# Toolbox of Countermeasures for Rural Two-Lane Curves

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Shauna Hallmark, Neal Hawkins, and Omar Smadi

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**16. Abstract**

The Federal Highway Administration (FHWA) estimates that 58 percent of roadway fatalities are lane departures, while 40 percent of fatalities are single-vehicle run-off-road (SVROR) crashes. Addressing lane-departure crashes is therefore a priority for national, state, and local roadway agencies. Horizontal curves are of particular interest because they have been correlated with increased crash occurrence.

This toolbox was developed to assist agencies address crashes at rural curves. The main objective of this toolbox is to summarize the effectiveness of various known curve countermeasures.

While education, enforcement, and policy countermeasures should also be considered, they were not included given the toolbox focuses on roadway-based countermeasures. Furthermore, the toolbox is geared toward rural two-lane curves.

The research team identified countermeasures based on their own research, through a survey of the literature, and through discussions with other professionals. Coverage of curve countermeasures in this toolbox is not necessarily comprehensive.

For each countermeasure covered, this toolbox includes the following information: description, application, effectiveness, advantages, and disadvantages.

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# Background

The Federal Highway Administration (FHWA) estimates that 58 percent of roadway fatalities are lane departures, while 40 percent of fatalities are single-vehicle run-off-road (SVROR) crashes (FHWA 2009). Addressing lane-departure crashes is therefore a priority for national, state, and local roadway agencies.

Horizontal curves are of particular interest because they have been correlated with overall increased crash occurrence. Glennon et al. (1985) reported that curves have approximately three times the crash rate of tangent sections and Preston (2009) reported that 25 to 50 percent of severe road departure crashes in Minnesota occurred on curves, even though curves only account for 10 percent of the system mileage.

Shankar et al. (1998) found a relationship between the number of horizontal curves per kilometer and median crossover crashes on divided highways. Farmer and Lund (2002) found that the odds of having a rollover on a curved section were 1.42 to 2.15 times greater than that of having a rollover on a straight section.

The majority of crashes on curves involve lane departures. A total of 76 percent of curve-related fatal crashes are single vehicles leaving the roadway and striking a fixed object or overturning. Another 11 percent of curve-related crashes are head-on collisions (AASHTO 2008).

Curve-related crashes have a number of causes including roadway and driver factors. Environmental factors, such as the roadway surface condition, and vehicle factors, such as the center of gravity, will also have an impact on a driver's ability to safety negotiate a curve.

McLaughlin et al. (2009) evaluated run-off-road (ROR) crashes and near-crashes in a Virginia Tech Transportation Institute (VTTI) 100 car study and found that ROR events were 1.8 times more likely on wet roads than dry, 7.0 times more likely with on roads with snow or ice than dry roads, and 2.5 times higher in the dark than during the daytime.

Degree of curve or radius of curve is the roadway factor most cited in the literature as having an impact on crash risk. Luediger et al. (1988) found that crash rates increase as degree of curve increases. Miaou and Lum (1993) found that truck crash involvement increases as horizontal curvature increases, depending on the length of curve. Vogt and Bared (1998) found a positive correlation between injury crashes and degree of horizontal on rural two-lane road segments. Zegeer et al. (1991) used a linear regression model and found that degree of curve was correlated positively with crashes on two-lane roads.

Schneider et al. (2009) evaluated truck crashes on horizontal curves in Ohio using a Bayesian analysis. The researchers found that curve length, volume, and degree of curvature were correlated to crash frequency.

Preston (2009) examined severe road departure crashes and found that 90 percent of fatal crashes and 75 percent of injury crashes occurred on curves with a radius of less than 1,500 feet.

Milton and Mannering (1998) reported that an increase in radius was associated with decreases in crash frequency.

Other factors that have been correlated to the frequency and severity of curve-related crashes include length of curve, type of curve transition, lane and shoulder widths (Zegeer et al. 1991), preceding tangent length (Milton and Mannering 1998), presence of spirals (Council 1998), grade (Fink and Krammes 1995), and required speed reduction between the tangent and curve.

Hassan and Easa (2003) found that driver misperception of curve sharpness was greatest when vertical curvature was combined with horizontal curvature, particularly when a crest vertical curve is superimposed on a severe horizontal curve or when a sag vertical curve is combined with a horizontal curve.

Driver errors on horizontal curves are often due to inappropriate selection of speed and inability to maintain lane position. The FHWA estimates that approximately 56 percent of ROR fatal crashes on curves are speed related. The amount of speed reduction needed to traverse a curve has an impact on frequency and severity of crashes (Luediger et al. 1988, Anderson et al. 1999, Fink and Krammes 1995).

Driver speed selection at curves depends on both explicit attentional cues and implicit perceptual cues (Charlton 2007). Driver perception of the apparent upcoming curve radius forms the primary basis for making speed and path adjustments. Perception of the sharpness of the curve can be by distorted by topography, presence of a vertical curve, and sight distance (Campbell et al. 2008).

Driver speed prior to entering a curve has a significant effect on ability to negotiate the curve successfully (Preston and Schoenecker 2009). Inappropriate speed selection and lane positioning can be a result of a driver failing to notice an upcoming curve or misperceiving the roadway curvature.

Driver workload plays an important role in driver speed maintenance. Distracting tasks such as radio tuning or cell phone conversations can draw a driver’s attention away from speed monitoring, detection of headway changes, lane keeping, and detection of potential hazards (Charlton 2007). Charlton found that drivers approached and entered curves at higher speeds when engaged in cell phone tasks than in non-distraction scenarios.

Other factors include sight distance issues, fatigue, and complexity of the driving situation (Charlton and DePont 2007, Charlton 2007). McLaughlin et al. (2009) evaluated ROR events in the 100 car study and found that distraction was the most frequently-identified contributing factor. Researchers also noted fatigue/impairment and maneuvering errors.

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# Overview

The main objective of this toolbox is to summarize the effectiveness of various known curve countermeasures. The toolbox focuses on roadway-based countermeasures. Education, enforcement, and policy countermeasures should also be considered, but are not the focus of this toolbox. Furthermore, the focus of this toolbox is on strategies for rural two-lane curves.

The research team identified countermeasures based on their own research, through a survey of the literature, and through discussions with other professionals. The list is not necessarily comprehensive. Each countermeasure that the team was aware of is summarized using the format outlined in Table 1.

**Table 1. Outline for countermeasure information in this toolbox**

| Subsection | Summarizes |
|---|---|
| Description | Countermeasure |
| Application | How the countermeasure has been applied, where the countermeasure is most effective, and so forth |
| Effectiveness | Studies showing the demonstrated effectiveness of each countermeasure, information about crash reductions and speed changes, with the assumption that speed change can be used as a crash surrogate |
| Advantages | Countermeasure advantages, such as low cost |
| Disadvantages | Countermeasure disadvantages, such as high cost or long-term maintenance |

Countermeasures serve two functions. The first is to reduce the likelihood of a vehicle leaving its lane (either running off the roadway or crossing into an adjacent lane) and the second is to minimize the consequences when a vehicle does leave the roadway (Torbic et al. 2004).

Strategies that are applied generally across a corridor to address lane departure crashes are not summarized in this toolbox, but should be considered as part of a comprehensive approach to reducing crashes on rural roadways. These other strategies include countermeasures such as the Safety Edge or use of guardrail or cable median barriers. This toolbox does not include design solutions, such as flattening a curve or side slopes, maintenance actions such as removing vegetation, or changing the roadway surface or shoulder treatment. In addition, be sure to note the following:

- The effectiveness of the various countermeasures are estimates only and will vary based on roadway, environmental, and operational conditions.
- Countermeasures that place a device within the roadway clear zone should follow the *Manual on Uniform Traffic Devices for Streets and Highways* (MUTCD) and national guidelines for crash worthiness. Countermeasures that include pavement marking or roadway surface treatments should meet skid-resistance requirements.
- Better delineation of the roadway may increase speeds given drivers are better able to gauge a curve’s sharpness.
- The MUTCD and state and local guidelines should be consulted before selecting countermeasures.

- Use of countermeasures, when not warranted, or overuse of countermeasures may result in driver non-compliance. As a result, agencies should select and apply countermeasures judiciously.
- Many of the devices listed are considered supplementary in that they supplement and do not replace traditional traffic control.

## Additional Information for Selecting Countermeasures

This toolbox summarizes various countermeasures. Other documents have summarized steps to identify problem locations, conduct safety audits and field visits, etc. As a result, this document does not attempt to summarize existing guidance on the topic.

The following resources may provide useful information on general strategies to address curve safety:

- *NCHRP Report 500: Volume 7: A Guide for Reducing Collisions on Horizontal Curves*. Torbic, Darren J., Douglas Harwood, David K. Gilmore, Ronald Pfefer, Timothy R. Neuman, Kevin L. Slack, and Kelly K. Hardy. National Cooperative Highway Research Program. Washington, DC. 2004.

  This report provides guidance for implementation of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan. The guide also describes countermeasures.

- *Driving Down Lane-Departure Crashes: A National Priority*. American Association of State Highway and Transportation Officials. April 2008. http://downloads.transportation.org/PLD-1.pdf.

  This guide provides general information about addressing lane departure crashes, provides background on various countermeasures, and provides steps to addressing lane-departure crashes.

- *Low-Cost Treatments for Horizontal Curve Safety*. McGee, Hugh W. and Fred R. Hanscom. U.S. Department of Transportation. Federal Highway Administration. FHWA-SA-07-002. December 2006. http://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa07002/index.cfm#toc.

  This guide provides information about low-cost treatments on curves.

## Manual on Uniform Traffic Control Devices Guidance

This toolbox provides information about rural curve treatments. The MUTCD (2009) covers some of the treatments. The MUTCD is considered the main source of information when selecting and applying traffic control devices. Guidance from the MUTCD supersedes any information provided in this toolbox.

## Crash Modification and Crash Reduction Factors

Either a crash reduction factor (CRF) or crash modification factor (CMF) is presented for most of the roadway countermeasures.

A CMF is a multiplicative factor to compute the expected number of crashes after implementing a given countermeasure. A CMF of 80 indicates that the expected number of crashes after the treatment would decrease by 20 percent.

If available, a table is presented for each treatment showing CMFs. (Currently, CMFs are used more commonly than CRFs.) In each table, CMFs referenced with a star (★) are based on both the referenced study and information from that study, which has been synthesized in the CMF Clearinghouse (www.cmfclearinghouse.org) as part of their "star quality rating" system. The number of stars is a qualitative rating used by the CMF Clearinghouse, based on study design, sample size, standard error, potential bias, and source of data. CMFs with no star next to the reference are from other studies where CRFs, CMFs, or crash reduction effects were noted.

CRFs have been converted to CMFs where applicable. A CRF is the expected percentage change in crash due to a particular treatment. A CRF of 20, for instance, indicates that a 20 percent reduction in crashes might be expected with use of the treatment. CRFs can be negative indicating an expected increase in crashes. CRFs are converted to CMFs using this formula: CMF = 1 – (CRF/100).

"A CRF [or CMF] should be regarded as a generic estimate of the effectiveness of a countermeasure. The estimate is a useful guide, but it remains necessary to apply engineering judgment and to consider site-specific environmental, traffic volume, traffic mix, geometric, and operational conditions, which will affect the safety impact of a countermeasure. The user must ensure that a countermeasure applies to the particular conditions being considered." (USDOT 2008). Users are encouraged to consult the source documents. When CRFs or CMFs were not developed specifically, available crash reduction information is provided in another table.

## Countermeasures Covered in this Toolbox

A "toolbox" of potential treatments to address safety at rural two-lane curves follows:

# Advance Curve Warning and Advisory Speed Signing

## Description

Advance curve warning signs are used to alert drivers to the presence of a curve. A speed advisory sign supplements warning signs when an engineering study indicates the need to advise drivers of a change in roadway alignment. The purpose is to inform unfamiliar drivers of a possible hazardous situation and recommend a comfortable and safe speed.

However, curve advisory speeds are often set inconsistently. Chowdhury et al. (1998) used a ball bank indicator and measured curve geometry and spot speeds at 28 locations and found that most agencies did not post advisory speeds consistent with generally recommended criteria.

## Application

The MUTCD (2009) includes setting curve advisory speeds and the use of curve warning and curve advisory speed signs**.** For horizontal curve signing to be effective, it should be displayed uniformly and consistently so that curves with similar characteristics, such as radius, super elevation, or sight distance, have similar messages (Bonneson et al. 2009).

Several alternative studies have reviewed current methods to set advisory speeds and proposed better methods:

- "Evaluation of Alternative Procedures for Setting Curve Advisory Speeds." Bonneson, James A., Michael P. Pratt, and Jeff Miles. *Transportation Research Record: Journal of the Transportation Research Board*. No. 2122. Transportation Research Board of the National Academies, Washington, DC. 2009. pp. 9-16.

- "Assessment of Traffic Control Devices Selection Guidelines for Horizontal Curves." Pratt, Michael P. and James A. Bonneson. *Transportation Research Record: Journal of the Transportation Research Board*. No. 2122. Transportation Research Board of the National Academies, Washington, DC. 2009. pp. 36-44.

- *Methodologies for the Determination of Advisory Speeds*. Seyfried, Robert K. and James L. Pline. Institute of Transportation Engineers, Traffic Engineering Council. Washington, DC. 2010.

## Effectiveness

Chowdhury et al. (1998) found that 90 percent of drivers exceeded posted advisory speeds with drivers being more likely to exceed posted advisory speeds at 40 mph or less as opposed to advisory speeds of 45 mph or more. However, although compliance was low, the researchers found that drivers did adjust their speeds.

Vest et al. (2005) evaluated different types of warning signs (Figure 1) to reduce speed on curves. The researchers tested sites on rural roadways with a sharp curve, history of speed-related incidents, long tangent section before the curve, no vertical grade, and no intersections, driveways, or commercial activity within the curve.

One treatment added bright orange flags on existing curve warning/ advisory speed signs. The speed studies showed a change in average speeds from an increase of 0.1 mph before the flags to a decrease of 1.3 mph at the point of curvature (PC) after the flags. These studies also found a decrease from 0.1 mph before the flags to a decrease of 1.0 mph after the flags within the curve as shown in Table 2.

**Figure 1. Combination advisory sign/horizontal alignment sign (Vest et al. 2005)**

**Table 2. Speed reduction for advisory signs**

| Sign Type | Speed Change | mph |
|---|---|---|
| Addition of flags on existing curve warning/advisory speed signs (Vest et al. 2005) | Mean at PC | -1.3 |
| | 85th percentile at PC | -1.8 |
| | Mean within curve | -1.0 |
| | 85th percentile within curve | 0.1 |
| Combination horizontal alignment and advisory speed (Vest et al. 2005) | Mean at PC | 0.5 |
| | 85th percentile at PC | 0.7 |
| | Mean within curve | -0.5 |
| | 85th percentile within curve | 0.0 |

Changes in 85th percentile speed ranged from an increase of 0.8 mph before the flags to a decrease of 1.8 mph after the flags at the PC and an increase of 0.1 mph within the curve after the flags.

The researchers also tested the combination of a horizontal alignment sign placed within the curve in addition to advisory speed signing as shown in Figure 1. The study found a 0.5 mph increase in average speed and a 0.7 mph increase in 85th percentile speeds at the PC. The researchers noted a decrease of 0.5 mph in mean speed and no change in 85th percentile speeds at the center of the curve.

Charlton and DePont (2007) evaluated various curve treatments using a simulator in New Zealand. Advance warning signs alone were not as effective at reducing speeds as when used in conjunction with chevron sight boards and/or repeater arrows.

A pooled fund study evaluated the impact of improved curve delineation (Srinivasan et al. 2009). The researchers conducted a before-and-after analysis using Empirical Bayes (EB) methods using 228 rural two-lane treatment sites in Connecticut and Washington. The study included control sites that were similar but did not receive the improved signing.

Treatments, which varied by site, included new chevrons, horizontal arrows, advance warning signs, post-mounted delineators, and upgrading existing signs with fluorescent yellow sheeting. In this study, the researchers reported a reduction in several types of non-intersection crashes as shown in Table 3. The researchers also noted that the treatment was more effective at sites with higher volume and on curves with a radius less than 492 feet.

**Table 3. CMFs for advisory signs**

| Sign Type | Crash Type | CMF |
|---|---|---|
| Advance curve warning (Elvik and Vaa 2004 ★) | Serious injury/ minor injury | 0.70 |
| | Property damage only | 0.92 |
| Combination horizontal alignment/advisory speed signs (Elvik and Vaa 2004 ★★★) | Serious injury/minor injury | 0.87 |
| | Property damage only | 0.71 |
| Chevron and curve warning signs (Montella 2009 ★★★, Srinivasan et al. 2009 ★★★★) | All crashes on principal arterial/freeways/expressways | 0.59 |
| | ROR crashes on principal arterial/freeways/expressways | 0.56 |
| | Fatal/serious injury/minor injury | 1.46 |
| | Nighttime | 0.66 |
| New fluorescent curve signs or upgrade existing curve signs to fluorescent sheeting (Srinivasan et al. 2009 ★★★★) | Head-on/non-intersection/ROR/sideswipe on rural two-lane | 0.82 |
| | Fatal/serious injury/minor injury on rural two-lane | 0.75 |
| | Nighttime on rural two-lane | 0.66 |

Montella (2009) evaluated crashes before and after installation of chevron signs, curve warning signs, and sequential flashing beacons on 15 curves in Italy using EB. All curves were characterized by a small radius (mean = 1,197 feet), large deflection angle, and sight distance issues. Chevrons and curve advisory signs were installed at five sites. Data were compared against untreated curves. CMFs from the various studies are shown in Table 3.

## Advantages

- Low cost

## Disadvantages

- Use of traffic control devices when not warranted can result in additional costs for maintenance and replacement

# Chevrons and Oversized Chevrons

## Description

Figure 2. Oversized chevrons on US 6 in Johnson County, Iowa (Tom Welch, Iowa DOT)

Chevrons provide additional emphasis and guidance for drivers. If spaced properly, chevrons can delineate the curve so that drivers can interpret the sharpness of the curve.

Table 2C-2 of the MUTCD (2009) recommends the size of chevron alignment (W1-8) signs by roadway type. Several agencies, including the Iowa Department of Transportation (DOT), have applied a larger chevron size to a roadway than suggested by this table (as shown in Figure 2)**.** The idea is that larger chevrons will be more prominent and visible to drivers**.** These larger chevrons may be particularly useful if sight distance issues exist.

## Application

Chapter 2 of the MUTCD (2009) covers standard application of chevrons. No standards exist for use of oversized chevrons. In general, standard chevrons signs are replaced with the next largest size specified in the MUTCD.

In contrast to chevron size, alternatives to the frequency and spacing around a curve have also been evaluated. A field study by the Texas Transportation Institute (TTI) evaluated the impact of varying the number of chevrons in view around a curve and developed an alternate spacing chart to assist maintenance personnel as reported in the following:

- “Spacing Chevrons on Horizontal Curves.” Rose, Elisabeth R. and Paul J. Carlson. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1918. Transportation Research Board of the National Academies, Washington, DC. 2005. pp. 84-91.

## Effectiveness

The effectiveness of oversized chevrons is unknown. Zador et al. (1987) evaluated the effectiveness of chevrons and other treatments on 46 sites in Georgia and 5 sites in New Mexico. Several control sites were also included and the researchers collected lateral placement data at each curve. The authors found that, at night, drivers moved away from the centerline and vehicle speed and placement variability were reduced slightly with the use of chevrons and raised pavement markings.

Jennings and Demetsky (1983) evaluated chevrons along several rural Virginia curves. The roadway segments had average daily traffic (ADT) between 1,000 and 3,000 vehicles per day (vpd). The researchers found that overall speed and speed variance decreased with the use of chevrons. The researchers also recommended chevron installation for curves greater than 7 degrees.

Wu et al. (2013) used a driving simulator to evaluate the impact of chevrons on driver behavior. They evaluated young male drivers who negotiated an urban expressway ramp with and without chevrons in China. They found an increase in fixation points and fixation duration when chevrons were different. They also found that braking and acceleration were more frequent with chevrons and concluded that chevrons encourage drivers to reduce speed.

Re et al. (2010) evaluated the application of chevrons and chevrons with a full-post retroreflective treatment at two curves in Texas. Both sites have paved shoulders and a posted speed limit of 70 mph for day and 65 mph for night. One site had an advisory speed of 45 mph while the second site had a speed of advisory of 50 mph.

Each treatment was applied to each site and the researchers collected speed and lateral position before and after using piezoelectric traffic classifiers. As shown in Table 4, the average speed with the chevrons in place was 1.4 mph lower and, with the full-post chevron treatment, the average speed was 2.2 mph lower. The 85th percentile speed decreased by 1.3 mph for the scenario with just chevrons and 2.2 mph for the full-post chevrons.

### Table 4. Speed reduction for chevron signs

| Sign type | Speed Change | mph |
|---|---|---|
| Chevrons (Re et al. 2010) | Mean: chevron | -1.4 |
| | 85th percentile: chevron | -1.3 |
| | Mean: chevron + post | -2.2 |
| | 85th percentile: chevron + post | -2.2 |

In most cases, the full-post chevrons reduced the percentage of vehicles exceeding 60, 65, and 70 mph. Centerline encroachments decreased by 78 percent with use of the post-mounted delineators (PMDs) and 88 to 93 percent for the chevron treatments.

A pooled fund study evaluated the impact of improved curve delineation (FHWA 2009) in the state of Washington. This study installed chevrons at sites where chevrons were not posted previously, as well as increased the number of chevrons at locations where they were present already. The authors noted a reduction in several crash types as shown in Table 5.

## Table 5. CMFs for chevrons

| Sign Type | Crash Type | CMF |
|---|---|---|
| Chevron and curve warning signs (Montella 2009 ★★★) | All crashes on principal arterial/freeways/expressways | 0.59 |
| | ROR crashes on principal arterial/freeways/expressways | 0.56 |
| | Fatal/serious injury/minor injury | 1.46 |
| | Nighttime | 0.66 |
| Chevron signs (Montella 2009 ★★★, Srinivasan et al. 2009 ★★★★) | All crashes on principal arterial/freeways/expressways | 0.63 to 1.27 |
| | ROR crashes on principal arterial/freeways/expressways | 0.90 |
| | Property damage only on principal arterial/freeways/expressways | 0.83 |
| | Fatal and injury crashes on principal arterial/freeways/expressways | 1.46 |
| | Nighttime on principal arterial/freeways/expressways | 1.92 |
| | Wet road crashes on principal arterial/freeways/expressways | 0.41 |
| | All crashes on rural two-lane | 0.96 |
| | Head-on/sideswipe on rural two-lane | 0.94 |
| | Fatal and injury crashes on rural two-lane | 0.84 |
| | Nighttime on rural two-lane | 0.75 |
| | Nighttime head-on/sideswipe on rural two-lane | 0.78 |

## Advantages

- Low cost

## Disadvantages

- Use of traffic control devices when not warranted can result in additional costs for maintenance and replacement

# Widening/Adding Paved Shoulders

## Description

Many rural two-lane roadways do not have paved shoulders due to right of way (ROW) and resource constraints. Some agencies add paved shoulders only through select horizontal curves on rural two-lane roadways. Provision of a paved shoulder provides additional space for recovery when a vehicle leaves the roadway.

Shoulder widening through a horizontal curve, even without paving, can add some safety benefits. Widening can be done for the inside or outside of the curve or both.

## Application

Iowa DOT design standards indicate that the addition of a paved shoulder section, or widening, should start where the super elevation transition begins before the PC, extend throughout the curve, and end after the normal crown is achieved beyond the point of tangency (Iowa DOT 2008).

## Effectiveness

Installation of a shoulder has a CRF of 9 for all crashes (USDOT 2008). Paving shoulders has a CRF of 15. Widening shoulders has the CRFs shown in Table 6 for ROR and fixed object crashes.

**Table 6. CMFs for widening/paved shoulders**

| Countermeasure | Crash Type | CMF |
|---|---|---|
| Installation of shoulder (USDOT 2008) | All | 0.91 |
| Pave shoulder (USDOT 2008) | All | 0.85 |
| Increase shoulder width from 0 to 10 ft (Yichuan et al. 2012 ★★★) | SVROR (fatal, serious, minor injury) | 0.29 |
| **Widen paved shoulder** | | |
| 3 to 4 ft (FHWA 2013 ★★★) | All | 0.97 |
| 3 to 6 ft (FHWA 2013 ★★★) | All | 0.93 |
| 3 to 8 ft (FHWA 2013 ★★★) | All | 0.88 |
| 2 to 4 ft (Pitale et al. 2009 ★★) | All – principal arterial | |
| Pave shoulder (Pitale et al. 2009 ★★) | All – principal arterial | 0.86 |
| **Widen paved shoulder** | | |
| From 0 ft to 2 ft | ROR and fixed object | 0.84 |
| From 0 ft to 4 ft | ROR and fixed object | 0.71 |
| From 0 ft to 6 ft | ROR and fixed object | 0.60 |
| From 0 ft to 8 ft | ROR and fixed object | 0.51 |

No information was available about the effectiveness of adding paved shoulders to only selected curves. However, adding paved shoulders in general has been shown to be effective. An NCHRP study by Jorgensen and Associates (1978) concluded that roads with paved shoulders have lower crash rates than roads with unpaved shoulders of the same width. Hallmark et al. (2010) found an 8.3 percent reduction in the expected number of total crashes each year after shoulders are paved.

Zegeer et al. (1992) evaluated the impact of shoulder width on crashes for state primary, state secondary, and rural two-lane roads in Kentucky. The researchers found that ROR, head-on, and opposite-direction sideswipe crash rates decreased as shoulder width increased from 0 to 9 feet, but the crash rates increased slightly for shoulders of 10 to 12 feet.

Hallmark et al. (2010) found a 4.4 percent reduction in total crashes and a 7.8 percent reduction in ROR crashes for every additional foot of right shoulder.

CMFs are shown in Table 6. Depending on the specifics of the widening or paving improvement, reductions from 3 to 71 percent have been reported. A summary of studies that assessed the crash impact of paved shoulders but did not develop CMFs is shown in Table 7.

**Table 7. Crash impacts for paved shoulders on rural roadways**

| Countermeasure | Crashes | Change for each additional ft of right shoulder (%) |
|---|---|---|
| Adding paved shoulders (Hallmark et al. 2010) | All | -4.4% |
| | ROR | -7.8% |

## Advantages

- Selectively adding paved shoulders to curves is not as cost-prohibitive as adding paved shoulders overall
- Additional or paved shoulders provide other benefits including maintenance benefits, space for stalled vehicles, and locations for enforcement personnel

## Disadvantages

- Cost

# Reflective Barrier Delineation

## Description

One of the strategies to reduce ROR crashes is to improve curve delineation. When barriers, such as guardrails, are present around a horizontal curve, the barriers provide a natural location to add reflective treatments. Reflective treatments can be placed so that the entire curve can be delineated.

**Figure 3. Panels of retroreflective sheeting to delineate curves**

Reflective barrier delineation can be particularly effective at night and during wet weather. Reflectors, such as raised pavement markers, or panels of retroreflective sheeting, as shown in Figures 3 and 4, can be used.

**Figure 4. Nighttime view of retroreflective sheeting (McGee and Hanscom 2006)**

## Application

Treatment can be applied only when barriers, such as guardrails, are present.

## Effectiveness

The FHWA has discussed design and application of retroreflective panels (McGee and Hanscom 2006). The authors report on a study where the Oregon DOT (ODOT) applied reflective barrier treatments. However, ODOT had not conducted any type of analysis to evaluate reflective barrier treatment effectiveness in reducing speed or crashes.

## Advantages

- Low cost
- Provides additional demarcation of roadside objects (guardrail, median barrier)
- Enhanced delineation at night and during wet weather

## Disadvantages

- Long-term maintenance and replacement costs

# High-Friction Treatments

## Description

A vehicle will skid during braking and maneuvering through a curve when the frictional demand exceeds the available friction between the roadway and tire. Targeting high-friction treatments to curves is one strategy that has been used to address problem locations.

Two different methods are used to increase the coefficient of friction between the roadway and tires. Pavement grooving creates longitudinal cuts in the pavement surface to increase directional control. This treatment is used typically only in concrete surfaces. Longitudinal grooves improve drainage, which can reduce hydroplaning (McGee and Hanscom 2006).

**Figure 5. High-friction treatment (The Transtec Group, Inc., highfrictionroads.com)**

The second treatment is the use of a high-friction surface (HFS) treatment, which applies a binder and aggregate material to select locations on either asphalt or concrete pavements. The treatment increases the coefficient of friction and improves skid resistance for dry and wet pavement conditions (Figure 5).

In most cases, the treatment can match the color of the roadway, but different colors are available typically from vendors if agencies want to consider additional visual delineation (McGee and Hanscom 2006).

## Application

McGee and Hanscom (2006) suggest that an appropriate application technique is the use of a portable grooving machine to install grooves 3/16 inch to 3/8 inch wide and 5/32 inch to 5/16 inch deep with eight grooves per foot at a random spacing. High-friction surface treatments are typically applied immediately prior to and through the curve.

Additional guidance on frictional characteristics and performance of pavement surfaces can be found in the following documents:

- "Guide for Pavement Friction: Background and Research." *NCHRP Research Results Digest 321*. National Cooperative Highway Research Program. May 2009.
- "Gaining Traction in Roadway Safety." Julian, Frank and Steve Moler. *Public Roads*. July/August 2008. Vol. 72, No. 1. www.tfhrc.gov/pubrds/08july/05htm.

## Effectiveness

McGee and Hanscom (2006) describe a program in New York that identified and installed high-friction treatments at sites with a two-year wet accident proportion that was higher than the average for roadways in the same county. The New York State DOT (NYSDOT) installed the treatment and reported a reduction in wet-road crashes of 50 percent and a reduction in total crashes of 20 percent.

Julian and Moler (2008) reported that high-friction surfaces reduced total crashes by 25 percent, fatal crashes on wet pavement by 14 percent, and fatal crashes on sharp curves by 25 percent.

A study by Reddy et al. (2008) evaluated a high-friction surface treatment applied by the Florida DOT (FDOT) on an on-ramp to I-75. The researchers assessed the change in friction factor using skid tests. Results showed an increase in friction number (FN) at 40 mph from 35 to 104. The researchers compared crash frequency before and after installation of the treatment and reported a decrease in average crashes from 2.5 to 2.0 per year.

The researchers also compared speeds before and after application of the treatment on the ramp using a radar gun, which collected spot speeds at various times of day under wet and dry conditions. Mean speeds decreased by about 6 mph for dry conditions and 3 mph for wet conditions as shown in Table 8. The number of vehicles traveling 25 mph over the speed limit decreased significantly under both wet and dry conditions.

### Table 8. Speed reduction for chevron signs

| Treatment | Speed Change | mph |
|---|---|---|
| Application of high-friction treatment to an on-ramp | Mean on dry roads | -6.0 |
| | Mean on wet roads | -3.0 |

The authors also summarized a study by the University of Iowa (UI) that evaluated nine projects where anti-icing and anti-skid treatments were applied. The authors reported that snow and ice were less likely to accumulate on the test sections than for control sections and that, when accumulations did occur, the researchers found no bonding of snow and ice to the pavement.

The UI researchers also concluded that fewer chemicals were needed to obtain safe driving conditions on the test sections as compared to the control sections. In addition, the researchers found a statistically-significant (Z-test) decrease in the number of vehicles that crossed the pavement edge line after application of the treatment.

Table 9 provides CMFs for improving pavement friction. The CMFs were not necessarily developed based on rural two-lane curves, but they do provide some measure of the treatment’s effectiveness. A summary of studies that assessed the crash impact of paved shoulders, but did not develop CMFs, is shown in Table 10. Crashes are not specifically for curves unless noted as such.

### Table 9. CMFs for surface friction

| Sign Type | Crash Type | CMF |
|---|---|---|
| Improve pavement friction (Lyon and Persuad 2008 ★★★★, Mayora and Pina 2008 ★★, Harkey et al. 2008 ★★★★★) | All | 0.59 to 1.27 |
| | Wet road | 0.22 to 0.85 |
| | Single vehicle | 0.70 |
| Improve pavement friction through grooving (USDOT 2008) | All | 0.63 to 0.79 |
| | ROR | 0.59 to 0.60 |

### Table 10. Crash impacts for surface friction

| Countermeasure | Crashes | Change (%) |
|---|---|---|
| Installation of high-friction treatment (McGee and Hanscom 2006, Julian and Moler 2008) | On wet roads | -14 to -50% |
| | Total | -20 to -25% |
| | Fatal on sharp curves | -25% |

## Advantages

- Improves roadway surface friction, which is particularly useful in wet conditions

## Disadvantages

- Cost

# Raised Pavement Markers

## Description

Raised pavement markers (RPMs) provide lane guidance as shown in Figure 6. When drivers cross RPMs, the RPMs may also provide a tactile warning alerting drivers that they have crossed the lane edge.

Retroreflective RPMs may be particularly helpful in delineating a curve at night and during wet weather. RPMs can also be recessed in areas where snowplows operate.

## Application

RPMs can be used either along the roadway edge (right) or centerline. However, maintenance may be an issue for areas where snowplows are used.

**Figure 6. RPMs used in the center of a curve**

## Effectiveness

Zador et al. (1982) evaluated both recessed and raised reflectorized pavement markers on the centerlines of 662 curve sections in Georgia. The curves evaluated had a degree of curvature greater than 6 degrees.

Results of a before-and-after analysis indicated that nighttime crashes were reduced by 22 percent compared to daytime crashes and nighttime single-vehicle (SV) crashes were reduced by 12 percent compared to other crash types. In some cases, additional devices, such as warning signs and chevrons, were placed at the site, so not all of the effect can be attributed to the RPMs.

Hammond and Wegmann (2001) evaluated the effects of RPMs on number of encroachments, encroachment distance, and average speed at two horizontal curves. The researchers tested RPMs spaced at 20 and 40 feet apart. The researchers found that high degrees of lane encroachment decreased by 7.5 percent, moderate degrees of lane encroachment decreased by 7 percent, and low degrees of lane encroachment decreased by 14.5 percent with the 40 foot spacing. Likewise, the researchers found similar results for the 20 foot spacing. However, the researchers didn’t find any conclusive results for changes in average speed.

The American Traffic Safety Services Association (ATSSA 2006) summarized several studies and reported that use of retroreflective RPMs could reduce total crashes from 7 to 10 percent and could reduce nighttime wet weather crashes by 24 to 33 percent.

Bahar et al. (2004) used data from six states to develop safety performance functions of snowplowable raised pavement markers. The authors found mixed results for rural two-lane roadways. In particular, the models indicated that at low volumes (< 5,000 vpd), and sharp roadway geometry, RPMs may be correlated to increased crashes.

Table 11 provides crash modification factors for raised pavement markers. The CMFs were not necessarily developed based on rural two-lane curves but do provide some measure of the treatment's effectiveness.

### Table 11. CMFs for raised pavement markers

| Sign type | Crash Type | CMF |
|---|---|---|
| Install snowplowable permanent RPM (Bahar et al. 2004 ★★★) | All nighttime | 0.67 to 1.13 |
| Install snowplowable permanent RPM for radius > 1,640 ft (Bahar et al. 2004 ★★★) | All nighttime | 0.76 to 1.16 |
| Install snowplowable permanent RPM for radius ≤ 1,640 ft (Bahar et al. 2004 ★★★) | All nighttime | 1.03 to 1.26 |
| Install RPM and transverse rumble strips (Elvik and Vaa 2004 ★★, Agent and Creasey 1986 ★★) | ROR serious and minor injury | 0.94 |
| | All | 0.47 |
| | Wet road all | 0.51 |
| | Nighttime all | 0.36 |

A summary of studies that assessed the crash impact of raised pavement markers, but did not develop CMFs, is shown in Table 12. Crashes are not specifically for curves.

### Table 12. Crash impacts for raised pavement markers

| Countermeasures | Crashes | Change (%) |
|---|---|---|
| Raised pavement markers (summarized from several studies by ATTSA 2006) | Total | -7 to -10% |
| | Nighttime wet weather | -24 to 33% |

## Advantages

- Low cost
- Provide improved superior delineation at night and during wet weather

## Disadvantages

- Requires regular maintenance to ensure the RPMs don't loosen and cause a secondary safety hazard
- May be damaged or removed during snowplow operations

# Edge Lines and Wide Edge Lines

## Description

The MUTCD provides warrants and provides guidance about edge lines on freeways and higher-class roadways. Edge line use on lower-class roadways is based on state and local guidelines and practices. Even when not warranted, use of edge lines is widely accepted as being beneficial to drivers (ATSSA 2006).

When applied, the typical edge line width is 4 inches. Some agencies have tried 8 inch wide edge lines, which can provide additional delineation, particularly for older drivers.

Drivers have reported that wider edge lines are more noticeable in their periphery vision and can be identified from a greater distance. This means wider edge lines may decrease driver workload, allowing drivers to focus on other complex driving tasks, particularly at night (Donnell et al. 2006).

Use of 8 inch versus 4 inch edge lines through a curve is shown in Figure 7.

**Figure 7. Before and after application of wider edge lines (Donnell et al. 2006)**

## Application

Typically, 4 inch edge lines are widened to 6 or 8 inch.

Studies have recommended that 8 inch wide edge lines be used only on roadways with 12 foot lanes, unpaved shoulders, and an ADT of 2,000 to 5,000 vpd (Fitzpatrick et al. 2000 and Neuman et al. 2003). In addition, Fitzpatrick et al. (2000) recommend that edge-line widening be used on rural two-lane roads with the following:

- Frequent heavy snowfall and use of deicing materials and abrasives that tend to deteriorate edge lines
- Pavement widths less than or equal to 22 feet
- Roads having paved shoulders more than 6 feet wide

Gates and Hawkins (2002) summarized that agency practice in implementing wider edge lines suggests they are likely to have the greatest benefit at these locations:

- Where a higher degree of lane delineation is perceived as necessary for all drivers
  - Horizontal curves
  - Roadways with narrow shoulders or no shoulders
  - Construction work zones
- Where low luminance contrast of markings is common
- Where older drivers are prevalent requiring added visibility under all conditions

Hughes et al. (1989) evaluated crashes on 24 foot wide rural roadways with less than 6 foot shoulders and ADT between 2,000 and 5,000 vpd. The authors recommend that wider pavement edge lines may be most appropriate and cost-effective on roadways having the following characteristics:

- ADT between 2,000 and 5,300 vpd
- Roadways with a total pavement width of 24 feet with unpaved shoulders
- Frequent rainfall

## Effectiveness

Sun et al. (2007) collected data on seven tangent and three curve sections with pavement widths less than 22 feet (vpd 86 to 1,855 vpd). The researchers compared lane position before and after installation of edge lines and found that vehicles tended to move away from the pavement edge when an edge line was present. The researchers also found that the number of vehicles crossing the centerline at night decreased.

Donnell et al. (2006) studied the effects of using a wider (8 inch) edge line on horizontal curves along rural, two-lane Pennsylvania highways. The researchers collected data at eight sites, four treatment sites that had an 8 inch edge line, and four comparison sites with a 4 inch edge line. The comparison sites were located upstream from the treatment sites.

The researchers measured vehicle lateral position using piezoelectric sensors and observed and noted lane-line encroachment with a human observer. The researchers compared results from the different sites and found a significant degree of variation, which amounted to no significant reduction in speed or encroachment due to the placement of the wide edge lines. The researchers also evaluated speed profiles and determined there was evidence that wider edge lines influence drivers to slow earlier at night.

McGee and Hanscom (2006) report on another study in New York, which found a 17 percent reduction in fixed object crashes with use of wider edge lines on rural two-lane roads.

Tsyganov et al. (2005) studied rural two-lane highways in Texas and compared crashes for highways with and without edge lines. The authors reported that use of edge lines reduced crashes by 26 percent, with the greatest benefit on curves with lane widths between 9 and 10 feet. The authors also suggested that use of an edge line had some safety impact in reducing nighttime speed-related crashes.

Cottrell et al. (1987) evaluated the safety impact of using 8 inch wide edge lines. The research comparison of crashes before and after installation on three two-lane rural road sections (60.7 miles long) indicated no significant reduction in crashes.

Hall (1987) evaluated 530 miles of rural two-lane highways and concluded that use of 8 inch wide edge lines did not have a significant impact on crash reduction.

Hughes et al. (1989) evaluated rural two-lane roads in Maine, Ohio, and Texas (with ADTs of 5,000 to 10,000 vpd) and reported that use of 8 inch wide edge lines compared to 4 inch wide edge lines did not reduce crash frequency.

A study by TTI compared crashes in Morris County, New Jersey before implementation of 8 inch wide edge lines on county roads to those after implementation (ATTSA 2006). The researchers found a decrease in fatal and injury crashes of 10 percent compared to a 2 percent overall decrease on control roads. The researchers noted a reduction in SV fatal and injury crashes of 33 percent for Morris County roads compared to a 22 percent decrease on other county roads used as a control.

Park et al. (2012) evaluated the crash reduction impacts of wider edge lines. They conducted a crash analysis in three states using different analyses for each state within a non-winter analysis period. A before-and-after study of the conversion of edge line width from 4 inch to 6 inch was conducted for data in Kansas using EB. An analysis of the change in edge line from 4 inch to 6 inch in Michigan was conducted using a time series analysis. Finally, a cross-sectional analysis of the difference between 4 inch and 5 inch edge lines was conducted for Illinois. Results are shown in Table 13.

### Table 13. CMFs for wider edge lines

| Treatment | Crash Type | CMF |
|---|---|---|
| Install wider markings with resurfacing (Potts et al. 2010 ★★★★) | Fatal and serious injury on rural principal arterials, expressways, and freeways | 0.89 |
| | Fatal and serious injury on unspecified rural roadways | 0.70 |
| Install wider markings without resurfacing (Potts et al. 2010 ★★★★) | Fatal and serious injury on all roadway types | 0.38 |
| | Fatal and serious injury on rural principal arterial, expressways, and freeways | 0.44 |
| Place 8 in. edge-line markings (Elvik and Vaa 2004 ★★★) | Serious and minor injury | 1.05 |
| Use of 4 in. edge lines (Miles et al. 2010) | All on rural two-lane | 0.93 |
| | Fatal, serious injury, and minor injury | 0.83 |
| | All daytime | 0.90 |
| | Daytime fatal, serious injury, and minor injury | 0.82 |
| | All nighttime | 0.98 |
| | Nighttime fatal, serious injury, and minor injury | 0.88 |
| | Single vehicle | 0.98 |
| | Single vehicle wet road | 0.80 |
| | Head-on and sideswipe | 0.85 |

The CMFs were not necessarily developed based on rural two-lane curves but do provide some measure of treatment effectiveness. A summary of crash impact of wider edge lines is shown in Table 14.

## Table 14. Crash impacts for wider edge lines

| Countermeasures | Crashes | Change (%) |
|---|---|---|
| Wider edge lines | Fixed object on rural two-lane roads | -17% |
| Use of 8 in. edge lines (Cottrell et al. 1987, Hall 1987, Hughes et al. 1989) | On rural two-lane roads | no change |
| Use of 8 in. edge lines (ATTSA 2006) | Fatal and injury on rural roads | -10% compared to -2% for control sites |
| | SV fatal and injury on rural roads | -33% compared to -22% for control sites |
| Increase edge line from 4 to 6 in. (Park et al. 2012) | Total | -17.5 to 19.4% |
| | Fatal and injury | no change to -36.5% |
| | Wet roads | -22.9 to 62.6% |
| | SV | -18.7 to 27.0% |
| | SV fatal and injury | no change to -36.8% |
| Increase edge line from 4 to 5 in. (Park et al. 2012) | Total | -30.1% |
| | Fatal and injury | -37.7% |
| | Wet roads | -34.7% |
| | SV | -37.0% |
| | SV fatal and injury | -42.2% |

Gates and Hawkins (2002) summarized the available literature about use of wider pavement markings and surveyed agencies about levels of implementation of wider pavement markings and reasons for use. Because crash studies showing the effectiveness of wider pavement markings were not widely available, the authors summarized indirect safety measures used to justify use of wider markings. Indirect safety measures include driver opinion, visibility measurements, and surrogate safety measures.

Results of the survey of state DOT, Canadian provincial DOTs, and toll road agencies indicate that the majority of agencies have implemented wider pavement markings to improve visibility overall. A number of agencies also use the wider markings specifically for older drivers.

Based on the available literature and summary of agency experience, the researchers concluded that wider pavement markings provide the following driver benefits/positive feedback from drivers as far as improvements:

- Visibility and long-range detection under nighttime driving conditions (with older drivers deriving the most benefits)
- Peripheral vision stimulation
- Lane keeping
- Driver comfort and aesthetics

In addition, some agencies had concluded that the wider markings have improved service life and greater durability from a visibility standpoint than 4 inch markings due to the increased surface area. However, these findings have not been quantified.

## Advantages

- May be most advantageous for older drivers and two-lane roadways
- Improved service life given a larger surface area may be able to withstand greater material loss due to snowplow abrasion, cracking, and chipping and still provide visibility as compared to a 4 inch edge line

## Disadvantages

- Extra cost for wide marking

# Transverse Pavement Markings

## Description

Transverse pavement markings are oriented perpendicular to the direction of travel. These markings can include a variety of patterns such as optical speed bars, converging chevrons, and herringbones.

Transverse markings are a low-cost solution and have been used in work zones and along horizontal curves to slow speeds (Katz 2004). Figure 8 shows several types of transverse markings.

## Application

When transverse bars are utilized, they are often either placed in sets or in a pattern in which the bars converge, giving drivers the perception that they're traveling faster than they are or that they are accelerating, when in fact they are not.

Transverse markings can be spaced at a fixed interval, but are frequently placed so that the spacing between markings narrows as the driver progresses forward. This spacing gives a driver the sense that they are speeding up, which ideally results in drivers slowing (McGee and Hanscom 2006).

This accelerated spacing assumes that the perception of speed rather than the actual speed affects driver behavior (Meyer 2001).

Several sources have suggested spacing of 4 bars per second. Bars are placed closer together based on how much a driver needs to slow to reach the target speed.

**Figure 8. Various on-pavement curve markings**

Table 15 shows guidelines for treatment distance (in feet) in advance of a horizontal curve based on the tangent and curve advisory speeds.

**Table 15. Transverse marking distance (feet) before curve (McGee and Hanscom 2006)**

| Curve Advisory Speed (mph) | Tangent Speed (mph) | | | | | |
|---|---|---|---|---|---|---|
| | 45 | 50 | 55 | 60 | 65 | 70 |
| 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 |

Optical speed bar treatments can vary in size but are typically 18 inches long by 12 inches wide. Use and placement of optical speed bars (also referred to as speed-reduction markings) are covered under Section 3B.22 of the MUTCD (2009).

The FHWA provides some guidance on installation of transverse treatments in the following document:

♦ *Low-Cost Treatments for Horizontal Curve Safety*. McGee, Hugh W. and Fred R. Hanscom. U.S. Department of Transportation. Federal Highway Administration. FHWA-SA-07-002. December 2006. http://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa07002/index.cfm#toc

## Effectiveness

### Optical Speed Bars

The Virginia DOT (VDOT) tested optical speed bars on a high crash section of Lee Chapel Road in Fairfax County (40 mph) (Arnold and Lantz 2007) as shown in Figure 9. The researchers collected speeds before installation of the optical speed bars, one week after installation, and three months after installation.

Figure 9. Optical speed bars (VDOT 2006)

The markings were thermoplastic pavement markings (18 by 12 inches). The bars were installed at both entrances to the high-crash section. At the northbound entrance, vehicle speeds increased at the first station by 0.1 for the one-week after period while, at other stations, speeds decreased by 0.2 to 3.9 mph at the one-week after period. At three months, speeds increased by 3.0 mph at the first station and by 1.7 mph at the third station. Speeds decreased by 1.8 and 1.6 mph at stations 2 and 4 at the three-month after period.

**Figure 10. Optical speed bar installation on a curve in Oregon**

Figure 10 shows another example of optical speed bars on a curve.

McGee and Hanscom (2006) indicated that studies in three states had yielded reductions in 85th percentile speed between 0 and 5 mph.

Latoski (2009) applied optical speed bars on a tangent section of a rural, two-lane highway in Mohave County, Arizona. Latoski's markings were slightly different from typical optical speed bars (see Figure 11).

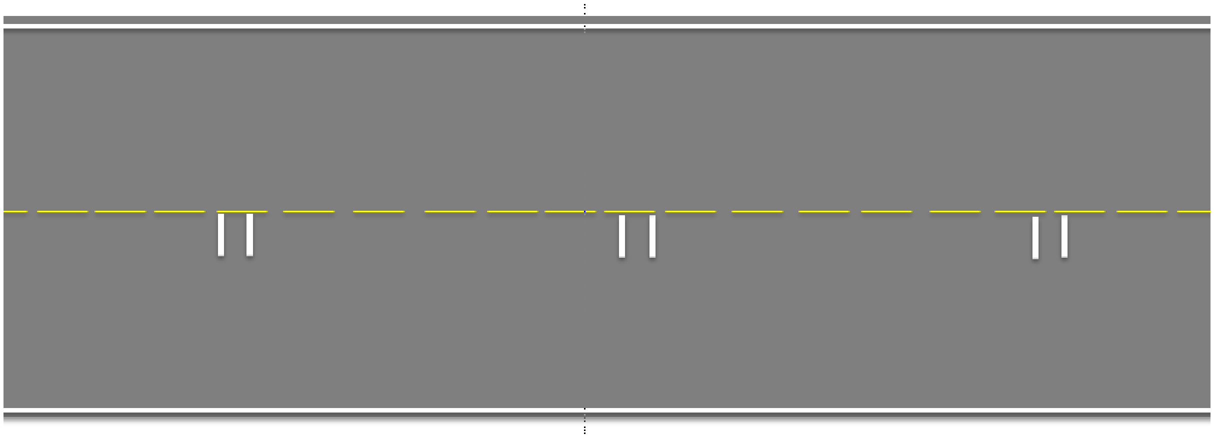


**Figure 11. Optical speed bar design used by Latoski (2009)**

Each 24 by 8 inch bar is placed transverse to the roadway with two markings spaced 8 inches apart. The spacing between pairs of bars decreases in the direction of travel to give the sensation to drivers that they are speeding up.

Latoski found a 2.0 mph decrease in both mean and 85th percentile speed immediately after installation. At three months, mean speed had decreased by 4.2 mph and 85th percentile speed had decreased by 5.0 mph.

Gates et al. (2008) evaluated the impact of transverse bars on a freeway curve (I-43 to I-94) in Wisconsin. Transverse bars (18 inches wide by 12 inches tall) were placed on the northbound and southbound freeway lanes in 1,000 foot sections.

The bars were placed with continuously decreasing (or accelerated) spacing to provide the perception of increasing speed, so that drivers would slow. The researchers found decreases of 1.1 to 5.0 mph in average speeds and up to 1.0 mph in 85th percentile speeds one month after installation.

Hallmark et al. (2007) evaluated optical speed bars as entrance treatments to rural communities. The bars were 12 inches (parallel to lane line) by 18 inches (perpendicular to lane line) as shown in Figure 12.

Figure 12. Transverse pavement markings as a rural gateway traffic calming treatment (Hallmark et al. 2007)

The treatments were installed at the south, east, and west community entrances. At the north site, no change in mean speeds occurred. At the west site, a decrease in mean speed of 1 mph was noted while, at the south site, mean speeds decreased by up to 1.9 mph. A decrease of up to 2 mph for the 85th percentile speed occurred at all three sites.

### On-Pavement Chevrons

On-pavement chevron markings have been used in several different situations. On-pavement chevron markings have been applied on freeway ramps, in advance of curves, and as the entrance treatment to rural communities. Figure 13 shows application of the treatment in advance of a community entrance on a rural two-lane roadway.

Figure 13. Converging chevrons at entrance to rural community (Hallmark et al. 2007)

Drakapoulos and Vergou (2003) evaluated the effect of on-pavement chevrons on a freeway-to-freeway connector in Wisconsin. The researchers placed 16 white chevrons in an increasingly close pattern over 610 feet. The researchers found mean speed reduction at the end of pattern from 64 mph to 49 mph (15 mph) and a 17 mph reduction in 85th percentile speed (from 70 mph to 53 mph).

Voigt and Kuchangi (2008) evaluated use of converging chevrons on a freeway-to-freeway ramp connector in El Paso, Texas. The researchers measured speed upstream, at the PC, and at the center of the curve before and after installation of the converging chevrons. The site had approximately 18,000 vpd with 2 percent heavy trucks. The posted advisory speed was 30 mph.

At the beginning of the curve, daytime mean and 85th percentile speeds decreased by about 0.7 mph and nighttime speeds decreased around 1.0 mph for the two-month after period. Mean speed decreased by 0.8 mph and 85th percentile speed decreased by 0.9 mph for the six-month daytime after period and both mean and 85th percentile speeds decreased by 1.7 mph for nighttime.

At the center of the curve, mean speeds during both the day and nighttime periods decreased by about 0.4 mph and 85th percentile speeds decreased by 0.6 mph and 0.8 mph for day and nighttime, respectively, for the two-month after period. At the six-month after period, both mean and 85th percentile speed during the day increased by about 1 mph. During the nighttime period, mean speed increased by 0.3 mph and 85th percentile speed increased by 0.5 mph.

The percentage of vehicles traveling 15 mph over the advisory speed decreased by 3.0 percent for the two-month after period and by 5 percent for the six-month after period at the PC, while increases of 0.4 and 6.4 percent occurred for the center of the curve at the two-month and six-month after periods, respectively.

Shinar et al. (1980) evaluated a converging chevron pattern as shown in Figure 14.

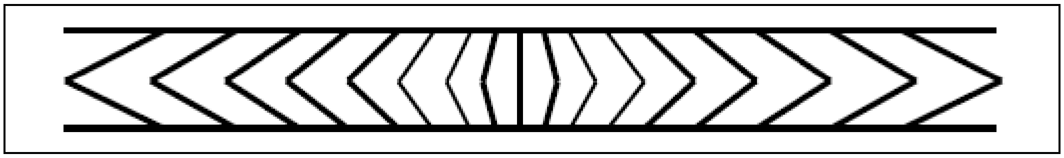


Figure 14. Wundt-Herring pavement marking layout (Shinar et al. 1980)

The treatment was placed across both lanes of traffic 318 feet upstream of a horizontal curve with the pattern ending at the center of the curve. The researchers reported a decrease of 6 mph in the 85th percentile speed.

ATSSA (2006) reported on a study in Columbus, Ohio where a converging chevron was applied at the approach to a double S curve. The two-lane roadway had a posted speed of 35 mph and an advisory speed of 15 mph. The researchers measured speeds before and 15 months after installation of the treatment and found a reduction in 85th percentile speed of 4 mph.

A converging chevron treatment was applied at the entrance to a rural community in Iowa (Hallmark et al. 2007). The chevrons were spaced consecutively closer and were thinner as drivers crossed them, as they entered the community, as shown in Figure 13. On-pavement speed signs were also placed at the termination of the chevrons. The posted speed limit within the community was 35 mph. A 1 to 3 mph reduction in mean speed occurred with a 1 to 4 mph reduction in 85th percentile speed.

### Herringbone

Charlton and DePont (2007) evaluated various curve treatments using a simulator in New Zealand. The study evaluated 48 participants who drove a simulator route, which replicated a 2.1 mile section of a state highway and a 2.2 mile section of level road with four horizontal curves with consistent radii (two with 53 mph and two with 41 mph curves).

The researchers studied several combinations of treatments including the following:

- Standard advance warning signs with a herringbone pattern pavement treatment
- Advance warnings with dashed-white centerline
- Advance warnings with double-yellow lines through the curves
- Advance warnings followed by centerline and edge-line rumble stripes

The herringbone pattern had similar speed reductions at the PC and curve center to the dashed-white centerline and double-yellow centerline. The authors noted that the herringbone pattern did result in greater flattening of the driver’s path through the curve compared to the other treatments.

Martindale and Urlich (2010) evaluated a herringbone pattern treatment that placed 4 inch transverse bars at a 60 degree angle at two different locations. Speeds were measured before and six months after placement of the treatment in the middle and at the end of treatment.

At six months, mean speeds decreased by 2.4 and 7.6 mph at the end of the treatment and decreased by 1.7 and 5.0 mph just upstream of the treatment. At the center of the treatment, speeds decreased at one site by 1.7 mph and had no statistically-significant change at the other. The 85th percentile speeds decreased by about 2.0 mph at the end of the treatment and decreased by 1.4 and 3.9 mph just upstream. At the center of the treatment, speeds decreased by 1.6 mph at one site and had no change at the other.

Martindale and Urlich (2010) installed a herringbone pattern treatment upstream of a narrow bridge on a rural two-lane roadway in New Zealand. A horizontal curve is located just before the bridge. The treatment begins about 328 feet before the bridge and extends 1,247 feet upstream beyond that.

The mean speed at the beginning of the treatment (1,345 feet upstream of the bridge) decreased by 1.6 mph at two weeks after and 7.6 mph at six months after the treatment was installed. The 85th percentile speed decreased by 1.8 mph and 2.0 mph at two weeks and six months after installation, respectively. All decreases were significant at the 95th level of significance.

At the center of the treatment (853 feet upstream of the bridge), there were no statistically-significant changes in either mean or 85th percentile speeds. Just downstream of the treatment (at 164 feet upstream of the bridge), no statistically-significant change in speeds occurred at two weeks after installation of the treatment. At six months after installation, mean speeds decreased 5.0 mph and 85th percentile speeds decreased by 3.8 mph at 6 months after installation.

### Transverse Lines

Vest et al. (2005) evaluated different types of warning signs to reduce speed on curves. The researchers tested sites on rural roadways with a sharp curve, history of speed-related incidents, long tangent section before the curve, no vertical grade, and no intersections, driveways, or commercial activity within the curve.

One treatment assessed was placement of transverse lines from the PC backward into the tangent section as shown in Figure 15. The transverse lines were spaced closer as drivers cross them to give the sensation of speeding.

Results of a speed study indicated that average speeds ranged from an increase of 2.3 mph to a decrease of 5.9 mph at the PC with almost no change in mean speed within the curve. Changes in 85th percentile speed ranged from an increase of 2.4 mph to a decrease of 3.6 mph at the PC.

**Figure 15. Equally-spaced transverse lines (Vest et al. 2005)**

Chrysler et al. (2009) examined the effectiveness of transverse line treatments placed on a set of S curves. The researchers measured change in speed from an upstream control point to the treatment and did not find a relevant reduction in speed from the before to after period.

Griffin and Reinhart (1995) reviewed 10 studies where transverse speed bars had been placed. Locations included roundabout approaches, stop-controlled intersections, upstream of interstate construction zones, and rural highways. The studies indicated a consistent speed reduction of 1 to 2 mph and reductions of up to 15 mph in 85th percentile speeds. The authors also indicated that a crash reduction occurred, although they did not state the magnitude. The authors also noted that speed reductions were higher during the day.

Katz et al. (2006) studied transverse speed bars with vehicle speeds at two rural horizontal curves and a highway exit ramp in New York, Texas, and Mississippi. The researchers collected data upstream of the curve and at the PC and found the optical speed bars were effective in reducing speeds.

At the exit ramp site, the researchers found an approximate 4 mph reduction immediately after and several months after installation of the treatment. The researchers also noted a 5 mph reduction in 85th percentile speed. At one rural curve site, the decrease in mean speed after adjusting for changes at the upstream control location was 4.6 mph. At the second rural curve site, the researchers found no statistical difference in average speed between the before and after periods.

Meyer (1999) studied the effectiveness of optical pavement marking bars as a means to alert drivers of an approaching work zone, reduce approaching vehicle speeds, and maintain a lower speed over a several-kilometer work zone.

The researchers selected a divided highway segment west of Topeka, Kansas that had annual average daily traffic (AADT) of 18,000 vpd, 20.5 percent of which was estimated to be heavy vehicles.

The work zone selected was a reconstruction project where both directions of traffic were to be carried on either the eastbound or the westbound lanes. Traffic was separated by tubular channelizers and reflective bricks.

The researchers used three patterns in this study, including a leading pattern, primary pattern, and work-zone pattern (see Figure 16).

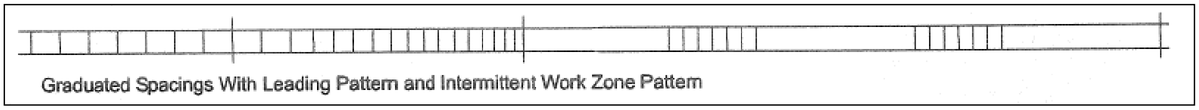


**Figure 16. Leading, primary, and work-zone bar pattern (Meyer 1999)**

Leading up to the deceleration area (which had the primary pattern), the leading pattern bars had consistent dimensions of 9 feet wide by 3.5 feet wide and a consistent spacing of 20 feet between bars. The primary pattern consisted of 29 bars that ranged from 42 inches to 24 inches wide (longitudinal) and converged at an estimated deceleration rate of 1 mph per second. The work-zone pattern consisted of four sets of six bars that were spaced 500 feet between sets.

The researchers collected data using pneumatic road tubes at 10 specified locations within the treatment and determined effectiveness by a change in 85th percentile speed. The researchers found that the optical bars reduced speeds and speed variations in situations that require drivers to decelerate from highway speeds to accommodate a highway work-zone project (Meyer 1999).

Hildebrand et al. (2003) also investigated work-zone traffic calming using transverse bars at a rural highway site in New Brunswick, Canada. The researchers conducted a simple before-and-after speed study over two days during day and nighttime hours. The data sets were comprised of about 100 vehicles in the day and 50 vehicles during the night.

The researchers’ speed measurement locations were upstream, immediately upstream, and downstream of the treatment, with speeds recorded for two days, one of which was close to the treatment installation. A test of comparison of two sample means and two sample variances were selected as the analysis methodology, which included a test at the 85 percent significance level.

The researchers concluded that the mean and 85th percentile speeds were reduced (statistically significant) by 2.1 mph and 2.4 mph and that the greatest reduction in speed occurred during the nighttime observations. Furthermore, the researchers concluded that the transverse bars provided an increased level of safety during nighttime conditions due to the high retroreflective capabilities of the pavement markings (Hildebrand et al. 2003).

VDOT installed transverse markings on US 460 at the entrances to a community where the speed transitions from 55 to 45 mph (Arnold and Lantz 2007) as shown in Figure 17.

Speeds at the eastbound entrance decreased by 1.2 and 9.6 mph at one location but increased by 4.7 and 9.8 mph at the second (one-week and three-month after periods, respectively). At the westbound entrance, speeds decreased by 5.1 and 5.6 mph for the one-week after period at the two data collection locations. At the three-month after period, speeds decreased by 3.4 mph at one location and increased by 1.4 mph at the second.

**Figure 17. Transverse markings on US 460 (Arnold and Lantz 2007)**

## Summary of Effectiveness for Transverse Treatments

Table 16 summarizes the effectiveness of various transverse treatments in reducing speeds.

**Table 16. Speed reduction for transverse pavement markings**

| Treatment | Speed Change | mph |
|---|---|---|
| Optical speed bars on a rural two-lane curve (Arnold and Lantz 2007) | Metric not stated | -3.9 to 3.0 |
| Optical speed bars on rural two-lane tangent section (Latoski 2009) | Mean | -2.0 to 4.2 |
| | 85th percentile | -5.0 to -2.0 |
| Optical speed bars on a freeway curve (Gates et al. 2008) | Mean | -1.1 to -5.0 |
| | 85th percentile | -1.0 |
| Converging chevrons on a freeway-to-freeway connector (Drakapoulous and Vergou 2003) | Mean | -15.0 to 1.0 |
| | 85th percentile | -17.0 to 1.0 |
| Converging chevron on curve (Shinar 1980) | 85th percentile | -6.0 |
| Converging chevron on double S-curve on rural two-lane roadway (ATSSA 2006) | 85th percentile | -4.0 |
| Herringbone (Martindale and Urlich (2010) | Mean | -7.6 to 0 |
| | 85th percentile | -3.9 to -1.4 |
| Transverse bars on rural curves (Vest et al. 2005, Katch et al. 2006) | Mean | -5.9 to 2.3 |
| | 85th percentile | -5.0 to 2.4 |
| Transverse bars on S-curves (Chrysler et al. 2009) | Metric not stated | no change |
| Transverse bars (Griffin and Reinhart 1995) | Mean | -2.0 to -1.0 |
| | 85th percentile | -15.0 |
| Transverse bars at work zone (Hildebrand et al. 2003) | Mean | -2.1 |
| | 85th percentile | -2.4 |

Table 17 provides crash modification factors for various transverse treatments. The CMFs were not necessarily developed based on rural two-lane curves but do provide some measure of the treatments' effectiveness.

Table 17. CMFs for transverse markings

| Treatment | Crash Type | CMF |
|---|---|---|
| Converging chevron pattern (Griffin and Reinhardt 1996 ★★★) | All: urban application | 0.68 |

## Advantages

- Low cost
- Cost-effective
- Don’t affect vehicle operation
- Don’t have an impact on emergency vehicles
- Don’t have an impact on drainage

## Disadvantages

- Additional maintenance required to install and maintain markings
- May be less effective in winter conditions when not visible

# Vertical Delineation

## Description

Vertical delineators or post-mounted delineators (PMDs) are usually flexible or rigid posts with some amount of reflective surface mounted along the roadside to provide additional delineation as shown in Figures 18, 19, and 20.

**Figure 18. Delineator posts along a curve (www.pexco.com/Pages/PexcoTrafficRDP.aspx)**

Vertical delineators are intended to warn drivers of an approaching curve. PMDs can provide drivers with a better appreciation of the sharpness of the curve, so they can select the appropriate speed before entering the curve, and provide them with continuous tracking information once they are within the curve to help position their vehicles within the travel lane while traversing the curve.

## Application

Delineator placement and spacing are covered in Section 3F of the 2009 Edition of the MUTCD.

A study by Chrysler et al. (2005) evaluated delineator spacing and color in a closed-course nighttime study with 24 drivers. The researchers found that drivers are not able to distinguish between single and double delineators, nor could they differentiate fixed versus variable-spaced delineators.

In addition, drivers did not understand the difference between yellow and white delineators. Consequently, the authors suggested use of fixed spacing and elimination of single versus double delineator distinction in the MUTCD.

**Figure 19. Retroreflective treatment on chevron posts day and night**

NCHRP Report 440 (Fitzpatrick et al. 2000) suggested that the cost of the post-mounted delineators is justified for roadways with 1,000 vpd or greater.

## Effectiveness

Figure 20. Post delineators on a curve

Carlson et al. (2004) evaluated several delineator treatments and concluded that vertical delineation of any type improves lane position at the entry and mid-point of horizontal curves.

Vest et al. (2005) evaluated different types of warning signs to reduce speed on curves. The researchers tested sites on rural roadways with a sharp curve, history of speed-related incidents, long tangent section before the curve, no vertical grade, and no intersections, driveways, or commercial activity within the curve.

Figure 21. Post-mounted delineators at 50 ft intervals (Vest et al. 2005)

One treatment evaluated placement of post-mounted delineators placed at 50 foot intervals as shown in Figure 21. Change in mean speed ranged from an increase of 1.6 mph to a decrease of 1.1 mph, while 85th percentile speeds increased 0.4 to 1.9 mph at the PC.

Within the curve, averages speeds ranged from no change to a decrease of 2.0 mph and from no change to a reduction of 2.0 mph in 85th percentile speeds.

Chrysler (2009) and Chrysler et al. (2009) assessed four types of vertical delineation including two types of PMDs (dot PMD and full-post), standard chevrons, and chevrons with full retroreflective posts in a closed-course nighttime driving test as shown in Figure 22.

Twenty drivers indicated when they could judge the sharpness of the curve. The drivers were able to assess the sharpness of the curve approximately 250 feet sooner for full PMD and approximately 250 feet sooner using the chevrons with reflectorized posts than they were using the baseline condition, which had only edge-line markings.

In addition, drivers were also shown photos of each treatment and asked to rank treatments by quality of delineation in defining sharpness of the curve. The drivers ranked the chevrons with reflectorized posts the highest and full PMD second.

Drivers also watched video on a laptop to judge when they could perceive the sharpness of the curve. Judgment times were shortest for the chevrons with reflectorized posts for almost all situations.

Re et al. (2010) evaluated application of chevrons and chevrons with a full-post retroreflective treatment at two curves in Texas. Both sites have paved shoulders and a posted speed limit of 70 mph day and 65 mph at night. One site had an advisory speed of 45 mph and the other had an advisory speed of 50 mph.

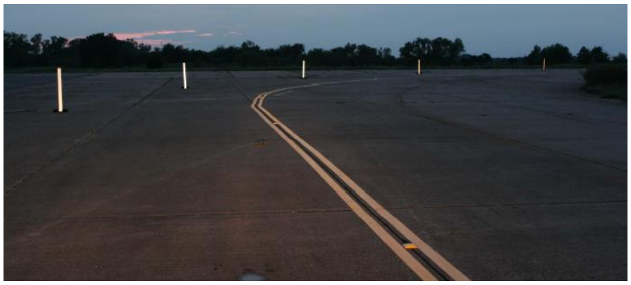
Each treatment was applied to each site and the researchers collected speed and lateral position before and after. Neither PMD showed a significant decrease in mean speed. Average speeds with the chevrons in place were 1.4 mph lower and, with the full-post chevron treatment, average speeds were 2.2 mph lower.

The 85th percentile speeds decreased by 1.3 mph for the scenario with only chevrons and 2.2 mph for the full-post chevrons. In most cases, the full-post chevrons reduced the percentage of vehicles exceeding 60, 65, and 70 mph. Centerline encroachments decreased by 78 percent with use of the PMDs.

Molino et al. (2010) evaluated four low-cost safety treatments on rural two-lane curves in a driving simulator with 36 participants. The test drive included a series of curves (radii of 100 or 300 feet and a deflection angle of 60 degrees) with a baseline condition (no treatments or edge lines) and four curve treatments. Drivers had to slow to negotiate all curves.

**Baseline (no delineators)**

**Standard post reflector (dot PMD)**



**Full post (full PMD)**

**Standard chevron (24 × 30 in.)**

**Full-post chevron**

**Figure 22. Sample treatments (Chrysler 2009)**

Treatments included the following:

- 4 inch edge lines
- Standard PMDs on one side of the roadway
- Standard PMDs on both sides of the roadway
- PMDs with sequential flashing light-emitting diode (LED) lights

The researchers found all PMDS were more effective in slowing drivers earlier and to a greater degree than just use of edge-line pavement markings. Acceleration was also flatter through the curve with the PMDs.

This simulator study also tested driver ability to detect curve direction and severity. Table 18 shows the results.

**Table 18. Driver ability to detect curve direction and severity (Molino et al. 2010)**

| | At Distance (ft) | |
|---|---|---|
| Treatment | Curve Direction | Curve Severity |
| None/baseline | 225 | 53 |
| Sequential flashing PMDs | 1,288 | 1,127 |
| PMDs on both sides of curve | 355 | 95 |
| PMDs one side of the curve | 426 | 116 |
| Edge lines | 249 | 72 |

PMDs = post-mounted delineators

Kallbert (1993) evaluated use of post-mounted delineators on rural two-lane roadways in Finland. During the nighttime, speeds increased after installation of the delineator on roadways with a speed limit of 49.7 mph by about 3.1 mph, but there were no significant changes in roadways with a speed limit of 62.1 mph.

Hallmark et al. (2012) evaluated addition of reflective material to existing chevron posts on four rural two-lane curves in Iowa as shown in Figure 23.

Figure 23. Reflective treatment added to existing chevron posts

The posted speed limit varied from 50 to 55 mph and the advisory speeds varied from 35 to 50 mph. Speed data were collected before and at one month after installation of the treatment.

Table 19 provides a summary of the speed effectiveness of PMDs from various studies.

### Table 19. Speed reduction for PMDs

| Treatment | Speed Change | mph |
|---|---|---|
| PMD (Vest et al. 2005) | Mean | -2.0 to 2.0 |
| | 85th percentile | -2.0 to 1.9 |
| Full-post reflective treatment added to chevron post (Re et al. 2010) | Mean at PC | -2.2 |
| | 85th percentile at PC | -.2.2 |
| Sequential flashing PMDs (Molino et al. 2010) | Not stated | -8.7 to -4.8 |
| PMDs on both sides of curve (Molino et al. 2010) | Not stated | -8.0 to -4.3 |
| PMDs one side of the curve (Molino et al. 2010) | Not stated | -6.9 to -3.6 |
| PMDs on rural two-lane roads in Finland (Kallbert 1993) | For roadways with speed limit of 49.7 mph | -3.1 |
| | For a roadways with speed limit of 62.1 mph | no change |
| Full-post reflective treatment added to chevron post on rural two-lane curves (Hallmark et al. 2012) | Mean at PC | -1.8 to 1.2 |
| | 85th percentile at PC | -2 to 0 |
| | Mean at center of curve | -1.3 to 0.6 |
| | 85th percentile at center of curve | -3 to 1 |

Schumann (2000) tested lane markings (4 inch) and lane markings plus PMDs (35 inch posts with two reflective banks) placed 2 feet from the edge of the roadway. The treatments were set up along a tangent section of a test route, which was a rural two-lane roadway.

Data were collected for test drivers in an instrumented vehicle. Drivers drove the route several times with the PMDs in place and then after the PMDS were removed. The research found that PMDs can provide long-range guidance at night for drivers.

*NCHRP Report 500, Volume 7: A Guide for Reducing Collisions on Horizontal Curves* (Torbic et al. 2004) lists PMDs as a tried strategy based on research by Zador et al. (1987), Agent and Creasey (1986), and Jennings and Demetsky (1985), and found that, although conflicting evidence about effectiveness exists, PMDs are most likely to be effective for sharp curves.

McGee and Hanscom (2006) report on use of delineators along a curve by the Ohio DOT (ODOT). The researchers reported a reduction of 15 percent in ROR crashes.

Montella (2009) evaluated crashes before and after installation of chevron signs, curve warning signs, and sequential flashing beacons in various combinations for 15 curves in Italy, compared against a reference group of 312 untreated curves using EB.

Overall, reductions of 28.2 percent were found in total crashes and 33.7 percent for nighttime. The researchers found that the treatment was most effective for curves with a radius of ≤ 984 feet with a 52.2 percent reduction for all crashes and 79.0 percent for nighttime crashes. Differences were statistically significant at the 95 percent level of significance.

Table 20 provides CMFs for PMDs. A summary of studies that assessed the crash impact of PMDs but did not develop CMFs is shown in Table 21.

### Table 20. CMFs for post-mounted delineators

| Treatment | Crash Type | CMF |
|---|---|---|
| Post mounted delineators (Elvik and Vaa 2004 ♦♦♦) | Serious and minor injury | 1.04 |
| Install post mounted delineators on curves (USDOT 2008, Gan et al. 2005) | All crashes | 0.70 to 0.80 |

### Table 21. Crash impacts for post-mounted delineators

| Countermeasures | Crashes | Change (%) |
|---|---|---|
| Installation of chevrons, curve warning signs, and sequential flashing beacons on curves (Montella 2009) | Total | -28.2% |
| | Nighttime | -33.7% |
| | Total on curves with radius ≤ 300 meters | -52.2% |
| | Nighttime on curves with radius ≤ 300 meters | -79.0% |

## Advantages

♦ Low cost

## Disadvantages

♦ Maintenance costs

# Rumble Strips and Rumble Stripes

## Description

Rumble strips and stripes (Figure 24) provide audible and vibratory alerts to drivers when their vehicles depart the travel lane and notify drivers that a steering correction is needed.

Figure 24. Edge-line and centerline rumble strips

## Application

Rumble strip/stripe designs can vary by strip/stripe pattern, installation method, distance from (or placement over) the edge of the travel lane, and the type of roadway on which the strips/stripes are installed.

The five most commonly used types of rumble strips/stripes are outlined in Table 22 and described further in the remainder of this chapter. The type of rumble strip/stripe selected and its placement should be based on a consideration of unconventional vehicle needs, available shoulder width, pavement age, and installation method.

Basic information about application of rumble strips is summarized in the next section. Other resources include the following:

- Nambisan, Shashi, and Shauna Hallmark. *Lane-Departure Countermeasures: Strategic Action Plan for the Iowa Department of Transportation*. Center for Transportation Research and Education, Iowa State University. Ames, Iowa. May 2011.

### Shoulder Rumble Strips

Table 22 provides a summary of types of shoulder rumble strips.

Milled-in shoulder rumble strips are installed by cutting or grinding the pavement surface as shown in Figure 25, typically using carbide teeth attached to a 24 inch diameter rotating drum. The indentations formed are approximately 1/2 inch deep, 7 inches wide. parallel to the travel lane, and 12 to 16 inches long, perpendicular to the travel lane (Umbs 2001).

The indentations are spaced approximately 12 inches from center to center and offset 4 to 12 inches from the edge of the travel lane. Some states place an asphalt fog seal over the rumble strips to prevent oxidation and moisture buildup (Umbs 2001).

Rolled-in shoulder rumble strips are installed using a steel wheel roller with half-sections of metal pipe or solid steel bars welded to the roller face. The compaction operation presses the shape of the pipe or bar into the hot-mix asphalt (HMA) shoulder surface. The resultant indentation (shown in Figure 25) is generally 1 inch deep and 18 to 35 inches long, perpendicular to the travel lane. The indentations are usually spaced 8 inches from center to center and offset 6 to 12 inches from the travel lane edge (Umbs 2001).

## Table 22. Application of various types of rumble strips (after Nambisan and Hallmark 2011)

| Type | Width (in.) | Length (in.) | Spacing (in.) | Depth (in.) | Height (in.) | Advantages | Disadvantages |
|---|---|---|---|---|---|---|---|
| Milled-in | 7 | 12–16 | 12 | 0.5 | n/a | Shallower indentations into the roadway<br>Can be installed on existing or new roadway shoulders | Difficult installation on older or worn pavement<br>Fog sealant that some manufacturers use on the rumble strips, may prevent edge line material from adhering to the surface |
| Rolled-in | 2–2.5 | 18–35 | 8 | 1 | n/a | Less expensive to install than other rumble strip designs<br>Can be installed as part of the pavement rolling operation | Indentations may not provide enough driver warning due to size<br>Installation depends on pavement temperature |
| Formed-in | 2–2.5 | 16–35 | 1 | 1 | n/a | Can be installed as part of the pavement installation process | Indentations may not provide enough driver warning due to size<br>More expensive than milled-in and rolled-in rumble strips<br>Contractor-dependent, with limited inspection techniques |
| Raised | varies | varies | varies | varies | 0.25–0.5 | Highly visible at night and in rainy conditions<br>Provides vehicle guidance at night | May not provide enough driver warning due to size and/or material<br>Relatively expensive installation and maintenance costs<br>Snow plow blade tends to remove the device |
| Edge-line | 7 | 4, 8, 12, 16 | 12 | .5 | n/a | Can be installed in the absence of a paved shoulder<br>Enhanced edge-line pavement visibility at night and in rainy conditions | Vehicles have a greater chance of traveling over rumble strip and pavement marking<br>Increased outside noise levels due to the greater chance of vehicles traveling over them |

Rolled-in rumble strips must be installed while the asphalt is at the proper temperature. Colder-than-optimal asphalt temperatures may lead to shallow indentations, while warmer-than-optimal asphalt temperatures may lead to problems with compaction and shoulder stability (Umbs 2001).

Formed-in shoulder rumble strips are installed by pressing a corrugated form onto a newly-placed and -finished concrete surface. The resulting indentations, shown in Figure 25, are about 1 inch deep and 2 to 35 inches long, perpendicular to the travel lane. The indentations may be continuous, but are generally in groups of five to seven depressions spaced about 50 feet apart and offset from the travel lane by about 12 inches (FHWA 2001).


**Milled-in (Morena 2003)**


**Rolled-in (Morena 2003)**


**Formed-in (Morena 2003)**


**Edge-line**

Figure 25. Different types of shoulder rumble strips

## Centerline Rumble Strips

Centerline rumble strips (CLRS) are generally specified to be installed where a high risk of cross-centerline crashes has been noted. However, to enhance safety, some states have adopted a general policy to install CLRS on all rural two- or four-lane undivided roadways eventually.

Most state transportation agencies place the CLRS on no-passing centerline pavement markings, while only a few agencies install CLRS on all types of centerline markings (Russell and Rys 2000).

Generally, CLRS are installed in no-passing areas, high-crash roadway segments, and high-crash curve locations to warn drivers of a change in roadway geometry. Some states have also installed CLRS on long stretches of straight roadways to help prevent cross-centerline crashes due to driver fatigue.

Many states specify the discontinuation of CLRS just prior to certain roadway structures, such as bridges and tunnels. Finally, a generally-accepted practice is to discontinue CLRS within rural driveways and intersections.

Several different centerline rumble strip patterns have been used as shown in Figure 26.

Commonly, rumble strips are 0.5 inch deep and spaced 12 inches from center to center. The length of the rumble strip varies from 4 to 18 inches, depending on the state transportation agency, design templates, or installation considerations. The following sections describe common CLRS patterns that have been used in the US.

## Edge-Line Rumble Stripes

For roads where paved shoulders are not a viable option due to cost, narrow shoulders, or ROW restrictions, an alternative process has been devised that involves milling narrow-width rumble strips directly along the existing pavement edge, followed by placement of standard edge-line pavement markings over the milled areas, resulting in rumble stripes. (These edge-line rumble strips are sometimes called rumble stripes.)

Continuous (Kar and Weeks 2001)

18 in. continuous (Iowa DOT)

Two sets of continous on outside of centerline markings (Troy 2007)

Alternating CLRS (Michigan DOT 2009)

Figure 26. Different types of centerline rumble strips

Some agencies are using edge-line rumble stripes on two-lane paved roadways with unpaved shoulders. Rumble strips grooved into the pavement edge can provide some alert to drivers crossing the edge line.

In addition, when the edge-line pavement marking is painted through the rumble strip, the grooved surface of the rumble strip facing the driver can provide a near-vertical surface, which enhances edge-line pavement marking visibility at night and during rainy conditions. Figure 27 shows an example of this treatment.

Figure 27. Edge-line rumble stripe on a rural Iowa highway (Hallmark et al. 2010)

Edge-line shoulder rumble strips/stripes increase edge-line marking visibility and longevity because part of the line paint is located within the rumble strip/stripe depression. This feature is particularly advantageous in climates where ice and snow are present, where raised pavement markers cannot be used due to probable snowplow damage.

## Effectiveness

Charlton and DePont (2007) evaluated various curve treatments using a simulator in New Zealand. The study evaluated 48 participants who drover a simulator route, which replicated a 2.1 mile section of a state highway and a 2.2 mile section of level road with four horizontal curves with consistent radii (two with 53 mph and two with 28 mph curves).

The researchers studied several combinations of treatments including standard advance warning signs with a herringbone pattern pavement marking, advance warnings with dashed white centerlines, advance warnings with double yellow lines through the curves, and advance warnings followed by centerline and edge-line rumble stripes. The researchers found that the centerline and edge-line rumble stripes had lower speeds at the PC and curve center than the other three treatments.

Anund et al. (2007) studied the effect of four types of rumble strips on sleepy drivers in an advanced moving driving simulator in Sweden and Finland. One set of rumble strips was roughly similar to what is used for edge-line rumble stripes with dimensions of 7 inches wide by 0.8 inch long at a spacing of 11.2 inches apart and a depth of 0.6 inch The researchers evaluated 35 subjects who had worked the night shift before participating in the study over a straight section of road alternating a particular type of rumble strips.

### Shoulder Rumble Strips

The NYSDOT and New York State (NYS) Thruway Authority similarly installed 4,000 miles of milled-in rumble strips on state highways for their joint Safe-Strip program. Using one year of uniform before-and-after crash data, the agencies found a 65 to 70 percent decrease in ROR crashes (Perrillo 1998).

A study encompassing 699 miles of state highways in Connecticut with milled-in shoulder rumble strips found that installing the rumble strips reduced SV fixed-object crashes by 33 percent and ROR crashes by as much as 48.5 percent based on a comparison of three years of before-after data (Smith and Ivan 2005).

### Centerline Rumble Strips

Persaud et al. (2004) conducted a before-and-after study to investigate the effectiveness of CLRS on more than 210 miles of rural undivided two-lane roads in seven states. An EB before-after analysis accounting for regression to the mean concluded that injury crashes decreased 14 percent and frontal and opposing-direction sideswipe injury crashes decreased 25 percent.

Kar and Weeks (2009) evaluated CLRS at 14 northern Arizona locations, including arterials, minor arterials, and collectors. A review of crash data three years prior to and three years after installation indicated that cross-centerline crashes accounted for 36 percent of the total fatal and serious injury crashes before installation. The authors found a 61 percent decrease in fatal and serious injury crashes after installation.

In a similar study that focused on a winding two-lane canyon highway, the Colorado DOT (CDOT) investigated the effectiveness of 17 miles of 12 inch long CLRS (Outcalt 2001). The authors compared four years of before and after data and found a 34 percent decrease in head-on crashes and a 36.5 percent decrease in opposite-sideswipe crashes. During the same period, AADT increased by 18 percent.

The data also indicated that the CLRS had drawbacks, including an increased danger to motorcyclists and bicyclists, increased noise levels, and accelerated wear on the centerline pavement markings.

A broader study of 518 miles of roadway conducted by the Washington State Department of Transportation (WSDOT) investigated the effectiveness of CLRS using a before-and-after crash analysis that compared one year of crash data before installation to six months of crash data after installation (Hammond 2008). The data indicated the reductions as shown in Table 23.

Similarly, an extensive before-and-after crash study performed in Minnesota showed that the installation of CLRS on selected two-lane highways led to a statistically-significant 25 percent reduction in fatal and severity crashes per year in the after period (Briese 2006). In addition, before-and-after crash data showed a 3 percent reduction in total crashes per year with a 9 percent increase in AADT for the studied segments.

## Table 23. CMFs for rumble strips

| Treatment | Crash Type | CMF |
|---|---|---|
| Install centerline rumble strips on rural two-lane roadways (USDOT 2008 and FHWA 2012) | All | 0.87 |
| | Fatal and injury | 0.82 |
| Install edge line rumble strips on rural two-lane roadways (USDOT 2008 and FHWA 2012) | All | 0.86 |
| | Injury | 0.85 |
| | Head-on | 0.45 |
| Install centerline and shoulder rumble strips (Sayet et al. 2010 ★★★★) | Fatal, serious injury for all on principal arterial | 0.82 |
| | All cross-median, frontal and opposing direction sideswipe, head-on, ROR | 0.79 |
| Install centerline rumble strips on tangent sections (Torbic et al. 2009 ★★★★★) | Injury for all in rural areas | 0.78 to 1.10 |
| | Injury head-on, sideswipe in rural areas | 0.33 to 0.57 |
| | All in rural areas | 0.90 to 1.02 |
| Install centerline rumble strips (Persuad et al. 2003 ★★★★) | All on rural principal arterials | 0.86 |
| | Head-on, sideswipe on rural principal arterials | 0.79 |
| Install centerline rumble strips on horizontal curves (Torbic et al. 2009 ★★★★) | All head-on, sideswipe in rural areas | 0.53 |
| | All in rural areas | 0.83 to 1.46 |
| | Injury for all types in rural areas | 0.63 to 1.1 |
| Install edge line rumble strips (Torbic et al. 2009 ★★★★) | ROR injury in rural areas | 0.57 to 1.31 |
| Install edge line rumble strips on horizontal curves (Pitale et al. 2009 ★★) | All on principal arterials | 0.85 |
| Install edge line rumble strips with shoulder < 5 ft (Torbic et al. 2009 ★★★★) | ROR injury in rural areas | 0.53 to 1.27 |
| Install edge line rumble strips with shoulder ≥ 5 ft (Torbic et al. 2009 ★★★★) | ROR injury in rural areas | 0.34 to 1.11 |
| Install continuous milled-in shoulder rumble strips (Carrasco et al. 2004 ★★★) | All SVROR in rural areas | 0.9 |
| | SVROR serious and minor injury in rural areas | 0.78 |
| | All in rural areas | 0.84 |
| Install continuous, rolled-in shoulder rumble strips (Griffin 1999 ★★★) | All SVROR on rural principal arterials and expressways | 0.79 |
| | SVROR serious and minor injury on rural principal arterials and expressways | 0.93 |
| Install shoulder rumble strips<br>(Torbic et al. 2009 ★★★★★,<br>Patel et al. 2007 ★★★★,<br>Sayed et al. 2010 ★★★★) | All in rural areas | 0.74 to 1.40 |
| | All on rural principal arterials and expressways | 1.00 to 1.11 |
| | All injury in rural areas | 0.56 to 1.07 |
| | All injury on rural principal arterials and expressways | 0.87 to 0.99 |
| | All ROR crashes in rural areas | 0.55 to 1.70 |
| | All ROR on rural principal arterials and expressways | 0.62 to 0.98 |
| | ROR injury in rural areas | 0.41 to 1.28 |
| | ROR injury on rural principal arterials and expressways | 0.77 to 0.97 |

### Edge-Line Rumble Stripes

The Mississippi DOT (MDOT) installed edge-line rumble stripes on a two-lane roadway and conducted a before-and-after crash study (ATTSA 2006). The study found that right-side ROR crashes were reduced by 25 percent after installing the rumble stripes.

TTI evaluated the impact of edge-line rumble stripes on traffic operations. The evaluation found that shoulder encroachment decreased by 46.7 percent after installing edge-line rumble stripes (Miles et al. 2005).

Pratt et al. (2006) evaluated centerline and edge-line rumble strips (ERS) where the rumble strips were placed directly on the marked edge line along a five-mile segment. The rumble strips were 0.5 inch deep, 7 inches long, and 12 inches wide at 12 inch spacing with a 4 inch edge line.

The researchers evaluated shoulder encroachments for both curved and tangent sections. The authors found a reduction of 46.7 percent for all categories of encroachments. Inadvertent shoulder encroachments decreased from 616 to 359 from the before to after period.

The researchers also recorded lateral encroachment onto the shoulder and noted a decrease in shoulder encroachment from 10.6 to 18.5 inches. The researchers also noted a 71.8 percent decrease in number of vehicles striking the right edge line.

A recent study of the Missouri Smooth Roads Initiative (SRI) included 61 sites and more than 320.5 miles of both edge-line rumble stripes and shoulder rumble strips. The authors conducted a before-and-after analysis using an empirical Bayesian analysis. Overall, the researchers found that the SRI program showed a statistically-significant 8 percent decrease in fatal and disabling injury crashes and a 6 percent decrease in fatal and all injury crashes. However, the analysis included only one year of after data (Potts et al. 2008).

Hallmark et al. (2011) evaluated edge-line rumble stripes along six sites in Iowa. One of the advantages that have been attributed to rumble stripes is additional visibility of the pavement marking. It is thought that the shape of the rumble stripe itself provides a raised (vertical) surface so that the markings are more visible at night and particularly when some amount of precipitation is on the pavement surface.

In addition, the depression protects part of the pavement marking, which can lead to reduced wear. Consequently, the researchers evaluated pavement marking wear over time. Iowa receives a significant amount of snow from December through March. Road maintenance in Iowa is aggressive and includes scraping and the use of salt and sand. As a result, winter maintenance is harsh on pavement markings.

The researchers visited several sites two years after application of the rumble stripes and conducted a qualitative assessment of pavement marking wear. At all of the sites, a significant portion of the regular pavement markings, which were flush with the pavement surface, had been worn away by the snowplows, while much of the marking within the rumble stripe remained. As a result, the rumble stripe was successful in preserving the pavement marking (as shown in Figure 28), which will lead to improved visibility.

One problem that the researchers noted with the rumble stripes is that material (sand, gravel, and dirt) tends to accumulate within the stripe as shown in Figure 29.

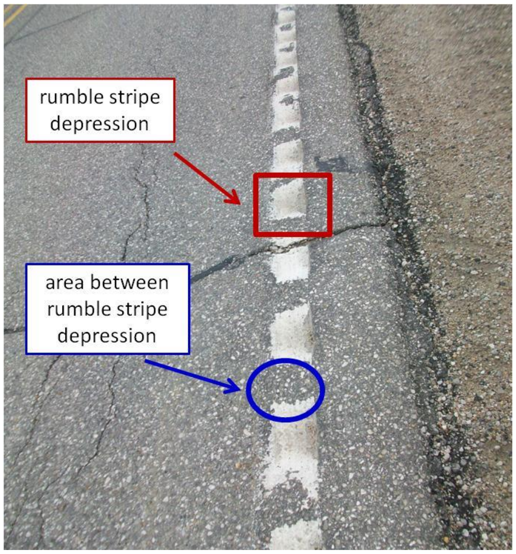


**Figure 28. Wear at Vandalia/ CR F-70 after two years (Hallmark et al. 2011)**

The team evaluated lane position before and after installation of edge-line rumble stripes as a surrogate measure of safety given only a short after period was available for a crash analysis.

Average offset from the lane center decreased by more than 1 foot for two locations during the daytime period. Average offset decreased by 0.2 to 0.6 feet for three sites and increased at one site by 0.4 foot.

The vehicle wheel path moved closer to the lane center for all six sites for the nighttime period but was not statistically significant at the 95 percent level of confidence for the CR W13 south and P53 locations.

The change was about 1.5 feet for three of the sites. On average, improvement in offset from the lane center was higher for the nighttime period than for the daytime period (Hallmark et al. 2011).

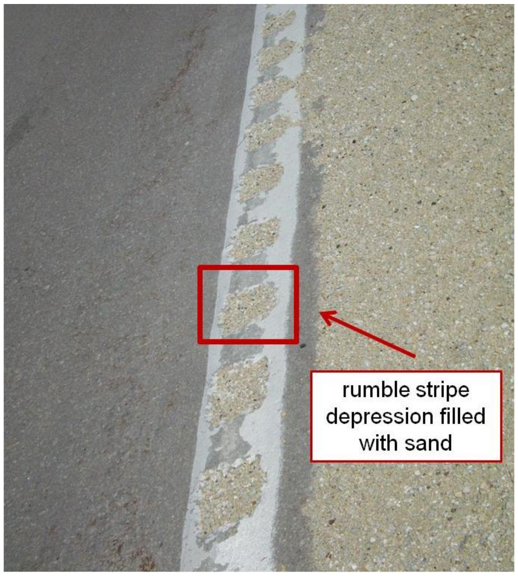


Figure 29. Rumble stripe depression filled with material (Hallmark et al. 2011)

In a summary of low-cost strategies, ATSSA (2006) indicated that, at one year after installation, edge-line rumble stripes can have retroreflectivity levels up to 20 times higher than an equivalent flat line under wet-weather conditions. The vertical face provides additional advantage during wet conditions and at night and the recess may protect paint against snowplow damage.

Table 23 provides CMFs for rumble strips. The CMFs were not necessarily developed based on rural two-lane curves but do provide some measure of treatment effectiveness. A summary of studies that assessed the crash impact of rumble strips but did not develop CMFs is shown in Table 24. Crashes are not specifically for curves unless noted as such.

## Table 24. Crash impacts for rumble strips

| Countermeasures | Crashes | Change (%) |
|---|---|---|
| Milled-in shoulder rumble strips (Perrillo 1998, Smith and Ivan 2005) | ROR | 49 to 70% |
| | SV fixed objects | 33% |
| Centerline rumble strips on rural two-lane (Persuad et al. 2004, Outcalt 2004, Briese 2006) | Total | 3% |
| | Injury | 14% |
| | Frontal and opposing-direction sideswipe injury | 25% |
| | Head-on | 37% |
| | Opposite sideswipe | 34% |
| | Fatal and major injury | 35% |
| Centerline rumble strips on arterial, minor arterials, and collectors (Kar and Weeks 2009) | Fatal and injury | 61% |
| Centerline rumble strips, road type not specified (Hammond 2008) | Fatal and serious injury | 28% |
| | All cross-centerline | 26% |
| | Fatal and serious injury for cross-centerline | 50% |
| Centerline and edge line rumble stripes (Pratt et al. 2006) | Fatal and major injury | 8% |
| Edge-line rumble stripes (ATTSA 2006) | Right side ROR | 25% |

## Advantages

- Paint lines placed within the rumble strip can improve visibility under wet conditions
- Can be placed in existing or new pavement

## Disadvantages

- Some agencies have received noise complaints
- Cost
- May affect bicyclist and horse-drawn vehicles
- Depressed grooves may fill with dirt or debris
- Increased danger for motorcycles and bicyclist
- Increased noise levels
- Accelerated wear on centerline markings

# On-Pavement Curve Signing

## Description

On-pavement markings show a curve sign in advance of the curve. The treatment may also show the speed limit. A common design is shown in Figure 30.

Figure 30. On-pavement curve sign

## Application

The Pennsylvania DOT (PennDOT) applied the advanced curve warning markings in advance of horizontal curves. Arnold and Lantz (2007) suggest avoiding use of the markings when there are intersecting roadways or driveways that could lead to driver confusion. The authors also suggest treating the most hazardous curve first when compound curves are present.

PennDOT used the MUTCD (2009) Table 2C-4 to determine where to place the advanced curve warning signs upstream of the PC.

Although no guidance was found for on-pavement posted speed markings, placing markings at the same location as for advisory signs would allow drivers sufficient time to react and adjust their speed.

## Effectiveness

Charlton (2007) used 30 volunteers in a driving simulator to look at three types of curve warnings over 28, 40.4, and 52.8 mph curves. Drivers reacted to hands-free cell phone tasks during the study to assess driver workload.

Curve treatments included a regular curve advisory and advisory speed sign, a chevron sight board with the curve advisory speed, and on-pavement markings with the curve advisory speed and transverse markings.

At the 52.8 mph curve, the chevron sight board was the most effective, especially at curve approach and entry points. Both the chevron sight board and pavement markings were accompanied by lower 40.4 mph curves speeds, and with cell phone tasks.

All of the warnings worked reasonably well for severe curves regardless of demands for cell phone tasks. However, at the 28 mph curve, driver speeds were lowest at all stages with presence of the pavement markings than for the other treatments.

Chrysler and Schrock (2005) examined the effectiveness of pavement markings consisting of words and symbols on reducing speeds on rural highway curves. The researchers tested four different markings including transverse lines, CURVE AHEAD, and CURVE 55 MPH pavement markings (Figure 31). The researchers also tested pavement markings with a curve symbol plus 50 MPH on an urban curve.

**Figure 31. On-pavement curve markings (Chrysler and Schrock 2005)**

Each of the markings was applied to the roadway with the majority applied 400 feet after the standard curve warning sign with text that was approximately 8 feet tall.

The researchers measured change in speed from an upstream control point to the treatment and found the following:

- No speed changes with the CURVE AHEAD signing
- Speeds reduced by 4 mph for the CURVE 55 MPH, although an analysis of variance indicated that the difference was not statistically significant
- Reduction of 7 mph for the curve symbol plus 50 MPH markings at the urban location (divided four-lane highway)

Retting and Farmer (1998) studied the use of pavement markings in the tangent section leading up to a curve and their effects of speed. The researchers conducted this study on a suburban two-lane secondary road in Northern Virginia.

The study site had a sharp left curve with a speed limit of 35 mph leading up to the curve and then an advisory speed of 15 mph. The researchers used before-and-after data collection on both a test site and a control site.

At the test site, 8 foot tall white letters spelled SLOW, along with two white lines perpendicular to the flow of traffic and a left curving arrow (similar to that shown in Figure 30).

The researchers recorded speed downstream of the PC but after the pavement markings on the test site and then upstream in the curve. Results showed a daytime decrease in mean speed of 1.1mph from 34.3 mph to 33.2 mph (1.1 mph) and a 5.6 percent decrease in drivers exceeding 40 mph.

At night, the researchers observed a decrease of 1.6 mph for the mean speed and a decrease in drivers exceeding 40 mph of 6.1 percent. Late night mean speed dropped 3.4 mph and drivers exceeding 40 mph dropped 16.9 percent.

Retting et al. (2000) evaluated use of the on-pavement SLOW marking on a sharp left curve with minimal sight distance on a rural two-lane road in Virginia. The roadway had 10 foot lanes with narrow shoulders. The word SLOW along with a left turn arrow were placed in advance of the curve with 18 inch edge lines after the markings in advance of the curve. Speeds were reduced from 34.3 to 33.2 mph.

Hallmark et al. (2012) installed on-pavement curve signs at two rural two-lane curves in Iowa as shown in Figur×e 32. DMC 99 has a posted speed limit of 55 mph with no advisory speed (780 vpd) and the treatment was placed at both entrances to the curve. CR L-20 has a posted speed limit of 55 mph (1,880 vpd) and the treatment was placed at the north and south entrances of the S curve, which has an advisory speed of 35 mph. Speed data were collected before and at one-month and twelve-months after installation.

**Figure 32. On-pavement treatment applied in Iowa**

Results for DMC 99 indicated that mean speeds decreased from 0.7 to 1.8 mph at the PC and decreased by 0.4 to 1.7 mph at the center of the curve. Change in 85th percentile speeds ranged from a decrease of 1 mph to an increase of 2 mph at the PC and up to a 1 mph at the center of the curve. The number of vehicles e×ceeding the posted speed limit by 5 mph increased slightly at the north PC with no changes in vehicles traveling at higher speed thresholds. Decreases of up to 14 percent resulted at the center of curve and south PC for vehicles traveling 5 or more mph over the posted speed limit and up to a 5 percent reduction in vehicles traveling 10 or more mph over resulted.

On CR L-20, mean speeds decreased from 0.6 to 1.0 mph at the PC and from 0.0 to 2.0 mph at the centers of the S curve. A 1 mph decrease in 85th percentile speed was noted at the PC and up to a 2 mph decrease resulted at the center of the S curve. Only moderate changes in the number of vehicles traveling 5 or more mph over the advisory speed resulted at the PC with decreases up to 4 percent, 7 percent, and 4 percent for vehicles traveling 10 or more, 15 or more, and 20 or more mph over, respectively. At the center of the curve, reductions of up to 8 percent in the percentage of vehicles traveling 5 or more mph over the advisory speed were recorded. Reductions of up to 16 percent in vehicles traveling 10 or mph over and up to 11 percent for vehicles traveling 15 or mph over also resulted. The change in vehicles traveling 20 or more mph over ranged from a decrease of 4 percent to an increase of 2 percent.

A summary of the speed reductions from various studies is shown in Table 25.

### Table 25. Speed reduction for on-pavement curve markings

| Treatment | Speed Change | mph or % |
|---|---|---|
| CURVE AHEAD (Chrysler and Schrock 2005) | From upstream control point to treatment | no change |
| CURVE XX MPH (Chrysler and Schrock 2005) | From upstream control point to treatment | -4 |
| Curve symbol plus XX MPH on urban four-lane divided (Chrysler and Schrock 2005) | From upstream control point to treatment | -7 |
| SLOW and two white lines on suburban two-lane with advisory speed of 15 mph (Retting and Farmer 1998) | Daytime mean | -1.1 |
| | Daytime exceeding posted by 5+ mph | -5.6% |
| | Nighttime mean | -3.4 |
| | Nighttime exceeding posted by 5+ mph | 16.9% |
| SLOW and arrow on rural two lane curve (Retting et al. 2000) | Mean | -1.1 |
| SLOW with arrow and two bars on rural curves (Hallmark et al. 2012) | Mean at PC | -0.6 to -2.0 |
| | Mean at center | 0.0 to -2.4 |
| | 85th percentile at PC | -1 to -2 |
| | 85th percentile at center | -2 to 1 |
| | Exceeding posted or advisory by 5+ mph at PC | -14 to 10% |
| | Exceeding posted or advisory by 5+ mph at center | -8 to 0% |
| | Exceeding posted or advisory by 10+ mph at PC | -6 to 0% |
| | Exceeding posted or advisory by 10+ mph at center | -16 to -1 |
| | Exceeding posted or advisory by 15+ mph at PC | -7 to 0% |
| | Exceeding posted or advisory by 15+ mph at center | -11 to -1% |
| | Exceeding posted or advisory by 20+ mph at PC | -6 to 0% |
| | Exceeding posted or advisory by 20+ mph at center | -4 to 2% |

## Advantages

- Low cost

## Disadvantages

- Markings are typically placed in the traveled way, which may result in additional maintenance costs

# Flashing Beacons

## Description

Flashing beacons are traffic signals with one or more signal sections that operate in a flashing mode (see Figure 33). Flashing beacons can be used to provide warning for various applications as described in Chapter 4L of the MUTCD (2009). Flashing beacons provide notice to drivers that conditions are changing ahead. Flashing beacons are used in conjunction with the appropriate signing.

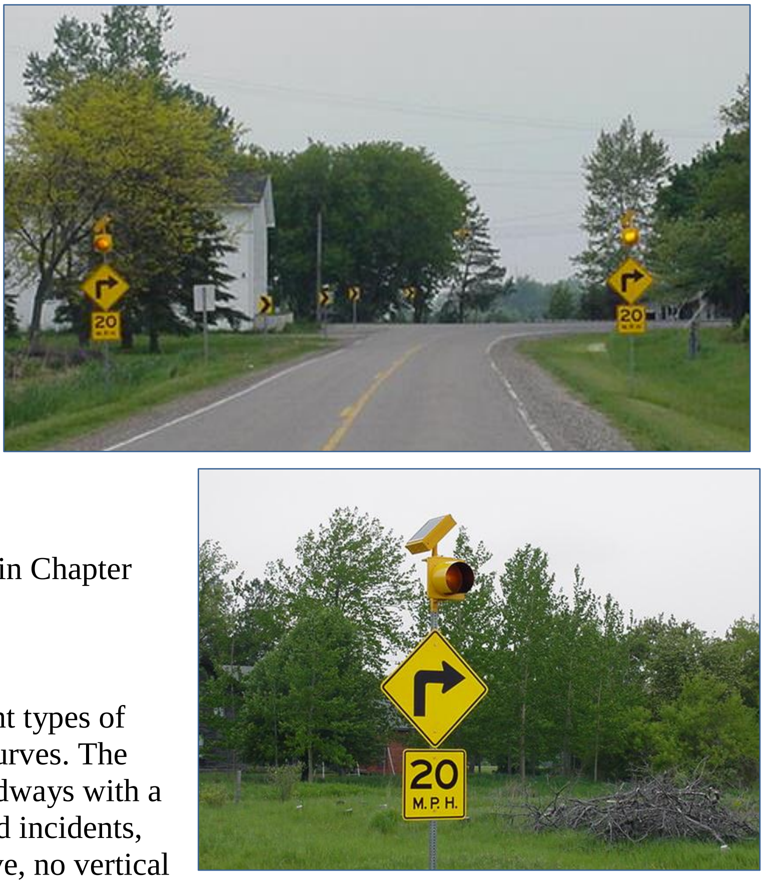


**Figure 33. Flashing beacons (Bowman 2012)**

## Application

Use of flashing beacons is covered in Chapter 4L of the MUTCD (2009).

## Effectiveness

Vest et al. (2005) evaluated different types of warning signs to reduce speed on curves. The researchers tested sites on rural roadways with a sharp curve, history of speed-related incidents, long tangent section before the curve, no vertical grade, and no intersections, driveways, or commercial activity within the curve.

At some sites, two 6 inch flashing lights were mounted on the upper portion of the sign as shown in Figure 34. The beacons were visible to drivers only at night.

**Figure 34. Flashing beacons on advisory curve sign (Vest et al. 2005)**

At one site, a decrease of 1.8 mph in average speeds occurred at the PC and a decrease of 0.2 mph occurred at the other (nighttime speeds). Only one site reported results at the center of the curve, showing a 0.8 mph increase in nighttime average speeds.

Janoff and Hill (1986) evaluated the impact of a flashing beacon, which was installed at a sharp horizontal curve (~ 45 degrees) on a four-lane undivided rural highway with a 25 mph advisory speed. Crashes were compared for a 22 month period before installation to a 22 month period after installation.

Table 26 provides crash modification factors for flashing beacons. Crashes are not specifically for curves unless noted as such.

### Table 26. CMFs for flashing beacons

| Treatment | Crash Type | CMF |
|---|---|---|
| Flashing beacons and curve warning signs (USDOT 2008) | All | 0.7 |

A summary of studies that assessed the crash impact of flashing beacons but did not develop CMFs is shown in Table 27. A 50 percent reduction in all crashes and a 91 percent reduction in speed-related/lost control, head-on, and fixed object crashes are noted.

### Table 27. Crash impacts for flashing beacons

| Countermeasures | Crashes | Change (%) |
|---|---|---|
| Single flashing beacon at center of curve (Janoff and Hill 1986) | All | -50% |
| | Speed-related/lost control, head-on, and fixed object | -91% |

## Advantages

- Low cost

## Disadvantages

- Requires a power source
- Little information on effectiveness is available

# Dynamic Curve Warning Systems

## Description

Dynamic curve warning systems (DCWSs) are traffic control devices that are programmed to provide a message to drivers exceeding a speed threshold (Figure 35). A DCWS consists of a speed-measuring device, which may be loop detectors or radar, and a message sign that displays feedback to drivers who exceed a predetermined speed threshold.

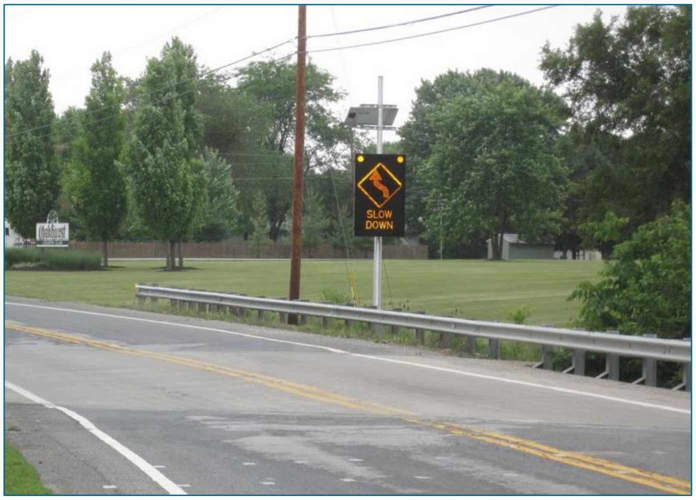
The feedback may be the driver’s actual speed, a message such as SLOW DOWN, or activation of a warning device such as beacons or a curve warning sign.

The utility of this particular intelligent transportation system (ITS) application is that these systems specifically target drivers who are speeding rather than all drivers. In this way, the system “interacts” with an individual driver and may lead to better compliance, given the message appears more personalized.

Dynamic speed feedback sign (DSFS) systems are one type of DCWS (top of Figure 35) that have been used to reduce vehicle speeds successfully and, subsequently, crashes in applications such as traffic calming on urban roads.

Another type of DCWS is a sequential dynamic curve warning system (SDCWS), which consists of a series of solar-powered, LED-enhanced chevron signs that are installed throughout a curve (Figure 36).

**Dynamic speed feedback sign**



**Dynamic curve advisory feedback sign**

**Figure 35. Two examples of dynamic driver feedback signs**

Typically, the system is set up via radar to flash only when a driver exceeds a set speed threshold. When the signs light up, they usually light up in sequence, as the driver progresses through the curve. When the system is not activated, drivers are presented with regular chevron signs.

The FHWA is currently evaluating the effectiveness of this system in four states (www.fhwa.dot.gov/hfl/partnerships/safety_eval/brochure_tapco.cfm).

## Application

Given DCWSs are often expensive, they have typically been applied selectively to high-crash curve locations. Sign vendors should also be consulted as to whether their systems are MUTCD-compliant.

## Effectiveness

Dynamic speed-activated feedback sign systems have been used in only a few cases to reduce speeds and warn drivers of upcoming curves. The systems have been used more extensively for a number of other related applications. A summary of information about curve- and non-curve-related applications follows.

Bertini et al. (2006) studied the effectiveness of a dynamic speed-activated feedback sign system on I-5 near Myrtle Creek, Oregon on a curve with an AADT of 16,750 vpd and an advisory speed of 45 mph.

Figure 36. Sequential dynamic curve warning system (FHWA 2012)

The system consisted of two displays that provided different messages to drivers based on the speed detected as shown in Table 28 and Figure 37.

Table 28. Advisory messages for I-5 dynamic speed-activated feedback sign system (Bertini et al. 2006)

| Sign Panel | Detected Speed (mph) | | |
|---|---|---|---|
| | Under 50 | 50-70 | Over 70 |
| 1 | CAUTION | SLOW DOWN | SLOW DOWN |
| 2 | SHARP CURVES AHEAD | YOUR SPEED IS XX MPH | YOUR SPEED IS OVER 70 MPH |

The DSFS system was put in place alongside one of the existing signs in both the north and southbound directions. Each system consisted of the actual dynamic message sign, a radar unit, a controller unit, and computer software.

Results indicated that, after installation of the DSFS system, passenger vehicle speeds were reduced by 2.6 mph and commercial truck speeds were reduced by 1.9 mph, with the results being statistically significant at the 95 percent confidence level. Results of a driver survey indicated that 95 percent of drivers surveyed said that they noticed the DSFS system and 76 percent said that they slowed due to the system.

A vehicle-activated curve warning sign was tested on three curves on two-lane roads in the United Kingdom as shown in Figure 38 (Winnett and Wheeler 2002). The signs were blank when drivers were under the 50th percentile speed.

Mean speeds were reduced by 2.1 to 6.9 mph and the speed reductions were maintained over time. Crash data were available for two sites and the researchers found that crashes decreased 54 percent at one site and 100 percent at the other.

The City of Bellevue, Washington evaluated DSFS systems as curve advisory warnings for two curves as shown in Figure 39. Both curves were on urban arterials with 35 mph speed limits and 25 mph advisory speeds. One sign showed a 3.3 mph reduction in 85th percentile speed and the other showed a 3.5 mph reduction.

Preston and Schoenecker (1999) also evaluated the safety effect of a DSFS on County Highway 54 in Minnesota, which is a two-lane rural roadway with a speed limit of 55 mph and an AADT of 3,250 vpd. The curve has an advisory speed of 40 mph.

The DSFS system had a changeable message sign and radar unit. The researchers conducted a field test over a

Northbound signs before and after

Southbound signs before and after

Figure 37. I-5 DSFS system in Oregon

four-day period with a unit that consisted of a closed circuit TV camera, a VCR, and a personal computer. (A portable trailer housed the entire system.)

The sign displayed the following:

- CURVE AHEAD from 6 to 10 a.m., 11 a.m. to 2 p.m., and 4 to 7 p.m.
- No message during other times of the day unless activated

The team randomly evaluated whether vehicles negotiated the curve successfully based on curve messages. Vehicles that crossed a left or right lane line on one or more occasions were defined as not navigating the curve successfully.

Figure 38. DSFS system in Norfolk, UK (Winnett and Wheeler 2002)

The team found that about 35 percent of the drivers who received the static message were unable to negotiate the curve successfully. Vehicles that received the CURVE AHEAD sign were more likely to negotiate the curve successfully, but the difference was not statistically significant. Only 26 percent of vehicles that received the CURVE AHEAD – REDUCE SPEED sign were unable to negotiate the curve successfully, and the difference was statistically significant at the 90 percent level of confidence.

Mattox et al. (2007) looked at the effectiveness of a DSFS system on secondary highways in South Carolina. This system consisted of radar device and a 4 by 4 foot yellow sign with 6 inch lettering reading YOU ARE SPEEDING IF FLASHING. In addition, there were two 1 by 1 foot orange flags and a type B flashing beacon light.

The researchers collected data in a before-and-after study upstream of the sign, at the sign, and downstream of the sign. Results showed a significant reduction in speed at the sign and downstream of the sign. Overall, mean and 85th percentile speeds were reduced by approximately 3 mph.

Figure 39. DSFS system in Bellevue, Washington (City of Bellevue 2009)

A report by the California Department of Transportation (Caltrans 2010) provided a summary of the effectiveness of safety treatments in one California district. A changeable message sign was installed at five locations along I-5 to reduce truck collisions. The study reported that truck crashes decreased from 71 to 91 percent at four of the sites while truck crashes increased by 140 percent at one site.

A study by the 3M Company evaluated driver speed back signs in the United Kingdom. Signs were tested at various locations in Doncaster including semi-rural roadways. The signs displayed the approaching driver speed. The sites had speed limits of 40 mph and reductions up to 7 mph in 85th percentile speeds.

Tribbett et al. (2000) evaluated dynamic curve warning systems for advance notification of alignment changes and speed advisories at five sites with 7,650 to 9,300 vpd in the Sacramento River Canyon on I-5 in California. Messages used by the researchers included curve warnings (shown in Figure 40) and driver speed feedback.

Decreases in mean truck speeds occurred for three sites (from 1.9 to 5.4 mph) and decreases in mean passenger speeds occurred for four sites (from 3.0 to 7.8 mph).

**Figure 40. Speed warning sign in the Sacramento River Canyon (Tribbett et al. 2000)**

A study by Hallmark et al. (2013) evaluated the effectiveness of two different types of DSFSs in reducing carshes on rural two-lane curves. One sign displayed a regualr speed feedback sign when drivers exceeed the posted or advisory speed and the other displayed the corresponding speed avisory sign when the driver exceeded the posted or advisory speed (Figure 41). Signs were installed on rural two-lane roads in six states. The researchers compared crashes before and after installation of the signs and CMFs are shown in Table 29.

**Figure 41. Dynamic speed feedback signs evaluated in six states**

### Table 29. CMFs for dynamic speed feedback signs

| Treatment | Crash Type | CMF |
|---|---|---|
| Installation of speed feedback signs on rural two-lane curves (Hallmark et al. 2013) | All in both directions | 0.95 |
| | All in the direction of the sign | 0.93 |
| | SV in both directions | 0.95 |
| | SV in the direction of the sign | 0.95 |

## Advantages

- Can be targeted to drivers who are exceeding a certain speed threshold

## Disadvantages

- Initial, installation, and maintenance costs

# Pavement Inset Lights

## Description

In-pavement lighting has been used in applications such as nighttime delineation of crosswalks. These lights have the ability to increase the visibility of horizontal curves, particularly during nighttime and wet weather (Figure 42).

## Application

In-pavement lighting is most appropriate for locations with a large number of nighttime or adverse weather crashes.

**Figure 42. In-pavement lighting (FHWA 2011)**

## Effectiveness

Shepard (1977) installed pavement inset lights along a 5.8 mile section of I-64 in Virginia. The intent was to provide guidance during foggy weather conditions. Unidirectional airport runway lights were installed in the pavement edge along each side of roadway in both directions with the lights spaced 200 feet apart on tangent sections and 100 feet on curves.

The researchers collected and analyzed traffic flow data before and after installation of the inset lights and evaluated vehicle speeds, headway, queues, and lateral placement. The researchers measured lateral placement by installing tape switches of different lengths on the right side of the traffic lane. The researchers collected data under six different fog-density categories.

The researchers found a significant decrease in mean speeds during the day while noting a significant increase in nighttime speed. The researchers also found an increase in speed differentials for various cases during day and night and a decrease in nighttime headway and queuing. The researchers noted that the lighting was effective only when fog of a certain density was present.

## Advantages

- Can be targeted to nighttime and wet-weather crashes

## Disadvantages

- Cost
- May require maintain regular maintenance to ensure lights are functioning
- Small potential for lights to dislodge and pose safety risk

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