-on, opposite direction sideswipe	2-lane undivided highway
Shoulder rumble strips	Low	Head-on and opposite direction sideswipe (in median), ROR	2-lane, multilane, and freeway
Widen edge lines	Low	Head-on, opposite direction sideswipe, SVROR	2-lane undivided highway
Enhance horizontal curve delineation	Low	Head-on, opposite direction sideswipe, SVROR	2-lane undivided highway at horizontal curves
Improve pavement friction	Moderate	Head-on, opposite direction sideswipe, SVROR	All road types (wet weather or high speed)
Roadway lighting	Moderate	Nighttime crashes	Intersection and curve locations for all roads
Reduce Likelihood of Head-On Crash			
Install centerline buffer area	Moderate	Head-on, opposite direction sideswipe	2-lane undivided highway
Widen median	High	Head-on and opposite direction sideswipe (in median)	Divided highway
Install alternating / periodic passing lanes	High	Head-on, opposite direction sideswipe, and same direction sideswipe	2-lane undivided highway
SafetyEdge^{SM}	Low	Head-on, opposite direction sideswipe, SVROR	2-lane, multilane, and freeway
Pave or widen shoulders	High	Head-on, opposite direction sideswipe, SVROR	2-lane, multilane, and freeway
Reduce Severity of Crash			
Cable median barrier	Moderate	Head-on and opposite direction sideswipe (in median)	Divided highway

Note: SVROR refers to single-vehicle run-off-road crashes

The individual summary sheets for a countermeasure include a safety state-of-practice review section. This content identifies information from applicable research related to the crash type, severity type, and estimated reduction in crashes. This state-of-practice review concludes with a general recommendation section that reviews the known effectiveness of a treatment. For the state-of-practice, the summary focuses on recent research studies that have received three-star ratings or higher at the FHWA Crash Modification Factors (CMF) Clearinghouse. For multistate studies, the selected values extend across more than one state and typically have a larger sample size. For treatments that do not have available studies in the CMF Clearinghouse, the study source is identified. For more information about the CMF Clearinghouse and the associated star rating, please refer to www.CMFClearinghouse.org.

In addition to providing information about the estimated percent reduction in crashes, the CMF is often identified. This value is a multiplicative adjustment factor that can be used to directly calculate the estimated number of crashes following implementation of a countermeasure. The CMF is derived from the percent crash reduction and is calculated as follows:

$$CMF = 1 - \frac{Percent\ Reduction\ in\ Crashes}{100}$$

If a countermeasure leads to an increase in crashes, the percent reduction will be a negative number, and the CMF will be greater than one. If a CMF value is less than one, this indicates that the associated countermeasure will help to reduce crashes. More information about using CMFs is provided in the *Quick Start Guide to Using CMFs* located at http://www.CMFClearinghouse.org/using_cmfs.cfm (*1*).

CHAPTER 3

Keeping Vehicles in Their Lanes

The best way to avoid opposite direction crashes is to reduce the opportunity for these crashes to occur. Where feasible, an effective way to eliminate or reduce the number of opposite direction crashes is to implement strategies that will help keep vehicles in their lanes. To achieve this objective, Table 3 summarizes countermeasures that can be deployed to help minimize lane departure events. Additional information about each of the identified countermeasures is included in this chapter. When selecting candidate countermeasures, it is important to confirm that the treatment does not already exist at the study site and that the countermeasure has a known effect on reducing crashes for the specific facility type.

Table 3. Countermeasures to keep vehicles in their lane.

Countermeasure	Project Cost	Crash Type	Facility Type
Install centerline rumble strips	Low	Head-on, opposite direction sideswipe	Two-lane undivided highway
Install shoulder rumble strips	Low	SVROR, head-on and opposite direction sideswipe (in median)	Two-lane, multilane, and freeway
Widen edge lines	Low	Head-on, opposite direction sideswipe, SVROR	Two-lane undivided highway
Enhance horizontal curve delineation	Low	Head-on, opposite direction sideswipe, SVROR	Two-lane undivided highway at horizontal curves
Improve pavement friction	Moderate	Head-on, opposite direction sideswipe, SVROR	All road types (wet weather or high speed)
Install roadway lighting	Moderate	Nighttime crashes	Intersection and curve locations for rural roads, urban corridors

SVROR = single-vehicle run-off-road

Install Centerline Rumble Strips

Treatment/Countermeasure: Install Centerline Rumble Strips	
Project Type/Cost:	**Low** / Moderate / High
Crash Type: Head-on, opposite direction sideswipe	
Facility Type/Characteristics: Two-lane undivided highway	

WHAT (Introduction)

Rumble strips are grooved or raised patterns on the roadway that produce audible and vibratory warnings when a vehicle's tires pass over them, thereby alerting drivers who may inadvertently encroach onto them. As the name suggests, centerline rumble strips are placed at the center of the road, either adjacent to or concurrent with centerline striping (Figure 2). The purpose of the centerline rumble strip is to provide warning to errant drivers who may be crossing into oncoming traffic. Intended for use on two-lane undivided highways, centerline rumble strips can help reduce head-on and opposite direction sideswipe crashes.

WHY (Safety State of the Practice)

Several studies have documented reductions in crash frequency, crash severity, or some combination of these measures following the installation of centerline rumble strips on rural two-lane undivided highways. Key findings are summarized in Table 4.

General Observations
Users can expect to see reductions ranging from 21 to 37 percent for head-on and opposite direction sideswipe crashes (CMF = 0.63 to CMF = 0.79) following installation of centerline rumble strips at rural two-lane highways.
The total number of crashes for a corridor equipped with centerline rumble strips varies, but generally the facility will experience a 4 to 14 percent reduction in total crashes (CMF = 0.86 to CMF = 0.96) following implementation.

WHERE (Application Issues)

Design

A lane width of 12 ft is optimal for locations with centerline rumble strips, but the rumble strips may be used on two-lane, undivided roadways with lane widths as narrow as 10 ft. This width is needed so that vehicles do not regularly encroach on the centerline rumble strips while traveling on a treated highway. The pavement surface and base layers must be at least 2 to 3 inches thick to avoid compromising the integrity of the pavement when applying depressed centerline rumble strips (*6*).

In the event it is necessary to establish priorities to determine deployment strategies, roads with travel lanes at least 20 ft wide should be considered as a priority for centerline rumble strips

(Photograph provided by Texas A&M Transportation Institute)

Figure 2. Milled centerline rumble strips.

Table 4. Summary of centerline rumble strip studies for rural two-lane highways.

Study Location(s)	Year	Percent Reduction in Crashes (%)				Source
		Crash Type		Crash Severity		
		Head-On Crashes (KABCO)	Opposite Direction Sideswipe (KABCO)	Injury Crashes (KABC)	Total Crashes (KABCO)	
CA, CO, DE, MD, MN, OR, WA	2003	21		15*	14	(*2*)
MN, PA, WA	2009	37		9	4	(*3*)
British Columbia	2010	29		NR	NR	(*4*)
KS	2012	NR	NR	34	NR	(*5*)

* Injury crashes were ABC (no K crashes recorded)
NR – not reported
Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse. For multistate studies, the selected values extend across more than one state and typically have larger sample sizes for locations where centerline rumble strips did not previously exist.

at locations where opposite direction crashes are likely such as rural two-lane highways with frequent curvature.

Operations

Centerline rumble strips may increase the noise in the surrounding community, especially where frequent passing occurs, such as the beginning of passing zones after long stretches of no passing. Noise may also be an issue where off-tracking is frequent due to larger vehicles, towing trailers, narrow lanes, or curvilinear alignment. Surveys have found motorcyclists do not have an issue with centerline rumble strips if they are aware of them. In some cases, vehicles in the travel lanes may shift laterally toward the shoulder at locations with centerline rumble strips. This lateral shift may increase the potential for ROR crashes and vehicle-bicycle collisions (drivers may crowd bicyclists rather than move left across the centerline rumble strip when passing the bicyclists).

Install Shoulder Rumble Strips

Treatment/Countermeasure: Install Shoulder Rumble Strips			
Project Type/Cost:	**Low**	Moderate	High
Crash Type: Single-vehicle ROR, median crashes (head-on or opposite direction sideswipe)			
Facility Type/Characteristics: Two-lane highways, multilane highways, freeways			

WHAT (Introduction)

Rumble strips are grooved or raised patterns on the roadway that produce audible and vibratory warnings when a vehicle's tires pass over them, thereby alerting drivers who may inadvertently encroach onto them. As the name suggests, shoulder rumble strips are placed along the shoulder of the road, either adjacent to or concurrent with edge line striping (Figure 3). The purpose of the shoulder rumble strip is to provide warning to errant drivers who may be inadvertently departing their travel lane toward the roadside. Designed primarily to prevent SVROR crashes, shoulder rumble strips may be installed on roadway shoulders with widths of at least 2 ft. On divided highways, the shoulder rumble strips can be installed on both the right (outside)

(Photograph provided by Texas A&M Transportation Institute)

Figure 3. Milled shoulder rumble strips.

shoulder as a countermeasure for roadway departure crashes and the left (median) shoulder to help deter cross-median crashes such as head-on and opposite direction sideswipe crashes.

WHY (Safety State of the Practice)

Several studies have documented reductions in crash frequency and severity following the installation of shoulder rumble strips on rural two-lane highways, rural multilane highways, and freeways. Key findings are summarized in Table 5. Though the ROR crashes may not be directly related to all opposite direction crashes, their values are shown in Table 5 and contrasted to total injury crashes. The influence of shoulder rumble strips on opposite direction crashes is not fully quantified and so has not been incorporated into the table.

General Observations
The influence that shoulder rumble strips have on total ROR crashes varies. Most studies observed a reduction in total ROR crashes following shoulder rumble strip application, but the study from MO and PA noted an increase in ROR crashes for rural multilane highways. In all cases, the placement of shoulder rumble strips appears to reduce the number of ROR injury crashes. For freeways, shoulder rumble strips reduce ROR injury crashes from 7 to 31 percent (CMF = 0.69 to CMF = 0.93). For rural multilane highways, the reduction ranges from 10 to 22 percent (CMF = 0.78 to CMF = 0.90). For rural two-lane roadways, the ROR injury crashes reduce from 18 to 36 percent (CMF = 0.64 to CMF = 0.82).

WHERE (Application Issues)

Design

Many states have a minimum shoulder width of 2 to 6 ft (commonly 4 ft) on which a shoulder rumble strip may be installed (*3*). This width provides space to install the rumble strips between the edge line and the edge of the paved surface. Some "rumble stripe" applications are applied on the edge line, but most rumble strips are offset 2 to 24 inches from the edge line. This offset distance varies by maintenance practices (i.e., resurfacing boundaries) and roadway functional purpose where higher speed facilities tend to have larger offsets. This lateral placement helps drivers to be less likely to regularly encroach on the shoulder rumble strips while traveling on a treated highway. The pavement surface and base layers must be at least 2 to 3 inches thick to avoid compromising the integrity of the pavement when applying depressed shoulder rumble strips (*6*).

Table 5. Summary of shoulder rumble strip studies.

Study Location(s)	Year	Percent Reduction in Crashes (%)			Source
		Crash Type	Crash Severity		
		ROR Crashes (KABCO)	Injury Crashes (KABC)	ROR Injury Crashes (KABC)	
Freeway					
CA, IL	1999	21	NR	7*	(*7*)
MO, PA	2009	10	-7	17	(*3*)
WY	2013	NR	NR	31	(*8*)
Rural Multilane					
MN	2004	10	17*	22*	(*9*)
MO, PA	2009	-40	-18	10	(*3*)
Rural 2-lane					
MN	2007	13	NR	18	(*10*)
MN, MO, PA	2009	16	-6	36	(*3*)

* Injury crashes were ABC (no K crashes recorded)
NR – not reported
Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse. For multistate studies, the selected values extend across more than one state and typically have larger sample sizes for locations where shoulder rumble strips did not previously exist.

In the event it is necessary to establish priorities to determine deployment strategies, locations with steep roadside slopes or narrow clear zones should be given priority for shoulder rumble strip applications.

Operations

Shoulder rumble strips may adversely affect certain types of vehicles (e.g., wide loads, vehicles towing trailers, bicycles, and motorcycles) and increase the noise in the surrounding community, especially if used near intersections, driveways, or other access points. The placement of bicycle-compatible shoulder rumble strips can help to accommodate cyclists along these facilities. This can be accomplished with short gaps in an otherwise continuous rumble strip pattern. For additional information about accommodating all users, please refer to the following FHWA web site: safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/accommodating-all-users.cfm.

Shoulder rumble strips may also shift the lateral placement of vehicles in the travel lane toward the centerline on undivided highways. This lateral shift in active traffic could increase the potential for opposite direction crashes unless there are centerline rumble strips in place as well.

Widen Edge Lines

Treatment/Countermeasure: Widen Edge Lines			
Project Type/Cost:	**Low**	**Moderate**	**High**
Crash Type: Head-on, opposite direction sideswipe, SVROR			
Facility Type/Characteristics: Two-lane undivided highways			

WHAT (Introduction)

The *Manual on Uniform Traffic Control Devices* (MUTCD) indicates that the purpose of an edge line is to delineate the edge of the roadway (*11*). Section 3B.06 of the MUTCD further

(Photograph provided by Thurston County, WA)

Figure 4. Wider edge lines.

notes that the wider edge lines provide greater emphasis to the markings (Figure 4). This type of delineation helps provide positive guidance to drivers and can be expected to minimize the number of roadway departure crashes. This treatment may also enhance the lateral position of a vehicle in the travel lane, thereby resulting in fewer opposite direction crashes.

WHY (Safety State of the Practice)

The MUTCD indicates that the use of wider edge lines provides greater emphasis to the edge of the road and can be expected to reduce the total number of crashes. As noted in Table 6, research has focused on widening edge lines from 4 to 6 inches. Previous researchers have also investigated the effect of widening both the edge lines and the centerline from 4 to 5 inches. Wider edge lines are expected to be less effective during cold-weather seasons at locations where these pavement markings are obscured by snow. For this reason, the Table 6 summary includes all year and non-winter information (for northern states subjected to inclement winter weather).

General Observations
Widening edge lines from 4 to 6 inches will help reduce the total number of opposite direction crashes by 43 to 54 percent (CMF = 0.46 to CMF = 0.57) during non-winter conditions (note that this statement assumes Kansas winter weather pavement marking occlusions are minimal). Similarly, wider edge lines will help reduce the total fatal and injury opposite direction crashes from 53 to 75 percent (CMF = 0.25 to CMF = 0.47) during non-winter conditions. This is equivalent to an average CMF value of approximately 0.36. Widening edge lines and centerlines from 4 to 5 inches has little to no impact on the total number of opposite direction crashes, but this change can be expected to reduce the fatal and injury opposite direction crashes by as much as 24 percent (CMF = 0.76) during non-winter conditions.

WHERE (Application Issues)

Design

Edge lines should not be constructed at intersection or driveway locations. The wider edge line application can be expected to perform best at rural locations with minimal access points

Table 6. Summary of wider edge line treatment studies at rural two-lane highways.

Study Location(s)	Year	Season	Percent Reduction in Crashes (%) — Crash Type: Total Segment Crashes (KABCO)	Crash Type: Total Opposite Direction (KABCO)	Crash Severity: Segment Fatal and Injury Crashes (KABC)	Crash Severity: Opposite Direction Fatal and Injury Crashes (KABC)	Source
Widen Edge line from 4″ to 6″							
KS	2012	All year	18	NR	37	NR	(*12*)
MI	2012	All year	19	NR	NA	NR	(*12*)
KS	2017	All year	NA	43	NA	53	(*13*)
MI	2017	Non-winter	19	54	NA	75	(*13*)
Widen Edge line and Centerline from 4″ to 5″							
IL	2012	All year	30	NR	38	NR	(*12*)
IL	2017	Non-winter	32	1	37	24	(*13*)
IL	2017	All year	23	-24	31	14	(*13*)

NR – not reported
NA – not applicable or does not meet the three-star rating criteria
Note: For Park et al. (2012) (*12*) the project selection process included projects with three-star ratings or more at the CMF Clearinghouse. The other 2017 values were developed as part of NCHRP Project 17-66 research efforts and have not yet been assigned a star rating.

as this type of rural environment results in uninterrupted, continuous pavement marking. In some cases, wider edge lines may be applied selectively at locations, such as horizontal curves, that may benefit from additional positive guidance. The use of the wider edge line for an entire segment could diminish any unique benefits at isolated horizontal curve locations.

Operations

The enhanced ability for drivers to see the edge lines by making the lines wider is likely to improve traffic operations. Fewer drivers can be expected to inadvertently veer from the lane. The improved positive guidance may result in increased operating speeds, particularly during nighttime conditions. The maintenance costs associated with the change in widths may increase marginally, but the frequency of edge line placement should not change due to this enhancement.

Enhance Horizontal Curve Delineation

Treatment/Countermeasure: Enhance Horizontal Curve Delineation
Project Type/Cost: **Low** Moderate High
Crash Type: Head-on crashes, opposite direction sideswipe, and single-vehicle ROR
Facility Type/Characteristics: Horizontal curves at two-lane undivided highways

WHAT (Introduction)

More than 25 percent of roadway fatalities occur at horizontal curve locations. These fatal crashes are most likely due to roadway departure, both at daytime and nighttime. Enhanced curve delineation serves a dual purpose: (a) alerts drivers as they are approaching the horizontal curves by providing them with visual cues, and (b) guides the drivers in lane keeping and speed reduction as they are navigating the curves. This becomes especially critical during nighttime

(Photograph provided by Federal Highway Administration)

Figure 5. Enhanced curve delineation.

conditions at locations not well lit. Enhanced delineation can be provided by installing pavement markings with high durability and retroreflectivity, as well as by posting signs ahead of the curve and along the horizontal curves. A common sign located in the curve is the chevron, which includes an arrow pointing toward the direction of travel (Figure 5). In some cases, agencies may exchange the sheeting on warning signs and/or chevrons or arrows with fluorescent yellow sheeting as a means of enhancing delineation.

WHY (Safety State of the Practice)

According to the MUTCD, published by the FHWA, delineators are effective aids for night driving (*11*); however, to date researchers have performed only a few safety evaluations to assess curve delineation enhancements. Table 7 outlines some of the crash reductions identified as part of two studies, one domestic and one international.

Table 7. Summary of enhanced horizontal curve delineation studies.

		Percent Reduction in Crashes (%)						
		Crash Type					Crash Severity	
Study Location(s)	Year	Total NI Crashes (KABCO)	NI Nighttime Crashes (KABCO)	Total HO, SS, & ROR Segment Crashes (KABCO)	HO, SS, & ROR Nighttime Segment Crashes (KABCO)	OD Crashes (KABCO)	Fatal and Injury Crashes (KAB)	Source
Rural Two-Lane Highways – New or Upgrade to Fluorescent Curve Signs								
CT	2009	18	34	18	35	NR	25	(*14*)
CT	2017	NR	NR	NR	NR	6	NR	(*13*)
Rural Two-Lane Highways – Add Chevrons at Horizontal Curves								
WA	2009	4	25	6	22	NR	16	(*14*)

NR – not reported
NI = non-intersection crashes
HO = head-on crashes
SS = sideswipe crashes
OD = opposite direction crashes
Note: For Srinivasan et al. (2009) (*14*) the project selection process included projects with three-star ratings or more at the CMF Clearinghouse. The other 2017 value was developed as part of NCHRP Project 17-66 research efforts and has not yet been assigned a star rating.

General Observations
As noted in Table 7, the user could expect a reduction of approximately 34 percent (CMF = 0.66) for non-intersection nighttime crashes when adding or upgrading curve warning signs to fluorescent sheeting. Similarly, head-on, sideswipe, and ROR nighttime crashes will reduce by approximately 35 percent (CMF = 0.65). These two observations are equivalent to an average CMF of 0.66. For locations where chevrons are added at the approach to horizontal curves, a reduction of approximately 25 percent (CMF = 0.75) can be expected for non-intersection nighttime crashes and a reduction of 22 percent (CMF = 0.78) is associated with crashes that are head-on, sideswipe, and ROR collisions. These two observations are equivalent to an average CMF of 0.77.

WHERE (Application Issues)

Design

The placement of enhanced curve delineation requires suitable roadside conditions so that the devices can be constructed and supported while maintaining the requirements for visibility. This application can present a challenge if a graded roadside condition at least 2 to 3 feet wide is not present. At locations with substantial superelevation or where the horizontal curvature reverses, the horizontal curve delineation may require unique adaptations.

Operations

Although the intent of enhanced horizontal curve delineation is to improve highway safety, the delineation treatments may also provide better lane keeping due to the increased visibility. The curve delineation enhancements can be expected to improve nighttime visibility at applicable locations.

Improve Pavement Friction

Treatment/Countermeasure: Improve Pavement Friction			
Project Type/Cost:	Low	**Moderate**	High
Crash Type: Head-on, opposite direction sideswipe, SVROR (applicable to wet weather or high speed locations)			
Facility Type/Characteristics: All roadway facilities			

WHAT (Introduction)

Poor roadway conditions are a contributing factor to highway fatalities. One of the attributing conditions is surface friction between the roadway pavement and the vehicle tires. Pavement friction is the force that resists the tires' motion on the pavement surface and is usually measured by the coefficient of friction. Many factors affect this coefficient, but generally as the coefficient value increases, it becomes more difficult for a vehicle to slide across the surface. Pavement friction is a key factor in keeping vehicles on the road when brakes are applied, especially as the vehicles navigate horizontal curves or drivers steer aggressively. Additionally, weather can impose wet or icy pavement conditions that contribute to reduced surface friction. Up to 70 percent of wet weather crashes could be minimized or potentially prevented by improving the pavement friction (*15*). This condition increases the possibility for the driver to fully maintain control of the vehicle during these inclement conditions. Due to extended use of the pavement, the surface friction tends to deteriorate over time. Enhancing pavement friction can reduce the possibility of crashes associated with less-than-optimal pavement friction conditions.

(Photograph provided by Federal Highway Administration)

Figure 6. HFST application (left lane) with original pavement (right lane).

For many locations, a pavement overlay will help to improve pavement friction; however, at extreme locations (sharp horizontal curves with marginal superelevation or critical intersections with high speed approaches), the improved friction may be accomplished by installing high friction surface treatments (HFST) (Figure 6). This treatment achieves enhanced skid resistance by incorporating a polymer binder with calcined bauxite. More information about HFST can be located at: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/high_friction/.

WHY (Safety State of the Practice)

Studies that focus on the effect of pavement friction on road safety generally show a reduction in crashes due to improved surface friction; however, these estimates vary across studies/location. This is to be expected given the variety of interacting factors such as location and area type, traffic volume, roadway geometry and posted speed limit, weather (rain and snowfall), pavement structure, and type of friction treatment. Table 8 presents a summary of the key findings from several studies that focused on assessing the safety impacts of enhanced pavement friction due to resurfacing.

The use of HFST is recent in the United States and several current assessment activities are ongoing. Table 9 summarizes the findings from a 2015 study that focused specifically on HFST applications at roadway segment (horizontal curve) locations.

General Observations
For resurfacing treatments, users can expect to see reductions in total segment crashes from 15 percent (rural two-lane CMF = 0.85) to 74 percent (urban two-lane CMF = 0.26) for total wet condition crashes. Users can also expect reductions of 4 percent (rural two-lane CMF = 0.96) to 40 percent (urban two-lane CMF = 0.60) for total crashes. Note that the lower values apply to rural locations, while the larger values extend to urban locations. For locations where HFST is applied, there can be from 24 up to 35 percent reductions in total crashes (CMF = 0.65 to CMF = 0.76). The total number of wet weather crash reductions at these locations can range from 52 to 86 percent (CMF = 0.14 to CMF = 0.48).

WHERE (Application Issues)

Design

Properties of pavement surface treatments have a direct impact on friction and, ultimately, safety. Thus, the selection of pavement materials or pavement surface treatment is a critical

Table 8. Summary of pavement friction resurfacing studies.

Study Location	Year	Road Type	Percent Reduction in Crashes (%): Crash Type: Wet Crashes (KABCO)	Crash Type: Total Crashes (KABCO)	Crash Severity: Wet Injury Crashes (KABC)	Crash Severity: Total Injury (KABC)	Source
NY*	2008	Rural 2-lane	15	4	NR	NR	(*16*)
		Rural multilane	65	32			
		Urban 2-lane	74	40			
		Urban multilane	46	14			
CA	2010	NR (open graded asphalt concrete)	41	NR	NR	NR	(*17*)
TX**	2014	2-lane	NR	NR	a = 212.97 b = 0.0189	a = 113.66 b = 0.0032	(*18*)
		4-lane undivided	NR	NR	NA	a = 136.07 b = 0.0077	
		4-lane divided	NR	NR	a = 358.23 b = 0.0319	a = 132.84 b = 0.0071	

NR – not reported
NA – not available
*This study also evaluated intersection friction, but the segment results are the only results reported in this table.
** Values represent the "a" and "b" coefficients in the following equation:

$$CRF = 100 - a(e^{-b})$$

Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse.

Table 9. Summary of HFST treatment study.

Study Locations	Year	Percent Reduction in Crashes (%): Wet Weather Crashes (KABCO)	Total Crashes (KABCO)	Source
KS, KY, MI, MT, SC, WI	2015	86	35	(*19*)
CO, KS, KY, MI, MT, SC, TN		52	24	

Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse.

aspect of pavement design and treatment selection. The materials selected for design must ensure necessary microtexture and macrotexture to provide good friction. Additionally, the materials must be durable to ensure that pavement friction is sustained over the lifespan of the pavement.

After the treatment has been provided, pavements are exposed to both traffic and weather elements throughout their life. These two primary factors can deteriorate the surface friction. This requires a balance between friction characteristics, long-lasting pavement surface, and cost.

Although state highway agencies recognize that some of the more expensive treatments generally improve pavement friction, these treatments are not typically installed to explicitly account for roadway safety. An exception to this practice is the HFST which is usually applied as a spot treatment in areas that exhibit a high number of crashes due to weather or driver behavior. Candidate HFST sites must have existing pavement that is in good condition prior to the HFST application.

Operations

Improved pavement friction helps to enhance lane keeping behavior at a treatment location. This enhancement will result in fewer cross-centerline and ROR events.

Install Roadway Lighting

Treatment/Countermeasure: Install Roadway Lighting
Project Type/Cost: Low **Moderate** High
Crash Type: Nighttime
Facility Type/Characteristics: Horizontal and vertical curves, intersections, urban corridors

WHAT (Introduction)

Lighting is used to provide additional illumination of the roadway to drivers during nighttime conditions. Lighting is often used at locations where a pattern of roadway departure crashes or opposite direction crashes has been identified. Common locations for roadway lighting include placement at curves where drivers may not be able to clearly see that the alignment of the roadway is changing, or at intersections where cross traffic and turning traffic may be unexpected and where drivers need enhanced nighttime visibility to successfully navigate the intersection (Figure 7).

WHY (Safety State of the Practice)

Studies have documented the effects of roadway lighting on nighttime crash frequency and severity. Table 10 summarizes studies focused on the assessment of roadway lighting. Crash categories apply to rural nighttime crashes where lighting was added at new locations.

General Observations
Users can expect to see a reduction ranging from 32 to 37 percent for **nighttime injury** crashes (CMF = 0.63 to CMF = 0.68) following installation of roadway lighting. **Total nighttime** crash reductions can be expected to range from 12 percent (CMF = 0.88) at intersection locations up to 32 percent (CMF = 0.68) for all road types.

WHERE (Application Issues)

Design

The warranting method described in the *FHWA Lighting Handbook* (*22*) contains considerations for number of lanes, lane width, median openings, access density, horizontal curve radius, vertical grades, sight distance, and presence of parking. In general, lighting on roadway segments is more often recommended when the road has a greater number of lanes, access points, vertical grades, and parking. Lighting is also preferred at locations with narrow lane widths, sharp horizontal curves, and limited sight distance. Lighting is particularly important at locations with active pedestrian traffic.

(Photograph provided by Thurston County, WA)

Figure 7. Roadway lighting at rural location.

Table 10. Summary of roadway lighting studies for nighttime crashes.

Study Location(s)	Year	Region Type (Configuration)	Percent Reduction for Type of Nighttime Crash (%) Total Nighttime Crashes (KABCO)	Injury Nighttime Crashes (KABC)	Single-Vehicle Crashes (KABCO)	Source
MN	2010	All (intersection)	12	NR	NR	(*20*)
FL	2014	All (all road types)	32	37	28	(*21*)
FL	2014	Urban (minor arterial)	26	32	37	

NR – not reported
Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse.

Challenges with the placement of roadway lighting occur when the location is remote and does not have available electrical power. In some cases, the cost of the required power may fall upon local agencies or adjacent property owners. In addition, some communities intentionally limit roadway lighting to help reduce related light pollution.

Operations

The *FHWA Lighting Handbook* (*22*) warranting method recommends lighting on roadway segments with lower percentages of signalized intersections, infrequent left-turn lanes, narrower median widths, higher operating or posted speed, and higher pedestrian activity. Glare is a concern for roadway lighting applications, particularly for older drivers and drivers with visual disabilities. A lighting system meeting the disability glare requirements of AASHTO and the Illuminating Engineering Society generally provides the needed control.

CHAPTER 4

Reduce Likelihood of Head-On Crashes

As noted in Chapter 3, the preferred way to eliminate opposite direction crashes is to find ways to help keep vehicles in their travel lanes. If a driver is not fully alert and inadvertently strays from the travel lane, an increased separation between opposing directions of travel can help to reduce the likelihood that an opposite direction crash will occur. Table 11 summarizes countermeasures that can be deployed to help achieve additional physical separation between opposing lanes. The cost of treatments tends to require some infrastructure enhancements, and so these countermeasures are generally more expensive to implement.

Table 11. Countermeasures to reduce likelihood of head-on crash.

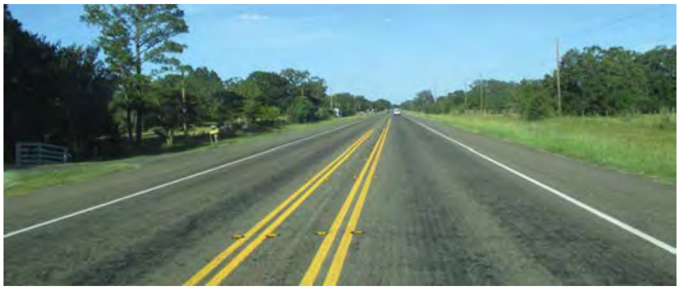
Countermeasure	Project Cost	Crash Type	Facility Type
Install centerline buffer area	Moderate	Head-on, opposite direction sideswipe	Two-lane undivided highway
Widen median	High	Head-on & opposite direction sideswipe (in median)	Divided highway
Install alternating / periodic passing lanes	High	Head-on, opposite direction sideswipe, & same direction sideswipe	Two-lane undivided highway
Install SafetyEdge^{SM} treatment	Low	Head-on, opposite direction sideswipe, SVROR	Two-lane, multilane, and freeway
Pave or widen shoulders	High	Head-on, opposite direction sideswipe, SVROR	Two-lane, multilane, and freeway

Install Centerline Buffer Area

Treatment/Countermeasure: Centerline Buffer Area	
Project Type/Cost:	Low / **Moderate** / High
Crash Type: Head-on and opposite direction sideswipe	
Facility Type/Characteristics: Two-lane undivided highways	

WHAT (Introduction)

The MUTCD (*11*) indicates that centerline pavement marking for two-way, two-lane highways should consist of passing and no passing zone markings, and that a single solid yellow



(Photograph provided by Texas A&M Transportation Institute)

Figure 8. Centerline buffer area.

line shall not be used to represent the centerline marking. In some instances, transportation agencies have observed operational and safety benefits by providing a narrow centerline buffer area that is separated by longitudinal pavement markings (Figure 8). This additional buffer area shifts the lateral placement of opposing direction vehicles.

WHY (Safety State of the Practice)

The use of a centerline buffer area introduces a greater physical separation between approaching vehicles. As shown in Figure 8, this configuration can accommodate passing zones while also maintaining a physical buffer between the active opposing lanes of travel. This treatment is largely untested; however, a recent analysis evaluated the centerline buffer area scenario for Texas highways (*13*). The study evaluated two-lane and four-lane rural highway locations with and without centerline buffer strips present. This research determined that the safety benefits decline and are not statistically significant for four-lane highway locations. For these multilane highways, the buffer area had little noticeable effect for SVROR crashes or opposite direction crashes.

For the two-lane highways, however, the centerline buffer area can be used to help reduce the number of opposite direction crashes. As the centerline buffer width increases, the percentage of opposite direction crashes also decreases (see Figure 9).

General Observations
As shown in Figure 9, the number of opposite direction crashes decreases as the centerline buffer area width increases. As an example, the CMF for a 2 ft wide buffer is approximately 0.65 (or a 35 percent reduction in opposite direction crashes). Similarly, a buffer median width of 10 ft is equivalent to a CMF value of 0.1 (or a 90 percent reduction).

WHERE (Application Issues)

Design

The construction of centerline buffer areas can be accommodated at locations where pavement widths are wide enough to accommodate the narrow buffer strip without otherwise compromising traffic operations. To accomplish this, the road should consist of paved shoulders, lanes widths that are (ideally) 12 ft in width, and a narrow buffer area. Construction of the centerline buffer area may occur as part of a widening or resurfacing project. If significant widening is required, the cost of implementing this treatment is likely to increase significantly.

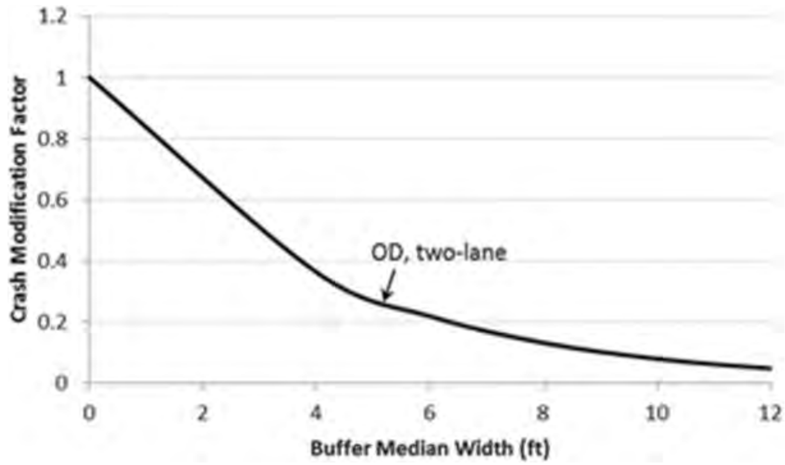


Figure 9. Centerline buffer area CMF for opposite direction crashes (2-lane rural).

Operations

The construction of a centerline buffer area can potentially result in an increase in vehicle speeds by shifting the lateral position of opposing vehicles. This operational effect may occur during daytime or nighttime conditions. The increase in vehicle speeds, however, can be associated with an increase in SVROR crashes, though this increase does not appear to be statistically significant.

Widen Median

Treatment/Countermeasure: Widen Median
Project Type/Cost: Low > Moderate > **High**
Crash Type: Median crashes (head-on, opposite direction sideswipe)
Facility Type/Characteristics: Divided highway

WHAT (Introduction)

Divided highways, by definition, include medians to physically separate opposing directions of traffic. Medians can take multiple forms, but generally fall into one of three categories: raised (e.g., curbed median island), depressed (e.g., grass/turf median with drainage), or flush (e.g., pavement markings only) (Figure 10). When the required ROW is available, widening a median increases the distance between opposing directions of traffic. This increased median width can reduce the likelihood of opposite direction crashes.

WHY (Safety State of the Practice)

Studies on the effect of median width have shown that increasing width reduces cross-median crashes, but the amount of reduction varies across studies. Key findings are summarized in Table 12. Study sites are separated into full access control at urban and rural locations.

The preferred method for studying crash effects and developing crash modification factors is to conduct a before–after study in which the treatment date is known, and the changes in

(Photograph by Texas A&M Transportation Institute)

Figure 10. Wide median treatment.

Table 12. Studies that evaluated wider medians at access controlled segments.

Study Location(s)	Year	Road Type	Change in Median Width: From (ft)	Change in Median Width: To (ft)	Percent Reduction in Crashes (%) – Crash Severity: All (KABCO)	Crash Severity: All (KABC)	Cross-Median Crash Type: 4-lane (KABCO)	Cross-Median Crash Type: ≥ 5-lane (KABCO)	Source
Urban Locations – Full Access Control									
NR	2008	NR	10	20	NR	NR	11	11	(*23*)
				30			20	21	
				40			29	29	
				50			36	37	
				60			43	44	
				70			49	50	
				80			54	55	
				90			59	60	
				100			64	65	
FL	2016	Arterial	NA	NA	*a* = -0.0048*	*a* = -0.0051*	NR	NR	(*24*)
			10	20	5	5			
				30	9	10			
				40	13	14			
				50	17	18			
				60	21	23			
Rural Locations – Full Access Control									
NR	2008	NR	10	20	NR	NR	14	NR	(*23*)
				30			26		
				40			37		
				50			46		
				60			54		
				70			60		
				80			66		
				90			71		
				100			75		
CA, NC, OH, PA, WA	2014	Freeway	NR	+1 ft	NR	NR	2	2	(*25*)

NR – not reported
*Values represent the "a" coefficients in the following equation:

$$CRF = 100(1- e^{[a \times (MW - \text{Base Width})]})$$

Where: MW = Proposed median width; Base Width = Existing median width.
Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse.

crashes before and after this date can be tracked; however, widening a median is a treatment that is not always "installed" in a manner that allows for a before–after study. It is unlikely that the median width on a highway will ever be changed without making other significant changes to the geometric cross section (*23*). In this case, the fact that there is a significant change other than the change in median width makes it more difficult to isolate the effects of the change in width in a before–after evaluation.

General Observations
Users can expect to see a reduction in cross-median crashes of 11 percent or more (CMF = 0.89 or lower). As median width increases, total crashes are associated with a reduction of at least 4 percent in total crashes, at least 3 percent in fatal and major injury crashes, and at least 2 percent in all other types of injury crashes. It should be noted that the studies listed in Table 12 generally found that wider medians led to fewer crashes, but there was a decreasing effect with incremental increases in median width; that is, widening a median from 10 ft to 30 ft typically had more of an effect than further widening a 30 ft median to 40 ft.

WHERE (Application Issues)

Design

Widening a median requires sufficient ROW to accommodate the wider cross section of the highway, unless travel lanes are removed as part of the redesign of the highway. Median widening can occur in conjunction with adding travel lanes in one or both directions. In addition to the construction cost of the highway, acquisition of ROW is typically a substantial cost in such projects. Environmental concerns (e.g., drainage, wildlife migration, etc.) may also present themselves during the design process.

Operations

Locations with wider medians may experience increased vehicle speeds. At nighttime, the additional lateral separation may reduce headlight glare from approaching vehicles.

Install Alternating/Periodic Passing Lanes

Treatment/Countermeasure: Install Alternating/Periodic Passing Lanes	
Project Type/Cost:	Low → Moderate → **High**
Crash Type: Segment-only crashes (head-on, opposite direction sideswipe, same direction sideswipe)	
Facility Type/Characteristics: Two-lane undivided highway	

WHAT (Introduction)

Periodic passing lanes are lanes added to one or both directions of a two-lane undivided highway to provide opportunities for passing of slower vehicles and the dispersal of traffic platoons (Figure 11). These passing lane configurations, also referred to as Super 2 corridors, can be implemented on existing two-lane roadways where there is a significant amount of slow-moving traffic, there is limited sight distance for passing, and/or the existing traffic volume has exceeded the two-lane highway capacity, creating the need for vehicles to pass on a more frequent basis. Passing lanes can help reduce crashes associated with passing on two-lane roads, such as head-on and sideswipe crashes.

(Photograph by Texas A&M Transportation Institute)

Figure 11. Alternating passing lanes.

WHY (Safety State of the Practice)

Several studies documented reductions in crashes with the installation of passing lanes on two-lane highways. Key findings are summarized in Table 13. Information specific to the opposite direction crash types, however, is not explicitly available.

General Observations
Users can expect to see a reduction ranging from 33 up to 42 percent (CMF = 0.58 to CMF = 0.67) in total crashes and a reduction of 29 to 42 percent (CMF = 0.58 to CMF = 0.71) in fatal and injury crashes. A 35 percent reduction in segment-only crashes can be expected. This is equivalent to a CMF equal to 0.65.

WHERE (Application Issues)

Design

The designer should consider the existing width of ROW, terrain, and structures to evaluate the feasibility of a Super 2 corridor and determine the best locations to install passing lanes with a minimum of ROW requirements, grading, and structure widening. It is preferable to avoid locating high-traffic intersections and driveways within the boundaries of a passing lane. Where passing lanes are terminated, the designer should confirm that the sight distance is suitable and that any conflicts with oncoming traffic can be avoided. The design should also accommodate constraints such as guard rail, guard fences, or narrow bridges (*29*).

Table 13. Summary of passing lanes studies for rural two-lane highways.

		Percent Reduction in Crashes (%)			
		Crash Type / Location	Crash Severity		
Study Location(s)	Year	Segment-Only Crashes (KABCO)	Total Crashes (KABCO)	Fatal and Injury Crashes (KABC)	Source
MI	2012	NR	33	29*	(*26*)
TX	2012	35	NR	42	(*27*)
WY	2016	NR	42	NR	(*28*)

NR – not reported
*Data set did not contain any fatal crashes.
Note: The project selection process included projects with three-star ratings or more at the CMF Clearinghouse.

Operations

Where terrain, available budget, and other considerations allow, the addition of another passing lane is preferred over adding length to an existing passing lane. Incremental benefits are minimal for passing lane lengths over two miles.

Install SafetyEdge℠ Treatment

Treatment/Countermeasure: Install SafetyEdge℠ treatment			
Project Type/Cost:	**Low**	Moderate	High
Crash Type: Head-on, opposite direction sideswipe, and SVROR			
Facility Type/Characteristics: Two-lane highways, multilane highways, and freeways			

WHAT (Introduction)

SafetyEdge℠ is a pavement edge treatment designed to mitigate roadway departure crashes (Figure 12). Rather than a vertical face with a potentially steep drop-off, the SafetyEdge℠ treatment shapes the edge of the pavement to a 30-degree slope, providing a surface more conducive to drivers correcting their paths and re-entering the roadway safely. The treatment involves the use of a specially designed but commercially available "shoe" device attached to the paver. Asphalt is extruded under the shoe, resulting in an edge with the desired shape that also provides more durability to resist raveling. Designed primarily to prevent roadway departure overcorrection crashes on roadways with asphalt surfaces, the SafetyEdge℠ may be installed on any paved road. The SafetyEdge℠ can be installed on all road types including two-lane highways, multilane highways, and freeways. For divided highways, a SafetyEdge℠ can be installed on the right (outside) shoulder and the left (median) shoulder to facilitate a vehicle's return to the travel lanes.

WHY (Safety State of the Practice)

SafetyEdge℠ treatments have been studied in a variety of settings. Several pilot projects focused on lessons learned from the installation procedure, but more recent studies have also focused on safety performance. Common target crashes include opposite direction crashes; however, in some studies this specific crash type is included in the total crash or ROR category. Key findings for several of these studies are summarized in Table 14.

General Observations
Users can expect to see reductions of approximately 19 percent (CMF = 0.81) for total head-on and sideswipe crashes. Fatal and injury crash reductions range from 6 to 16 percent (CMF = 0.84 to 0.94) following the installation of a SafetyEdge℠ treatment at rural two-lane highways. This is equivalent to an average crash reduction of 11 percent (CMF = 0.89).

WHERE (Application Issues)

Design

Ideally, the pavement edge should be thick enough so that there is adequate pavement depth to form the angled surface unique to the SafetyEdge℠ treatment. As with conventional paving, the graded material adjacent to the SafetyEdge℠ should be brought flush with the top of the pavement following paving, and this activity should be scheduled as part of a regular maintenance effort. The SafetyEdge℠ concept is that when drop-offs recur, they will not be vertical,

(Photograph provided by Texas A&M Transportation Institute)

Figure 12. SafetyEdge^{SM} prior to grading the earthen shoulder.

Table 14. Summary of SafetyEdge[SM] studies for two-lane segments.

Study Location(s)	Year	Percent Reduction in Crashes (%)					Source
		Crash Type			Crash Severity		
		All Crash Types (KABCO)	ROR Crashes (KABCO)	Head-On and Sideswipe (KABCO)	All Crash Types (KABC)	ROR Crashes (KABC)	
GA, IN	2011	9	14	NR	17	23	*(30)*
GA, IN*	2011	7	5	NR	6	20	*(30)*
IA	2017	13**	12	NR	16**	8	*(31)*
KS	2017	NR	NR	NR	NR	35	*(31)*
FL, IA, NC, OH, PA	2017	1	21	19	11	NR	*(31)*

NR - represents crash reductions that were not reported or did not meet the three-star filter criteria.
* Values based on unpaved shoulder locations only. Unless otherwise indicated, the study assessed paved shoulder locations.
** Iowa crash types were defined as non-intersection crashes only.
Note: The selection process included studies with three-star ratings or more at the CMF Clearinghouse.
For multistate studies, the selected values extend across more than one state and typically have larger sample sizes.

and the pavement edge will retain a shape that will not induce tire scrubbing. The SafetyEdge[SM] is often included as part of projects to rebuild or rehabilitate existing paved shoulders in need of maintenance, but this treatment can also be used at locations where there is currently little or no paved shoulder width and the responsible agency plans to pave or overlay the road.

Operations

SafetyEdge[SM] is particularly applicable for roadways during resurfacing, even if they have been resurfaced multiple times and have uneven edges of pavement. This treatment enables drivers traveling at highway speeds to more easily return to the travel lane after one or more tires drop off the paved surface.

Pave or Widen Shoulders

Treatment/Countermeasure: Pave or Widen Shoulder	
Project Type/Cost:	Low / Moderate / **High**
Crash Type: Head-on, opposite direction sideswipe, SVROR	
Facility Type/Characteristics: Two-lane highways, multilane highways, and freeways	

WHAT (Introduction)

Shoulders provide a place where a driver can intentionally steer the vehicle off the travel lanes for a variety of reasons (e.g., maintenance or refuge of a disabled vehicle, use of a personal communications device, rest for a fatigued driver, etc.). Shoulders also provide a place for drivers who unintentionally leave the travel lanes to correct their travel path and safely return to the road. Shoulder paving is recognized (*32*) as a positive countermeasure to reduce a shoulder drop-off hazard that will help stray vehicles resume normal travel, accommodate stopped vehicles to avoid encroachment of the travel way, provide access to emergency vehicles, protect pavement structural integrity, and facilitate highway maintenance work (Figure 13).

WHY (Safety State of the Practice)

Studies on shoulder width and shoulder paving have shown there are benefits to having a nominal paved shoulder width, though that benefit could decrease as paved width increases beyond a certain value. Key findings from selected studies are summarized in Table 15. Though the findings differ for facility type and location, widening narrow shoulders to provide additional recovery space for an errant vehicle can help to reduce the number of crashes.

General Observations
Based on previous studies, widening existing shoulders produces incremental benefits, though that incremental benefit may decline for very wide shoulder widths.

WHERE (Application Issues)

Design

Paving an existing width of unpaved shoulder typically does not have a large design impact, other than ensuring appropriate drainage and accounting for adjacent roadside appurtenances or objects (e.g., culverts, guardrails, etc.). Appropriate cross-slope transitions need to be maintained for drainage without causing a tripping or rollover hazard for vehicles using the shoulder. Adding width to an existing shoulder requires the necessary ROW be available, so acquisition costs could be a sizable portion of the economic component of these widening projects. Adding width may also require moving roadside objects or otherwise accommodating their presence (e.g., lengthening culverts, relocating guardrails, etc.). If extended shoulder paving along the entire length of the road segment is not feasible, select widening at locations with horizontal

(Photograph provided by Texas A&M Transportation Institute)

Figure 13. Shoulder pavement candidate.

Table 15. Summary of shoulder pavement studies.

Study & Location	Year	Before (ft)	After (ft)	Percent Reduction in Crashes (%) Total Crashes (KABCO)	Percent Reduction in Crashes (%) Injury Crashes (KABC)	Source
Urban – Divided Median – widen inside paved shoulders for principal arterials, other freeways and expressways at interchange influence areas (8′ outside paved shoulder)						
FL	2012	4	6	24	NR	(*32*)
			8	36		
			10	22		
			12	-4		
Urban – Divided Median – widen inside paved shoulders for principal arterials, other freeways and expressways at interchange influence areas (10′ outside paved shoulder)						
FL	2012	4	5	43	NR	(*32*)
			6	44	53	
			8	-22	22	
			10	2	34	
			11	-29	-17	
			12	5	1	
Rural Two-Lane Roads – opposite direction crashes (including SVROR)						
TX	2019	1 to < 4	≥ 4	10	50	(*13, 33*)
Rural Two-Lane Roads – previously unpaved shoulders – opposite direction crashes						
TX	2019	0	2 to 3	28	64	(*13, 33*)
		0	≥ 4	-1	36	

NR – not reported
Note: For 2012, the Florida study (*32*) included studies that received a three-star rating or more at the CMF Clearinghouse. The NCHRP Project 17-66 team developed the other 2019 value as part of that project. The CMF currently does not have a star rating assignment.

curvature may be more cost effective since vehicles are more likely to off-track at curved locations.

Operations

Although the original intention of shoulder paving is to enhance highway safety, wider widths of paved shoulders are likely to be associated with higher speeds of travel. As such, the net safety effect of shoulder paving is a combination of several possibly confounding effects: the benefits of allowing for the safe recovery of stray vehicles, and the detrimental tendencies of inviting voluntary shoulder stops, faster travel, and occasional shoulder use for travel (*32*).

CHAPTER 5

Reducing Severity of Crash

This chapter covers the cable median barrier countermeasure that may prevent opposite direction crashes as well as a broader range of crash types. Table 16 summarizes this cable median barrier countermeasure. This treatment focuses on restricting the vehicle's path so that a vehicle can have an opportunity to safely redirect and enter the road or impact a more forgiving object in exchange for the more hazardous crash. The cost of this type of treatment also varies more than those in Chapter 3 and Chapter 4, as some locations will require very minor adjustments while others often require the purchase of additional ROW or the construction of additional infrastructure. There may also be significant added expense associated with ongoing maintenance activities such as that required for the cable median barrier.

Table 16. Countermeasure to reduce severity of crash.

Countermeasure	Project Cost	Crash Type	Facility Type
Install cable median barrier*	Moderate	Head-on and opposite direction sideswipe (in median)	Divided highway

* Though other barriers such as rigid concrete barrier or guardrail may be considered, the cable median barrier is a unique treatment specifically targeted toward opposite direction crashes in or adjacent to a roadway median.

Install Cable Median Barrier

Treatment/Countermeasure: Install Cable Median Barrier			
Project Type/Cost:	Low	**Moderate**	High
Crash Type: Median crashes (head-on or opposite direction sideswipe)			
Facility Type/Characteristics: Divided highway			

WHAT (Introduction)

A cable median barrier is a longitudinal barrier used to contain or redirect errant vehicles that leave the roadway by keeping them from encountering terrain features and roadside objects or permitting vehicles to enter opposing travel lanes (Figure 14). The most typical cable median barrier is a three-strand steel cable barrier system connected to a series of posts (*34*).

(Photograph provided by Texas A&M Transportation Institute)

Figure 14. Cable median barrier.

WHY (Safety State of the Practice)

Cable barrier absorbs more of the energy in the crash than semi-rigid or rigid barrier, and therefore is more likely to result in a less severe crash. Several studies have documented cable median barriers applied at multiple locations with an emphasis on their potential to reduce cross-median crashes. Table 17 summarizes key findings from related studies.

General Observations
Based on previous studies, users can expect to see a reduction in cross-median crashes as well as opposing direction crashes of approximately 91 to 96 percent for principal arterial interstates in rural regions. Reductions of 62 to 65 percent can be expected for interstate and freeway cross-median crashes. Iowa noted a 62 percent reduction in fatal crashes while Utah observed a 44 percent reduction in fatal plus incapacitating injury crashes. It should be noted that PDO crashes may increase following an installation of cable median barriers, because vehicles that previously could have recovered in the median undamaged now strike the cable barrier, resulting in damage to the vehicle and the cable barrier. This potential increase in PDO crashes is often more than offset by the reduction in severe crashes.

WHERE (Application Issues)

Design

The designer should consider the width and slope of the median when installing cable median barriers. Missouri Department of Transportation's (DOT's) *Engineering Policy Guide* for their cable median barrier program (*39*) recommends that for medians at least 30 ft wide, the cable barrier should be installed 4 ft down-slope of the edge of the shoulder. For medians narrower than 30 ft, the cable barrier should be installed per the graphs in *NCHRP Report 711* (*40*). Care should also be taken when installing cable barrier at horizontal or vertical curve locations, and

Table 17. Summary of cable median barrier studies.

Study Location(s)	Year	Median Width (ft)	Area Type	Percent Reduction in Crashes (%) CM+ (KABCO)	Cross-Median Crashes (KABCO)	Cross-Median Crashes (K)	Cross-Median Crashes (KA)	Source
Principal Arterial Interstate								
IN	2009	30-50	Rural	91	NR	NR	NR	(*35*)
IN	2009	>50	Rural	96	NR	NR	NR	(*35*)
UT	2011	NR	All	NR	62	NR	44	(*36*)
IA	2018	NR	NR	NR	NR	62	NR	(*37*)
Principal Arterial Other Freeways and Expressways								
WA	2013	NR	NR	NR	65	NR	NR	(*38*)

NR – not reported
CM+ refers to cross-median crashes plus frontal and opposing direction sideswipe and head-on
Note: The selection process included studies with three-star ratings or more at the CMF Clearinghouse.

cable barriers should be installed as far away from the traveled way as possible while maintaining the proper orientation and performance of the system.

Missouri DOT (*39*) also recommends that new cable median barrier be installed on a corridor-wide basis. A corridor should have similar geometry, traffic volumes, and crash histories. The placement of cable median barrier on this corridor should also be configured with a logical termini location. Intermittent, short length cable median barrier should be used sparingly.

Operations

A potential concern commonly noted in the literature is whether cable median barriers pose additional risk to motorcyclists, though research has generally shown that cable barriers are not much different from other types of barriers in their effects on motorcyclists who strike them. Both the Missouri DOT and the Cooner et al. (*41*) guidelines provide recommendations for accommodation of emergency responders. Cooner et al. recommend that the maximum distance between breaks in the cable barrier system that allow emergency vehicle access should be 3 miles, and emergency response agencies should have educational materials to provide them with clear and concise guidance on when and how to safely cut the cable when a vehicle is entangled after an impact. Missouri DOT (*39*) indicates that emergency crossovers for freeways should be spaced approximately 2.5 miles apart; additional crossovers near sparsely spaced interchanges may be required to facilitate snow removal.

References

1. FHWA. *Quick Start Guide to Using CMFs*. FHWA Report FHWA-SA-17-007. Available at http://www.cmfclearinghouse.org/collateral/fhwasa17007.pdf. Accessed August 17, 2017.
2. Persaud, B.N., R.A. Retting, and C. Lyon. *Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads*. Insurance Institute for Highway Safety, Arlington, Virginia, September 2003.
3. Torbic, D. J., J. M. Hutton, C. D. Bokenkroger, K. M. Bauer, D. W. Harwood, D. K. Gilmore, D. K. Dunn, J. J. Ronchetto, E.T. Donnell, H. J. Sommer III, P. Garvey, B. Persaud, and C. Lyon. *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*. Transportation Research Board of the National Academies, Washington, D.C., 2009, 181pp.
4. Sayed, T., P. deLeur, and J. Pump. Impact of Rumble Strips on Collision Reduction on British Columbia, Canada Highways: Comprehensive Before-and-After Safety Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2148, 2010, pp. 9–15.
5. Rys, M., D. Karkle, and E. Russell. *Study of KDOT Policy on Lane and Shoulder Minimum Width for Application of Centerline Rumble Strips*. Report No. K-TRAN:KSU-10-7. Kansas Department of Transportation. Topeka, Kansas, 2012.
6. Himes, S., H. McGee, S. Levin, and Y. Zhou. *State of the Practice for Shoulder and Center Line Rumble Strips Implementation on Non-Freeway Facilities*. Report No. FHWA-HRT-17-026. Federal Highway Administration Office of Safety. Washington, D.C., March 2017.
7. Griffith, M.S. Safety Evaluation of Rolled-in Continuous Shoulder Rumble Strips Installed on Freeways. *Transportation Research Record: Journal of the Transportation Research Board, No. 1665*, 1999.
8. Coulter, Z.C., and K. Ksaibati. *Effectiveness of Various Safety Improvements in Reducing Crashes on Wyoming Roadways*. Report No. MPC 13-262, Mountain Plains Consortium. Fargo, North Dakota, 2013.
9. Carrasco, O., J. McFadden, P. Chandhok, and R. Patel. "Evaluation of the Effectiveness of Shoulder Rumble Strips on Rural Multilane Divided Highways in Minnesota." Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., January 2004.
10. 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.
11. Federal Highway Administration. *Manual on Uniform Traffic Control Devices, 2009 Edition*. FHWA, Washington, D.C., 2009.
12. Park, E.S., P.J. Carlson, R.J. Porter, and C.K. Anderson. Safety Effects of Wider Edge Lines on Rural, Two-Lane Highways. *Accident Analysis and Prevention*, Vol. 48, 2012, pp. 317–325.
13. Dixon, K.K., S. Geedipally, E.S. Park, R. Srinivasan, B. Lan, M. Brewer, S. Das, L. Wu, C.V. Zegeer, and E. Rista. *NCHRP Project 17-66 Final Report: Guidance for Selection of Appropriate Countermeasures for Opposite Direction Crashes*. Transportation Research Board of the National Academies, Washington, D.C., 2020.
14. Srinivasan, R., J. Baek, D. Carter, B. Persaud, C. Lyon, K. Eccles, F. Gross, and N. Lefler. *Safety Evaluation of Improved Curve Delineation*. Report No. FHWA-HRT-09-045, Federal Highway Administration, Washington, D.C., 2009.
15. FHWA. Pavement Friction Fact Sheet. Available at https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/pavement_friction.pdf. Accessed August 15, 2017.
16. Lyon, C., and B. Persaud. Safety effects of a targeted skid resistance improvement program. *Transportation Research Record: Journal of the Transportation Research Board, No. 2068*, 2008, pp. 135–140.
17. Oh, S., D.R. Ragland, and C.Y. Chan. "Safety performance of experimental pavement types in California using before-and-after comparisons." TRB 89th Annual Meeting CD-ROM, Paper 10-2876, Transportation Research Board of the National Academies, Washington, D.C., 2010.

18. Pratt, M.P., S.R. Geedipally, A.M. Pike, P.J. Carlson, A.M. Celoza, and D. Lord. *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves.* Report No. FHWA/TX-14/0-6714-1. Texas Department of Transportation. Austin, Texas. May 2014.
19. Merritt, D.K., C.A. Lyon, and B.N. Persaud. *Evaluation of Pavement Safety Performance,* Report No. FHWA-HRT-14-065, Federal Highway Administration, Washington, D.C., 2015.
20. Donnell, E.T., R.J. Porter, and V.N. Shankar. *A Framework for Estimating the Safety Effects of Roadway Lighting at Intersections.* Safety Science, Vol. 48(10), pp. 1436–1444, 2010.
21. Abdel-Aty, M.A., C. Lee, J. Park, J. Wang, M. Abuzwidah, and S. Al-Arifi. *Validation and Application of Highway Safety Manual (Part D) in Florida.* Florida Department of Transportation. Tallahassee, Florida, May 2014.
22. Lutkevich, P., D. McLean, and J. Cheung. *FHWA Lighting Handbook*. Office of Safety, Federal Highway Administration, Washington, D.C., August 2012.
23. Hadi, M.A., J. Aruldhas, L. Chow, and J. Wattleworth. Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression. *Transportation Research Record, No. 1500*, 1995, pp. 169–177.
24. Park, J., and M. Abdel-Aty. Evaluation of Safety Effectiveness of Multiple Cross Sectional Features on Urban Arterials. *Accident Analysis and Prevention*, Vol. 92, pp. 245–255, 2016.
25. Graham, J., D. Harwood, K. Richard, M. O'Laughlin, E. Donnell, and S. Brennan. *NCHRP Report 794: Median Cross-Section Design for Rural Divided Highways*. Transportation Research Board of the National Academies, Washington, D.C., 2014.
26. Bagdade, J., A. Ceifetz, M. Myers, C. Redinger, B.N. Persaud, and C.A. Lyon. *Evaluating Performance and Making Best Use of Passing Relief Lanes*. Report No. RC-1565, Michigan Department of Transportation, December 2012.
27. Park, B., K. Fitzpatrick, and M. Brewer. Safety Effectiveness of Super 2 Highways in Texas. *Transportation Research Record: Journal of the Transportation Research Board, No. 2280,* 2012, pp. 38–50.
28. Schumaker, L., M.M. Ahmed, and K. Ksaibati. Policy Considerations for Evaluating the Safety Effectiveness of Passing Lanes on Rural Two-Lane Highways with Lower Traffic Volumes: Wyoming 59 Case Study. *Journal of Transportation Safety & Security*, 2016.
29. Brewer, M.A., S.P. Venglar, L. Ding, K. Fitzpatrick, and B. Park, *Operations and Safety of Super 2 Corridors with Higher Volumes.* Report No. FHWA/TX-11/0-6135-1, Texas Department of Transportation, Austin, Texas, 2011.
30. Graham, J.L., K.R. Richard, M.K. O'Laughlin, and D.W. Harwood. *Safety Evaluation of the SafetyEdge Treatment.* Report No. FHWA-HRT-11-024, Office of Safety Research and Development, Federal Highway Administration. McLean, Virginia, 2011.
31. Federal Highway Administration. *Safety Effects of the SafetyEdge^{SM}. Technical Summary of Crash Modification Factors.* Report No. FHWA-HRT-17-044, Office of Safety, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2017. Document available at: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/pdf/safety_edge_techbrief.pdf. Accessed on July 16, 2017.
32. Li, Z., K. Kepaptsoglou, Y. Lee, H. Patel, Y. Liu, and H.G. Kim. Safety Effects of Shoulder Paving for Rural and Urban Interstate, Multilane, and Two-Lane Highways. *Journal of Transportation Engineering*, Vol. 139, No. 10. American Society of Civil Engineers, Washington, D.C., 2013, pp. 1010–1019.
33. Fitzpatrick, K., W.H. Schneider, and E.S. Park. *Comparisons of Crashes on Rural Two-Lane and Four-Lane Highways in Texas.* Report No. FHWA/TX-06/0-4618-1. Texas Department of Transportation, Austin, Texas, 2005.
34. Coulter, Z.C., and K. Ksaibati. *Effectiveness of Various Safety Improvements in Reducing Crashes on Wyoming Roadways.* Report No. MPC 13-262, Mountain Plains Consortium. Fargo, North Dakota, 2013.
35. Villwock, N.M., N. Blond, and A.P. Tarko. Safety Impact of Cable Barriers on Rural Interstates. TRB 88th Annual Meeting Compendium of Papers CD-ROM, Washington, D.C., 2009.
36. Olsen, A.N., G.G. Schultz, D.J. Thurgood, and C.S. Reese. Hierarchical Bayesian Modeling for Before and After Studies. TRB 90th Annual Meeting Compendium of Papers DVD, Washington, D.C., 2011.
37. Savolainen, P.T., T.J. Kirsch, R. Hamzeie, M.U.M. Johari, and E. Nightingale. *In-Service Performance Evaluation of Median Cable Barriers in Iowa.* InTrans Project 15-546. Iowa Department of Transportation, Ames, Iowa, May 2018.
38. Olson, D., M. Sujka, and B. Manchas. *Cable Median Barrier Program in Washington State.* Report No. WA-RD 812.1. Olympia, WA, June 2013.
39. Missouri Department of Transportation. *A Comprehensive Analysis of and Direction for MoDOT's Cable Median Barrier Program*. MoDOT. Jefferson City, Missouri, July 31, 2007.
40. Marzougui, D., U. Mahadevaiah, F. Tahan, C.D. Kan, R. McGinnis, and R. Powers. *NCHRP Report 711: Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems.* Transportation Research Board of the National Academies, Washington, D.C., 2012.
41. Cooner, S.A., Y.K. Rathod, D.C. Alberson, R.P. Bligh, S.E. Ranft, and D. Sun. *Development of Guidelines for Cable Median Barrier Systems in Texas*. Report No. FHWA/TX-10/0-5609-2. Texas Department of Transportation, Austin, Texas, 2009.

Abbreviations and Acronyms

CMF	Crash modification factor
DOT	Department of Transportation
HFST	High friction surface treatment
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
OD	Opposite direction (crashes)
PDO	Property damage only
ROR	Run-off-road
ROW	Right-of-way
SVROR	Single-vehicle run-off-road

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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