Low-Cost Treatments for Horizontal Curve Safety

Course No: C08-020
Credit: 8 PDH

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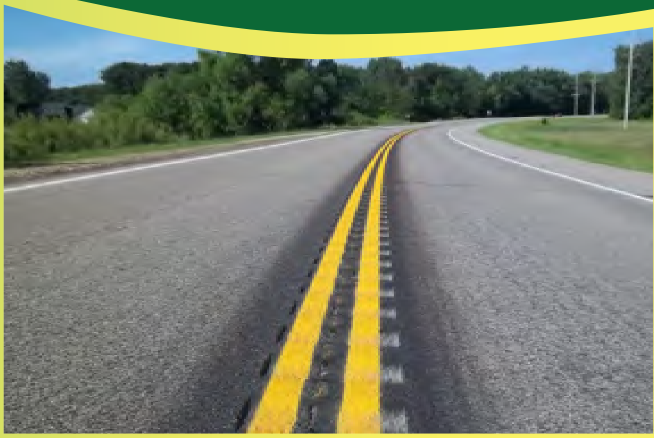

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Federal Highway Administration

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Quality Assurance Statement

TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-SA-15-084	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Low-Cost Treatments for Horizontal Curve Safety 2016		5. Report Date January 2016 6. Performing Organization Code
7.Author(s) Richard Albin, Victoria Brinkly, Joseph Cheung, Frank Julian, Cathy Satterfield, William Stein, Eric Donnell, Hugh McGee, Ann Holzem, Matthew Albee, Jonathan Wood, Fred Hanscom		8. Performing Organization Report No.
9. Performing Organization Name and Address Pennsylvania Transportation Institute Pennsylvania State University 201 Transportation Research Building University Park, PA 16802 Vanasse Hangen Brustlin, Inc (VHB) 8300 Boone Blvd., Suite 700 Vienna, VA 22182-2626		10. Work Unit No. 11. Contract or Grant No. DTFH61-12-C-00032
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Safety 1200 New Jersey Ave., SE Washington, DC 20590		13. Type of Report and Period Final Report, April 2014 – January 2016 14. Sponsoring Agency Code FHWA
15. Supplementary Notes The contract manager for this report was Joseph Cheung.		

16. Abstract

FHWA created the Low-Cost Treatments for Horizontal Curve Safety in 2006 (McGee and Hanscom, 2006). There have been many advances in highway safety since that initial 2006 guide. The purpose of this publication is to serve as an update to the 2006 Low-Cost Treatments for Horizontal Curve Safety. The primary audience for this publication is local transportation agencies. This publication provides information specifically relating to lower volume two-lane roads and the agencies that manage them. It will help transportation agencies and their construction crews understand the available countermeasures and how to select and apply them.

17. Key Words: horizontal curves, systemic approach, low-cost countermeasures, two-lane roads	18. Distribution Statement No restrictions.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 94	22. Price

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

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ACRONYMS

AADT	Average Annual Daily Traffic
ADT	Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
Caltrans	California Department of Transportation
CMF	Crash Modification Factor
DOT	Department of Transportation
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
HFST	High Friction Surface Treatment
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
ICWS	Intersection Conflict Warning System
IDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
ITE	Institute of Transportation Engineers
KYTC	Kentucky Transportation Cabinet
LED	Light-Emitting Diode
LON	Length of Need
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program

NHTSA	National Highway Traffic Safety Administration
NJDOT	New Jersey Department of Transportation
NYSDOT	New York State Department of Transportation
PC	Point of Curvature
PDO	Property Damage Only
PennDOT	Pennsylvania Department of Transportation
ROR	Run-Off-Road
RPM	Raised Pavement Marker
RSA	Road Safety Audit
SEAHC	Surface Enhancements at Horizontal Curves
SSP	Safety Strateg Planic
SV	Superelevation Variance
usRAP	United States Road Assessment Program

CHAPTER 1. INTRODUCTION

SAFETY PROBLEMS AT HORIZONTAL CURVES

In 2013, there were 5.7 million crashes reported in the United States, including 32,719 fatalities and more than 2.3 million injuries (*NHTSA*, 2014). More than half of the 2013 fatalities occurred as a result of roadway departure crashes. Vehicles are more likely to leave the travel lane of a roadway where the roadway alignment changes direction. These locations are known as horizontal curves.

A comprehensive, four-state study by Glennon et al. (1985) found that the average crash rate for horizontal curves on two-lane rural highways is three times higher than on tangent road segments. The authors also found that the average single-vehicle run-off-road crash rate was four times higher on horizontal curves than on tangent segments. The severity of roadway departure crashes on horizontal curves was also higher than roadway departure crashes on tangent segments. A more recent study by Hummer et al. (2010) found similar results. An analysis of North Carolina crash data found that curve collisions have more than three times the fatality rate of collisions on all roads statewide. One study on different combinations of horizontal and vertical curve alignments found that crash frequency increases with decreasing horizontal curve radius, decreasing horizontal curve length, increasing grade difference, and increasing percent grade (Bauer and Harwood, 2014).

A Guide for Reducing Collisions on Horizontal Curves (*NCHRP Report 500*, Volume 7) further illustrates the problem. The *NCHRP Report 500*, Volume 7, reports that nearly 25 percent of people who die each year on the Nation's roadways are killed in vehicle crashes at curves. About 75 percent of all fatal crashes occur in rural areas, and more than 70 percent are on two-lane secondary highways, many of which are local roads. Approximately 76 percent of the curve-related fatal crashes involve single vehicles leaving the roadway and striking trees, utility poles, rocks, or other fixed objects or overturning. Another 11 percent are head-on crashes, the result of one vehicle drifting into the opposing lane when a driver tries to cut the curve or redirect the vehicle after having run onto the shoulder.

In 2012, a team comprised of the Federal Highway Administration (FHWA) Office of Safety, Office of Safety Research and Development, and Resource Center Safety and Design Technical Services developed *Safe Roads for a Safer Future – A Joint Safety Strategic Plan (SSP).* The vision presented in the SSP works "toward zero deaths and serious injuries on the Nation's roadways." This publication provides agencies with information to help them deploy the appropriate countermeasures on horizontal curves in support of this vision.

PUBLICATION PURPOSE AND SCOPE

The *NCHRP Report 500*, Volume 7, identified several strategies to address the specific safety problem at horizontal curves. These strategies meet one of the following two objectives:

- Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway

centerline or leaving the roadway at a horizontal curve.
- Minimize the damaging consequences of a vehicle leaving the roadway at a horizontal curve.

Although the *NCHRP Report 500*, Volume 7, provides information about each strategy, transportation professionals indicated that a document providing practical information on where, when, and how to apply a safety countermeasure or design feature—including examples and costs—would be valuable to local road agencies. To respond to this need, the FHWA created the *Low-Cost Treatments for Horizontal Curve Safety* (McGee and Hanscom, 2006). There have been many advances in highway safety since that initial 2006 guide. The purpose of this publication is to serve as an update to the 2006 *Low-Cost Treatments for Horizontal Curve Safety*. The primary audience for this publication is local transportation agencies.

An agency can apply a number of strategies or countermeasures to a single horizontal curve or a winding road section to address a safety problem. This publication primarily includes those engineering countermeasures that are relatively low-cost, such as signage and pavement markings. More moderate or higher cost treatments including varying degrees of infrastructure changes are also provided as appropriate, including superelevation, cross section, and shoulder adjustments.

This publication presents summary information and is not meant to cover all aspects of an individual countermeasure in detail. Rather, this publication provides information specifically relating to lower volume two-lane roads and the agencies that manage them. It will help transportation agencies and their crews understand the available countermeasures and how to select and apply them. Where appropriate, and when information was available, this publication provides the following for each countermeasure:

- *Description*: General description of the countermeasure.
- *Design*: Identification of which design elements or materials to use.
- *Applications*: How to apply the countermeasure(s).
- *Effectiveness*: A countermeasure's effectiveness in improving safety.
- *Relative Cost*: Identification of the relative cost, such as low-cost (e.g. signs, pavement markings), moderate cost, or high cost (e.g., changes to infrastructure).

ABOUT THE *MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES (MUTCD)*

References to the FHWA's *Manual on Uniform Traffic Control Devices (MUTCD)* (FHWA, 2009) occur throughout this document (Figure 1). The *MUTCD* defines the standards for all traffic control devices that road managers install and maintain to help regulate, warn, and guide drivers safely on the Nation's roadways and streets, such as signs, signals, and pavement markings. All States are required to adopt either the Federal *MUTCD* (FHWA) or a State *MUTCD* that is in substantial conformance to the Federal *MUTCD*. Some States adopt the Federal *MUTCD* with a State Supplement. An agency should consult State laws regarding traffic control devices.

The *MUTCD* also defines conditions about what, where, and how to place or install a traffic control device. In different chapters of this publication you may see a countermeasure and the designation that the *MUTCD* states "shall be used." Shall means something is a standard—a practice or device that is specifically required or mandated—or, in the case of "shall not be used," explicitly prohibited. The *MUTCD* may designate other countermeasures as guidance, which indicates that a practice or device is recommended and should be used in typical situations, with modifications allowed for a specific location if an engineering study or engineering judgment indicates the deviation to be appropriate. Finally, the *MUTCD* provides for options, which are presented as "may" statements.

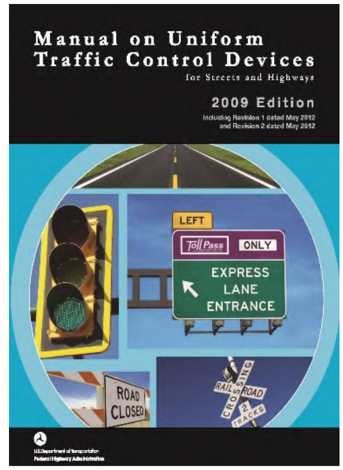


Figure 1. Photo. The MUTCD provides standards and guidance for installation, placement, and use of traffic control devices.

To learn more about the *MUTCD*, visit the *Manual on Uniform Traffic Control Devices*.

In addition to the traffic control devices required by the MUTCD (per "shall" statements), road agencies should consider installing other devices at horizontal curves, especially at curves that data or experience identify as having a safety problem.

Agencies generally apply traffic control devices uniformly based on the sharpness of the curve. This uniformity provides drivers with a consistent message on which to base their driving expectations. The *MUTCD* provides specific recommendations and requirements for uniform application of these devices. Agencies may apply treatments to a single, problematic curve that has a history of crashes, or they may also choose to install countermeasures at curves with similar characteristics across the roadway network. These system-wide, preventative measures are known as systemic improvements, and are discussed further in Chapter 2. Any additional use should be based on the information and recommendations contained in an engineering study or an engineer's judgment. Factors to consider include:

- The difference between the posted speed limit and advisory speed.
- Geometric features of the curve including its length, radius, shoulders, and roadside features.
- Available sight distance approaching and within the curve limits.
- Unexpected geometric features within the curve, such as an intersection, change in grade, change in curve radius, or visual cues that violate driver expectations.
- A sudden change in alignment after many miles of consistently straight roadway.
- Traffic volume.
- Risk characteristics including crash frequency and crash severity.

ABOUT THE *HIGHWAY SAFETY MANUAL* AND CMF CLEARINGHOUSE

Throughout this publication readers will also see reference to the American Association of State Highway and Transportation Officials' (AASHTO) *Highway Safety Manual* (*HSM*) (AASHTO, 2010) and the FHWA Crash Modification Factor (CMF) Clearinghouse. The *HSM* includes technical content related to road safety fundamentals, the road safety management process, and crash prediction methods for several roadway types. It also includes CMFs for many roadway geometric design elements and traffic control devices. When applicable, this publication uses safety effect estimates from the *HSM* when describing the benefits of a horizontal curve safety countermeasure.

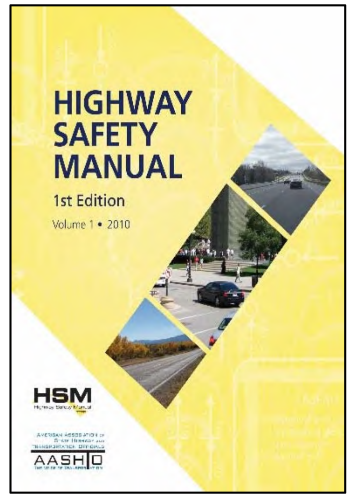


Figure 2. Photo. The Highway Safety Manual provides road safety fundamentals and management as well as crash prediction methods. Source: AASHTO.

The CMF Clearinghouse is the largest collection of CMFs for geometric design elements and traffic control devices available in the United States. The CMF Clearinghouse employs a "star rating" system to indicate the quality of the CMF based on factors such as the evaluation method, sample size, and standard error. The star rating system ranges from "1" (least reliable) to "5" (most reliable rating). This publication provides the star rating for each CMF discussed. Readers of this publication are encouraged to refer to the CMF Clearinghouse for specific horizontal curve safety issues not covered in this publication.

INFORMATION IN THIS PUBLICATION

The following considerations should be taken into account when reading and using the information contained in this publication:

- The publication includes estimates of the effectiveness of the countermeasure in reducing crashes where such evaluation information is available. However, agencies should not expect to obtain exactly these crash reduction values at a specific location, as the actual observed effectiveness of a countermeasure will vary from site to site.
- Some countermeasures included in this publication use supports or posts, such as signs, which make them an obstacle that could be hit. The *MUTCD* states that roadside sign supports in the clear zone shall be breakaway, yielding, or shielded with a longitudinal barrier or crash cushion. Information on breakaway sign supports and the definition of clear zone can be found at Breakaway Hardware.

PUBLICATION ORGANIZATION

The FHWA encourages readers to use the information presented in this publication to evaluate problems and identify appropriate countermeasures for problem curve sections. Applying these countermeasures will help agencies reduce roadway departure crashes and resulting injuries and fatalities.

The rest of this publication is organized into the following chapters:

CHAPTER 2. THE TWO COMPONENTS OF SAFETY IMPROVEMENT: SITE ANALYIS AND THE SYSTEMIC APPROACH

The most effective safety improvement process has two components:

1. **A site analysis component**. Data analysis is used to identify locations where a clear safety problem exists. Treatment of these locations may include higher-cost strategies. This can be thought of as the reactive component of a safety program.
2. **A systemic component.** Data analysis is used to identify risk factors associated with a particular type of severe crash and to identify locations at higher risk. Normally, lower-cost strategies are then deployed at a larger number of these high-risk locations. This can be thought of as the proactive component of a safety program.

Systemic Safety Improvement:
An improvement widely implemented based on high-risk roadway features that are correlated with high severity crash types.
—*Systemic Safety Project Selection Tool, FHWA*

The priority of a safety improvement program should be preventing fatal and serious injury crashes. In fact, the purpose of the Federal Highway Safety Improvement Program (HSIP) is stated in law as follows:

> *The purpose of the highway safety improvement program shall be to achieve a significant reduction in traffic* ***fatalities and serious injuries*** *on all public roads, including non-State-owned public roads and roads on tribal land.*

How a safety program and data analyses are focused—severe crashes versus total crashes—influences the degree to which a particular safety problem is addressed with the systemic approach versus the more traditional site analysis approach. With a program where all crashes are used as the performance measure, high crash locations will be more prevalent and treatment strategies will tilt more heavily toward addressing high crash locations. In contrast, a program that uses severe crashes as the performance measure will use a stronger systemic component as severe crash locations are not as concentrated.

This is particularly true for severe roadway departure crashes, which tend to be highly scattered across the rural and local roads system (see Figure 3). This does not mean that severe crashes are random. They tend to be overrepresented at locations with high risk characteristics, horizontal curvature being one of those.

A safety improvement process should include both components: treating high severe crash locations where they exist as well as systemically addressing locations or segments at higher risk. Both components will provide optimal results with good data and data analysis. FHWA's *Systemic Safety Project Selection Tool* (2013) provides analytical techniques for determining a reasonable balance between the implementation of spot safety improvements and systemic safety improvements.

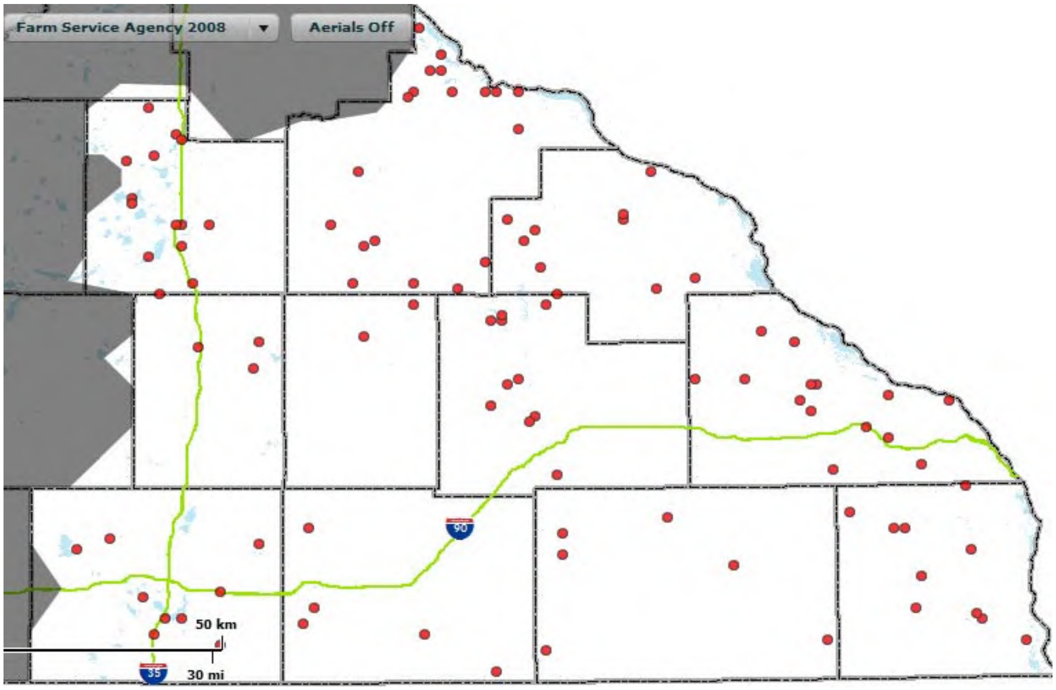


Figure 3. Map. Severe (K and A) roadway departure crashes at curves over a five year period in Minnesota's southeastern District. The wide dispersion of crashes indicates that a traditional site analysis/spot location approach will not sufficiently address this type of severe crash. Source: Minnesota Crash Mapping Analysis Tool, MnDOT.

ALL PUBLIC ROADS—ADDRESSING THE LOCAL SYSTEM

In addition to a focus on prevention of fatal and serious injury crashes, the most effective safety programs also consider all public roads, including those under local jurisdiction.

In most States, an examination of crash data demonstrates that focusing safety investment only on higher-level facilities such as the Interstate System and State highways will not sufficiently address the severe roadway departure crashes most prevalent on horizontal curves.

> **Importance of the local system:**
> From 2010–2012, approximately 39 percent of fatalities in the United States occurred on the local system of roads.
> —Fatality Analysis Reporting System

The Fatality Analysis Reporting System (FARS) is a national database of fatal highway crashes in the United States. FARS does not break down highway fatalities by State versus local jurisdiction, but the "Route Signing" field can provide a useful approximation of the magnitude of the fatal crash problem that occurs on the local system of roads. Using this method, FARS data suggests that from 2010–2012 approximately 39 percent of fatalities in the United States occurred on the local system. There were 39 States with 30 percent or higher fatalities on local roads and streets.

To most effectively improve safety at horizontal curves, it is important to analyze data on both the State and local systems. Spot locations where severe crashes are concentrated are even less common on the local system, and data analysis of the complete roadway network will add further support for including a strong systemic component.

The Pennsylvania Department of Transportation (PennDOT) experienced a higher percentage of fatal curve-related crashes on rural roads due to the predominance of horizontal curves. To combat this, PennDOT identified priority curves by examining crash frequency, crash rate, and crash severity. PennDOT then systemically implemented curve improvements, such as oversized fluorescent yellow advanced curve warning signs, advanced curve pavement markings, correction of any shoulder drop offs within the curve, chevron delineation, and curve widening. A three-year before/after analysis of locations where a combination of these countermeasures were implemented between 2000 and 2008 resulted in the following:

- 17-percent reduction in overall crashes.
- 44-percent reduction in fatal crashes.
- 40-percent reduction in major injury crashes.

See Appendix A for more information.

A CHANGE IN MINDSET

For some agencies, improving safety at spot locations on State highways has been the traditional approach, making up the bulk of safety improvement projects. Shifting to a systemic approach to prevent severe roadway departure crashes at curves along all public roads may require a change in mindset.

Determining answers to the following questions through data analysis is an effective first step in the process:

1. Are there a large number of severe (fatal and serious injury) crashes scattered widely across the system? If possible, plot them spatially as shown in Figure 3.
2. Are the types of safety improvement projects funded in relative alignment with the findings of question 1? If mostly high-cost projects at high-crash locations are being implemented, does this approach align with how severe crashes are located and dispersed?
3. What is the distribution of severe crashes on the State system as compared to local system? If there are severe crashes occurring on the local system, are safety funds made available to local agencies so that severe crashes are reduced on all public roads?

In 2010, the Minnesota Department of Transportation (MnDOT) began incorporating a systemic approach in all of Minnesota's counties after many years of exclusively using the traditional reactive approach to safety. MnDOT performed a network screening on their horizontal curves and found five risk-factors associated with high-crash curves. MnDOT addressed these curves with countermeasures such as center line rumble strips, advanced signing, 2-foot shoulder paving with Safety Edge^{SM} and edge line rumble strips, 6-inch edge line, and most commonly, chevrons. MnDOT has seen a drop in roadway departure crashes because of these efforts. See Appendix B for more information.

Figures 4 through 7 are examples of low-cost systemic treatments that can be applied to a large number of high-risk curve locations.

Figure 4. Photo. Delineation with chevrons. Source: MnDOT.

Figure 5. Photo. Centerline rumble strips.

Figure 6. Photo. Adding narrow paved shoulders (2 feet) to existing top width. Includes rumble strips and Safety Edge^{SM}. Source: MnDOT.

Figure 7. Photo. Delineation with enhanced (6-inch) edge lines.

ADDITIONAL RESOURCES

More information on the systemic approach to safety is available at the following resources:

- *A Systemic Approach to Safety – Using Risk to Drive Action*. FHWA Office of Safety website on the systemic approach.
- *The Systemic Safety Project Selection Tool.* FHWA guide that includes a step-by-step process for conducting systemic safety analysis; analytical techniques for determining a reasonable balance between the implementation of spot safety improvements and systemic safety improvements; and, a mechanism for quantifying the benefits of safety improvements implemented through a systemic approach.
- The United States Road Assessment Program (usRAP) is a validated system of protocols for rating roadway segments for safety. Using video logs coded in 100-meter segments, usRAP produces a proactive safety investment plan based on the observed design features of the road. usRAP's predictive modeling ensures that highway authorities can make data-driven safety management decisions—even before deaths and injuries occur, or in the absence of crash data. FHWA cites specific tools, such as usRAP, as an example of ways to implement safety analysis approaches, not as an endorsement of usRAP over others. The Roadway Safety Foundation is the primary supporter of usRAP. Contact the Roadway Safety Foundation at info@roadwaysafety.org.

CHAPTER 3. MARKINGS

Curve delineation can be critical for a driver to navigate roadways successfully. This is of particular importance for nighttime driving, when cues to changes in alignment (such as trees and guardrail) may not be readily visible. Pavement markings located within the driver's focus provide continuous information to help drivers position their vehicles in the roadway correctly. As such, pavement markings provide a good first option for horizontal curve countermeasures on paved roadways of sufficient width. Delineators—a retroreflective device mounted on a post or roadside barrier along the side of the roadway—also provide the driver with visual cues to the roadway alignment, although they are point sources and placed slightly outside the main focus area. Placing other markings (especially to reduce speeds) on the pavement in advance of the curve can also help drivers successfully negotiate curves.

The following discussion provides information on pavement marking countermeasures, marking material options, and maintenance and cost considerations. All example markings are from the *MUTCD* unless otherwise noted.

LONGITUDINAL PAVEMENT MARKINGS

Center lines and edge lines are the primary types of longitudinal pavement markings on two-lane roads. They delineate the travel lane for the driver, assist in lane placement to avoid collisions with other vehicles, and provide a preview of changing roadway alignment. Unless center lines and edge lines are required for the entire roadway, the *MUTCD* permits their use at specific locations, such as around a curve. However, since markings typically have a shorter life-span than many other devices, particularly at curves where vehicles cross these lines more frequently, the life-cycle cost of markings should be considered before installing them only at curves.

The *MUTCD* Sections 3A.05 and 3A.06 provide guidance on colors, widths, and patterns for longitudinal pavement markings. This publication, which focuses on two-lane roads, will highlight yellow markings used to delineate the separation of traffic traveling in opposite directions and white markings used to delineate the right-hand edge of the roadway. Normal line widths are 4 to 6 inches and wide lines are at least twice the width of a normal line.

Center Line

When considering pavement markings to delineate a curve, the center line is usually the first countermeasure to apply (Figure 8). A center line helps drivers keep their vehicles on the correct side of the road (MUTCD Sections 3B.01 and 3B.02).

Figure 8. Photo. Center line for No Passing on horizontal curve.

Design

For any section of two-way, two-lane roadway, where passing is allowed in both directions, the basic center line marking is a broken, or dashed, yellow line. On some curves where the horizontal curvature, vertical curvature, or other conditions reduce the passing sight distance for one or both directions of travel below the minimum values given in Part 3 of the *MUTCD*, a solid yellow line is used to inform motorists of the no-passing regulation where the restriction exists for either direction of travel. For segments where passing is prohibited in both directions, a solid yellow line is used for both directions (i.e., double line pattern), separated by a gap approximately equal to the width of a normal line. To be effective at night when approximately half the crashes occur, the pavement marking must be retroreflective.

Applications

Table 1 summarizes *MUTCD* criteria for center line markings of two-way roads.

Table 1. MUTCD requirements for center line markings on paved two-way streets.

	Area type	Road Class		Lanes	Avg. Daily Traffic (ADT)	Travel Width (feet)
REQUIRED	Urban	Collectors	Arterials	2	6,000 +	20+
	All	All		3+		
RECOMMENDED	Urban	Collectors	Arterials	2	4,000+	20+
	Rural	Collectors	Arterials	2	3,000+	18+
MAY CONSIDER	Any	Any		2	Any	16+

Adding center lines at curves, even if it not required or recommended per the *MUTCD,* is worth considering as these center lines provide delineation of the change in alignment to the driver. For example, in some Minnesota counties, severe crashes were over-represented on curves with ADTs between 400 and 1000 vehicles per day. This would indicate there may be a benefit to striping curves in that range of volumes, even though it is lower than what is required or recommended by the *MUTCD*. Also, the Speed Typology Study (Council et al., 2010) indicated most speed-related crash problems on horizontal curves are on collector and local routes.

The MUTCD also states that "engineering judgment should be used in determining whether to place center line markings on travel ways less than 16 feet wide because of the potential for traffic encroaching on the pavement edges, traffic being affected by parked vehicles, and traffic encroaching into the opposing lane." Placing a center line marking only in the curve may be appropriate, but it must follow the design parameters to indicate appropriate passing requirements, as the MUTCD states that "a single solid yellow line shall not be used as a center line marking on a two-way roadway."

Therefore, the addition of this pavement marking should be the first countermeasure considered, at a minimum, when an agency identifies a curved section of roadway as a potential safety problem and the road segment does not have a center line. When the curve carries a low traffic volume (fewer than 400 vehicles per day), the pavement is less than 16 feet wide, or it is an unpaved road, consider using post delineators, chevrons, or curve warning signs in lieu of a center line.

Effectiveness

A variety of studies exist on center lines, but none of these are specific to the application of center lines placed only in horizontal curves. One study suggests that there is a connection between improved retroreflectivity of the yellow center line and reduced crashes on rural two-lane roads (Carlson et al., 2013). The CMF Clearinghouse lists two reduction factors for the installation of center lines on roadway segments (both CMFs are 3 stars), with a 1-percent decrease for injury crashes and a 1-percent increase for property damage only (PDO) crashes (Elvik and Vaa, 2004). However, significant reductions in serious and minor injury crashes can also be realized:

- 45-percent reduction when center lines, edge lines, and delineators are installed on roadway segments (CMF is 4 stars) (Elvik and Vaa, 2004).
- 14-percent reduction when center lines and edge lines are installed at sites with higher incidences of crashes (CMF is 3 stars) (Al-Masaeid, 1994).
- 24-percent reduction when center lines and edge lines are installed on rural highways (CMF is 4 stars) (Elvik and Vaa, 2004).

Relative Cost:

This countermeasure is low cost.

Edge Line

The edge line pavement marking defines or delineates the edge of a roadway (*MUTCD*, Sections 3B.06 and 3B.07) (Figure 9). It provides a visual reference to guide motorists and helps reduce drifting onto the shoulder and roadside area. Edge lines provide the added benefit of guidance away from the glare of oncoming headlights. When used with the center line or adjacent lane line for a multilane road, it defines the travel lane for the road user.

Figure 9. Photo. Edge lines.

Design

Edge line markings are a solid white line at the right edge of the travel lane for undivided roads.

Applications

The Missouri Department of Transportation (MoDOT) has found that applying an edge line to two-lane rural roads with AADT between 400 and 1,000 vehicles per day has reduced total crashes for all crash types by 15 percent. The study also found that the application has reduced severe crashes by 19 percent. See Appendix C for more information.

The *MUTCD* requires edge lines not only for freeways and expressways, but also for "…rural arterials with a traveled way of 20 feet or more in width and an ADT of 6,000 vehicles per day or greater." Edge lines are recommended for "…rural arterials and collectors with a traveled way of 20 feet or more in width and an ADT of 3,000 vehicles per day," and any other paved roadways where an engineering study identifies a need for edge line markings. Edge lines may be used on other roadways, with or without center lines, based on engineering judgment, but the risk of head-on crashes where center lines are not used must be considered.

As with the center line, edge lines may be applied just prior to and within the curved section, as delineation of the curve is usually more critical than for tangent sections. Also, the edge line width can be increased to provide a better visual perspective of the roadway. Figure 10 and Figure 11 show the same stretch of road with a 4-inch edge line and with an 8-inch edge line, respectively. As can be seen in these photos, the curve of the road is better delineated in Figure 11.

Figure 10. Photo. Roadway with 4-inch edge line.

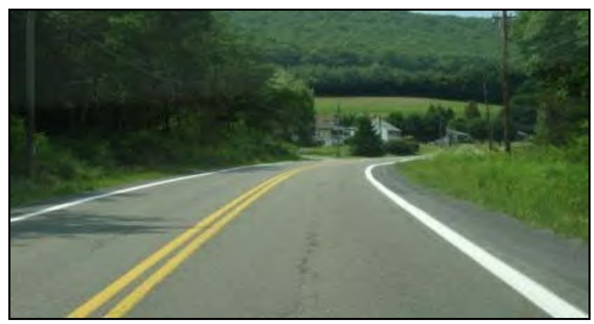


Figure 11. Photo. Roadway with 8-inch edge line.

Effectiveness

Several studies indicate that using edge lines results in crash reductions on two-lane roads. The CMF Clearinghouse lists five reduction factors from a single study for the installation of edge lines on curves, with a 26-percent or 33-percent reduction for all crash types in rural applications (CMF is 3 stars). The larger reduction was for 9-foot lanes while the smaller included lanes up to 11 feet wide. Specifically for run-off-road crashes, reductions of 11-percent were found for urban applications (CMF is 3 stars) and 13-percent for rural applications (CMF is 2 stars). Furthermore, the CMF Clearinghouse lists a 4-percent reduction for speed-related crashes in rural applications (CMF is 2 stars) (Tsyganov, 2009). A 2012 study shows that 5-inch or 6-inch line widths provide safety benefits on rural two-lane roads beyond the more typical 4-inch width (Park et al., 2012). Although the 2012 study's findings are not specific to horizontal curves, the safety benefits realized on tangent segments can also potentially also apply to curves.

Relative Cost

This countermeasure is low cost.

OTHER LONGITUDINAL DELINEATION

Delineators may also be used to communicate the roadway alignment to the driver. Delineators can be used on roads that are not paved and play a slightly different role than pavement markings since they are placed outside the edge of the traveled way.

Delineators

A delineator is a retroreflective device mounted above the roadway surface and along the side of the road in a series to indicate roadway alignment (Figure 12). Delineators are the only longitudinal guidance devices that can be used for unpaved roads. For paved or unpaved roadways, delineators are most effective at night and during adverse weather when the roadway is wet or covered in snow.

Figure 12. Photo. The color of delineators must match the color of the adjacent edge line. Source: Texas Transportation Institute.

Design

The retroreflective portion of the delineator is typically either a circular button reflector or a rectangular piece of sheeting with a minimum diameter/width of 3 inches. They are usually mounted on flexible or lightweight breakaway posts 4 feet above the pavement, except where barriers are present. For more information on delineators on barriers, see Chapter 6.

Chapter 3F of the *MUTCD* requires the color of the delineators to match the color of the adjacent edge line. For example, on a curve on a two-way road, the edge lines on both sides of the road are white, which means that if delineators are used on the left and/or right side of the road they must also be white.

Applications

Delineators should be placed 2 to 8 feet outside the outer edge of the shoulder, or if appropriate, in line with the roadside barrier. The delineators should be placed at a constant offset, to appropriately reflect the alignment. An exception to this occurs where an obstruction is between the pavement edge and the line of delineators. In this case, the line of delineators must be transitioned to be within the innermost edge of the obstruction. Delineators should be spaced 200 to 530 feet apart on mainline tangent sections. On approaches to and within curves, they should be spaced as recommended in Table 3F-1 of the *MUTCD*. The goal on curved alignments is to have several delineators simultaneously visible to the driver to show the direction and sharpness of the curve.

Effectiveness

There is no published research documenting the safety effects of installing delineators specifically on horizontal curves as of yet. One study has shown a 4-percent increase in injury crashes and a 5-percent increase in property damage crashes when delineators are installed in rural areas (both CMFs are 3 stars) (Elvik and Vaa, 2004). However, the same study showed that the combination of center lines, edge lines, and delineators led to a 45-percent reduction of injury crashes on all roadway types (CMF is 4 stars) (Elvik and Vaa, 2004).

Relative Cost

This countermeasure is low cost.

The cost of post delineators applied to a single curve will vary depending upon the number and the material used for the post and reflector. These devices also need to be maintained, but due to their location, do not typically require the significant traffic control (such as lane closures) that is often required to maintain pavement marking and raised pavement markers (RPMs).

ADVANCE MARKINGS FOR CURVES

Pavement markings in advance of horizontal curves provide highly conspicuous, supplementary warning information and the potential to increase safety. The two pavement markings options discussed in this section are especially important for reducing speeds at curve locations where signs have proved ineffective.

Speed Advisory Marking in Lane

Advisory speed warnings provide essential information directly related to drivers' safe negotiation of curves. The marking supplements the curve warning sign with advisory speed plaque, by providing the same information in the driver's direct line of sight, emphasizing the message to the driver.

Figure 13. Photo. Pavement marking for advanced curve warning.

An example speed advisory pavement marking is illustrated in Figure 13. In this example, the markings display is "CURVE—55—MPH." An arrow symbol may be substituted for the word "CURVE" and provides the driver additional information if the curve is not visible due to alignment issues such as a crest vertical curve.

Design

Refer to Section 3B.20 of the *MUTCD* for design and application criteria.
Elongated letters as specified in the Pavement Markings section of *Standard Highway Signs and Markings* are required. The elongation makes the letters easier to read by approaching

motorists. Pavement marking word messages are designed with the first word in the message placed closest to the approaching driver. [NCHRP Report 600] contains design guidelines as to which markings are effective in reducing speeds at horizontal curves and which markings are not as effective (p. 20-4) (see Figure 14).

Reduce speeds in horizontal curves

Curve arrow and“50 mph” text | “Curve 55 mph” text | Transverse lines | “Curve Ahead” text

Figure 14. Illustration. Design Guidelines for Pavement Markings to Reduce Speeds at Horizontal Curves. Source: NCHRP Report 600.

The advance distance at which such markings are applied depends on both the approach speed and design speed of the curve. Agencies should base advance placement distances on specific approach and curve speeds, which should be the same as advance distances prescribed for warning signs, as provided in Table 2C-4 of the *MUTCD* shown in Table 2.

Table 2. Table 2C-4 from the MUTCD: Guidelines for Advance Placement of Warning Signs.

Posted or 85th-Percent ile Speed	**Advanced Placement Distance**								
	Condition A: Speed reduction and lane changing in heavy traffic	Condition B: Deceleration to the listed advisory speed (mph) for the condition							
		0	**10**	**20**	**30**	**40**	**50**	**60**	**70**
20 mph	225 ft	100 ft	N/A	—	—	—	—	—	—
25 mph	325 ft	100 ft	N/A	N/A	—	—	—	—	—
30 mph	460 ft	100 ft	N/A	N/A	—	—	—	—	—
35 mph	565 ft	100 ft	N/A	N/A	N/A	—	—	—	—
40 mph	670 ft	125 ft	100 ft	100 ft	N/A	—	—	—	—
45 mph	775 ft	175 ft	125 ft	100 ft	100 ft	N/A	—	—	—
50 mph	885 ft	250 ft	200 ft	175 ft	125 ft	100 ft	—	—	—
55 mph	990 ft	325 ft	275 ft	225 ft	200 ft	125 ft	N/A	—	—
60 mph	1,100 ft	400 ft	350 ft	325 ft	275 ft	200 ft	100 ft	—	—
65 mph	1,200 ft	475 ft	450 ft	400 ft	350 ft	275 ft	200 ft	100 ft	—
70 mph	1,250 ft	550 ft	525 ft	500 ft	450 ft	375 ft	275 ft	150 ft	—
75 mph	1,350 ft	650 ft	625 ft	600 ft	550 ft	475 ft	375 ft	250 ft	100 ft

Applications

This countermeasure does not have an established guideline; however, the *MUTCD* allows for use of word, symbol, or arrow markings to supplement signs as determined by engineering judgment. This application is probably more appropriate for higher speed roads where the curve advisory speed is significantly lower than the posted speed, curves where crash reports indicate speed-related issues, and corridors where speed studies indicate excessive speeding.

Effectiveness

Currently, the CMF Clearinghouse does not have a countermeasure listed for speed advisory markings in the lane. The *NCHRP 600 Human Factors Guidelines for Road Systems* found that the "Curve-55-MPH" text reduced speeds on a rural road by 4 mph (Chrysler and Schrock, 2005). In addition, the *NCHRP 600 Human Factors Guidelines for Road Systems* found that when the curve arrow and "50 mph" text were tested on an urban roadway, vehicles significantly reduced their speeds by 10-percent at the entrance to the curve. There was also an 11- to 20-percent reduction in vehicles exceeding the speed limit (Chrysler and Schrock, 2005). Another study in the *NCHRP 600* tested the a curve arrow with "SLOW" text on a suburban road and found it reduced the percentage of drivers exceeding the speed limit by more than 5 mph during the daytime and late night timeframes, but not during the evening (Retting and Farmer, 1998). Overall, after testing other combinations of symbols, words, and advisory speeds, the markings that provided advisory speeds or an action performed most effectively.

Relative Cost

This countermeasure is low cost.

Speed Reduction Markings (also known as Optical Speed Bars)

Speed reduction markings are transverse stripes spaced at gradually decreasing distances (*MUTCD,* Section 3B.22). The rationale for using them is to increase drivers' perception of speed and cause them to reduce their speed. As spacing between bars gradually narrows, drivers sense they have increased speed and will slow down to keep the same time between each set of bars (Figure 15). Durable marking materials are preferred because of the exposure to traffic volume over time.

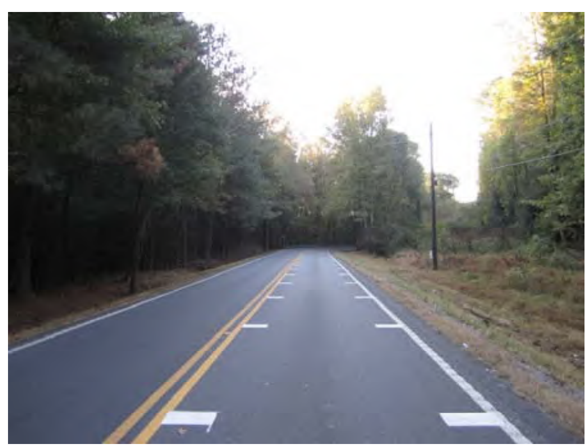


Figure 15. Photo. Optical speed bars are designed to reduce vehicle speed. Source: KLS Engineering.

Design

These white transverse stripes are only allowed where longitudinal lines are present on both sides of the lane. They must be installed perpendicular to the center, edge, or lane lines. They should be no greater than 12 inches wide, and should not extend more than 18 inches into the lane

(*FHWA*, 2009). The spacing between the transverse markings are progressively reduced from the upstream to the downstream end of the marked portion of the lane, to produce a gradual slowing from a vehicle's initial approach speed to the advisory curve speed. The goal is to achieve the slowing before the vehicle enters the curve.

The total length of the paving-marking segment depends upon the speed difference between the higher approach speed and the lower curve speed. Table 3 suggests approximate lengths, which may be used as guidelines. The basis for the numbers is to produce a comfortable speed reduction.

Table 3. Guideline for length (feet) of speed reduction markings segment in advance of curve (Katz, 2004).

		Approach Speed, mph					
		45	**50**	**55**	**60**	**65**	**70**
Curve Speed, mph	**15**	300	385	470	565	670	785
	20	275	350	440	535	640	755
	25	235	315	405	500	600	720
	30		270	360	450	560	670
	35			300	400	500	620
	40				335	440	555
	45					370	480
	50						405

Applications

Speed reduction markings should be reserved for unexpected horizontal or vertical curves or other feature where drivers need to decelerate in advance of the feature. The countermeasure should supplement, and not substitute for, appropriate warning signs and other traffic control devices. Agencies should avoid applying speed reduction markings to long roadway sections just to reduce traffic speed, because overuse could jeopardize the visual effect of the countermeasure. In addition, this countermeasure has been shown to be most effective in locations with unfamiliar drivers.

Effectiveness

Speed reduction markings are currently not listed in the CMF Clearinghouse, but are discussed in three relevant studies. The first study, using data from New York, Mississippi, and Texas, suggests transverse pavement markings can effectively reduce average speeds, median speeds, 85th percentile speeds, and speed variance before and after the curve both immediately after and in the long term (Katz, 2004). Speed reductions downstream of the curves varied from 0 to 5 mph. The second study, looked at speeds in advance of, within, and at the end of a 0.37-mile segment on a two-lane road with inadequate vertical and horizontal curves (Arnold and Lantz, 2007). Speeds decreased at all key locations, with statistically significant reductions of 1 to 3 mph. Speed reductions were greater in the first 90 days after installation. The third study analyzed 19 sites in Alabama, Arizona, and Massachusetts, using 2 different markings designs.

The study found minor effects on vehicle operating speeds that were inconsistent (Boodlal, 2015).

Relative Cost

This countermeasure is low cost.

PAVEMENT MARKING MATERIALS, MAINTENANCE, AND COSTS

Material Considerations

Road agencies commonly use a variety of paint-based materials, or more durable materials such as thermoplastic, for center line and edge line markings. The specific material to be used may depend on an agency's equipment or willingness to contract the work. Transverse markings, such as word, symbol, and arrow markings or the speed reduction markings discussed above are typically applied with a durable marking due to the amount of wear to which they are subjected by their placement within the lane. Additional information regarding various marking materials is available in the ITE *Traffic Control Devices Handbook*, Chapter 9: Pavement Markings and Markers.

Other materials used by agencies to improve visibility of longitudinal lines include a variety of RPMs and "profiled" markings. These markings are particularly beneficial under wet nighttime conditions, where the retroreflectivity of the normal, flat markings is obscured. Note that the *MUTCD* recommends against use of RPMs either as a substitute or supplement to the edge line. The rationale is that under wet night conditions when only the RPMs are visible, edge line RPMs can confuse drivers who could misinterpret them as marking the lane line. Chapter 5 also discusses the use of rumble stripes as a supplement to center line and edge line pavement markings.

RPMs

In many situations, agencies will install RPMs to supplement or substitute for center line or lane lines. There are a variety of types, including reflective, non-reflective, and internally illuminated versions. Figure 16 and Figure 17 provide examples of RPMs. In geographic areas where snow is common, the reflective device is encased in an iron casting and recessed below the pavement surface in a grooved section to prevent damage by snow plows, as shown in Figure 17. The RPM color must conform to the color of the line for which it is used. RPMs may be used as vehicle

Figure 16. Photo. Retroreflective raised pavement marker (yellow for center line).

Figure 17. Photo. Snowplowable Retroreflective raised pavement marker.

positioning guides, to supplement or substitute for certain markings, as described in MUTCD Sections 3B.11 through 3B.14.

Agencies typically apply the markers within a long roadway section, which is advantageous as it provides a longer visual range of delineation for motorists, especially at night (if retroreflective) and during wet conditions. RPMs also work well when applied to a single curve or a winding section of roadway. However, on curves the spacing must typically be reduced to adequately to show the alignment. The RPMs may also provide an auditory warning to the motorist who drives over them.

Effectiveness

While studies of the operational effects of RPMs have shown they can reduce the variation in lane placement and move vehicles away from the center line, studies of crash effects have produced mixed results. A study in the *HSM* indicates a 24-percent crash reduction on two-lane roadways with gentle curvature (less than 3.5 degrees) and relatively high volumes (greater than 15,000 vehicles per day) (CMF is 4 stars), but increased crashes for roadways with sharper curvature (greater than 3.5 degrees) regardless of the volume conditions (Bahar et al., 2004). It has been hypothesized that the increased crash frequency results from higher speeds because motorists feel safer with the RPMs providing alignment information even under wet nighttime conditions.

The same study also indicates that installing snowplowable, permanent RPMs on rural highway horizontal curves with radii less than 1,640 feet leads to an increase in total nighttime crashes of 3 percent to 43 percent, depending on traffic volumes. For rural horizontal curves with radii greater than 1,640 feet, use of snowplowable, permanent raised pavement markers leads to a 16-percent increase in total nighttime crashes for AADTs less than 5,000 vehicles per day (CMF is 5 stars), and a 1-percent to 24-percent decrease in total nighttime crashes for AADTs greater than 5,000 vehicles per day (CMFs are 3 to 4 stars) (Bahar et al., 2004).

Relative Cost

While more expensive than standard paint and thermoplastic markings, this countermeasure is low cost.

For RPMs, material costs vary significantly depending on whether the device includes the metal casing to make it snowplowable. The epoxy used to adhere the devices to the pavement must also be figured into the materials cost. However, the labor costs are often the more significant factor, particularly if the devices need to be recessed into the pavement. In considering the life cycle cost for RPMs, agencies should also factor in inspection and repair of the devices.

Profiled Pavement Markings

Agencies apply thermoplastic markings to create a profile marking, which enhances the visibility of the marking, particularly in nighttime conditions, and may also produce a slight rumble effect. Figure 18 shows an example of a profiled pavement marking.

Figure 18. Photo. An example of profiled pavement markings. Source: Caltrans.

A few agencies have used this countermeasure successfully, but no research at this time provides definitive results. As such, no rating for these markings are included in the CMF Clearinghouse. As snow plowing can destroy this marking, its use is typically limited to non-snow zone locations. The California Department of Transportation (Caltrans) has used two types—raised and inverted profile patterns, as shown in Figures 19a and 19b. The Oregon Department of Transportation has also used profiled markings both on top of the road surface (smooth or patterned) and recessed in the pavement surface.

Maintenance Considerations

Regardless of the marking countermeasures used, road agencies should consider maintenance needs when deciding what countermeasure(s) to use and the most cost-effective materials for the job. Maintenance activities should be carried out on a regular basis to ensure continued safe travel.

Pavement markings need to be restriped as they lose their visibility over time. Specifically, pavement markings that are made of paint-based materials have a relatively short service life—one to two years. How long an agency's pavement markings last depends on material type, installation quality, climate, and traffic volume. Markings of thermoplastic material will last approximately twice as long as paint-based materials. To maintain their effectiveness, pavement markings must be visible, especially at night and during other conditions of limited visibility. An agency's regular inspection and restriping programs are critical to ensuring pavement markings provide needed visibility for motorists.

Like pavement markings, pavement markers are subject to wear. RPMs should be inspected, and repaired or replaced regularly. The retroreflective lenses degrade or may be cracked by traffic, and adhesion of the marker may be lost. This is particularly important with snowplowable RPMs, as there have been reports of isolated incidents of loose RPMs becoming projectiles. The heavy casings of these RPMs have been reported to cause some serious injuries and few agencies have chosen to no longer use these devices.

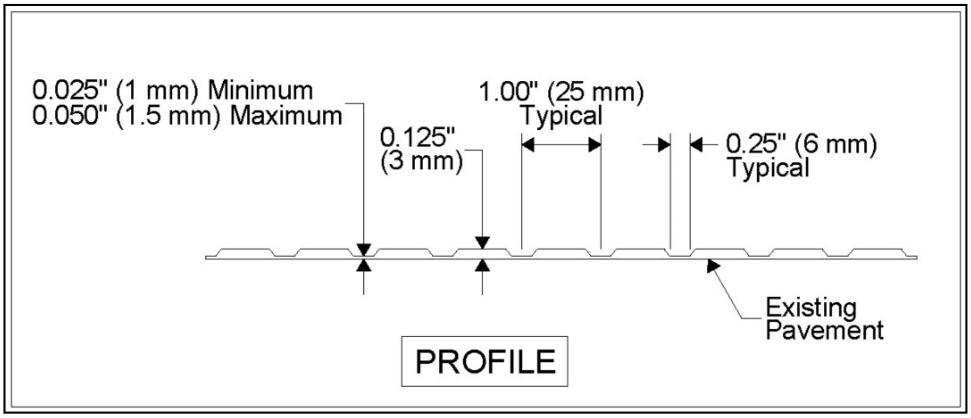


Figure 19a. Illustration. An inverted profile where depressions are made every 1 inch along the stripe.

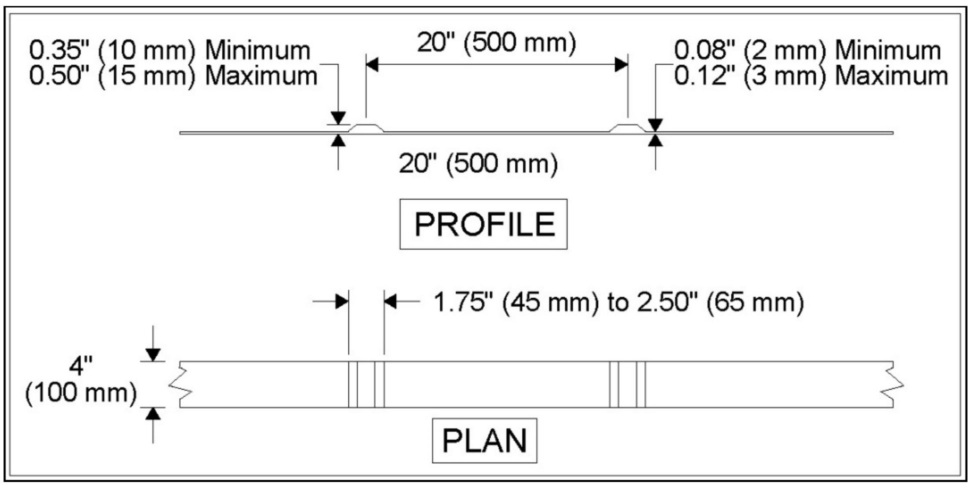


Figure 19b. Illustration. A raised profile where a thicker layer of thermoplastic is applied on 20-inch centers along the stripe.

Cost Considerations

The cost to apply pavement markings varies, depending on several factors. When applying pavement markings, an agency should consider the life-cycle cost. For example, paint has a lower initial cost than most durable materials, but paint likely needs to be reapplied every year. In comparison, a thermoplastic or epoxy material is likely to last for several years but is more expensive in initial cost. Life cycle cost needs to include or consider the cost of the materials, and the cost of the labor and traffic control needed to perform maintenance or replacement. The life of pavement markings varies greatly between agencies that need to plow their roads and those who do not.

Other cost considerations include whether the agency's own crew or a contractor performs the work and the number of horizontal curve locations that need markings. Markings placed in the lane tend to wear more quickly than longitudinal markings, and longitudinal markings on curves tend to wear more quickly than those on tangent sections. Due to these factors, and the changing cost of materials, it is not feasible to provide a cost estimate in this publication.

However, the MoDOT conducted a benefit/cost evaluation of their pavement markings program, which showed an 11-percent reduction in fatal and injury crashes and an 11.2 benefit-cost ratio (Potts et al., 2011).

CHAPTER 4. SIGNS

There are several signing options that road agencies should consider installing at a horizontal curve, especially curves with attributes that data or experience identify as potentially problematic.

Agencies should apply signing devices uniformly, based on the sharpness of the curve. This uniformity provides drivers with a consistent message on which to base their expectations. The *MUTCD* provides specific recommendations and requirements for uniform application of many of these basic devices. The *MUTCD* requires that the use of warning signs shall be based on an engineering study or engineering judgment. Factors to consider include:

- The difference between the posted speed limit and recommended advisory speed.
- Geometric features of the curve to include its length, radius, shoulders and roadside features.
- Sight distance to and around the curve.
- Unexpected geometric features within the curve, such as an intersection, change in grade, change in curve radius, or visual cues that contradict the roadway alignment.
- A sudden change in alignment after many miles of consistently straight roadway.
- Traffic volume.
- Crash data.

Many curves need only the basic horizontal alignment warning signs. The decision to add one or more of the other basic or enhanced treatments at a specific curve will be influenced by the factors noted above, but should be prefaced by an assessment at the system and corridor level. The assessment may reveal unnecessary devices that should be removed, improperly placed devices that should be moved, or required or recommended devices that are missing. Providing uniformity may be all that is necessary to address an identified safety concern. If the problem is not resolved by using a uniform application, then additional devices should be considered.

The following discussion provides a summary of basic and enhanced signage, followed by a discussion on maintenance considerations applicable to signs. All example signs are from the *MUTCD*.

BASIC SIGNING COUNTERMEASURES

Advance Warning Signs

Warning signs call attention to unexpected conditions on or adjacent to a roadway. The *MUTCD* prescribes several Horizontal Alignment signs to give drivers advance warning of a horizontal curve, as illustrated in Figure 20.

For a single curve section, use one of these four signs in advance of the curve:

- Turn (W1-1).
- Curve (W1-2).
- Hairpin Curve (W1-11).
- 270-degree Loop (W1-15).

For sections with more than one curve in close proximity, use one of these three warning signs in advance of the first curve:

- Reverse Turn (W1-3).
- Reverse Curve (W1-4).
- Winding Road (W1-5).

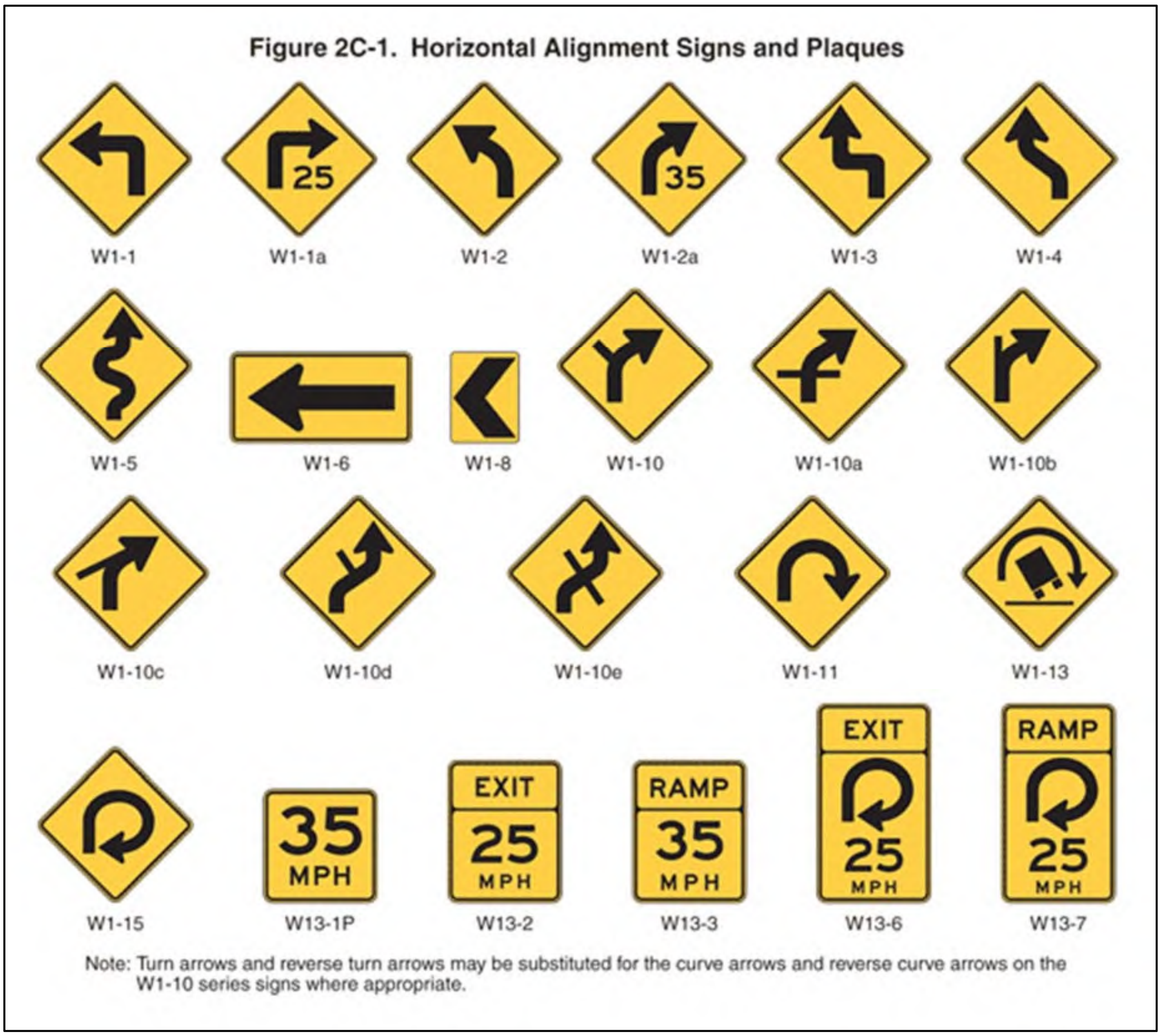


Figure 20. Illustration. Figure 2C-1 from the MUTCD.

Design and Application

The *MUTCD* requires the use of a warning sign be based on an engineering study or engineering judgment, but the *MUTCD* also has specific requirements for warning signs based on traffic volume and curvature. For freeways, expressways, and roadways with more than 1,000 AADT that are functionally classified as arterials or collectors, refer to Table 2C-5 from the 2009 *MUTCD* (shown in Table 4) to determine those signs that are required or recommended for use based on the difference in posted speed limit and advisory speed. This table provides uniform guidelines for placement of not only advance warning signs but also chevrons, which provide a consistent message to the driver if applied uniformly. The criteria in Table 2C-5 may also be used for local roads and those with less than 1,000 ADT, based on engineering judgment. Warning signs sizes should follow *MUTCD* Tables 2C-2 and 2C-3, and the signs should be located per Table 2C-4 (*MUTCD*, Section 2C). Further information on design and application is discussed under the individual devices.

Table 4. Horizontal Alignment Sign Selection (MUTCD Table 2C-5 Excerpt).

	5 mph	10 mph	15 mph	20 mph	25 mph or more
• **Turn (W1-1)** • **Curve (W1-2)** • **Reverse Turn (W1-3)** • **Reverse Curve (W1-4)** • **Winding Road (W1-5)** • **Combination Horizontal Alignment / Intersection (W1-10)** ***(see MUTCD, Section 2C.07 to determine which sign to use)***	Recommended	Required	Required	Required	Required
• **Advisory Speed Plaque (W13-1P)**	Recommended	Required	Required	Required	Required
• **Chevrons (W1-8)** • **One Direction Large Arrow (W1-6)**	Optional	Recommended	Required	Required	Required

Note: "Required" indicates that the sign and/or plaque shall be used, "Recommended" indicates that the sign and/or plaque should be used, and "Optional" means that the sign and/or plaque may be used.

For horizontal curves where a Horizontal Alignment sign is not required or recommended, engineering judgment should be applied to determine whether a sign is needed. For instance, a roadway with center line and edge line pavement markings, where the alignment change is not unexpected and where there is no crash history, may not need a sign. For those curves that do need advance warning signs, use the Curve sign unless the advisory speed is 30 mph or less, in which case the Turn sign is required. Use the Hairpin Curve sign when the change in horizontal alignment is 135 degrees or more. The Loop sign indicates a change of approximately 270 degrees in direction, such as cloverleaf interchange ramps, and is not addressed in this publication.

The two sequential curves signs (left turning followed by right turning or vice versa) are Reverse Turn (W1-3) and Reverse Curve (W1-4). These should be used when the tangent distance between the two curves is less than 600 feet. The guidance on which one to use is the same for selecting a Turn or Curve sign and agencies should base their decision on the advisory speed, as with the single Turn and Curve signs. For road segments with three or more alignment changes in opposite directions in relatively close proximity, the Winding Road (W1-5) sign may be used.

Depending on the geometry of the curve or sets of curves, place the appropriate sign the distance in advance of the point of curvature, as shown in *MUTCD* Table 2 C-4 presented in Chapter 3. This type of sign, and others discussed in this publication, should be located as described in *MUTCD* Section 2A.16.

Materials

Traffic signs of all types use retroreflective sheeting to ensure they are visible to drivers at night or in periods of low light. In the interest of improved visibility and sign life, many agencies have transitioned from using engineering grade to high-intensity grade and even prismatic sheeting. Information regarding various available sheeting types can be found in the *Traffic Sign Retroreflective Sheeting Identification Guide*. Higher grades generally can be seen from a further distance and typically last longer.

Effectiveness

The CMF Clearinghouse lists two "advance static curve warning signs" countermeasures, which report a 30-percent decrease in all minor and serious injury crashes (CMF is 1 star) (Elvik and Vaa, 2004) and an 8-percent decrease in all property damage only (PDO) crashes (CMF is 1 star) (Elvik and Vaa, 2004). However, both of these countermeasures received a rating of only one star, indicating the quality or confidence in the results of the study is not reliable.

Relative Cost

This countermeasure is low cost.

Advisory Speed Plaque

An Advisory Speed plaque (W13-1P) is a sign placed below a Horizontal Alignment sign (discussed in previous section) to advise motorists of the safe speed through the curve(s). It does not indicate the legal speed limit. Figure 21 shows an example of an advisory speed plaque.

Design and Application

The *MUTCD* requires an advisory speed plaque when an engineering study indicates a need. It is also required for roadways with more than 1,000 ADT whenever the difference between the advisory speed and the posted speed is 10 mph or greater and recommended at 5 mph difference in speeds according to Table 4. An engineering study is required to determine the appropriate advisory speed. The *MUTCD* outlines established practices that are appropriate for determining the recommended advisory speed for a horizontal curve that include an accelerometer, a design speed equation, or a 16-, 14-, or 12-degree ball bank indicator depending on the speed range.

Figure 21. Photo. Advisory Speed Plaque.

See FHWA-SA-11-22, *Procedure for Setting Advisory Speeds on Curves* and the ITE *Traffic Control Devices Handbook* for additional methods of determining the advisory speed.

Effectiveness

The CMF Clearinghouse does not include any studies specifically for adding combination horizontal alignment/intersection warning signs along two-lane rural highway road segments.

Relative Cost

This countermeasure is low cost.

Combination Curve/Intersection Signs

An intersection near or within a curve adds another potential problem and more information for the driver to process. The combination Horizontal Alignment/Intersection sign (W1-10 Series) quickly communicates to the driver what to expect in advance.

The *MUTCD* states that turn arrows and reverse turn arrows may be substituted for the curve arrows and reverse curve arrows on the W1-10 series signs where appropriate (Figure 22).

Design and Application

The signs shown in Figure 22 are used in lieu of the horizontal alignment signs previously listed in Figure 20 and should comply with the provisions of both curve warning signs and with intersection warning signs. The symbol design should approximate the configuration of the intersecting roadway(s). However, no more than one Cross Road or two Side Road symbols should be displayed on any one combination Horizontal Alignment/Intersection sign.

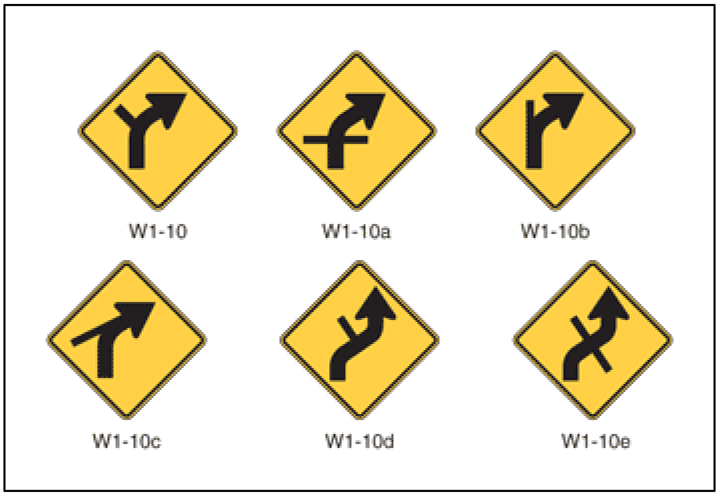


Figure 22. Illustration. Excerpt from Figure 2C-1 of the MUTCD.

The design and application of the combination Horizontal Alignment/Intersection sign is accordance with the appropriate Turn or Curve sign requirements.

Effectiveness

To date, no research has documented the safety effects of installing a combination horizontal alignment/intersection sign.

Relative Cost

This countermeasure is low cost.

SUPPLEMENTAL DEVICES IN A CURVE

Some curves will still violate driver expectancy with only advance warning signs. In those cases, additional traffic control devices used within the curve itself help guide motorists through the curve. These include combination curve/speed signs, chevrons, large arrow signs, and delineators.

Combination Horizontal Alignment/Advisory Speed Sign

When additional emphasis is needed to reduce speeds, agencies can add a combination Turn/Advisory Speed (W1-1a) sign or a combination Curve/Advisory Speed (W1-2a) sign. This sign is used as a supplement to—not a replacement for—the advance Horizontal Alignment sign and Advisory Speed plaque, and is placed at the beginning of the turn or curve (i.e., the point of curvature). The sign is intended to remind motorists of the need to slow down as they begin to negotiate the alignment change.

Design and Application

The *MUTCD* contains no guidance as to when to use these signs, so it is up to an agency's engineering judgment. It is probably best not to use it when the distance from the advance horizontal alignment sign and the point of curvature is 200 feet or less because the two signs would be too close together. The advisory speed on the combination Horizontal Alignment/Advisory Speed sign should be based on the advisory speed for the curve using recommended engineering practices.

Effectiveness

The *HSM* Table 13-30 shows a 13-percent decrease for injury crashes and 29-percent decrease for non-injury crashes associated with the installation of combination horizontal alignment/advisory speed sign (Elvik and Vaa, 2004). The CMF Clearinghouse lists the same CMFs with 3-star ratings, suggesting that the combined horizontal alignment/speed advisory sign safety effectiveness estimates are moderately reliable.

Relative Cost

This countermeasure is low cost.

Chevron Alignment Sign

Chevron Alignment (W1-8) signs emphasize and guide drivers through a change in horizontal alignment. Because of their pattern, size, and placement with at least two of the signs in view of the motorist, they define the direction and sharpness of the curve, the best of all the traffic control devices. When the chevron sign is used, agencies also need one of the advance curve warning signs previously discussed. Figures 23 and 24 illustrate a before and after installation.

Figure 23. Photo. Before, without chevrons.

Figure 24. Photo. After, with chevrons. Chevrons provide advanced alignment of a curve.

Design and Application

Except on roads functionally classified as local or with volumes less than 1,000 ADT, the use of Chevron Alignment signs are to be in accordance with *MUTCD* Table 2C-5, which recommends use of chevrons where the difference between the advisory speed and posted speed is 10 mph, and requires their use when that difference is 15 mph or greater (see Table 4). Use at lower speed differences or on other roads is optional, based on engineering judgment. An agency may use chevrons instead of or in addition to standard delineators.

Chevrons are one of very few signs without a border, and are installed at a height of at least 4 feet above the roadway surface. Install a series of these signs on the outside of a turn or curve, positioned in line with approaching traffic at approximately a right angle to a driver's line of sight. On two-lane, two-way roads, use two-sided chevron signs properly aimed to guide traffic traveling both directions.

The spacing of the chevrons is measured from the point of curvature (PC) and should be as shown in the *MUTCD* Table 2C-6 (Table 5). The spacing is based on the advisory speed and radius of the curve. Figure 25 illustrates a layout of these devices on a curve with a retroreflective strip on the posts for increased conspicuity.

Table 5. Typical Spacing of Chevron Alignment Signs (MUTCD Table 2C-6).

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

Effectiveness

The CMF Clearinghouse lists a 4-percent to 25-percent reduction in crashes when chevrons are installed on rural highway curves (CMF is 4 stars) depending on the crash type (Srinivasan, 2009). There are even greater reductions when chevron installations are combined with advance curve warning signs and/or flashing beacons. In addition, according to *NCHRP Report 559*, chevrons have been shown to reduce vehicle encroachments onto the center line in curves where the degree of curvature is more than seven degrees (Lyles and Taylor, 2006).

Figure 25. Photo. Chevrons assist the driver in navigating curves. Source: Texas Transportation Institute.

Relative Cost

This countermeasure is low cost.

The cost to apply chevrons to a curve will vary with the number of signs installed. It is not uncommon for one or more of the chevrons in problem curves to be periodically knocked down, so it is advisable for an agency to keep a supply of signs.

One-Direction Large Arrow Sign

The One-Direction Large Arrow sign (W1-6) is used to define a sharp change in horizontal alignment, as seen in Figure 26. Usually only one of these signs per direction is used for a horizontal curve or turn.

Nothing in the *MUTCD* limits using multiple signs along the curve, but it may be more reasonable to use a series of Chevron (W1-8) signs. The Large Arrow sign is installed only on the outside of a turn or curve in line with, and at approximately a right angle to approaching traffic.

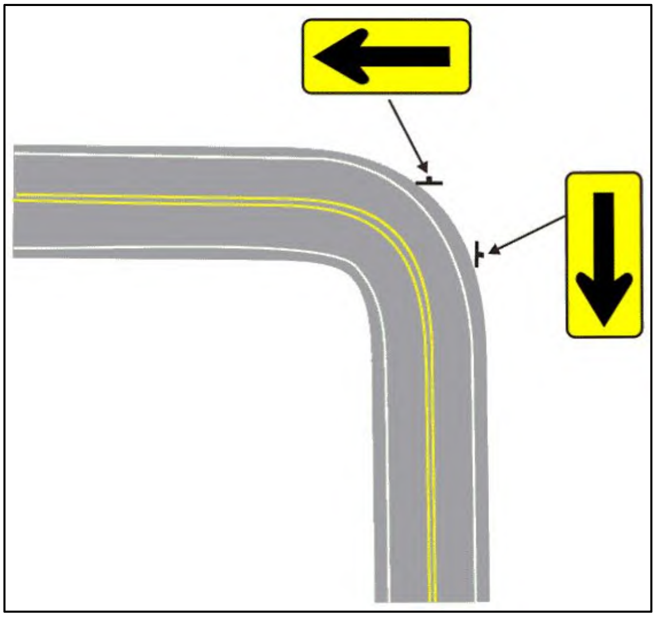


Figure 26. Illustration. Typical installation location of one-direction large arrow signs on a horizontal curve. Source: MoDOT Engineering Policy Guide.

Design and Application

The Large Arrow sign may be used either as a supplement or alternative to Chevron signs in accordance with the information shown in Table 2C-5. If a Large Arrow sign is used with Chevron signs, it would take the place of a Chevron and not obstruct or be obstructed by a Chevron. Based on standard practice, this sign is limited to sharper curves (i.e., turns).

Effectiveness

To date there has been no research on the safety effectiveness of installing a large arrow sign, and therefore, it is not listed as a countermeasure by the CMF Clearinghouse.

Relative Cost

This countermeasure is low cost.

In 2010, the Ohio Department of Transportation introduced a Horizontal Curve Program which focused on upgrading and installing various signage at curves to address problematic locations. Individual districts conducted site field reviews, evaluated existing conditions and countermeasures onsite, and selected the appropriate signs to be installed at the site. Figure 27 shows a curve on a rural, two-lane road before signage updates and Figure 28 shows the same curve after signage updates through the Horizontal Curve Program. Images courtesy of Ohio DOT. See Appendix D for more information.

Figure 27. Photo. Before signage updates.

Figure 28. Photo. After signage updates.

ENHANCED SIGNING COUNTERMEASURES

Most basic devices described above can be improved in different ways to increase the number of drivers who perceive and react to them. The sooner a motorist is able to see a device and recognize its meaning, the more time there is to respond. The following enhanced signage countermeasures have proven effective in enhancing driver perception.

Larger Devices

The *MUTCD* prescribes the use of the "conventional road" sizes for typical situations. The minimum size is not recommended, but the *MUTCD* allows their use on low-speed roadways where the reduced letter size remains adequate for the warning or where physical conditions prevent using a larger size. The *MUTCD* also states that oversized and larger signs "…should be used for those special applications where speed, volume, or other factors result in conditions where increased emphasis, improved recognition, or increased legibility is needed, as determined by engineering judgment or study" (*MUTCD*, Section 2A.11). A horizontal curve identified for safety improvements would likely meet this condition.

Effectiveness

To date there has been no research documenting the safety effects of installing larger warning signs. Therefore, these signs are not listed as a countermeasure by the CMF Clearinghouse.

Relative Cost

This countermeasure is low cost.

Doubling-Up Devices

As seen in Figure 29, "doubling-up" simply refers to situations where agencies install a second, identical sign on the left side of the roadway. Agencies can do this for the basic signs discussed in this chapter. Doubling-up increases the opportunity for the motorist to see the sign, and respond to the message. Doubling-up is also a candidate countermeasure when visibility of the single right-hand side sign is less than desirable.

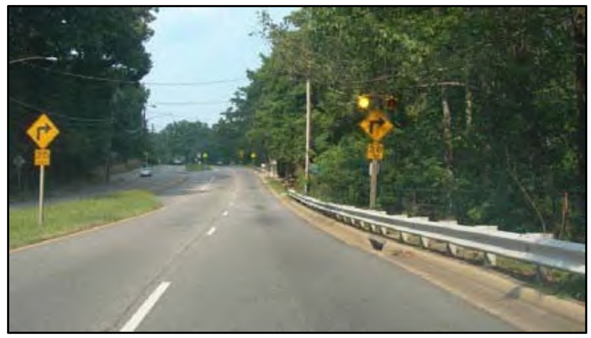


Figure 29. Photo. Doubling-up of the sign was used at this site because tree limbs partially blocked the right side sign.

Effectiveness

To date there has been no research documenting the safety effects of doubling-up curve warning signs, and therefore, it is not listed as a countermeasure by the CMF Clearinghouse.

Relative Cost

This countermeasure is low cost.

Retroreflective Strip on Sign Post

A strip of retroreflective material may be used on warning sign supports to draw more attention to the sign during nighttime conditions (*MUTCD,* Section 2A.21). If used, the strip of retroreflective material shall be at least 2 inches in width, placed along the full length of the sign support to within 2 feet of the roadway surface, and its color shall match the background color of the warning sign.

Effectiveness

To date there has been no research documenting the safety effects of installing a retroreflective strip on the posts of curve warning signs. However, a study from Iowa has shown that installing a retroreflective strip on chevron sign posts led to moderate reductions in the mean and 85^{th} percentile operating speeds along curves (Hallmark et al., 2012). This same study also indicated that there was a statistically significant reduction in the percentage of vehicles exceeding the posted speed limit by more than 10 mph.

Relative Cost

This countermeasure is low cost.

Highly Retroreflective and Fluorescent Sheeting

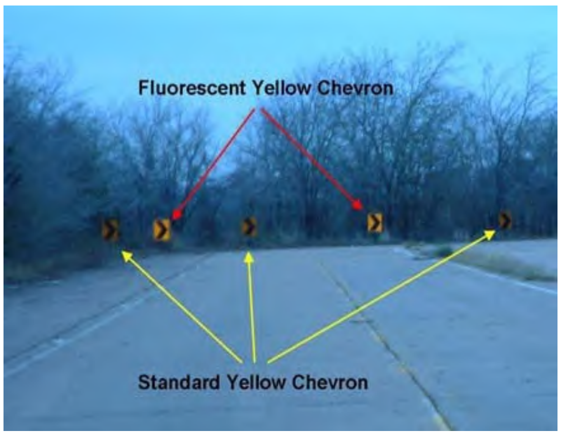


Figure 30. Photo. Stimulus photo illustrating enhanced chevron visibility. Source: Texas Transportation Institute.

Another way to make signs more visible or more noticeable to motorists is to use highly retroreflective sheeting and fluorescent sheeting. As noted earlier in this chapter, the retroreflective sheeting for signs is available in different grades. Signs made with prismatic sheeting increase visibility from a longer distance at nighttime visibility. For more information on types of retroreflective sheeting, see *Traffic Sign Retroreflective Sheeting identification Guide*. Use of fluorescent yellow increases the visibility of warning signs, especially at dawn or dusk, as seen in Figure 30. This visual advantage works day and night.

Effectiveness

Initial research based on eye-tracking data indicates that upgrading conventional yellow chevrons to fluorescent yellow, while not affecting speed or lane placement, improves driver perception of the signs. This improved driver performance effect suggests a potential safety effect.

The CMF Clearinghouse lists an 18-percent to 35-percent reduction in various crash types on rural highways when new fluorescent curve signs are installed or existing curve signs are upgraded to fluorescent sheeting (Srinivasan et al., 2009). To date, no CMFs have been developed regarding improved retroreflectivity of signs.

Relative Cost

This countermeasure is low cost.

Flashing Beacons

Using flashing beacons with a warning sign is another way to gain motorists' attention, as seen in Figure 31. The beacons are typically used with one of the advance Horizontal Alignment signs for a horizontal curve. There are no published guidelines for when they are appropriate, but it is reasonable to limit them to locations where other countermeasures have not solved a safety problem. One factor limiting the use of beacons is the availability of an accessible power source, although agencies can use reliable solar power panel systems.

Figure 31. Photo. Typical arrangement of signs and flashing beacons.

The beacons used for this countermeasure are the circular yellow sections from a standard traffic signal. Agencies can install this with one or more beacons, but Figure 31 shows a typical arrangement. The beacons can be flashed either alternately or simultaneously. To prevent the flashing light from masking the sign message, locate the beacon signal housing at least 12 inches outside of the nearest edge of the sign.

Effectiveness

To date there has been no research documenting the safety effects of installing flashing beacons with warning signs, but when flashing beacons are installed in combination with curve warning signs and chevrons, the CMF Clearinghouse lists a 37-percent to 76-percent reduction in various crashes (CMFs are 3 stars) (Montella, 2009).

Relative Cost

This countermeasure is moderate cost.

Dynamic Curve Warning System

Agencies can enhance curve warning systems by using supplemental beacons and/or messages that activate when a motorist approaches the curve at a high speed. A typical dynamic curve warning system combines a speed measuring device (such as loop detectors or radar) with flashing beacon and a variable message sign. The system is designed to slow high-speed vehicles as they approach and enter a horizontal curve. It works by measuring the speeds of approaching vehicles and providing messages to speeding drivers to slow down to an advisory speed. Agencies can develop these systems using off-the-shelf technology. The advantage of this countermeasure is that the device has a much greater effect on high-speed vehicles than a static curve warning sign. A variety of these systems are deployed in the United States, as the examples in Figures 32 and 33 demonstrate.

Figure 32. Photo. Speed Actuated Sign, Augusta, ME.

Figure 33. Photo. Flashing Beacon on Warning Sign, Augusta, ME.

Application

Because even the least expensive system is much more costly than static signs, agencies should limit their application to locations with high crash rates, especially those involving fatalities and injuries, and where other less expensive devices have failed to solve the problem.

One dynamic system application involves a radar speed detection device coupled with warning signs and activated flashing beacons. The Texas system, illustrated in Figures 34 and 35, advises drivers detected driving more than 5 mph over the 25-mph curve advisory speed limit to reduce their speed. A radar detector measures speeds and displays them using a speed display sign stating: “YOUR SPEED IS…” A W1-1 warning sign is located 625 feet in advance of the curve, and the overhead sign is located in the point of curvature. The radar is set to start processing the speed data about 300 feet before a vehicle reaches the overhead sign.

Figure 34. Photo. Texas System curve advisory speed limit sign. Camp County, Texas.

Figure 35. Photo. Texas System curve advisory speed limit sign. Camp County, Texas.

Effectiveness

A recently completed project by FHWA evaluated the effectiveness of low-cost, speed-activated dynamic curve warning systems on speeding and safety on horizontal curves in rural roadways. The study found a 5-percent (CMF is 5 stars) to 7-percent (CMF is 4 stars) crash reduction depending on the crash type and direction of the crash (Hallmark et al., 2015). Other studies have shown that they can reduce vehicle speeds in horizontal curves. For example, Oregon experienced a 3-mph decrease in speeds at the Myrtle Creek installation on I-5 (Bertini et al., 2006). Another study found that average speeds dropped between 1 and 8.8 mph and concluded that dynamic curve warning signs have larger impacts at curves with lower advisory speeds and on reducing the number of higher speed vehicles (Knapp and Robinson, 2012). A study published by California DOT found that an advanced curve warning system on an interstate route in Northern California led to over 68 percent of drivers to reduce their speed (Tribbett et al., 2000).

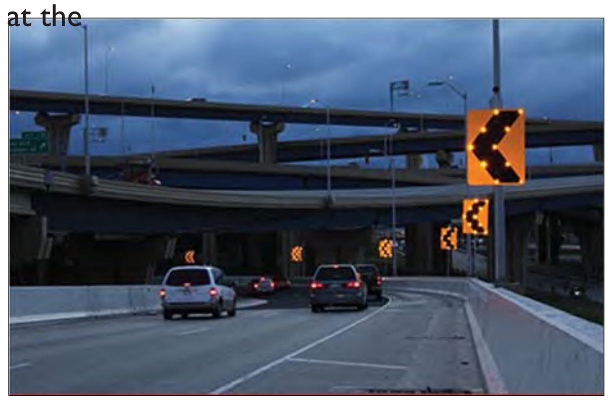


Figure 36. Photo. Example of Sequential Dynamic Curve Warning System.

Sequential Dynamic Curve Warning Systems (SDCWS) have been implemented as a countermeasure on two-lane rural highway curves as a means to reduce vehicle operating speeds and improve curve delineation. SDCWS are horizontal curve chevron signs with solar powered flashing lights embedded in the sign, as shown in Figure 36. Four States collectively installed 12 SDCWS along horizontal curves on two-lane rural highways. These sites were identified based on a high-crash history, as well as vehicle operating speeds that exceeded the posted speed limit. The study has found that both operating speeds and crash frequency have been reduced by SDCWS installations. See Appendix E for more information.

Relative Cost

The cost of these systems varies, depending upon the specific design and the availability of a power source. This countermeasure is moderate cost.

SIGN MAINTENANCE

Regardless of whether an agency has basic or enhanced signage countermeasures, road agencies should consider maintenance requirements when deciding what countermeasure to use, and carry out maintenance activities on a regular basis to ensure continued safe travel. These maintenance activities include:

Figure 37. Photo. Example of a Chevron sign on the ground.

- **Replace or repair damaged or knocked down signs.** Signs that are damaged through vandalism, accidents, or storms, as seen in Figure 37, should be repaired or replaced as soon as feasible.
- **Replace faded signs and those with low levels of retroreflectivity.** The various signs discussed in this report are visible at night because they are made with retroreflective sheeting material. Few, if any, are illuminated by external lighting. Even though the retroreflectivity of sheeting material has improved to provide brighter and longer lasting signs, all signs deteriorate over time. Signs lose their color and retroreflectivity and eventually they are no longer visible to motorists from a distance, as seen in Figure 38. Therefore, the MUTCD requires agencies to use an assessment or management method designed to maintain sign retroreflectivity at or above the minimum levels in Table 2A-3. For alternative methods see [Maintaining Traffic Sign Retroreflectivity] (FHWA-SA-07-020). Replace any signs found to be ineffective as soon as practical.

Figure 38. Photo. Low Retroreflectivity sign example.

- **Cut back foliage to improve the sight distance through the curve and increase visibility of traffic control devices.** Agencies can improve safety at a horizontal curve by maintaining the longest possible sight distance through the curve and to the various traffic signs. During the growing season, grass, weeds, brush, and tree limbs can limit a driver's view of the road and signs, as seen in Figure 39. This is why agencies should make periodic inspections of the roadway to identify and correct these situations. For more information, see Chapter 5 of this publication.

Figure 39. Photo. Curve warning sign covered by foliage.

More practical tips for controlling vegetation overgrowth are found in FHWA's *Vegetation Control for Safety*.

CHAPTER 5. PAVEMENT COUNTERMEASURES

Low-cost countermeasures that improve pavement surfaces or involve minor reconstruction in curve sections are also available. These improvements will function alone or can be completed with the use of signs and pavement markings as outlined in Chapters 3 and 4. This chapter describes several pavement countermeasures that could reduce roadway departure crashes. These countermeasures can be implemented independently as a safety project or incorporated into a pavement preservation or 3R (rehabilitation/restoration/resurfacing) program. While most of the countermeasures in this guide are only applicable at curves, this chapter includes countermeasures that are applicable at both curves and tangent sections. Some of the countermeasures covered in this chapter are "moderate cost" when implemented alone, however, costs may be "low" when incorporated into 3R projects or other planned projects.

SKID RESISTANCE PAVEMENT COUNTERMEASURES

Maintaining the appropriate amount of pavement friction is critical for safe driving. Low pavement friction allows vehicles to skid and lose control, which has been related to many severe crash types. Agencies can address this issue by monitoring the pavement friction values and improving them when they fall below a certain level. Two conventional approaches to solve this issue are repaving with thin overlays or repaving using microsurfacing. Generally, both methods are reserved for long sections of roadway, and both restore the pavement friction number when the mixes are designed properly. These measures usually can produce friction numbers in the 40s to 50s, as measured by skid trailers, depending on the aggregate used, as opposed to a low friction value in the 20s and 30s. See *NCHRP 108*, Guide for Pavement Friction and *Evaluation of Pavement Safety Performance*.

Locations with higher operating speeds or those with demanding geometric conditions may require pavement with higher friction capabilities. Such locations are typically found in horizontal curves, steep grades, combination of grades and curves, and the approach to intersections. Friction can be improved on curves to address geometric characteristics unsuited to the road's operating speeds. These critical locations where the need for friction is greatest also tend to lose friction more quickly than flat tangential sections. These high friction demand locations are typically short sections that can be addressed by high friction surface treatments (HFST).

Wet pavement surfaces also reduce pavement friction and can cause skidding. Excessive water on pavement surfaces can result in hydroplaning, but more often crashes are caused by loss of friction due to smaller amounts of water on the road since it takes very little water on the surface to reduce friction by 20 to 30 percent, as shown in Figure 40. Marginal pavement friction numbers can lead to skidding crashes either from speeding vehicles or wet weather. Wet weather is a major contributing factor in roadway departure crashes and most agencies monitor locations for wet weather crashes. Having higher pavement friction makes the microtexture friction loss due to wet weather less critical but does not address hydroplaning. Cross slope, drainage improvements, and macrotexture address hydroplaning but can be equally related to the condition of each vehicle's tires. Additional information on practices to reduce wet weather skidding crashes can be found in *State Practices to Reduce Wet Weather Skidding Crashes*.

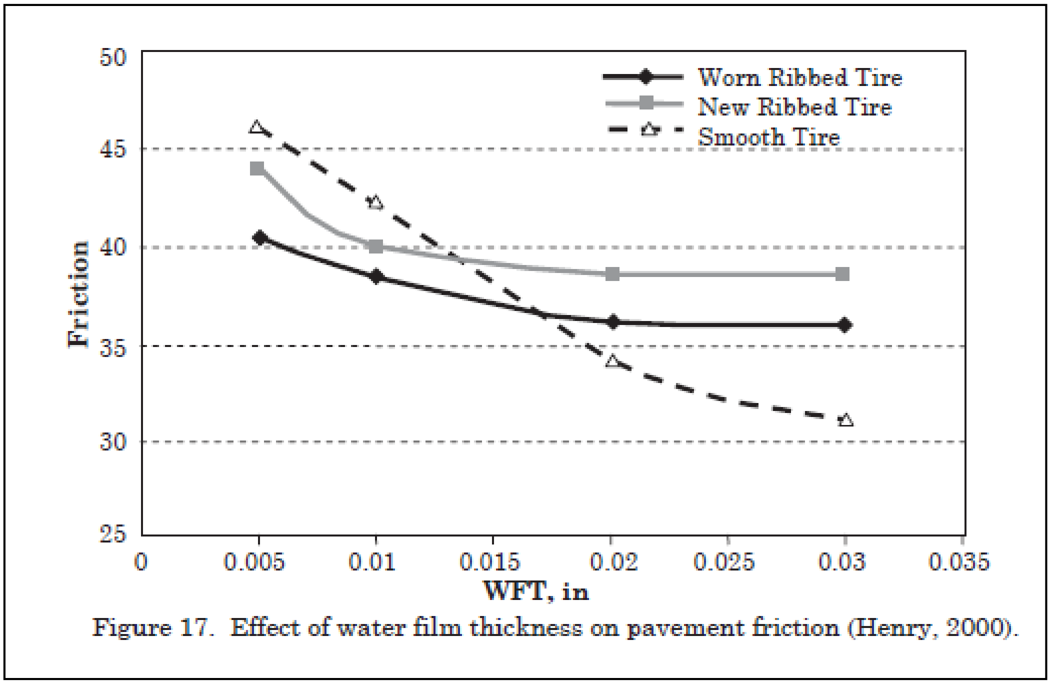


Figure 40. Graph. Figure 17 from NCHRP 108, Guide for Pavement Friction.

A variety of skid resistance surface countermeasures are available. While HFST may have a higher unit cost than traditional friction improvement courses, they can often be applied in small quantities at spot locations for a relatively low project cost. In addition, where cross-section problems exist, such as lack of appropriate superelevation, this approach can be a low cost but effective alternative to address the problem.

High Friction Surface Treatments (HFST)

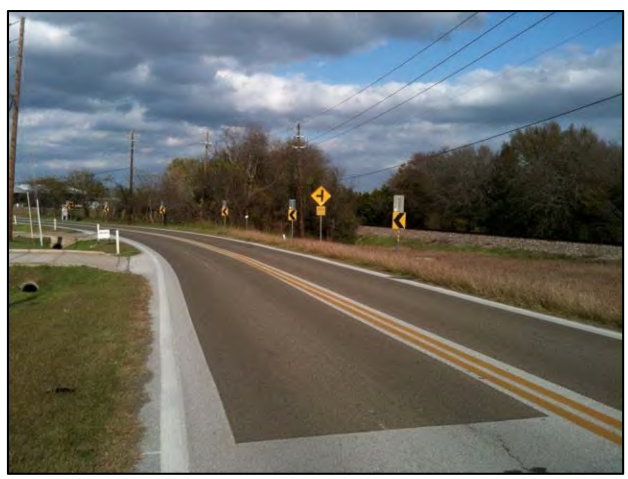


Figure 41. Photo. HFST on a horizontal curve.

HFST is an evolving technology that has demonstrated the ability to dramatically and immediately reduce crashes and related injuries and fatalities. When friction demand exceeds conventional pavement friction capability, high-quality aggregate is applied to existing or potential high-crash areas to help motorists maintain better control in dry and wet driving conditions. HFST uses calcined bauxite aggregate, which has demonstrated the best friction characteristics (microtexture) and polish resistance. Proper gradation needs to be specified to provide proper macrotexture. The binder layer is usually a polymer material. The darker layer of pavement in Figure 41 is an example application of HFST. The National Center for Asphalt Technology's (NCAT) High Friction Surface Treatment Alternative Aggregates Study provides discussion and research results on different aggregate types for HFST.

Applications

HFST can be applied to concrete surfaces or asphalt pavement materials and is available from many manufacturers and contractors. While the aggregate is specialized and generally not produced locally, it is not proprietary. The binder material is usually proprietary but there is ample competition in the industry. Recent innovations in the application method have evolved. HFST have been installed with simple hand tools for many years, but this is slow and a well-trained crew is necessary to attain good quality installations. Some of the installers that work nationally have recently developed equipment for mechanical applications. The equipment varies by the contractor. Some have incorporated more sophisticated equipment for monitoring the quality of the application. Also, application speed varies with the different equipment and aggregate distribution method. The mechanical approach can be more cost effective for large quantity projects, projects with lane closure limitations or multiple small projects. Recent breakthroughs have provided products that are designed to provide quick curing rates even in cold temperatures.

Effectiveness

HFST has been tried at a wide variety of countermeasure sites across the country as part of the FHWA's Surface Enhancements at Horizontal Curves (SEAHC) program. Preliminary crash data indicates benefit-cost ratios were as high as 50 to 1. Kentucky alone placed this countermeasure on 30 curves at the beginning of their Roadway Departure Safety Implementation Plan in 2009 and observed a crash reduction of 70 percent to 75 percent at these curves. A Texas Transportation Institute study, *Using High Friction Surface Treatments to Improve Safety at Horizontal Curves*, compiled crash reductions from other HFST application studies.

To further illustrate Kentucky's success with HFST, the Kentucky Transportation Cabinet saw tremendous results from one exit ramp on Interstate 75 in Fayette County. In the three years prior to HFST treatment, the ramp had 28 roadway departure crashes (18 wet crashes and 10 dry crashes). In the two and half years since the HFST installation, crashes have nearly been eliminated. The ramp has been the scene of a single crash, which was a dry crash. See Appendix F for more information.

HFST is a durable and effective safety countermeasure for roadway departure crashes, especially as a spot application in critical locations. See Appendix G for additional information on the use of HFST in the United States.

Relative Cost

This countermeasure is moderate cost.

Pavement Grooving

Pavement grooving is a pavement countermeasure technique to apply longitudinal or transverse cuts onto the pavement surface to increase or restore pavement friction. This is used on concrete pavements and is especially effective in reducing wet-weather crashes by improving the drainage characteristics of the pavement. Potential side effects include increase of vehicular noise (particularly for transverse grooving), possible reduced driver comfort (particularly for longitudinal grooving) and potentially premature wearing of the pavement surface. New grooving techniques have been recently marketed to reduce sound for longitudinal grooving.

Effectiveness

New York State DOT evaluated the pavement grooving treatment and found that wet pavement-related crashes were reduced by 55 percent, and the total for both wet and dry pavement crashes were reduced by 23 percent. Various studies cited in the *NCHRP Report 500*, Volume 7, Strategy 15.2.A8 shows significant crash reductions after applying the pavement grooving countermeasure.

Relative Cost

This countermeasure is moderate cost.

Superelevation

Providing superelevation at the curve to help keep vehicles on the road is one of the key geometric design elements that affects crashes on a curve. Superelevation is designed for driver comfort during the acceleration through the curve, and works with friction between the tires and pavement to assist vehicles in maneuvering through curves. Figure 42 provides an illustration of a cross section of a superelevated section. Superelevation is occasionally inadequately designed, lost over time due to settling and/or overlays, or not included as part of the original design consideration due to factors such as traffic volume, constructability, and adjacent land use. As a result, curves with inadequate superelevation may pose a safety problem.

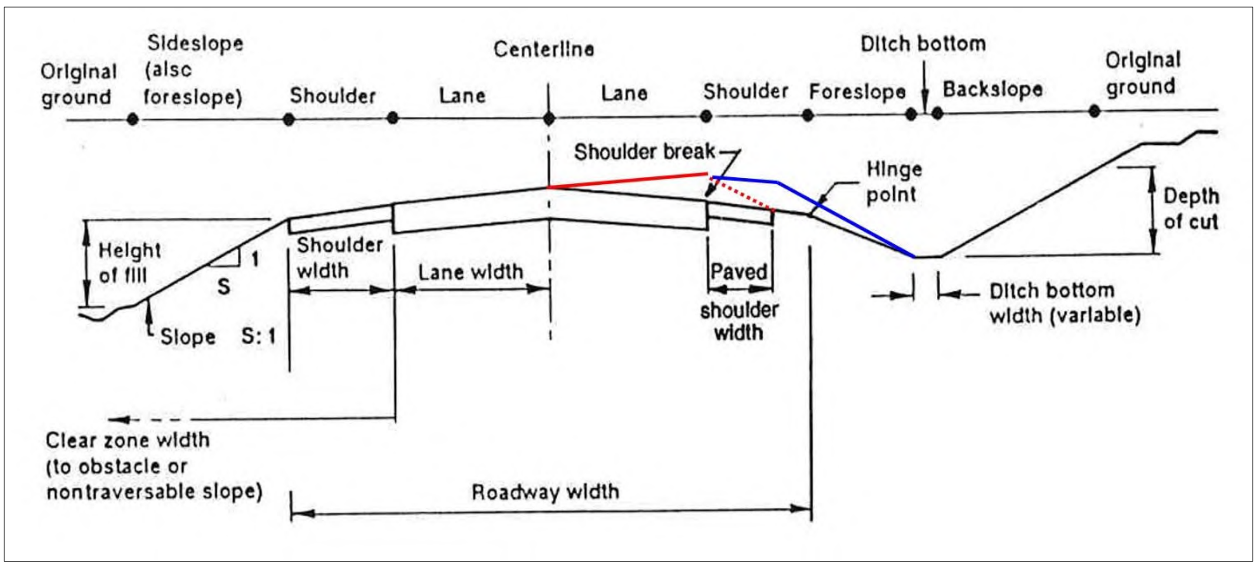


Figure 42. Illustration. A typical cross section of a normal crown with the red and blue lines showing a typical cross section of a superelevated section.

According to the *HSM*, crash prediction models indicate that inadequate superelevation increases curve crashes. Research results indicate that safety can be enhanced when the superelevation is improved or restored along curves where the actual superelevation is less than the optimal superelevation. However, it should be noted that the increase in driver comfort associated with increasing superelevation may increase speeds.

During routine pavement projects under the pavement preservation program, deficiencies in superelevation should be addressed. Other issues related to superelevation that the designer should pay attention to during routine pavement projects are the slope break between the edge of pavement and the adjacent shoulder. The designer should also have guidance on maximum recommended algebraic differences between the traveled way and the shoulder slopes. Refer to Chapter 3, Section 3.3 of AASHTO's publication "*A Policy on Geometric Design of Highways and Streets*" (2011) for more details on superelevation design.

When restoring superelevation, special attention is required to maintain proper drainage. A sufficient grade should be maintained along the superelevation transition to provide sufficient drainage where the cross-slope is level or close to level. Care should also be taken to ensure reverse curves have appropriate transition distance.

Effectiveness

The *HSM* provides a function for calculating CMFs for horizontal curves based on superelevation variance (SV), which is provided in Chapter 10 for two-lane rural highways.

Relative Cost

This countermeasure is moderate to high cost, depending on extent of correction and scale of project.

SHOULDER COUNTERMEASURES

The probability of recovering from a run-off-the-road incident is increased if a vehicle is provided with a shoulder, the portion of the roadway outside of the travel lane where a driver can reclaim control of the vehicle. The shoulder is also designed to accommodate stopped vehicles (when sufficiently wide) and to provide side support for the roadside in close proximity to the travel lane. Shoulders can be graded (level surface) or useable (rounding on outside edge). Rounding is simply a gradual change in slope from the usable shoulder to the foreslope.

This area can be further enhanced if the recovery is not impeded by surface irregularities such as potholes, edge drop-offs, or ruts. Such irregularities may make a vehicle more difficult to control. Shoulder countermeasures that promote safe recovery include shoulder widening, shoulder paving, and the installation of the Safety Edge℠. While each strategy could be covered separately, the effectiveness is related, and the treatments can often be completed as a "package" during roadway resurfacing. These pavement countermeasures within the shoulder area enable the vehicle's recovery to be made in a more controlled fashion and reduce the risk of overturning or crossing into the opposing lane.

Shoulder Widening

Shoulders are a safety feature because they provide space that allows drivers to get out of the travel lane and avoid crashes. This feature is particularly important in horizontal curves where vehicles typically use more of the travel lane than in straight sections. By widening the shoulders or providing a shoulder where one previously did not exist, drivers have more recovery area to regain control in the event of a roadway departure.

Applications

Shoulder widths can vary from approximately no shoulder on minor rural roads to 12 feet on major roads where the entire shoulder may be stabilized or paved. Agencies should stabilize widened shoulders and minimize steepening of roadside slopes. As Figures 43 illustrates, agencies can widen shoulders on both the inside and outside. If space is only available to one side, widening the outside shoulder will most likely provide the greater benefit.

Figure 43. Photo. Widening on the inside and outside of the curve.

Effectiveness

Table 6 shows the percent change in crashes (including single vehicle run-off-road and multiple vehicle head-on and sideswipe crashes) in comparison to a road with 6-foot shoulders. The table suggests that roads with shoulder widths less than 6 feet will have more crashes than a road with 6-foot shoulders. Conversely, roads with shoulder widths 8 feet or more will have fewer crashes than a road with 6-foot shoulders. Although the table was developed for rural two-lane roads, and is not limited to horizontal curves, it is reasonable to expect the maximum benefit from shoulder widening can also be realized for horizontal curves.

Table 6. Percent change in crashes relative to providing a 6-foot shoulder on rural two-lane roadway segments (Modified from* HSM *Table13-7).

Shoulder Width	Percent change in crashes in comparison to roads with 6-foot shoulders		
	Average Annual Daily Traffic (AADT) (vehicles/day)		
	< 400	400-2,000	> 2,000
0 ft	+ 10%	Between +10% and +50%, depending on AADT	+ 50%
2 ft	+ 7%	Between +7% and +30%, depending on AADT	+ 30%
4 ft	+ 2%	Between +2% and +15%, depending on AADT	+ 15%
6 ft	0%	0%	0%
8 ft or more	- 2%	Between -2% and -13%, depending on AADT	– 13%

** Crash types: Single vehicle run-off-road, multiple vehicle head-on, opposite direction sideswipe, and same-direction sideswipe.*

Relative Cost

This countermeasure is high cost.

Shoulder Paving

When right-of-way permits, replacing unstable or narrow shoulders with paved shoulders increases the total usable width of the roadway. This improves safety for all road users (motorized and non-motorized). With this extra paved roadway, vehicles have an increased capacity for recovery if they leave the travel lanes. Paving shoulders can also be accompanied by Safety Edge[SM] and rumble strips. Figure 44 shows an example of a shoulder paving operation.

Figure 44. Photo. Shoulder paving operation.

Applications

While limited budgets may influence an agency's decision to upgrade to paved shoulders on two-lane tangent sections, the resulting benefit-cost ratio from fewer crashes on curves with paved shoulders deserves consideration. In some cases, widening shoulders may be more desirable than widening lanes.

Effectiveness

The CMF Clearinghouse lists only one CMF for paving the shoulder through a curve. It indicates an increase in crashes (CMF is 1 star) (Pitale et al., 2009). Other research results for paving shoulders (not exclusively within curves) indicate that paving shoulders reduces crashes.

Relative Cost

This countermeasure is high cost.

*Safety Edge^SM^*

Figure 45. Photo. Pavement with and without the Safety Edge^SM^.

Safety Edge^SM^ is a paving technique used system-wide to improve pavement durability and reduce crashes by shaping and consolidating the pavement edge into a 30-degree wedge, as demonstrated in Figure 45. The shape of the edge allows controlled recovery for drivers returning to the pavement after straying due to inattention. The added durability of the edge reduces the tendency of the pavement to ravel, providing a consistent pavement width. It should be noted that the recommended practice is to bring the adjacent shoulder material or roadside vegetation up even with the pavement surface, thereby covering the Safety Edge^SM^ after the paving is complete (Figure 46). The shape of the Safety Edge^SM^ is exposed at various times over the life of the pavement, as this material settles or is dislodged by traffic.

Figure 46. Photo. Backfilling against newly installed Safety Edge^SM^.

The Safety Edge[SM] is formed while paving and therefore, is not appropriate as a spot countermeasure for curves. However, this countermeasure is particularly helpful at curves where the roadway departure crashes it addresses are prevalent. It is the ultimate systemic countermeasure, which when applied on every paving project, will provide added safety wherever a driver leaves the pavement. The cost is a very minor addition to the cost of the paving process under which it is applied.

Most State DOTs now use Safety Edge[SM] as a standard practice and therefore have appropriate specifications and drawings for use in contract documents. Additional information is available in FHWA's *Safety Edge[SM] Design and Construction Guide*.

Effectiveness

Safety Edge[SM] has been proven for many years based on physical tests with vehicles. In addition, a recent study showed it could reduce total crashes by approximately 6 percent on two-lane roads (CMF is 4 stars) (Graham et al., 2011). The FHWA Office of Safety is sponsoring a project to estimate an updated CMF for the Safety Edge[SM] paving technique on two-lane rural highways. Results from this evaluation are anticipated in December 2016.

Relative Cost

This countermeasure is very low cost.

Rumble Strips and Rumble Stripes

Longitudinal rumble strips are milled or raised elements on the pavement intended to alert inattentive drivers through vibration and sound that their vehicles have left the travel lane. There are a number of possible applications that can be used:

- **Shoulder rumble strips** are installed on a shoulder near the edge of the travel lane. They significantly reduce run-off-road crashes.
- **Edge line rumble strips** are very similar to shoulder rumble strips, but placed at the edge of the travel lane in line with the edge line pavement marking, and therefore often called a rumble stripe.
- **Center line rumble strips** are installed at or near the center line of an undivided roadway, and may be comprised of either a single or double line of rumbles. They reduce cross center line crashes such as head-on collisions and some run-off-road left crashes.
- **Rumble stripes** are either edge line or center line rumble strips where the pavement marking is placed over the rumble strip. This countermeasure increases nighttime visibility of the pavement marking.

Because rumble strips apply to a human behavior problem rather than a roadway deficiency, they are best applied as a systemic countermeasure. Driver inattentiveness or drowsiness cannot be predicted by location; however, the type of system where application will be most effective can often be predicted from previous crash experience, using factors such as ADT or roadway classification.

Milled rumble strips have been shown to be more effective than other types of rumble strips at creating noise loud enough to alert inattentive and fatigued drivers (*NCHRP Report 641,* 2009). Milled rumble strips can also be installed at any time on new or existing pavements. In regions where plowing is not an issue, various types of raised rumble strips may be used as an alternative. Figure 47 shows a milled centerline rumble stripe, and Figure 48 shows a milled edge line rumble stripe.

Figure 47. Photo. Milled Center Line Rumble Stripes.

Figure 48. Photo. Milled Edge Line Rumble Stripes. Source: KYTC.

For more information on rumble strip design and installation, see FHWA technical advisories at:

- T5040.39, Shoulder and Edge Line Rumble Strips.
- T5040.40, Center Line Rumble Strips.
- *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*.

Effectiveness

The CMF Clearinghouse contains a large number of CMFs for installing rumble strips on various types of roads and conditions. *NCHRP Report 641* indicates that installing shoulder rumble strips on two-lane rural roads result in a 15-percent to 29-percent reduction in crashes, depending on the crash type (CMF is 5 stars). The same report also indicates that installing center line rumble strips on two-lane rural roads result in a 9-percent to 44-percent reduction in crashes, depending on the crash type (CMF is 5 stars). Studies have shown that the crash reductions for center line rumble strips in curves and tangents are approximately the same.

Relative Cost

This countermeasure is low cost.

CHAPTER 6. ROADSIDE IMPROVEMENTS

Previous chapters have primarily addressed countermeasures to help keep vehicles on the roadway. However, even with these countermeasures, many drivers will still leave the roadway and encroach onto the roadside, particularly on the outside of horizontal curves. Research by Glennon, Neuman, and Leisch (1985) found that roadside character (including roadside slope, clear-zone width, and coverage of fixed objects) appeared to be the most dominant contributor to the probability that a roadway curve has a high reported crash rate.

Once a driver leaves the roadway, the focus of safety efforts is to reduce the potential that they will encounter a slope or ditch likely to induce a rollover or an obstacle that could result in injury. Where it is not possible to flatten slopes or remove all obstacles, then the focus is to minimize the resulting severity through the use of crash barriers and other safety hardware.

Chapter 5 discussed countermeasures such as shoulder widening and the use of the Safety Edge[SM] to reduce crashes caused by edge drop-offs. Chapter 6 will focus on other roadside countermeasures that would typically be outside of the pavement, such as the clear zone, and will also discuss barrier considerations that are appropriate for curved sections. While some of these countermeasures may not be considered "low cost," focusing these countermeasures on curves may be cost effective for the entire roadway safety picture. It is important to keep in mind and evaluate the tradeoffs of various safety investments.

Clear Zone

A clear roadside that is relatively flat and free of trees and other non-breakaway features, makes it more likely that a driver will be able to regain control. AASHTO defines the clear zone as "the unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles." The AASHTO *Roadside Design Guide* provides suggested values for the Design Clear Zone.

> The New Jersey Department of Transportation (NJDOT) has implemented a Pole Mitigation Program to relocate utility poles with three or more reoccurring pole collisions. NJDOT has also piloted energy absorbing poles made of fiberglass that collapse on impact and do not break away into the roadway. See Appendix H for more information.

The suggested clear zone values are based on studies that found that 80 percent of vehicles that left the road stopped within 30 feet of the travelled way. While the values have been adjusted to account for speed, sideslope, and the probability of encroachment (based on traffic volume), it can still be assumed that there will be vehicles that go farther than the suggested values.

The AASHTO *Roadside Design Guide* also provides an adjustment for the outside of horizontal curves. This adjustment is a multiplier based on the sharpness of the curve (radius) and the design speed. For example, for a curve with a radius of 1,475 feet and a design speed of 55 mph, an adjustment factor of 1.3 is suggested which means that the Design Clear Zone should be increased by 30 percent.

Applications

Clear zones are useful for providing sight distance along curves and recovery areas for vehicles that inadvertently leave the roadway. Thus, agencies should be cautious to avoid adding new fixed objects such as poles or trees in the clear zone, especially within the vicinity of horizontal curves (see Figure 49). Clear zones also decrease the risk of having animals near the roadway. More information on clear zones can be found in the *Roadside Design Guide* (*AASHTO*, 2011).

Figure 49. Photo. Fixed objects (trees) located within clear zone.

Effectiveness

The CMF Clearinghouse contains several CMFs for increasing the clear zone. While these CMFs are not unique to curves, clear zone improvements in curves may have greater affect since crashes are over-represented. For example, FARS data indicates that 48 percent of fatal crashes occurring on curves involve trees. In many cases improving the clear zone may be a low-cost countermeasure if it involves the removal of shrubs and trees.

CMFs in the CMF Clearinghouse indicate that increasing the distance to roadside obstacles from 3.3 to 16.7 feet reduces all crash types and severities by 22 percent (CMF is 5 stars). The CMF Clearinghouse also indicates that increasing the distance from 16.5 feet to 29.5 feet results in a reduction of 44 percent of all crash types and severities (CMF is 5 stars). These reductions are not specifically for curved road sections.

Relative Cost

The cost for this countermeasure can range from low to high depending upon the amount of earthwork and grading needed and the fixed objects that need to be removed or relocated.

Clear Zone Maintenance

Once a clear zone is established, it needs to be maintained. Maintaining clear zones free of trees while they are still saplings is typically less costly and controversial than removing them when the trees are mature. Agencies should develop a policy for maintenance of the clear zone. Without an established policy, in many cases it may become difficult for maintenance forces to keep up with clear zone maintenance. Figure 50 shows an example of clear zone maintenenace.

Refer to FHWA-SA-07-018, *Vegetation Control for Safety A Guide for Local Highway and Street Maintenance Personnel*, for more information.

Figure 50. Photo. Removing brush as part of clear zone maintenance. Source: Texas DOT.

Slope Flattening

After a vehicle leaves the travelled way and traverses over the shoulder, the steepness of the sideslope is a critical factor in their ability to keep the vehicle stable, regain control of the vehicle, and avoid obstacles. The ideal roadside, from a vehicle stability standpoint, would be flat (slopes of 1V:10H are considered essentially flat). The AASHTO *Roadside Design Guide* considers foreslopes that are 1V:4H or flatter to be traversable and recoverable, meaning that the driver could bring the vehicle under control and even stop on these slopes. Slopes that are between 1V:3H and 1V:4H are considered traversable but non-recoverable, meaning in most cases the driver will not be able to recover until reaching a flatter slope. Slopes steeper than 1V:3H are considered critical slopes, meaning the vehicle could become unstable on these slopes to the point that the risk of the vehicle overturning is increased. Depending on the height of the slope, a barrier might be considered for critical slopes.

While it may not be practical to flatten all slopes along a corridor, flattening the slopes on the outside of curves may provide a significant benefit. FARS data indicates that 45 percent of overturn fatal crashes occur on curves. As a cost-saving measure, agencies can re-purpose material excavated from other locations to flatten slopes.

Side slopes often are steeper on the outside of curves due to superelevation of the curve. Caution is recommended when using a "barnroof design" on the outside of horizontal curves. A typical barnroof design exists where the slope immediately past the shoulder is flattened significantly but then breaks into a much steeper slope, generally to keep the slope inside of the right-of-way, as seen in Figure 51. While the flatter slopes outside of the shoulder facilitate recovery, if a vehicle goes past the slope break, it will probably go to the bottom of the slope. Since vehicles can be expected to go farther from the roadway when they leave on the outside of a curve, there is a higher probability of encroaching on this steeper slope. In addition, crashworthy hardware—such as sign supports—may not function as intended when placed on slopes steeper than 1V:6H.

When ditches near roads are not traversable, the resulting roadside may be a particular safety concern for run-off-road crashes. This safety concern can be attributed to ditches that can trap a wheel and guide the vehicle into a fixed object, or cause loss of vehicle stability in the transition to the backslope.

Figure 51. Photo. Typical barnroof slope design. Source: Alaska DOT.

Application

The *Roadside Design Guide* recommends rounding the bottom of the ditch to make the ditch traversable. When this is not possible, other options include installing a barrier and partially filling the ditch with small aggregate. Some limited research in Sweden indicated that flattening ditches using aggregate improves the traversability of the ditch (Kelkka, 2009).

Effectiveness

The CMF Clearinghouse contains several CMFs for slope flattening. These CMFs include flattening side slopes from 1V:3H to 1V:4H, which has an expected crash reduction of 42 percent for injury crashes and 29 percent for PDO crashes (CMF is 5 stars). CMFs for flattening sideslopes from 1V:4H to 1V:6H include a 22-percent reduction in injury crashes and a 24-percent reduction in PDO crashes (CMF is 5 stars). While these CMFs were not developed specifically for horizontal curves, it is expected to be greatly beneficial on curves because of the higher potential for roadway departures at these locations.

Relative Cost

The cost for this countermeasure can be high depending upon the amount of earthwork and grading needed and the possibility of right-of-way acquisition.

Slope Maintenance

While slopes generally don't require a lot of maintenance, if there are areas where drainage runoff is concentrated, there may be a need to reestablish slopes periodically. Care is needed for ditch cleaning activities to reduce the potential for steepening the slopes.

Roadside Barriers

As previously noted, roadway departure crashes tend to be over-represented on curves. When measures such as delineation and signing discussed previously have not been sufficient to reduce the number of roadway departure crashes, and it is not feasible to clear obstacles and flatten slopes, roadside barriers may be an appropriate treatment. In some cases a barrier, such as the one seen in Figure 52, may be appropriate on curves for certain conditions as noted above (e.g., side slopes, clear zone) where they may not be deemed suitable on tangents. In either case, the use of barriers requires engineering judgment to assess the trade-offs.

Figure 52. Photo. Barrier along inside and outside of horizontal curve.

There are three types of barriers that might be appropriate for curved sections:

- **Cable barrier**: A flexible barrier made from wire rope supported between frangible posts.
- **Guardrail**: A semi-rigid barrier usually either a steel box beam or W-beam. These deflect less than flexible barriers; so they can be located closer to objects when space is limited.
- **Concrete barrier**: A rigid barrier that does not deflect. These are not typically used on rural two-lane roads.

Applications

Traffic barriers placed on or in the vicinity of horizontal curves deserve special attention. Most barriers, while not specifically designed and tested on curves are used because there are no other alternatives. Barriers placed along a curved highway may be hit at higher angles and, depending on the superelevation and placement relative to a slope break point, vehicles may hit the barrier higher than normal. In many cases where there is a significant degree of curvature, the impact speed may be reduced, which can help compensate for some of the placement issues.

A proprietary precast concrete or steel barrier was tested on a curve with a radius of 100 feet. This system, called the Safe-T-Curve Barrier System, was tested in accordance with *NCHRP 350*, TL3 (62 mph at a 25-degree angle) and deflected approximately 27 inches. While this type of a system may not be appropriate for most installations, it may be appropriate in locations where the barrier is hit frequently.

Effectiveness

The CMF Clearinghouse contains several CMFs for adding new guardrail along embankments. CMFs indicate reductions in run-off-road crashes of 47 percent for injury crashes (CMF is 5 stars), 44 percent for fatal crashes (CMF is 4 stars), and 7 percent on PDO crashes (CMF is 3 stars). There are no specific CMFs for installing guardrail along horizontal curves. It is important to note that adding barriers may increase PDO crashes in some cases, but this should be offset by the reduction in severity of all crashes.

Placement

When a barrier is to be placed on a curve, the position of the barrier relative to a slope break may also affect its performance. If the shoulder is not constructed with the superelevation of the travel lanes, there is a potential for a vehicle to be partially airborne if it hits the barrier. This will result in the vehicle hitting the barrier higher than normal. The ideal conditions for barrier performance would be to have the superelevation continue across the shoulder. If this is not practical, using taller barriers may be appropriate.

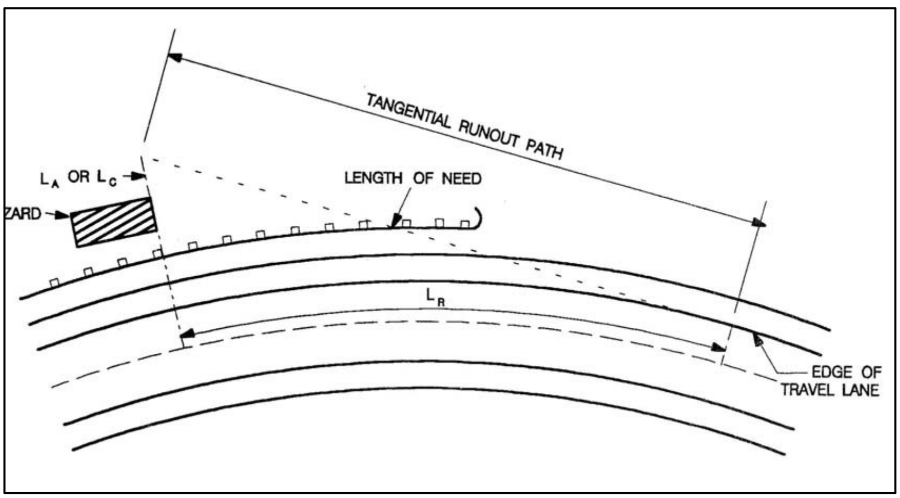


Figure 53. Illustration. Figure 4.4 from the FLH* Barrier Guide *shows length of need (LON) on the outside of a horizontal curve hazard.

Terminating a barrier in the vicinity of a horizontal curve may require special attention. The AASHTO *Roadside Design Guide* and the Federal Lands Highway (FLH) *Barrier Guide* provide some guidance for determining the Length of Need (LON) when an obstacle to be shielded is in the vicinity of a curve. Figure 53 indicates that the LON section of the barrier should intersect a runout path that extends from the farthest point of the obstacle to be shielded to a tangent point on the curve. While this may result in less barrier than on a tangent, the theory is that vehicles that depart the roadway prior to the tangential runout path will not be traveling in the direction of the obstacle.

Relative Cost

This countermeasure is moderate cost.

Barrier Maintenance

Refer to the FHWA-SA-08-002, *W-beam Guardrail Repair: A Guide for Highway and Street Maintenance Personnel*, for general information on the maintenance of barriers.

Delineation on Barriers

Barriers that are placed along a highway are usually not visible to the driver at night unless there is lighting or they are delineated. Delineating a barrier not only gives the indication that a barrier is present but also provides the driver with information on the alignment of the roadway.

Applications

There are several methods that can be used to delineate barriers, as shown in Figures 54 through 58. For W-beam guardrail, delineators can be attached in the web of the W-beam with clips held in place by the post bolts. They can also be installed on the posts.

Figure 54. Photo. Retroreflective panels in the web of a W-beam. Source: Michigan DOT.

Several States have experimented with using retroreflective paint, tapes or panels in the web of the W-beam. Concrete barriers can also be delineated by similar products to those used for W-beam guardrails. Metal "butterfly" delineators should not be used where the bolt holds the rail to the post. This acts as a washer and may prevent the proper performance of the guardrail in a crash.

Figure 55. Photo. Delineators held in place with post bolts and installed on post.

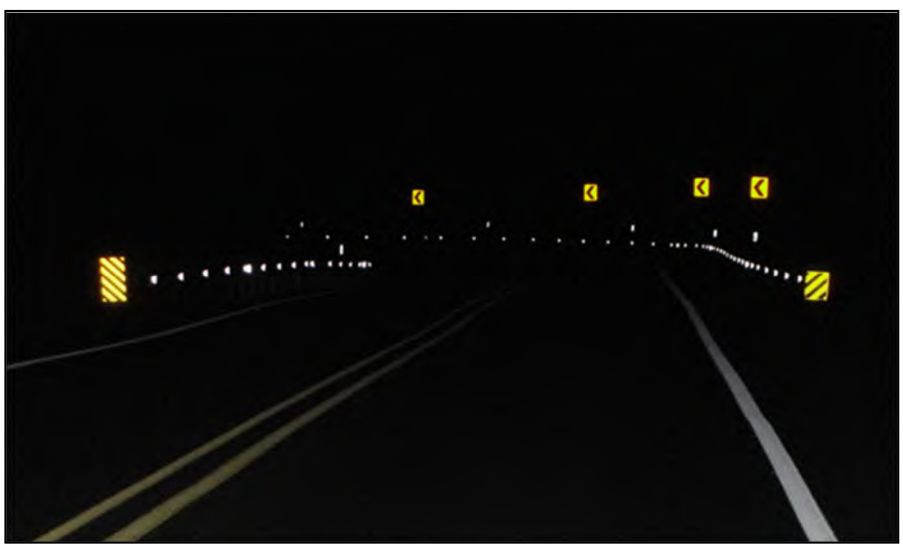


Figure 56. Photo. Delineators installed on post, nighttime view. Source: Michigan DOT.

Figure 57. Photo. Delineated concrete barriers. Source: Michigan DOT.

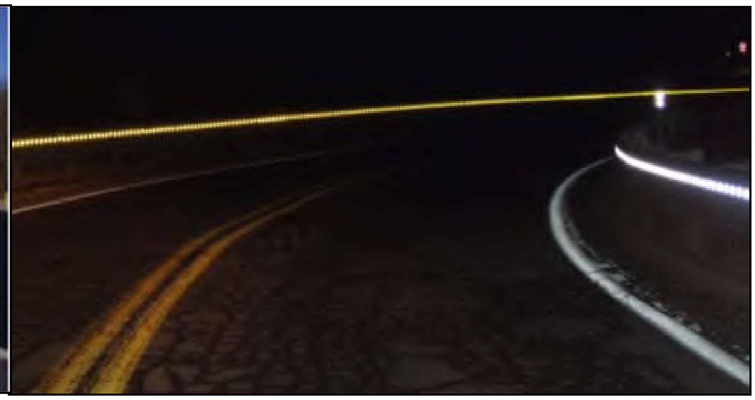


Figure 58. Photo. Delineated concrete barriers, nighttime view. Source: Michigan DOT.

Effectiveness

To date there has been no research on the safety effectiveness of delineation on barriers, and therefore, is not listed as a countermeasure by the CMF Clearinghouse.

Relative Cost

The countermeasure is low cost.

Maintenance

Barrier delineation does require maintenance to ensure that it will continue to function. Periodic cleaning of the delineation may be needed to remove dirt and road spray. There will also be increased costs for repair as these products will have to be replaced.

CHAPTER 7. ADDRESSING INTERSECTIONS IN CURVES

When an intersecting roadway is located within a curve, it presents a unique safety challenge. *NCHRP Report 600 Human Factors Guidelines for Road Systems* points out that the demands on drivers approaching and navigating horizontal curves include visual demands, vehicle control demands, and speed selection. The closer a driver is to the curve, the harder it is for the driver to effectively assimilate information relating to anything other than navigating the curve. The geometry often limits the available sight distance for safe maneuvering and the physical constraints of the intersecting roadway often limit the application of signing and other delineation. Figure 59 shows an example of an intersection within a curve.

The AASHTO *Policy on Geometric Design of Highways and Streets* recommends that "the alignment should be as straight and the gradient as flat as practical" at intersections to allow for easy recognition of the potential conflicts. It further states that "an intersection on a sharp curve should be avoided or designed to compensate for potential adverse grade and reduced sight distance." However, many agencies have existing intersections with less than ideal design.

Figure 59. Photo. Dotted edge line extensions at an intersection within a curve.

A study by Indiana Department of Transportation (INDOT) found that curvature was a significant factor in the relative safety of intersections where the major road is a four-lane divided highway. The same study stated that full curvature and superelevation increased crashes by 30 percent in comparison to tangent intersections (Savolainen and Tarko, 2004).

This chapter discusses treatments unique to the combination of intersections and curves as well as modifications that may be appropriate to options discussed in previous chapters to address this situation. Similar to Chapter 5, the cost of some of these countermeasures may be less expensive if the work is completed as part of larger scheduled projects, such as reconstruction or resurfacing, rather than as independent safety projects.

DELINEATION TREATMENTS

Adjusting Signs and Markings for the Intersecting Roadway

Where an intersecting roadway is within the curve, the traditional means of delineating the roadway alignment is often interrupted. Center line and edge line markings are typically not continued through the intersection. The edge line marking is of particular concern if the intersecting roadway has a wide throat. The *MUTCD* allows dotted edge line extensions consisting of 2-foot line segments and 2- to 6-foot gaps through intersections along the mainline, as illustrated in Figure 60. In fact, the MUTCD guidance recommends this treatment to help guide motorists through the intersection. As discussed in Chapter 3, providing center line or edge line markings on the approach and through the curve in corridors where markings are otherwise not present channelizes vehicles through the curve. This is particularly beneficial when an intersecting roadway is present within the curve.

Similarly, where chevrons or delineators would typically be used to provide delineation, the discontinuance through the intersection may leave a significant portion of the curve lacking delineation. Adjusting the location of the remaining chevrons or delineators may be appropriate to delineate the maximum curve length. A combination of a curve sign and intersection sign can also be used, which is discussed in Chapter 4. Providing a visible stop line on the minor road approach may also be helpful, especially where the stop line can be seen from a significant distance from the intersection or where crashes indicate stop sign violations.

Smooth Lane Narrowing

A combination of treatments used at intersections that are particularly beneficial where there is curvature on either the major or minor road has been dubbed "smooth lane narrowing." As seen in Figure 60, the treatment narrows the lane width approaching the intersection with a combination of markings and rumble strips. The narrowing is accomplished by gradually tapering out from the center. The rumble strips are milled in along both the left and right sides of each direction of travel, with longitudinal center and edge line markings added. The combination of rumble strips and markings to narrow the lanes reduces operating speeds on the intersection approach. When a curve is present, the preferred design is to narrow the lanes on the approach to the curve. The paved width is not changed in this countermeasure, but the narrower lane width continues throughout the entire length of the curve. The rumble strips and markings are discontinued at the intersection, as seen in Figure 61. Using smooth lane narrowing on intersection approaches has been found to reduce all crashes by 32 percent and fatal and injury crashes by 34 percent. Additionally, 85th percentile speeds were reduced by roughly 5 mph. More information on the design of smooth lane narrowing can be found in *Crash Impacts of Smooth Lane Narrowing with Rumble Strips at Two-Lane Rural Stop Controlled Intersections*.

Figure 60. Photo. Pavement markings narrow the travel lane as the driver approaches the intersection.

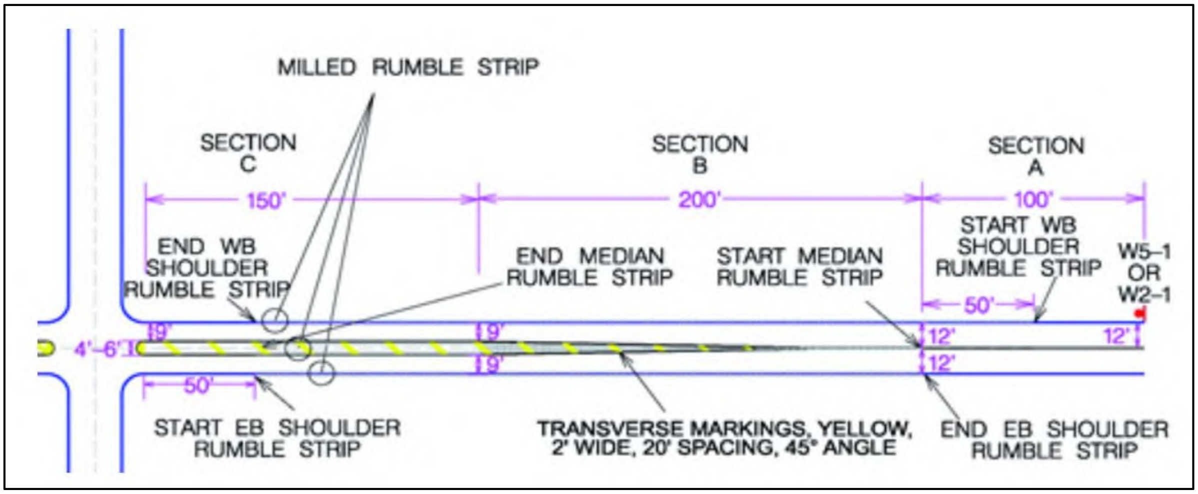


Figure 61. Illustration. Smooth lane narrowing typical design.

ADDRESSING VISIBILITY ISSUES

Intersections often pose challenges to drivers who do not always see traffic approaching. If there is horizontal or vertical curvature near the intersection, this increases the difficulty. Standard intersection practices may need to be adjusted when there are alignment changes, and treatments that improve intersection visibility may prove even more beneficial at curves with intersections.

Visual Traps

A visual trap occurs when the road curves, but visual cues such as breaks in the tree line or the continuation of power poles lead a driver to think the road continues straight. An example of this is illustrated in Figure 62. Frequently, a roadway that intersects the curve is one of the visual miscues. In such cases, additional emphasis should be placed on warning the driver and delineating the curve to overcome the driver expectation of a tangent roadway. Delineators, chevrons, or pavement marking signs are treatments appropriate to address this issue. Also, advanced markings within the lane may be appropriate. See Chapter 3 and 4 for additional information on use of these treatments.

Figure 62. Photo. An example of a visual trap exists when a crest vertical curve blocks the view of the upcoming horizontal curve (top photo). What appears to be a continuation of the road in the distance is actually an intersecting roadway in the midst of a curve (bottom photo).

Intersection Sight Triangles

In the typical rural curve with an intersection, the minor road will be stop-controlled. Assuming the intersecting roadway is aligned perpendicular to the curve of the main roadway and is at or near the center of the curve, the sight distance issues on the outside of curve are similar or perhaps even better than for a tangent roadway section. Providing appropriate sight triangles will often be adequate. The intersection on the inside of the curve, however, is restricted by the geometry and requires the driver to have more mobility to see over-the-shoulder to view oncoming traffic, as seen in Figure 63. If the intersection is not near the center of the curve, sight triangles may cut across the curve and require significantly more clearing, as illustrated in Figure 64. If the terrain is not flat, it may be necessary to cut into slopes to provide the adequate minimum intersection sight distance. The use of and location of guardrails on grades should also be considered as it could interrupt the sight lines for intersections in and near curves.

Figure 63. Photo. Sight distance is limited due to the intersection being inside the curve.

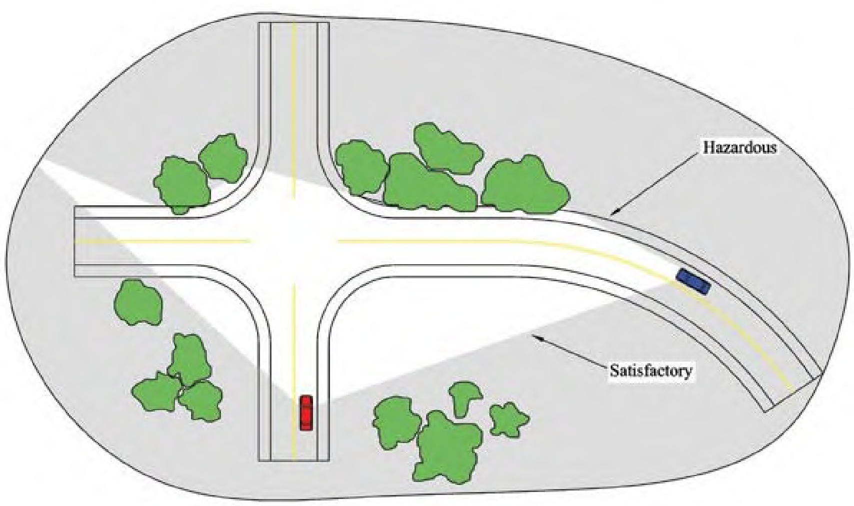


Figure 64. Illustration. Limiting the growth of vegetation is important to maintain appropriate sight triangles.

Where providing the appropriate intersection sight distance is not feasible, the intersection may need to be re-configured. In certain limited cases, an “All-Way” stop-controlled intersection may be appropriate. Careful consideration to speeds and traffic volumes are appropriate before making the decision to change the intersection to an “All-Way STOP.” Typically a roundabout would be preferred to this type of control.

Intersection Conflict Warning Systems (ICWS)

Another option for an intersecting roadway with limited sight distance is a dynamic warning sign as shown in Figure 65. The ICWS can be designed to either detect vehicles on the minor road and indicate their presence to drivers on the main road, or indicate to the driver on the minor road when there is oncoming traffic on the mainline. The CMF Clearinghouse lists a 32-percent reduction for all crash types when installing a "Vehicles Entering When Flashing" system (advanced post-mounted signs on the major road and detection loops on the minor road) at stop-controlled intersections (CMF is 4 stars) (Simpson and Troy, 2013). This CMF applies to intersection-related crashes, but does not explicitly consider intersections located along horizontal curves. More information on this treatment may be found in *Stop-Controlled Intersection Safety Through Route Activated Warning System*.

Figure 65. Photo. A dynamic warning sign alerts drivers in real time of other users in the roadway.

Lighting

The presence of lighting has been shown in improve safety at intersections. The INDOT study of intersections with curvature found that crashes tended to be overrepresented during nighttime conditions (Savolainen and Tarko, 2004). The effect of lighting is generally limited to nighttime crashes, since lighting does not generally improve daytime visibility. The CMF Clearinghouse indicates that the presence of intersection lighting is associated with an 11.9-percent reduction in total nighttime crashes (CMF is 3 stars) (Donnell et al., 2010). The presence of fixed illumination is associated with a 2-percent increase in total daytime crashes on rural roadways (CMF is 2 stars) (Bullough et al., 2012), presumably due to the presence of fixed objects near the intersection.

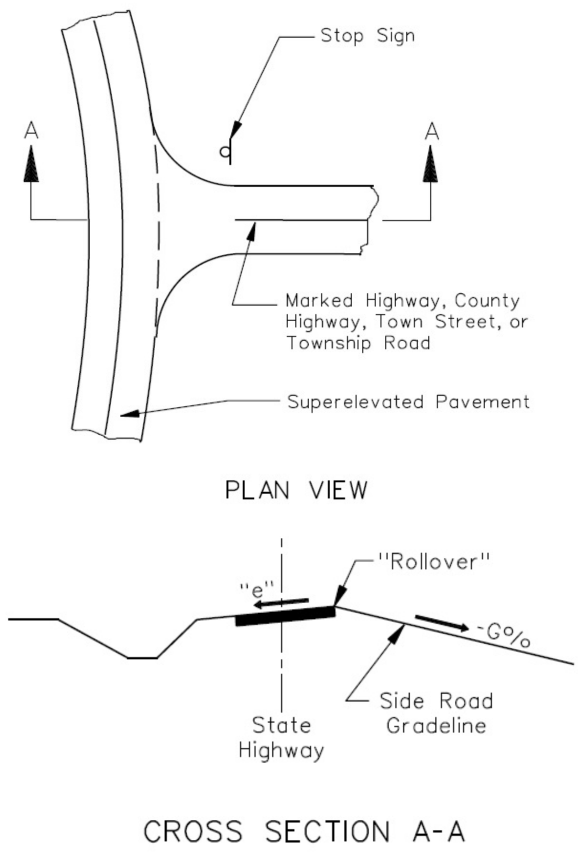
PAVEMENT IMPROVEMENTS

Improve Friction

HFST are particularly beneficial at horizontal curves with an intersection. The treatment, which is described in detail in Chapter 5, may need to be extended depending on the location of the intersection within the curve. In addition, it may be appropriate to extend the treatment to the minor road if it has a high speed approach or crashes indicate a need.

Adjust Superelevation for an Intersecting Roadway

When an intersecting roadway is within the curve, adjustments need to be made to superelevation. This is different than the corrections to superelevation that was discussed in Chapter 5. State design manuals often provide guidance on how to accomplish this, such as the example in Figure 66 provided by Illinois DOT.



Type of Improvement Category	Maximum Superelevation Rate "e" for Intersections on Curve	Rollover Guidelines
"New Construction" at an important crossroad	4% Desirable Maximum	5% Desirable Maximum 6% Maximum
To remain in place with "Reconstruction" at an important crossroad	6% Maximum	7% Desirable Maximum 8% Maximum
To remain in place with "Reconstruction" at a minor crossroad	8% Maximum	9% Desirable Maximum 10% Maximum

Figure 66. Illustration. Excerpt showing the design of superelevation from Figure 36-1.E of Illinois DOT's Bureau of Design & Environmental Manual. Source: Illinois DOT.

Pave Intersection Approach on Gravel Roads

When the road intersecting the curve is unpaved, the result is often either a drop-off at the edge of the pavement or aggregate from the unpaved road gets on the paved portion of the curve. When there is a drop-off, the resulting issue is described in Chapter 4. Loose aggregate on the paved portion of the roadway can result in reduced friction between vehicle tires and the pavement. A solution that can be used for both of these issues is to pave a portion of the approach on the leg of the intersection that is unpaved, as illustrated in Figures 67 and 68.

Figure 67. Photo. Intersection with paved approach.

Figure 68. Photo. Intersection with aggregate scattered on paved roadway.

CHANGING INTERSECTION CONFIGURATION

When an intersection is at or near a horizontal curve, it is not uncommon for the location or the configuration of the intersection to cause safety concerns. The issue may be traffic on the major road not seeing or recognizing that a vehicle ahead is stopped while waiting to turn. Or, drivers on either the major or minor road may have difficulty seeing each other due to the alignment, as shown in Figure 69. Low-cost solutions cannot always address these stated intersection sight distance concerns. When considering higher cost solutions, it is important to address the most severe and more frequent crash types.

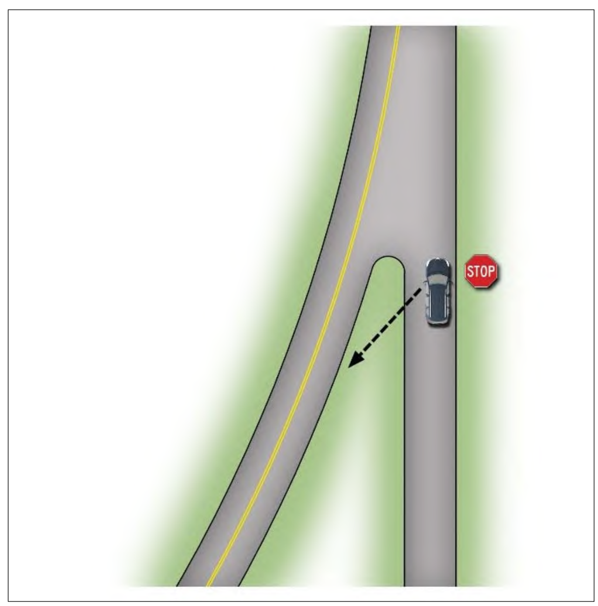


Figure 69. Illustration. Intersection with a skewed approach with an arrow indicating the driver's line of sight.

Roundabouts

Roundabouts are one of the most efficient ways to reconfigure an intersection, particularly when there is existing curvature. A roundabout is a circular intersection with yield control for all legs approaching the intersection. As illustrated in Figure 70, roundabouts typically provide the most efficient flow of traffic, reduce severe crashes, and can often be built at the same or lower cost than the more traditional options discussed below.

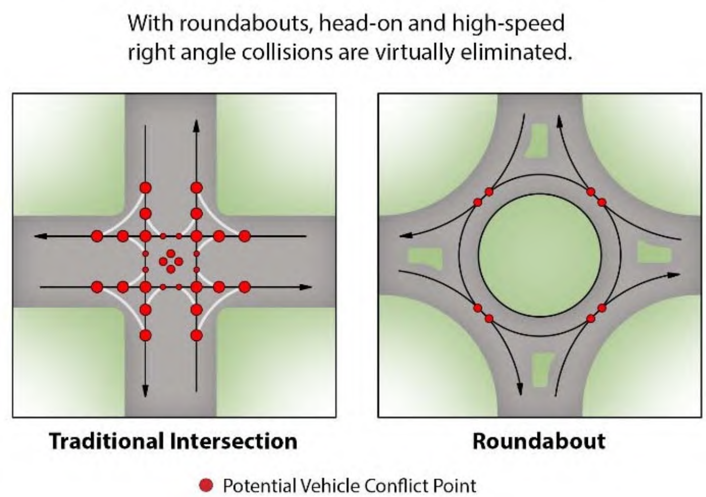


Figure 70. Illustration. Comparison of potential conflict points between a traditional intersection and roundabout.

Roundabouts use roadway curvature and islands to reduce speeds of approaching vehicles. Most importantly, roundabouts reduce the points of conflict. Drivers need only check for traffic on their left before entering the circulating roadway. Crash types within a roundabout tend to be sideswipe and rear-end, which are typically less severe than the angle crashes that are more common at a traditional intersection. Severity is also typically reduced because speeds are slower at a roundabout. Traffic flow is smooth because each approaching vehicle only waits if there is a not an opening in within the circular portion of the roadway.

Where a skewed intersection currently exists—which is common within horizontal curves—redesigning the intersection with a roundabout allows more flexibility in alignment than the standard practice of realigning the minor roadway to make the intersection perpendicular (shown in Figures 71, 72, and 73). In addition, the roundabout will typically result in significantly greater crash reductions because all turning movements at the intersection are safer due to the reduced speeds and conflict points. The *HSM* states that by converting from a two-way stop control mechanism to a roundabout, a location can experience an 82-percent reduction in severe (injury/fatal) crashes and a 44-percent reduction in overall crashes. It also indicates that by converting a signalized intersection to a roundabout, a location can experience a 78-percent reduction in severe (injury/fatal) crashes and a 48-percent reduction in overall crashes (AASHTO, 2010).

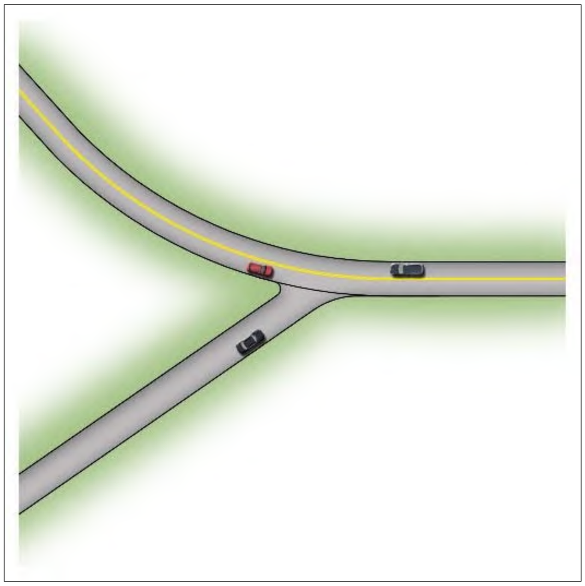


Figure 71. Illustration. Typical skewed intersection within a curve.

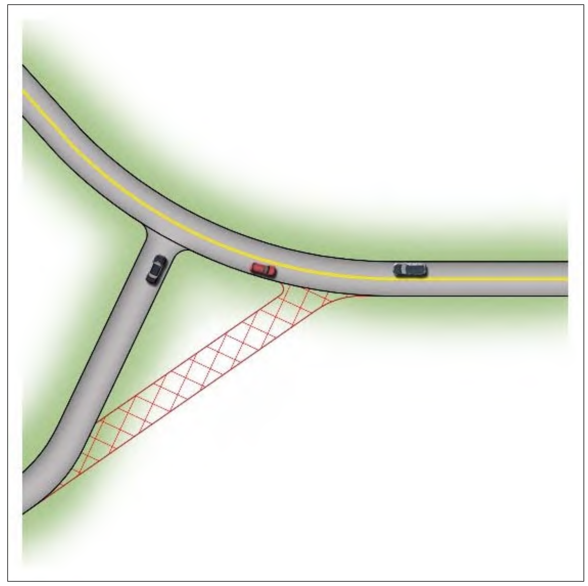


Figure 72. Illustration. Re-aligning a skewed intersection to provide a perpendicular intersection.

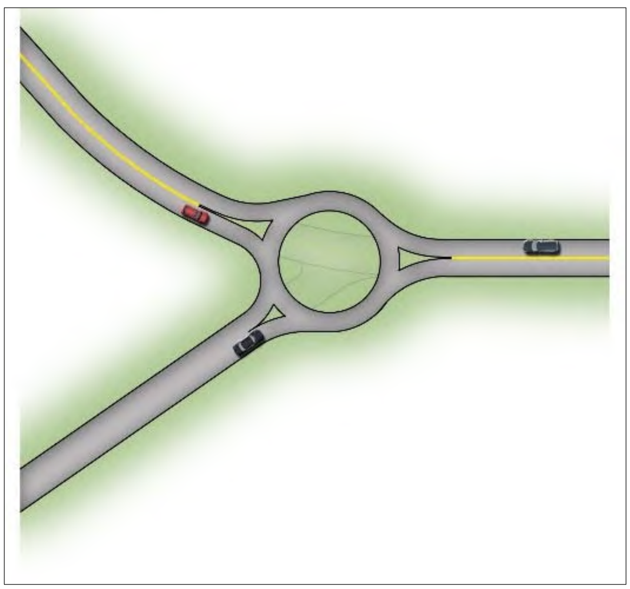


Figure 73. Illustration. Reconfiguring the intersection with a roundabout.

Add Turn Lanes

If turning movements at the intersection within a horizontal curve are the primary safety concern and a roundabout is not feasible to resolve the issue, adding turn lane for the primary turning movement may resolve the problem. Left turn lanes on the major roadway remove turning vehicles from the high-speed through lane. If existing widths allows room to change the lane configuration with little or no additional pavement widening, restriping to add turn lanes can be very cost effective. The CMF Clearinghouse indicates that providing a channelized left-turn lane at a three-leg intersection on the major-road approach is associated with a 27-percent reduction in all crashes (CMF is 3 stars) (Elvik and Vaa, 2004). The CMF Clearinghouse also indicates that providing a right-turn lane on one major approach to a stop-controlled intersection is associated with a 14-percent reduction in all crashes (CMF is 3 stars) (Harwood et al., 2002). While these are not specifically for intersections within curves, it would be expected that intersections within curves would experience the same benefits in safety.

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GLOSSARY

Term	Description
Acrylic material	Binder material used in high friction surface treatment that holds the aggregate firmly to the pavement.
ADT	Average Daily Traffic – the traffic volume of a road measured in vehicles per day.
Advisory speed plaque	A sign that is placed below a Horizontal Alignment sign to advise motorists of the safe speed through the curve.
Ball bank indicator	An inclinometer that is used for determining safe curve speeds for horizontal curves.
Cable barrier	A flexible barrier made from wire rope supported between frangible posts.
Calcined bauxite aggregate	A hard, coarse aggregate used in high friction surface treatment.
Clear Zone	The unobstructed traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles, as defined by AASHTO.
CMF	Crash Modification Factor – a multiplicative factor used to compute the expected number of crashes after implementing a countermeasure.
CMF Clearinghouse	A website that provides the largest collection of CMFs for geometric design elements and traffic control devices available in the United States.
Compound curves	Two or more tangential, consecutive curves.
Concrete safety shape	A rigid barrier that does not deflect.
Curve delineation	Treatments that enhance the conspicuity of a curve (e.g., wider edge line, higher retroreflectivity of signs, post-mounted delineators, chevrons, raised pavement markings).
Delineators	A device mounted above the roadway surface and along the side of the road in a series to indicate roadway alignment.

Epoxy material	Binder material used in the application of high friction surface treatment that hold the aggregate firmly to the pavement.
FARS	Fatality Analysis Reporting System – a nationwide census providing annual data regarding fatal injuries in motor vehicle traffic crashes.
Guardrail	A semi-rigid barrier usually either a steel box beam or W-beam that deflect less than flexible barriers.
HFST	High Friction Surface Treatment – a thin layer of aggregate bonded to the pavement surface designed to increase friction and compensate for sharp curves.
Milled	Milled rumble strips are made by a machine with a rotary cutting head, creating a smooth, uniform, and consistent groove in the pavement. They cause tire noise and vehicle vibration when traversed.
MUTCD	Manual on Uniform Traffic Control Devices – defines the standards used by road managers nationwide to install and maintain traffic control devices on all public streets, highways, bikeways, and private roads open to public traffic.
Pavement grooving	A pavement countermeasure technique to apply longitudinal or transverse cuts onto the pavement surface to increase or restore pavement friction.
Pavement raveling	Deterioration of the pavement surface caused by aggregate particles becoming dislodged.
Retroreflective	A material or device that reflects light back to its source.
RSA	Road Safety Audit – a formal safety performance examination of an existing or future road or intersection by an independent, multidisciplinary team.
Safety Edge℠	A paving technique used system-wide to improve pavement durability and reduce crashes by shaping and consolidating the pavement edge into a 30 degree wedge.
Superelevation	The banking of a horizontal curve.

Systemic approach	The analysis of crash data on a system-wide basis that considers identifying factors that indicate higher risks for severe crashes.

APPENDIX A: LOW-COST SAFETY IMPROVEMENTS IN PENNSYLVANIA

BACKGROUND

A higher percentage of fatal curve-related crashes occur on rural roads—particularly on two-lane rural roads—due largely in part to the predominance of horizontal curves on typical rural roads. In 2013, more than 13 percent of fatal crashes in Pennsylvania occurred due to Curve Driver Error Crashes, many of which involved roadway departures. To address curve-related crashes, the Pennsylvania Department of Transportation (PennDOT) provided guidance to the districts on the implementation of enhanced sign and marking improvements for curves that exhibit a higher than expected crash frequency. PennDOT identified priority curves by examining crash frequency, crash rate, and crash severity.

Figure A-1. Photo. An orange flag supplementing the reverse curve warning sign and speed advisory plaque. Chevrons were also used to delineate the curve.

PROGRAM DETAILS

Pavement markings in advance of horizontal curves provide additional warning information, and can also be considered at curve locations where signs alone have been shown to be insufficient. Systematic implementation of improvements on curves is taking place throughout Pennsylvania and include one or more of the following strategies:

- Oversized fluorescent yellow advance curve warning signs that could be doubled up (i.e., both sides of the roadway), with optional flashing yellow LED solar powered beacons.
- Advanced curve pavement markings including a “SLOW” legend or “XX MPH” advisory speed marking as an alternate. *(NOTE: Since the PennDOT program began, the* NCHRP Report 600 *has since been released and contains design guidelines as to which markings are effective in reducing speeds at horizontal curves and which markings are not as effective (p. 20-4)).*
- Correction of any shoulder drop offs within the curve.
- Chevron delineation around the curve.
- Curve widening.

PennDOT estimates there have been between 500 to 600 applications of the low-cost safety improvements throughout the State, many of which have been State funded.

RESULTS

PennDOT Districts have found this combination of treatments, when utilized correctly, effectively contributes to combatting curve-related crashes. Data suggests these safety treatments have improved safety on specifically identified horizontal curves. Overall, Curve Driver Error Crashes have fallen from a five-year average of 6,798 in 2007 to 5,060 in 2012. A three-year before/after analysis of locations where a combination of these countermeasures were implemented between 2000 and 2008 resulted in the following:

- Decrease in overall crashes from 1,452 to 1,200 (17-percent reduction).
- Decrease in fatal crashes from 27 to 15 (44-percent reduction).
- Decrease in major injury crashes from 65 to 39 (40-percent reduction).

When the treatment was first introduced, there were concerns of motorcycles slipping on the paint (2001); but over time, the treatments have become widely accepted and the general public have not voiced any other concerns.

CONSIDERATIONS

PennDOT stresses the importance of sound engineering judgment when selecting the combination of countermeasures for implementation. Additionally, speed limit compliance, geometric features of the curve, sight distance, and traffic volume must be taken into consideration when implementing this treatment. Finally, high friction surface treatment should be considered as another possible countermeasure where wet pavement/curve related crashes occur at a higher rate.

As noted, *NCHRP Report 600* has since been released and contains design guidelines as to which markings are effective in reducing speeds at horizontal curves and which markings are not as effective.

CONTACT INFORMATION

The Traffic and Safety Section of PennDOT provided the information for this case study. Visit http://www.penndot.gov/ for more information. All images are courtesy of PennDOT.

APPENDIX B: SYSTEMIC IMPROVEMENTS IN MINNESOTA

BACKGROUND

Horizontal curves only comprise 10 percent of the rural roadway network in Minnesota; yet from 2003 to 2011, 20 percent of crashes occurred on curves (when reviewed in five-year increments). The crash data revealed that over 25 percent of the fatal and serious injury crashes occurred at curves. Moreover, over 30 percent of the fatal and serious injury roadway departure crashes occurred at curves.

In 2007, the Minnesota Department of Transportation (MnDOT) completed and delivered the first phase of County Safety Plans and District Plans in an effort to improve curve safety. MnDOT started with studies in Olmsted County in Southern Minnesota, and then expanded to 20 other counties and eventually, all 87 counties. The first phase of the analysis examined data from 2003-2007 and revealed there were nearly 6,900 curves in the State, 77 fatal crashes, 150 A injury (serious) crashes, 349 B injury (moderate) crashes, 394 C injury (minor) crashes, and 1,117 Property Damage Only (PDO) crashes. It took approximately three years to complete the analysis process and the data range kept moving as data became available. The final analysis used county data from 2007-2011. From the analysis, MnDOT identified five risk factors these high-crash curves had in common, including:

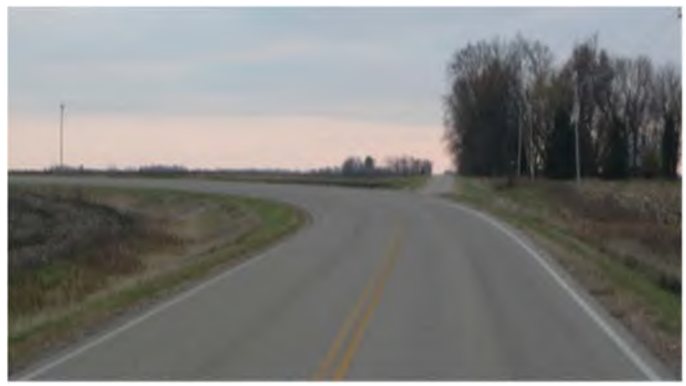

Figure B-1. Photo. Example of a visual trap; one of MnDOT's five risk factors for horizontal curves.

1. Radii, typically between 500 and 1,200 feet.
2. Average Daily Traffic (ADT) volume between 500 and 1,000 vehicles per day, depending on the region.
3. Intersection in the curve.
4. Presence of a visual trap.
5. Prior crash history (i.e., if the curve has had a severe crash in the study period).

Beginning in 2010, action was taken to address the curves that exhibited three or more of the five risk factors with the systemic approach to reduce crashes (http://safety.fhwa.dot.gov/systemic).

PROGRAM DETAILS

Despite some hesitancy to supplement the traditional reactive approach to safety with a proactive approach, the program was launched in all 87 counties and 8 districts in 2010. MnDOT has also since recommended treating thousands of curves on state-maintained roads.

County and district traffic engineers are provided a list of high risk curves and recommended potential project types to select from. Based on that list, each county and district is responsible for submitting candidate projects and, if selected, contract and construction administration on their system.

As part of their systemic program, MnDOT has recommended installing several countermeasures including edge line and center line rumble strips, advanced signing, 2-foot shoulder paving adding rumble strips and Safety Edge[SM], 6-inch edge lines, intersection lighting when there is an intersection in a curve, and delineators. Chevrons have been the most commonly installed countermeasure as part of this program. The districts received funds from direct capital funds, Highway Safety Improvement Program (HSIP), and Section 164 safety funds. Counties received funding from HSIP in addition to their own capital program. MnDOT's "sharing" of the Federal HSIP funds with local agencies was critical to the success of the program. Without those funds the plans would not have been able to be implemented on the county/local system.

Figure B-2. Photo. MnDOT installed chevrons as part of their Systemic Safety Improvements Program.

RESULTS

Minnesota has recorded a drop in roadway departure crashes from 2009 to 2013. Although definitive data are not yet available, it is assumed that the systemic safety improvement program contributed to the decrease in crashes. Detailed information about the performance of individual curves will be needed in order to further quantify the program effectiveness. Additionally, the general public has provided MnDOT with unsolicited positive feedback in response to the treatments, especially regarding the chevrons, enhanced (6-inch) edge lines, and lighting.

CONSIDERATIONS

MnDOT noted that effective communication with the general public and local agencies has played a large part of the program's success. The approval of the public is a crucial aspect of moving a program from idea to reality. MnDOT noted that while the Highway Safety Manual (*HSM*) is an important tool for modeling to show proposed projects' safety benefits, the general public do not generally have the background knowledge to understand the methodology. They may even become suspicious that the agency is masking information or motivations behind the numbers. MnDOT showed consideration for the public by creating programmatic goals and objectives that were accessible and easy to understand, which in turn contributed to the public's support of the program.

CONTACT INFORMATION

Brad Estochen and Derek Leuer from MnDOT provided the information for this case study. Visit http://www.dot.state.mn.us/ for additional information. All images are courtesy of MnDOT.

APPENDIX C: APPLICATION OF EDGE LINES IN MISSOURI

BACKGROUND

Horizontal curves are the primary location for roadway departure crashes in Missouri—accounting for approximately two-thirds of the run-off-road crashes in the State. The Missouri Department of Transportation (MoDOT) is responsible for over 33,000 centerline miles of roadways; and in an effort to address this problem, the agency proposed using a systemic safety approach to add an edge line to many of the two-lane rural roads in 2008. With approximately 18,000 miles of roadway on the Missouri State system that carry less than 1,000 vehicles daily, MoDOT was limited by budgetary restraints to restripe every mile. Therefore, MoDOT needed a way to prioritize the roads in need of improvement.

PROGRAM DETAILS

MoDOT chose to apply an edge line stripe to state-maintained roads with an Annual Average Daily Traffic (AADT) volume between 400 to 1,000 vehicles per day. Roads with an AADT greater than 1,000 vehicles per day were assumed to already have an edge line, while roads with an AADT less than 400 vehicles per day were assumed to only have a center line stripe (which is sufficient for a low volume road).

Figure C-1. Photo. Application of edge line at a horizontal curve.

Once MoDOT identified the treatment locations, they were able to move the process forward by first changing internal policy and receiving management approval. The next step was for individual districts to provide estimated initiation timelines and completion dates for the project. One district in particular was ambitious and completed their striping within one year.

All Missouri districts are now required to restripe every other year but are not required to take on additional miles below the 400 vehicles per day AADT threshold.

RESULTS

A simple before-after analysis of the locations treated with an edge line stripe showed a total of 576 crashes from 2006 to 2008—105 of which involved a fatality or severe injury. After edge lines were added to these roadways, the two-year after data (2010-2011) showed that total crashes decreased 43 percent to 327 crashes, and crashes involving a fatality or severe injury decreased 56 percent to 46 crashes. A more sophisticated empirical Bayes analysis found that the addition of edge lines reduced total crashes for all crash types by 15 percent. The analysis also revealed that the treatment reduced severe crashes by 19 percent. MoDOT utilized the Systemic Safety Project Selection Tool for the evaluation.

MoDOT has not received any negative feedback regarding the new edge lines from the general public or local agencies.

CONSIDERATIONS

MoDOT recommends that agencies use a systemic approach to safety, especially with regards to edge lines. Since it is not feasible to stripe and maintain every road in the State, MoDOT suggests treating sites with higher volumes as those roads will have a greater probability of a crash occurring. The improvement process should be data-driven to ensure justification of location prioritization. The local county agencies would benefit from installing edge lines on their roadway system, even though they lack the data to properly identify the roads that may warrant the treatment.

CONTACT INFORMATION

John Miller from MoDOT provided the information for this case study. Visit http://www.modot.org/ for more information. All images are courtesy of MoDOT.

APPENDIX D: UPGRADING CURVE SIGNING IN OHIO

BACKGROUND

Over 50 percent of Ohio's fatalities involve roadway departure—many of which were a result of high-speed lane departure crashes on the State's rural roads. In response to this issue, the Ohio Department of Transportation developed a systemic program to address roadway departures at curves. In 2010, Ohio DOT introduced a Horizontal Curve Program for state-maintained roads. The agency focused their efforts on upgrading and installing various signage at curves to address the problem. Ohio DOT chose these countermeasures due to the low-cost and their ability to be installed at hundreds of locations by all 12 districts in the State. Ohio oversees 42,250 interstate, U.S., and State route lane miles and maintains approximately 500,000 signs. The 12 districts within Ohio DOT are responsible for maintaining State and Federal roadways. The program was widely accepted by the districts in Ohio, seeing it as a realistic and achievable step to address the high number of fatalities and injuries prevalent along curves. Much of the success of the program can be attributed to effective communication and coordination between the central Ohio DOT office and the districts.

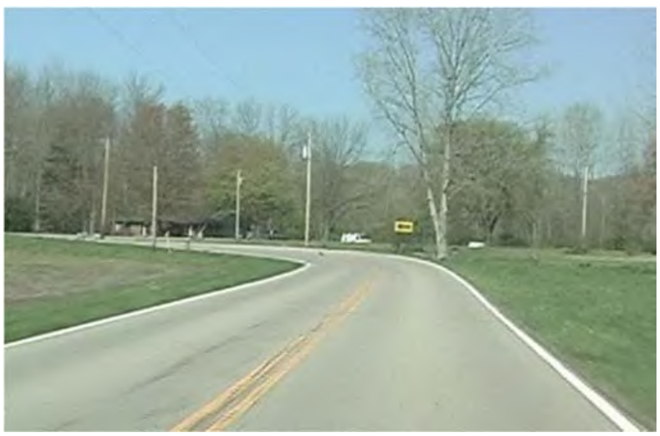

Figure D-1. Photo. A curve on a rural, two-lane road before signage updates through the Horizontal Curve Program.

Figure D-2. Photo. A curve on a rural, two-lane road after signage updates through the Horizontal Curve Program.

PROGRAM DETAILS

To facilitate implementation for the districts, Ohio DOT's central office in Columbus provided each district a list of curve locations ranked by crash frequency. A total of 576 sites were selected by using a threshold of 6 or more crashes over a 5-year period on 0.3 mile segments to flag problematic locations. Next, individual districts conducted site field reviews, evaluated existing conditions and countermeasures onsite, and selected the appropriate signs to be installed at the site. The first round of upgrading curve signage began in 2010 and the districts used funds from High Risk Rural Roads or Highway Safety Improvement Program. Ohio DOT's systematic program is currently implementing additional curve sign upgrades that were developed through an FHWA Roadway Departure Plan, a 2-year program will finish in summer 2015. This effort is funded through other Federal safety dollars that are set aside from Ohio DOT's safety program total each year specifically for systemic improvements.

RESULTS

As of late 2014, Ohio DOT is in the process of analyzing the safety effectiveness of the sign upgrades, starting with the locations treated in 2010. The results of the signage upgrade from the Horizontal Curve Program have been received positively by the general public and local agencies alike. The districts noted that treating problematic curves is easy to implement when the central DOT office provides them with the necessary tools (i.e., the list of high-crash curves and sign order forms). Also, drivers are pleased that the signs provide proper guidance around curves, especially at nighttime.

CONSIDERATIONS

A key aspect of the program's success is the cooperation between the DOT main office and the individual State districts. The central DOT office supplies the data, which allows the districts to focus time and staff on site visits and implementation of the appropriate solutions. For agencies considering a similar program, Ohio DOT emphasized the importance of having a data-driven program. Crash data enables Ohio DOT to generate the crash lists and prioritize locations for Districts to address.

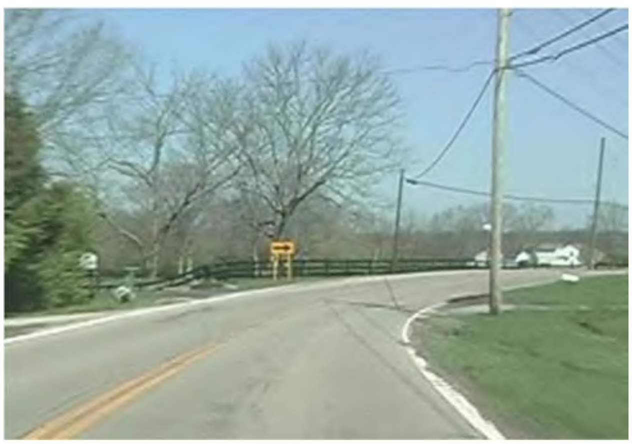

Figure D-3. Photo. A curve on a rural, two-lane road before signage updates through the Horizontal Curve Program.

Figure D-4. Photo. A curve on a rural, two-lane road after signage updates through the Horizontal Curve Program.

CONTACT INFORMATION

Michael McNeill from Ohio DOT provided the information for this case study. Visit http://www.dot.state.oh.us/ for more information. All images are courtesy of Ohio DOT.

APPENDIX E: APPLICATION OF SEQUENTIAL DYNAMIC CURVE WARNING SYSTEMS (SDCWS)

BACKGROUND

Roadway departure crash rates are three times higher at horizontal curve locations relative to tangent segments of roadway. Sequential Dynamic Curve Warning Systems (SDCWS) have been implemented as a countermeasure on two-lane rural highway curves as a means to reduce vehicle operating speeds and improve curve delineation. The anticipated benefit of implementing SDCWS is reductions in total and severe crashes.

COUNTERMEASURE DETAILS

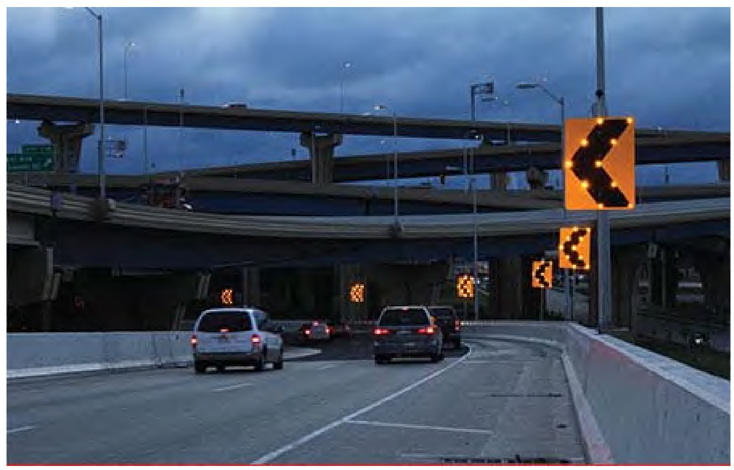

Figure E-1. Photo. SDCWS.

SDCWS are horizontal curve chevron signs with solar powered flashing lights embedded in the sign. The flashing lights can be simultaneous (i.e., each sign is flashing at the same time as the other signs); or, more often, there may be a pattern associated with the flashing lights (i.e., a sequence of lights moving toward or away from the driver). In the latter case, this is typically accomplished by having each sign flash at least once per second, with each flash lasting at least 100 milliseconds. Each sign begins flashing at a time that is offset relative to the adjacent sign, producing a sequential flashing effect.

The States of Missouri, Texas, Washington, and Wisconsin collectively installed 12 TAPCO SDCWS's along horizontal curves on two-lane rural highways as part of an FHWA Highways for Life evaluation. Because there were only 12 SDCWS locations included in the study sample, only one manufacturer's product was selected for implementation in the evaluation to ensure consistency in system design and application. The TAPCO system was selected as a typical representation of SDCWS's. The study sites were identified based on a high-crash history, as well as vehicle operating speeds that exceeded the advisory (if present) or posted speed limit.

All curves selected for treatment with SDCWS were on a two-lane rural paved road and have the following:

- A posted speed limit of 50 mph or higher.
- Existing chevrons.
- No railroad crossing or major access points within the curve.
- At least 10 non-animal related crashes in the previous 5 years (preferably high-speed related crashes),

- No major rehabilitation or changes in alignment in the previous 5 years,
- No rehabilitation or alignment changes planned in the 2 years following installation of the SDCWS.

All installations of SDCWS at the curves occurred between June and September of 2012. A total of 24 similar horizontal curves in the same States were used as a control group, without SDCWS.

Speed data were collected before installation, and 1, 12, 18, and 24 months after installation of the SDCWS. Crash data were also compiled for each of the SDCWS and control sites, including five years before and two years after implementation.

RESULTS

The results showed that vehicle operating speeds were lower at the beginning and midpoint of horizontal curves for all periods after the SDCWS were installed. The mean and 85th-percentile speeds were 1.1 to 1.7 mph lower in the 1, 12, 18, and 24 month periods after installing the SDCWS. The results were generally consistent when comparing speeds at the beginning and the midpoint of horizontal curves. The percentage of vehicles exceeding the posted and advisory speed limits was also lower after installing the SDCWS, and results were generally consistent across all time periods after implementation. The change in the fraction of vehicles exceeding the advisory speed by 20 mph or more decreased by an average of 32 percent at the beginning of the horizontal curve. Similarly, the change in the fraction of vehicles exceeding the advisory speed by 15 mph or more decreased by an average of 30 percent at the beginning of the horizontal curve. The fraction of vehicles exceeding the advisory speed by 20 mph or more at the midpoint of the curve decreased by 26 percent, while the fraction of vehicles exceeding the advisory speed by 15 mph or more declined by 16 percent after SDCWS installation. The results of the study suggest that SDCWS have long-term and consistent effect on vehicle operating speeds. While the magnitude of the effect was relatively small, there was a pronounced effect on those vehicles substantially exceeding the advisory speed.

With regards to safety, a simple before-after analysis of crash data found that the total number of crashes per year declined by 17 to 91 percent at 7 locations after the SDCWS was installed. At 2 sites, the total number of crashes per year increased by 7 and 11 percent. At three locations, no crashes were reported after the SDCWS were installed, so simple before-after safety comparisons could not be made. Research is underway to develop crash modification factors for SDCWS.

CONSIDERATIONS

The research referenced in this case study identified candidate sites for the SDCWS based on high crash histories (at least 5 crashes in previous 5 years) and excessive speeds on the same horizontal curves. Excessive vehicle operating speeds were defined as those with either of the following conditions:

Mean speed exceeded the advisory speed limit by 5 mph or more, or, if an advisory speed was not posted, exceeded the posted speed limit by 5 mph or more.

85th percentile speed exceeded the advisory speed limit by 5 mph or more, or exceeded the posted speed limit by 5 mph or more, if an advisory speed was not present.

A radar device on the sign can detect vehicles 300 feet in advance of the horizontal curve. The SDCWS is set to activate only when it detects approaching vehicles exceeding a certain speed threshold. The threshold is commonly at or slightly below the advisory speed of the curve. A wireless communication system maintains synchronization among the chevron signs within the system.

CONTACT INFORMATION

Julie Zirlin at the FHWA provided information for this case study. Visit https://www.fhwa.dot.gov/accelerating/ for more information. Images are courtesy of FHWA.

REFERENCES

Smadi, O., N. Hawkins, S. Hallmark, and S. Knickerbocker. *Evaluation of the TAPCO Sequential Dynamic Curve Warning System*. Report No. FHWA-HIF-13-040, Federal Highway Administration, Washington, DC, June 2013.

Smadi, O., N. Hawkins, S. Knickerbocker, S. Hallmark, and A. Pike. *Evaluation of the TAPCO Sequential Dynamic Curve Warning System*. Report No. FHWA-HIF-13-040, Federal Highway Administration, Washington, DC, June 2013.

APPENDIX F: APPLICATION OF HIGH FRICTION SURFACE TREATMENT IN KENTUCKY

BACKGROUND

Between 2004 and 2008, more than 60 percent of all fatal crashes on Kentucky's roads were roadway departure crashes. In an effort to address this, the Kentucky Transportation Cabinet (KYTC), in conjunction with the Federal Highway Administration (FHWA), developed the *2009 Kentucky Roadway Departure Safety Implementation Plan,* which established a strategic approach to reducing the number of roadway departure crashes on State roads. This statewide program is funded through the Highway Safety Improvement Program. As of summer 2014, KYTC has applied High Friction Surface Treatments (HFSTs) at more than 100 sites—many at locations that present multiple risk factors, such as multiple curves.

PROGRAM DETAILS

As part of the Roadway Departure Safety Implementation Plan, KYTC applied HFST to a number of state-maintained curves and ramps. HFSTs are a thin layer of specially engineered, durable, high friction aggregates placed as a topping on a polymer binder. These aggregate systems have long-lasting skid resistance and make the overlay more resistant to wear and polishing. Additional details are available at EDC 2012 Initiatives – High Friction Surface Treatment.

KYTC initially used a "black spot" approach to select treatment sites—selecting sites that had experienced the highest number of overall crashes. After this initial effort, KYTC continued to identify additional locations in need of improvement. KYTC regularly performs a screening prioritization, which scans the entire roadway network to identify wet-road crashes for additional candidates for HFST. After the site evaluation, pavement condition is examined for HFST application feasibility.

Figure F-1. Photo. A truck in the process of applying HFST to a curve.

In 2014, Kentucky updated the *Roadway Departure Safety Implementation Plan* and now uses a *Highway Safety Manual* (*HSM*) methodology to identify roadway segments and ramps as candidates for surface treatment. KYTC develops Safety Performance Functions and uses an empirical Bayes method to help identify curves/ramps that are candidates for surface treatment. More information is available at Introduction of Safety Performance Functions.

RESULTS

Almost immediate positive impacts were experienced at the 30 initial sites KYTC applied HFST. And multiple sources provided positive feedback on the program, including drivers, governing agencies, and policy makers. Data have shown a 70- to 75-percent reduction in crashes at the treated sites. Due to this success, several local agencies have expressed interest in implementing HFSTs.

One site in Fayette County—Exit 113 on Interstate 75—is illustrative of this success. In the 3 years prior to HFST treatment, the ramp had 28 roadway departure crashes (18 wet crashes and 10 dry crashes). In the two and half years since the HFST installation, crashes have nearly been eliminated and the ramp has been the scene of a single crash, which was a dry crash. Ramp signage was also updated at the same time as the HFST installation.

CONSIDERATIONS

KYTC did not have outside guidance when it first began applying HFSTs due the relative newness of the treatment. Despite this, KYTC was able to apply numerous surface treatments in a short amount of time. KYTC staff suggests that other agencies should take the time to complete a thorough evaluation of each site when considering HFSTs. Also, agencies should implement a hierarchy of countermeasures, such as:

- Consider repaving.
- Apply alternative surface treatment.
- Consider other non-pavement treatments.
- Apply high friction surface treatment, if necessary.

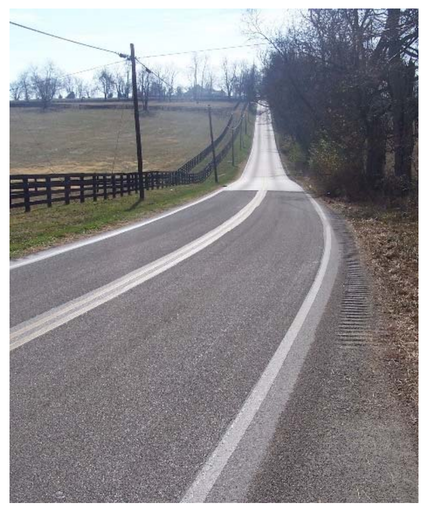

Figure F-2. Photo. A horizontal curve with HFST.

KYTC is pleased with the program and will continue to address the safety of curves and ramps with the *HSM* methodology. The application of HFST successfully decreased roadway departures and consequently, serious injuries and fatalities in Kentucky. With the help of Kentucky's leadership in the Roadway Departure Safety Plan, HFSTs are growing in popularity across the nation.

CONTACT INFORMATION

Tracy Lovell from the KYTC provided the information for this case study. Visit http://transportation.ky.gov/ for more information. All images are courtesy of the KYTC.

APPENDIX G: EVERY DAY COUNTS – HIGH FRICTION SURFACE TREATMENTS

The Federal Highway Administration's Every Day Counts (EDC) initiative is designed to identify and deploy innovations aimed at shortening project delivery, enhancing the safety of our roadways, and improving environmental sustainability. To ensure that the benefits of using HFST are attained quickly by a high percentage of the United States market, the EDC initiative has established an aggressive program to rapidly accelerate HFST deployment and adoption. As part of the subsequent EDC2 initiative, an implementation plan was created to serve as a roadmap for rapid, successful implementation of HFST, including technical guidance and assistance, benchmarking, marketing and communications, training, and project demonstrations that will highlight best practices. These treatments generated widespread interest during EDC2, and by the end of the two-year cycle, the number of States using HFSTs had grown from 14 to 39. As of the end of October 2015 that number has reached 42 states (including Puerto Rico, the U.S. Virgin Islands, and Federal Land) and 14 States have made the use of HFSTs a standard practice for reducing crashes at critical locations.

FHWA selected calcined bauxite as the aggregate of choice for HFSTs as it is high-quality, durable, resistant to polishing, and provides long lasting value as compared to other natively available aggregates. A recent study by National Center of Asphalt Technology to examine pavement surface friction performance of bauxite and seven alternative aggregate sources ranked calcined bauxite as the top performing aggregate.

Visit the EDC 2 HFST web site for more information about the EDC2 HFST program and resources.

BENEFITS

- **Reduce crashes, injuries, and fatalities.** Wisconsin DOT placed HFST on a ramp in Milwaukee in October 2011 that has experienced 87 crashes in one year and to date has only two crashes at this location. Additionally, the National Cooperative Highway Research Program (NCHRP) 617 indicates a crash reduction of 20 percent for all intersection crashes.
- **Benefits outweigh costs.** A recent before-and-after study from South Carolina DOT for a series of curve installations indicates a cost-benefit ratio of about 24 to 1.
- **Relatively low in cost compared to geometric improvements.** The square-foot cost of HFST is not cheap, but its durability makes it worth the cost since the treatments are long-lasting and the life-cycle cost is excellent.
- **Durable and long-lasting.** HFST provide a durable and long-lasting solution to pavement locations where insufficient friction is a contributing factor in crashes.

- **Customizable to specific State and local safety needs.** Road owners can use where most needed, such as two-lane urban or rural roads at horizontal curves, areas near steep grades, areas at or near lane changes and rural and urban intersections.
- **Produce negligible environmental impacts and minimal impact on traffic.** Project lengths are short and the materials set up very quickly so the treatments can often be applied in hours, requiring minimal impact on traffic as compared to a conventional pavement overlay project.

Key activities delivered during the EDC 2 cycle:
http://safety.fhwa.dot.gov/roadway_dept/pavement_friction/high_friction/

- Case Studies, Noteworthy Practice and Fact Sheets showcasing HFSTs
- HFST Education Video
- Demonstration of HFST installations at four states.
- AIDs Grant to help State DOTs to mainstream HFSTs in their States
- STIC Grant to help State DOTs to have HFSTs technology sharing with other states and locals.

APPENDIX H: UTILITY POLE MANAGEMENT IN NEW JERSEY

BACKGROUND

Objects permanently fixed in the clear zone of a roadway, such as trees and utility poles, may present obstacles for vehicles that depart the travel lane. Researchers from Rowan University, in Glassboro, New Jersey, identified approximately 260 sites on New Jersey State Highways with multiple utility pole crashes from the years 2003 to 2005. Researchers identified these sites by ranking poles with three or more recurring pole hits in one location, in accordance with the New Jersey Department of Transportation (NJDOT) Roadway Design Manual Section 8.2.4 under "Utility Poles." The poles were also ranked by the crash hit/severity ratio of five or greater.

The Utility Management Unit of NJDOT is responsible for implementing the Pole Mitigation Program based on the list created by the Rowan University researchers. The Pole Mitigation Program is a formal program to proactively identify and remediate high risk utility pole crash sites in an effort to reduce crashes and injuries. Locations of poles that were within limits of active projects in design and planning stages were (and are currently) forwarded to the Division of Project Management for approval to be included in the mitigation program. NJDOT subsequently focused on the top 20 locations that were not a part of any active design projects from the original list of 260 sites.

PROGRAM DETAILS

One aspect of the Pole Mitigation Project is to pilot energy absorbing poles at some locations. The applicability of the poles is limited due to height and electrical appurtenance restrictions. NJDOT is using special poles made of fiberglass that collapse on impact and do not break away into the traffic. Initially NJDOT found it difficult to secure participation from the major utility companies on this project. However, upon holding informative discussions with the utility companies, NJDOT and the companies successfully reached an agreement to replacing and installing fiberglass poles when possible in accordance with all standards and guidelines and as specified in the NJDOT Utility Accommodation Policy. As a result of this coordination, six fiberglass poles have been installed.

Figure H-1. Photo. A close-up of the energy absorbing utility poles used as a part of NJDOT's pilot project.

RESULTS

After installation of the poles, the utility companies periodically conduct an inspection and submit a report to NJDOT as a part of the agreement. NJDOT can analyze the performance data of the poles and can establish policy regarding the usage of non-wooden poles. The utility companies have also agreed to replace the fiberglass poles if one is hit and damaged. NJDOT has made plans for data collection to establish a database containing the crash types based on geometry of the roadway in addition to other information that will be helpful to target sites where crashes with poles could be a problem.

Figure H-2. Photo. NJDOT used utility poles made from fiberglass that would collapse upon impact and not break away into the road.

CONSIDERATIONS

NJDOT recognizes the value in safeguarding the motoring public and minimizing the risk on the roadway and roadside. NJDOT highly recommends other agencies to initiate a clear zone management program, such as utility pole mitigation, if the resources are available.

CONTACT INFORMATION

NJDOT provided the information for this case study. Visit http://www.state.nj.us/transportation/ for more information. All images are courtesy of NJDOT.

For More Information:

Visit http://safety.fhwa.dot.gov/roadway_dept/

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FHWA-SA-15-084