
Lane Departure Safety Countermeasures: Strategic Action Plan for the Iowa Department of Transportation

**Final Report
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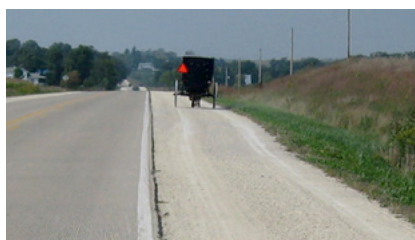
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16. Abstract <p>Lane departure crashes are the single largest category of fatal and major injury crashes in Iowa. The Iowa Department of Transportation (DOT) estimates that 60 percent of roadway-related fatal crashes are lane departures and that 39 percent of Iowa's fatal crashes are single-vehicle run-off-road (SVROR) crashes.</p> <p>Addressing roadway departure was identified as one of the top eight program strategies for the Iowa DOT in their Comprehensive Highway Safety Plan (CHSP). The goal is to reduce lane departure crashes and their consequences through lane departure-related design standards and policies including paved shoulders, centerline and shoulder rumble strips, pavement markings, signs, and median barriers.</p> <p><i>Lane-Departure Safety Countermeasures: Strategic Action Plan for the Iowa Department of Transportation</i> outlines roadway countermeasures that can be used to address lane departure crashes. This guidance report was prepared by the Institute for Transportation (InTrans) at Iowa State University for the Iowa DOT. The content reflects input from and multiple reviews by both a technical advisory committee and other knowledgeable individuals with the Iowa DOT.</p>			
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Introduction to Lane-Departure Safety Countermeasures for Iowa

Run-off-road (ROR) crashes are a serious traffic safety concern. The Federal Highway Administration (FHWA) (2009) estimates that 58 percent of roadway fatalities are lane departures, while 40 percent of fatalities are single-vehicle run-off-road (SVROR) crashes. ROR crashes also account for around 1 million injuries annually.

The majority of road departure crashes, two-thirds, occur in rural settings (FHWA 2011). Rural undivided two lane roads are particularly problematic with an estimated 24 percent of highway fatalities occurring on that type of roadway.

Road departure crashes account for one-third of all recorded traffic fatalities in the US with two-thirds of these crashes occurring in rural settings (FHWA 2008)

Lane departure crashes are the single largest category of fatal and major injury crashes in Iowa. The Iowa Department of Transportation (DOT) estimates that 60 percent of roadway-related fatal crashes are lane departures and that 39 percent of Iowa's fatal crashes are SVROR crashes (Iowa DOT 2006).

Addressing roadway departure was identified as one of the top eight program strategies for the Iowa DOT in their Comprehensive Highway Safety Plan (CHSP). The goal is to reduce lane departure crashes and their consequences through lane departure-related design standards and policies including paved shoulders, centerline and shoulder rumble strips, pavement markings, signs, and median barriers.

Once installed, lane departure countermeasures should be maintained, even if the highway segments with the highest density of related crashes no longer appear on an updated Iowa DOT map (unless the countermeasure is specifically found to not be effective for that highway segment).

Lane Departure Safety Countermeasures: Strategic Action Plan for the Iowa Department of Transportation outlines roadway countermeasures that can be used to address lane departure crashes. This guidance report was prepared by the Institute for Transportation (InTrans) at Iowa State University for the Iowa DOT. The content reflects input from and multiple reviews by both a technical advisory committee and other knowledgeable individuals with the Iowa DOT.

Table 1 provides an overview of the information in each chapter.

Table 1. Summary of chapter content

Chapter	Discusses
1	Paved shoulders
2	Pavement Safety Edge
3	Shoulder rumble strips and edge-line rumble strips
4	Centerline rumble strips
5	High-tension median cable barriers
6	Countermeasures for horizontal curves

ter of this report.

For the countermeasure (or set of related countermeasures) covered in each chapter, the chapter generally includes, as appropriate, the countermeasure(s):

- At a glance
- General description
- Design variations
- Performance/research verification/effectiveness
- Iowa guidance/current practice
- Proposed guidance/changes (sometimes including candidate locations)

Introduction References

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Chapter 1:

Paved Shoulders

Paved Shoulders At a Glance

- Paved shoulders provide additional space for errant vehicles and lateral support for the pavement structure
 - Paved shoulders benefit not only motor vehicle operators but also other road users, such as bicyclists and Amish horse and buggy drivers
 - Several studies have found that paved shoulders can significantly reduce the total number of crashes
 - Paved shoulders provide maintenance benefits by reducing pavement edge drop-off and shoulder repairs
-

General Description

Paved shoulders play an important role in highway design, providing additional recovery space for errant vehicles and lateral support for the pavement structure (See Figures 1.1 and 1.2). The benefits of paved shoulders include reduced numbers of certain types of crashes, increased roadway capacity, reduced maintenance needs, a potential increase in pavement longevity, and improved facilities for bicyclists and other alternative road users (Souleyrette et al. 2001).



Figure 1.1. Two-lane highway with fully-paved shoulders



Figure 1.2. Two-lane highway with partially-paved shoulders

Performance/Research Verification

Several studies have evaluated the impact of shoulder width and/or the provision of paved shoulders on safety. In general, these studies have indicated that wider shoulders and paved shoulders correlate to a decreased number of crashes.

In general, sufficiently-wide paved shoulders are believed to have important safety benefits. For example, McGehee and Hanscom (2006) list paved shoulders as a strategy to improve horizontal curve safety in the guidance document, “Low-Cost Treatments for Horizontal Curve Safety.” In addition, out of 109 Iowa law enforcement personnel, who responded to a survey about the safety effectiveness of paved shoulders, 83 percent felt that paved shoulders reduced the number of run-off-road (ROR) crashes and improved safety on Iowa highways. More than 25 percent indicated they had experienced close calls where paved shoulders helped avoid a crash or personal injury. Officers also reported that paved shoulders provide a safe place to conduct traffic stops (Hallmark et al. 2009).

Overall Crash Reduction

In a recent study of the crash reduction benefits of paved shoulders, Hallmark et al. (2009) conducted a before and after crash analysis to assess the impact of adding paved shoulders. Data were collected for 220 roadway segments, including 143 sections where paved shoulders had been added since 1984 and 77 control sections without paved shoulders.

Generalized linear models were used to investigate the relationship between crash reduction and implementation of paved shoulders. Separate models were developed for total crashes, ROR crashes (which included all road departure crashes), and single-vehicle ROR (SVROR) crashes (which included only road departures involving a single vehicle). Crash data were available from 1984 to 2007. The model for each independent variable considered over-dispersion and excess zeroes.

The model for number of total crashes per quarter indicated that the total amount of right shoulder, presence of a median, speed limit, addition of a paved shoulder, and years after addition of a paved shoulder were statistically significant. The effect of paved shoulders varied over time depending on the years after treatment. Because the effect of paved shoulders varies over time, one year after treatment, the decrease in total crashes for sections with paved shoulders for each quarter is 8.9 percent greater than for no treatment. At 10 years, the decrease is 15.9 percent greater.

The model for ROR crashes indicated that the amount of total right shoulder width available, presence of a divided median, speed limit, and years after paved shoulders were installed were all statistically significant. The effect of paved shoulder on ROR crashes by quarter varied over time, depending on the years after treatment. One year after treatment, 1.3 percent fewer crashes are expected for sections with paved shoulders than for control sections. At 10 years, sites with paved shoulders have 13.5 percent fewer ROR crashes than control sites.

The model for SVROR crashes indicated that total amount of right shoulder width available, presence of a divided median, speed limit, and years after paved shoulders were installed were all statistically significant. The effect of paved shoulder on SVROR crashes by quarter varied over time, depending on the years after treatment. One year after treatment, the expected number of SVROR crashes per quarter is 1.6 percent less than for no treatment. At 10 years, SVROR crashes are 16.4 percent lower for sections with paved shoulders than for sites with no treatment.

In a study conducted 35 years earlier, Heimbach et al. (1974) found similar results. Crash rates for rural two-lane highways with paved shoulders were compared to crash rates for highways with grass or unstabilized shoulders. The authors found that crash rates were significantly lower on roadways with paved shoulders.

However, not all studies have concluded that paved shoulders offer a significant safety benefit. For example, Abboud (2001) evaluated roadway segments where 2 and 4 foot wide paved shoulders had been installed, but the author did not find a statistically-significant decrease in crashes due to installation of paved shoulders.

Souleyrette et al. (2001) evaluated rural two-lane and four-lane divided, non-Interstate freeways in Iowa, but, due to limited data, could not discern any statistically-significant relationship between crash rates and the presence of paved shoulders.

Crash Reduction and Shoulder Width

The width that paved shoulders add to the roadway also provides crash reduction benefits. An important study of shoulder width was National Cooperative Highway Research Program (NCHRP) Report 197 (1978), which analyzed the relationship between highway design features and safety. Different linear regression models were developed based on traffic volume, curve radius, and shoulder type (paved, unpaved, or no shoulder). The study reported no significant difference between 22 and 24 foot wide pavements, but the wider pavements had lower crash rates than 22, 20, and 18 foot wide pavements. In general, the crash rate decreased as shoulder width increased,

except on roadways with a volume of less than 1,000 or greater than 5,000 vehicles per day (vpd). In addition, paved shoulders had a lower crash rate than unpaved shoulders.

Zegeer et al. (1981) found similar results during a comparative analysis of shoulders on Kentucky state primary, state secondary, and rural two-lane roads. Only paved or dense-graded shoulders were considered shoulders, because grass and soil are not suitable for driving (See Figure 1.3). The authors found that ROR and opposite-direction crash rates decreased as shoulder width increased. The reduction in crash rate depended on the amount of shoulder widening; based on the results of the study, widening the shoulders on a rural two-lane roadway from 1.6 to 8.2 feet reduced ROR and opposite-direction crashes by 16 percent.

Souleyrette et al. (2001) cited a Minnesota DOT (Mn/DOT) study that found similar results: using at least 4 foot wide paved shoulders can reduce crashes by up to 15 percent (Preston 1979).

Harwood et al. (2000) also found that wider shoulders tended to have fewer crashes on rural two-lane highways. Using a 6 foot wide paved shoulder as a base value, the authors determined the accident modification factor (AMF) of an 8 foot wide paved shoulder under different traffic volumes, or the crash increase that could be expected if 8 foot shoulders were used instead of 6 foot shoulders.

An AMF greater than 1.0 indicates that more crashes were expected for the 8 foot shoulder than the 6 foot shoulder. The authors found that the AMF for an 8 foot wide paved shoulder is 0.98 for 400 vpd and 0.87 for more than 2,000 vpd, with the AMF varying linearly between the two vpd values.

For a roadway with no shoulders, the AMF is 1.10 for 400 vpd and 1.50 for more than 2,000 vpd, with the AMF varying linearly between those vpd values. While the authors did not



Figure 1.3. Typical earth unpaved shoulder

explain the difference between paved and gravel shoulders, the study also found that turf shoulders performed worse than paved or gravel shoulders, with an AMF of 1.11.

A study by Zegeer and Council (1992) generally found that increasing shoulder width can help reduce several types of crashes, including ROR, head-on, and sideswipe crashes. In addition, the number of crashes can be further reduced by 3 to 6 percent when the shoulders are paved. In a later study by Zegeer and Council (1994), it was found that adding an 8 foot wide paved shoulder may reduce related crashes by up to 49 percent.

Crash Reduction and Roadway Type

Various studies have shown that paved shoulders can reduce crashes on roadways of different types and volumes. For example, an Australian study by Armour (1984) found that, for both tangent and curve sections, the crash rate of rural roads with unsealed shoulders was three to four times the crash rate for rural roads with sealed shoulders.

Another study in Australia evaluated the safety impact of paving shoulders on two-lane rural roads (Ogden 1997). A before and after analysis was conducted using control sites, and most paving installations involved paving an existing shoulder. The results showed that shoulder paving was correlated with a statistically significant 41 percent reduction in casualty crash frequency.

A study by Turner et al. (1981) reviewed crash rates for three types of rural highways with traffic volumes from 1,000 to 7,000 vpd: two-lane highways with and without paved shoulders and four-lane undivided without paved shoulders. The study concluded that full-width paved shoulders are effective in reducing crashes, particularly ROR crashes.

In a similar study, Rogness et al. (1982) found that using full-width paved shoulders was effective in reducing the number of crashes on rural two-lane roads. Corroborating these findings, Souleyrette et al. (2001) summarized an Israeli study that found that the presence of paved shoulders on high-volume, two-lane rural roadways increased capacity and reduced crashes up to 70 percent (Polus et al. 1999).

Unconventional Vehicle Accommodations

In addition to crash reduction benefits, paved shoulders provide a safe and comfortable ride for unconventional vehicles.

For bicycles, Harkey and Stewart (1997) evaluated roadways with vehicle speeds at or below 50 mph, lane widths of at least

11 feet, and minimal horizontal and vertical sight restrictions and found that bicycle lane widths (paved shoulder widths) as narrow as three feet improve safe interactions between motorists and bicyclists. However, the authors indicated that roadways with significant curvature and large truck traffic may require wider bicycle lanes.

The Federal Highway Administration (FHWA) agrees that bicycle lanes or paved shoulders of approximately 3 feet could improve the segment level of service by an entire letter grade, on an A to F scale. To provide a level of service concept for bicyclists, the FHWA (1999) developed the bicycle compatibility index (BCI). According to the BCI implementation manual, the presence or absence of a bicycle lane or paved shoulder will have the greatest effect of any variable on the comfort level of bicyclists.

Paved shoulders also improve ride quality for other unconventional vehicles. A survey of an Amish community in Davis County, Iowa indicated that horse and buggy drivers preferred fully-paved shoulders, because drop-offs between the paved lane and a gravel shoulder can cause problems for both the horse and buggy (See Figure 1.4).

A similar survey of an Amish group in Buchanan County, Iowa revealed that this group preferred a 10 foot wide shoulder when possible. The respondents commented that pavement edge drop-off creates a problem for getting off and on the roadway to make way for faster vehicles, but they did not necessarily prefer paved shoulders. When shoulders are paved, the respondents prefer asphalt over concrete, because they feel that concrete is hard on the horses (Hawkins et al. 2009).



Figure 1.4. Horse and buggy traveling along an unpaved shoulder with edge drop-off (Hawkins, InTrans)

Maintenance

Evidence suggests that paved shoulders may be easier to maintain than gravel shoulders. Hallmark et al. (2009) conducted a survey of Iowa Department of Transportation (Iowa DOT) district field maintenance personnel to record their subjective assessment of pavement performance after the addition of paved shoulders. Almost 90 percent of the maintenance personnel who responded approved of the Iowa DOT's paved shoulder guidelines and about 90 percent felt that using paved shoulders reduced the time required to maintain shoulders and perform edge rut repair. Nearly 80 percent felt that paved shoulders reduce the cost of shoulder maintenance.

Iowa DOT Guidance

The Iowa DOT Design Manual (2008) indicates that paved shoulders improve safety by reducing ROR crashes, and that they provide maintenance benefits by reducing pavement edge drop-off and shoulder repairs. Guidelines for sizing and placement of shoulders are based on a project by project review and the final decision is left up to each Iowa DOT District.

Current Practice for Paved Shoulders

Use of full-width paved shoulders:

- Interstates
- Along inside and outside of curves with degree of curve greater than 6 degrees
- At locations near metropolitan areas where a large number of pedestrian, bike, or turning traffic are expected
- When a designated bike trail is present

Six-foot-wide paved shoulders:

- Where no shoulder rumble strip is used due to noise concern
- Two-lane roadways where average daily traffic (ADT) greater than 5,000 vpd
- Urban expressways
- Rural expressways where ADT greater than 10,000 vpd

Four-foot-wide paved shoulders:

- On all National Highway System (NHS) projects where full-width or 6 foot paved shoulders are not used
- Roadways where ADT greater than 3,000 vpd

On roadways that are non-NHS, shoulders should be considered based on a combination of the following factors:

- High design year ADT, even if current year ADT doesn't warrant paved shoulders
- Segments with a high ROR crash rate
- Segments with a high number of horizontal curves
- Segments with steep grades because storm runoff can cause erosion of shoulder rock on steep grades
- High truck volumes
- Where roadway segments experience continuing problems with edge rut
- To maintain continuity of shoulder width along a corridor
- If rumble strips are desired, the paved shoulder width should be at least 4 foot
- When pavement has been or may be widened multiple times
- When cost differential between the cost for 4 foot paved shoulders is similar to that of pavement widening
- If bicycle accommodation is warranted

Wider shoulders may be appropriate if paved shoulders are warranted for bicycle accommodation. The Iowa DOT Office of Systems Planning should be consulted for guidance in this decision. For example, if a state highway is within a statewide trail corridor, 6 foot paved shoulders may be recommended.

Proposed Guidance

It is recommended that the Iowa DOT follow the existing policy and re-evaluate the policy as needed in the future.

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Chapter 2:

Pavement Safety Edge

Pavement Safety Edge At a Glance

- Pavement edge drop-off is a vertical elevation difference between two adjacent roadway surfaces, usually a paved roadway surface and an unpaved shoulder
 - A typical pavement edge drop-off-related crash occurs when a vehicle leaves the roadway and the driver attempts an immediate return to the roadway
 - 2006 study results showed Iowa's pavement edge drop-off-related crashes were two times more likely to result in a fatality than other crashes on similar rural roadways and that these types of crashes were also more likely to result in a fatality than other types of ROR crashes (on similar roadways)
 - The most common solution to pavement edge drop-off is maintenance of unpaved shoulders; but, Iowa also uses a design feature called the Safety Edge
-

Background

ROR crashes are a serious traffic safety concern. ROR crashes account for 38 percent of US highway fatalities and one million injuries each year. It is also estimated that 24 percent of highway fatalities occur on two-lane undivided rural roads (Taylor and Meczowski 2002). Neuman et al. (2003) also estimated that 39 percent of national fatal crashes are SVROR crashes.

Lane departure crashes are the single largest category of fatal and major injury crashes in Iowa. The Iowa DOT estimates that 52 percent of roadway-related fatal crashes are lane departures and that 39 percent of Iowa's fatal crashes are single-vehicle ROR crashes.

Pavement edge drop-off poses a particular hazard when vehicles leave the roadway (See Figure 2.1).



Typical vertical pavement edge on Portland cement concrete



Typical rounded edge on asphalt

Figure 2.1. Typical pavement edges

Pavement edge drop-off is a vertical elevation difference between two adjacent roadway surfaces, usually a paved roadway surface and an unpaved shoulder. Edge drop-offs are potential safety hazards because significant vertical differences between surfaces can reduce vehicle stability and affect a driver's ability to handle a vehicle. These edges are difficult for vehicles to remount after leaving the roadway if much of the pavement edge is exposed.

A typical pavement edge drop-off-related crash occurs when the driver attempts an immediate return to the roadway and tire scrubbing occurs. Scrubbing is a condition in which the tire sidewall is forced into the pavement edge, resulting in friction between the tire and pavement. Some drivers compensate for scrubbing by increasing the steering angle.

When the right front tire finally remounts the pavement, a sudden loss in friction between the tire and the surface of the pavement edge occurs, resulting in a loss of control (Ivey et al. 1984).

The FHWA (2010) estimates 160 fatalities and more than 11,000 injuries annually that are related to an unsafe pavement edge. A Georgia Tech study evaluated 150 fatal crashes on rural two-lane roads in Georgia and found that edge drop-off was present in 55 percent of the crashes (Georgia Tech 2004 and Dixon 2004).

A study by Hallmark et al. (2006) evaluated crashes in Iowa for 2002 to 2004 and found that pavement edge drop-off may have been a contributing factor in around 18 percent of rural ROR crashes on paved roadways with unpaved shoulders. The study also found that pavement edge drop-off-related crashes were two times more likely to result in a fatal crash than other crashes on similar rural roadways. These crashes were also more likely to result in a fatal crash than other types of ROR crashes on similar roadways.

The FHWA indicates that drop-offs of three or more inches can be considered dangerous (Roche 2009). Hallmark et al. (2006) suggested a similar result with drop-offs of 2.5 inches or more having a higher relationship to pavement edge drop-off-related crashes.

Solutions to Address Pavement Edge Drop-Off

The FHWA (2009) suggests several treatments to address pavement edge drop-off, including:

- Resurface shoulders when roadways are resurfaced and
- Address edge drop-off depths more than 2 inches on high-speed roadways through timely maintenance.

Humphreys and Parham (1994) made several recommendations for addressing pavement edge drop-off based on their research, including:

- Require that shoulder materials be pulled up to the new surface as a non-pay item,
- Require that appropriate signing remain installed along the roadway to inform the motoring public of the existence of a low shoulder condition,
- Require that a 30 degree angle asphalt fillet be installed as a part of the roadway resurfacing along the edge of the roadway, and
- Combinations of the above.

The most common solution to pavement edge drop-off is maintenance of unpaved shoulders. However, because rural roads in Iowa commonly feature granular or earth shoulders, maintenance to address a recurrence of erosion and wear along the pavement edge, which contributes to edge drop-off, requires a significant amount of effort.

The Safety Edge

The FHWA began a demonstration project of the Safety Edge based on results of research, which indicated that a sloped pavement edge surface could be more easily traversed by a vehicle leaving its lane and attempting to remount the pavement than one without the edge. The Safety Edge is a design feature that creates a fillet along the outside edge of the paved section of a roadway.

The Safety Edge is placed during asphalt overlay using a device that extrudes and shapes the asphalt at the pavement edge into an approximately 30 degree fillet shape, as shown in Figure 2.2. Figure 2.3 shows application of the Safety Edge during resurfacing and Figure 2.4 shows the formed edge immediately after resurfacing.

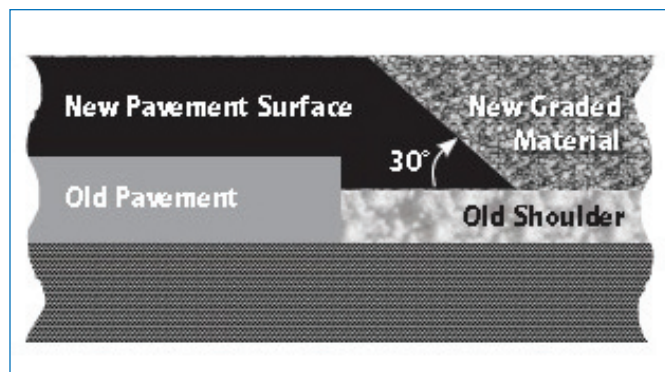


Figure 2.2. 30 degree Safety Edge fillet shape (FHWA 2009)

The shape created by the Safety Edge reduces the likelihood that scrubbing will occur and provides a gradual, rather than abrupt, transition back to the roadway as a vehicle remounts the pavement surface. The Safety Edge provides this benefit before shoulders have been pulled back up after resurfacing, as well as when the unpaved shoulder material migrates away from the pavement edge due to wear or erosion.

Effectiveness of the Safety Edge

Little information is available about the actual effectiveness of the Safety Edge in reducing crashes, because the concept has not been widely used. However, the concept of the Safety Edge has been suggested by researchers. Humphreys and Parham (1994) suggested that a 45 degree angle asphalt fillet placed at the lane edge would be useful in addressing over-corrections, even for unpaved or eroded shoulders. Neuman et al. (2003) also suggest creating a 45 degree wedge during



Figure 2.3. Application of the Safety Edge during resurfacing



Figure 2.4. Pavement edge shape resulting from application of the Safety Edge

pavement resurfacing in their NCHRP 500 series report, “A Guide for Addressing Run-off-Road Collisions.” (They also indicate that more data are necessary to determine if the wedge is effective.)

A pooled fund study is in progress to evaluate the effectiveness of using the Safety Edge along with pavement resurfacing projects. The study includes two-lane rural roads with less than 4 foot paved shoulders and multilane roads with paved shoulders of 4 feet or less (Graham et al. 2008). The study evaluates treatment sites that were resurfaced with the Safety Edge and comparison sites that were resurfaced without the Safety Edge. The study evaluates drop-off, including a crash analysis after the treatments were in place for one year. The researchers plan to conduct further analyses when more data are available.

For the analysis, the study divided roadways by characteristics and created homogenous sections. Analyses were conducted in Georgia and Indiana. Georgia had 242 sites available with a total of 705 miles for all roadway types. Indiana had 148 sites with 519 miles for all roadway types.

Graham et al. (2008) measured drop-off along both control and treatment sections before and during the first year after resurfacing in Georgia and Indiana. They collected whether drop-off was 2 inches or more. They conducted logistic regression to compare whether drop-off was less likely to occur with the Safety Edge in place. Results at one year after the sites were resurfaced suggested that resurfacing with the Safety Edge is slightly more effective in reducing the proportion of extreme drop-offs than resurfacing without the Safety Edge.

A crash analysis was also conducted using crash data for five years before resurfacing and one year after resurfacing. A before and after analysis using Empirical Bayes (EB) indicated that crashes generally increased after resurfacing for all sites, which may be due to the higher speeds sometimes associated resurfacing a road to a better condition than previously encountered. Although the data were limited and a one-year after period is not sufficient to determine statistical significance, results of the analysis suggest that the Safety Edge treatment is effective in reducing crashes. The study also showed that the proportion of fatal and injury crashes decreased after resurfacing, but the researchers couldn’t isolate an effect due to the Safety Edge.

In addition, the researchers obtained costs for resurfacing sites with and without the Safety Edge and found that the cost of applying the Safety Edge was minimal in actual application. They also calculated the extra material that would be necessary for placement of the Safety Edge and reported that the estimated cost for use of the Safety Edge is around \$955 per mile, when the treatment is applied along both sides of the roadway.

Benefits of the Safety Edge

The major benefit of using the Safety Edge is that it provides a sloped surface, which aids vehicle re-entry before shoulders have been pulled up during construction or when drop-off forms before maintenance has occurred (which results in improved safety).

Additionally, although verification tests are not yet available, the Safety Edge provides compaction at the pavement edge that may help maintain the pavement edge, as shown in Figures 2.5 and 2.6, resulting in increased pavement edge durability.



Pavement edge after resurfacing without Safety Edge



Pavement edge after resurfacing with Safety Edge

Figure 2.5. Pavement edges immediately after resurfacing (Roche 2009)

Other benefits of the Safety Edge (Roche 2009) include:

- Provides temporary safety during construction while pavement edge face is exposed
- Some states do not require contractors to pull up shoulders immediately after construction, which results in increased production for contractors given that shoulder work can be done after overlay is completed,
- Provides a permanent solution for drop-off,
- Can reduce tort liability by showing “Due Care,” and
- Minimal hardware, labor, or material costs.



Pavement edge after resurfacing without Safety Edge



Pavement edge after resurfacing with Safety Edge

Figure 2.6. Pavement edges six years after resurfacing (Roche 2009)

Although it provides a safety benefit, the FHWA emphasizes that the Safety Edge is not an alternative to flush shoulders (Roche 2009). Routine maintenance of shoulders should still be conducted.

Safety Edge Hardware

Two types of devices are commercially available that can be used to create the Safety Edge during asphalt overlay.

TransTech Systems, Inc. worked with FHWA Southern Research Center and the Georgia DOT (GDOT) to develop the first device to create the Safety Edge. The device consists of a mounting plate that can easily attach to the screed face of all varieties of asphalt paving machines. This device implements an integral self-adjusting spring that allows the device to follow the roadside surface, independent of the other components of the paver. A robust screw allows the adjustment for setting a position below the screed.

The component that makes the Safety Edge includes a curved runner that, in conjunction with the self-adjusting spring, helps the device to adapt to any obstacles it may encounter. The device has an angled surface that precompacts the asphalt as it enters the device and continues on to the wedge-forming surface. The final angle is created when the roadway is compacted. Figure 2.7 shows the Safety Edge installation hardware as developed by TransTech Systems.

The second commercially-available device is the Advant-Edger. It is similar to the TransTech Safety Edge Maker™ (SEM) with the major difference being that the Trans Tech hardware connects to the screed rather than the end gate. The Advant-Edger is shown in Figure 2.8 and attached to a paver in Figure 2.9.



Figure 2.7. GDOT safety wedge hardware (FHWA 2009a)



Figure 2.8. Advant-Edger device

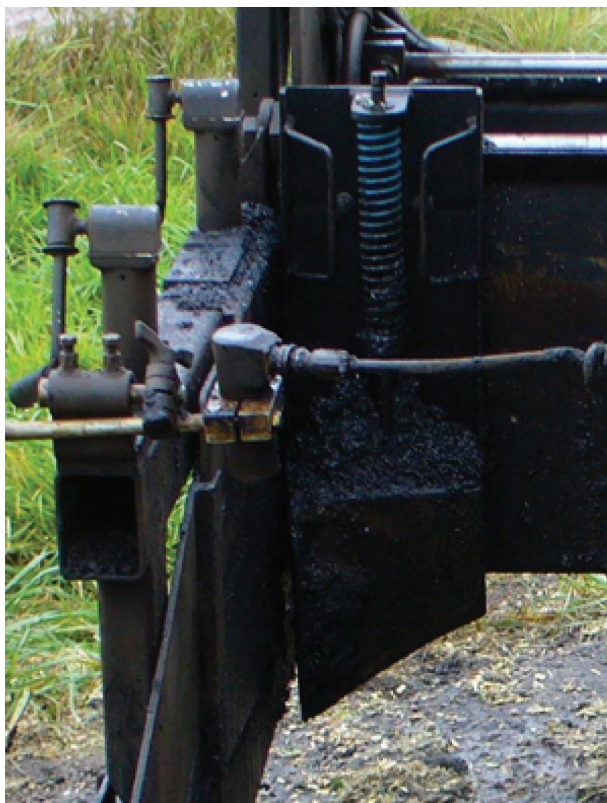


Figure 2.9. Advant-Edger device in use

Iowa DOT Guidance

The Iowa DOT has current guidance for use of the Safety Edge.

Current Policy Guidance for the Safety Edge

The Iowa DOT Design Manual (2010) requires use of the Safety Edge on all primary highways unless one of the following is met:

- Roadway is an interchange ramp or loop
- Roadway or shoulder has curbs
- Paved shoulder width equal to or greater than 4 foot

Current Design Guidance for the Safety Edge

The Design Manual provides plans for placement of the Safety Edge for both Portland cement concrete (PCC) and hot mix asphalt (HMA) paving and overlays. Part of that standard is shown in Figures 2.10 and 2.11

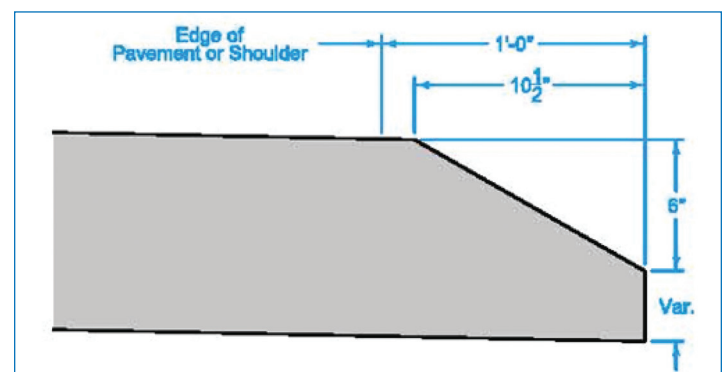


Figure 2.10 Iowa DOT design standard for the Safety Edge for PCC

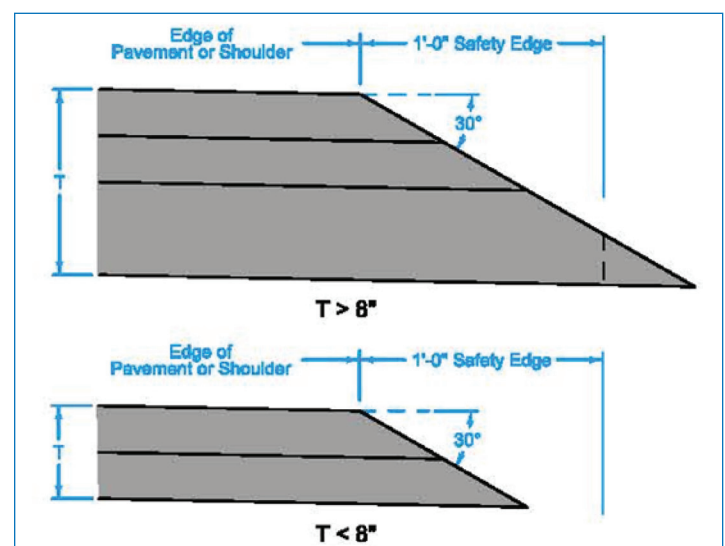


Figure 2.11 Iowa DOT design standards for the Safety Edge for HMA with pavement thicknesses greater than and less than 8 inches

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Chapter 3:

Shoulder Rumble Strips and Edge-Line Rumble Stripes

Shoulder Rumble Strips and Edge-Line Rumble Stripes At a Glance

- Shoulder rumble strips are narrow, linear bands of indentations or bumps installed between the lane edge line and the paved roadway shoulder
 - Edge-line rumble stripes are narrow, linear bands of indentations or bumps installed on the pavement's edge, through which the edge line marking is painted
 - According to the FHWA, shoulder rumble strips are proven safety countermeasures for reducing lane departure crashes
 - These treatments are currently deployed in most state new construction or reconstruction projects on high-volume and designated federal or state routes
-

General Description

Rumble strips are raised or grooved patterns placed in the pavement surface perpendicular to the direction of traffic. The interaction between the tires and rumble strips creates both an audible warning (rumbling sound) and physical vibration, which alert the driver they are leaving their lane, so they can take corrective actions.

To alert drivers they are departing from the travel lane, rumble strips can be installed on a paved shoulder (shoulder rumble strips) or on the pavement edge line (edge-line rumble strips). When rumble strips are installed on the pavement edge, edge line markings are usually painted over them; thus, the term “stripes.”

When the lane line is painted through the rumble strips, it also provides enhanced visibility at night and rain events, given that the contour of the rumble strip drains water, providing a reflective back wall that still retains its retroreflectivity (FHWA 2011).

These versatile treatments can be installed during construction or reconstruction or as retrofits to existing pavements. They are relatively inexpensive to install and maintain and can have a high benefit-to-cost ratio.

Figure 3.1 illustrates the features of a shoulder rumble strip application on the paved shoulder of a two-lane roadway and Table 3.1 defines the terms used in the figure.

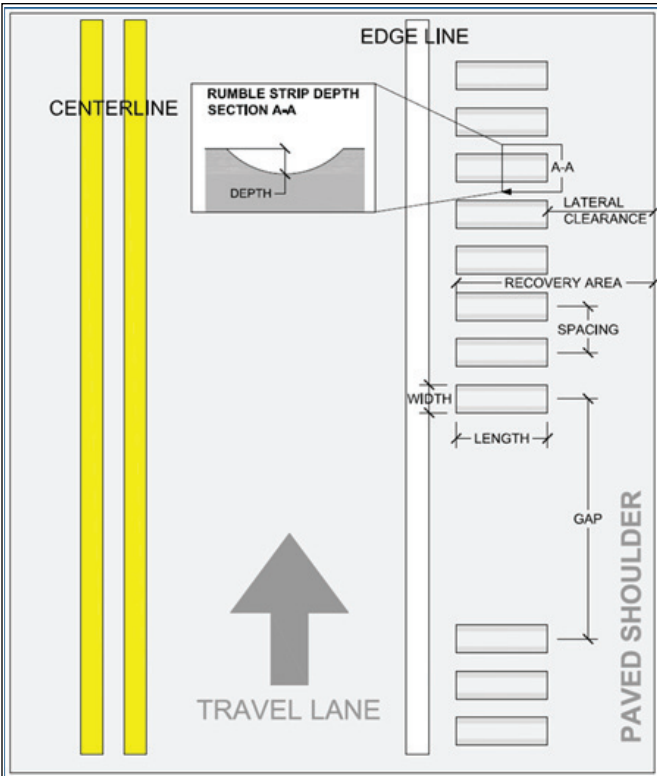


Figure 3.1. Features of shoulder rumble strip installation

Table 3.1 Shoulder strip application terms

Width	Rumble strip dimension parallel to the travel lane
Length	Rumble strip dimension lateral to the travel lane
Spacing	Dimension between rumble strips parallel to the travel lane, typically measured from center to center
Depth/Height	Depth at the center of the rumble strip within the pavement, or height at the center of the rumble strip above the pavement
Recovery Area	Distance from the inside edge of the rumble strip to the edge of the shoulder or to a fixed object in the clear zone
Lateral Clearance	Distance from the outside edge of the rumble strip to the edge of the shoulder or to a fixed object in the clear zone
Gap	Distance between groups of rumble strips (optional)

Design Variations

Shoulder rumble strip designs and installation methods are based on several considerations:

- Shoulder material and width
- Traffic characteristics, including unconventional vehicle needs
- New or retrofit application
- Type and age of pavement
- Maintenance considerations
- Cost

Basic design features for the four most commonly used types of shoulder strips—milled-in, rolled-in, formed-in, and raised—are summarized in Table 3.2 and discussed in the following sections.

Accommodation for Other Road Users

Many vehicles other than cars and trucks, such as bicycles, travel on Iowa’s primary and paved secondary roads where shoulder rumble strips are recommended for motor vehicle safety. To accommodate these other road users and provide a safe and enjoyable experience for all travelers, it is strongly recommended that highway agencies identify potential unconventional traffic, contact local interest groups, and address unconventional vehicle design issues before installing shoulder rumble strips or edge-line rumble strips.

One accommodation for bicycles, for example, is to leave gaps between groups of indentations that allow bicyclists to travel from one side of the rumble strips to the other without traveling directly over the rumble strips. Such a gapped shoulder rumble strip application is shown in Figure 3.2.

Table 3.2 Design features for four types of shoulder rumble strips/edge line rumble stripes

Type	Width (inches)	Length (inches)	Spacing (inches)	Depth (inches)	Height (inches)	Advantages	Disadvantages
Milled-in	7	12–16	12	0.5	n/a	Shallower indentations into the roadway Can be installed on existing or new roadway shoulders	Difficult installation on older or worn pavement 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 Can be installed as part of the pavement rolling operation	Indentations may not provide enough driver warning due to size 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 More expensive than milled-in and rolled-in rumble strips Contractor-dependent, with limited inspection techniques
Raised	varies	varies	varies	varies	0.25–0.5	Highly visible at night and in rainy conditions Provides vehicle guidance at night	May not provide enough driver warning due to size and/or material Relatively expensive installation and maintenance costs Snow plow blade tends to remove the device



Figure 3.2 Bicyclist accommodation allows for travel between rumble strips without crossing over them (Cohn, Bay City Times ©2010 Michigan Live LLC)

Milled-in (Asphalt or Concrete, Retrofit or New)

Milled-in shoulder rumble strips, shown in Figure 3.3, are installed by cutting or grinding the pavement surface, typically using carbide teeth attached to a 24 inch diameter rotating drum.

The indentations are about 1/2 inch deep, 7 inches wide (parallel to the travel lane), and 12 to 16 inches long (perpendicular to the travel lane). The indentations are spaced about 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).



Figure 3.3. Milled-in shoulder rumble strips (Morena 2003)

Potential advantages: Can be installed on new or existing pavement; more shallower indentation into the roadway than other designs

Potential disadvantages: Installation may be difficult on older or worn pavement; in edge-line rumble stripe installations, application of asphalt fog seal may prevent the edge line markings from adhering adequately

Rolled-in (Hot Mix Asphalt, New or Reconstruction)

Rolled-in shoulder rumble strips, shown in Figure 3.4, 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 surface. The resulting indentation 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).

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).

Potential advantages: Less expensive to install than other rumble strip designs

Potential disadvantages: Must be installed as part of the pavement rolling operation; satisfactory installation depends on asphalt being the appropriate temperature; the rolled surface provides a smoother indentation, which may not provide the same amount of vibration as milled-in rumble strips.



Figure 3.4. Rolled-in shoulder rumble strips (Morena 2003)

Formed-in (Concrete, New or Reconstruction)

Formed-in shoulder rumble strips, shown in Figure 3.5, are installed by pressing a corrugated form onto a newly-placed and finished concrete surface. The resulting indentations are about 1 inch deep and 18 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 about 12 inches (Umbs 2001).

Advantages: Can be installed as part of the pavement installation process

Disadvantages:

- The formed-in surface provides a smoother indentation, which may not provide the same amount of vibration as milled-in rumble strips
- Contractor-dependent, with limited inspection techniques



Figure 3.5. Formed-in shoulder rumble strips (Morena 2003)

Raised (Asphalt or Concrete, Retrofit, or New)

Several raised rumble strip products are available with a variety of materials and installation methods. The elements may consist of raised pavement markings, marking tape affixed to the pavement surface, extruded pavement marking material with raised portions throughout the length, or an asphalt material placed as a raised bar on the shoulder surface.

One bicycle-friendly type designed by the California Department of Transportation (Caltrans) is illustrated in Figure 3.6. The height of the raised element may vary from 1/4 to 1/2 inch. Spacing and width across the shoulder vary widely (Umbs 2001).

Potential advantages: Highly visible at night and in rainy conditions; provides vehicle guidance at night

Potential disadvantages: relatively expensive installation and maintenance costs; snow plow blade tends to remove the device



Figure 3.6. Caltrans raised (or inverted-profile) shoulder rumble strip made of thermoplastic (Neuman 2003)

Performance/Research Verification

In general, research shows that lane departure crashes have decreased 20 to 50 percent on roadways where shoulder rumble strips or edge-line rumble strips were installed as described in the following sections. Other research suggests that drivers may “overreact or panic” to rumble-strip auditory and/or vibratory warnings, which may result in a loss of vehicle control (Griffith 1999).

The following summary of pertinent research is organized by focus of study (auditory and vibratory alerts, crash reduction, and cost-benefit analysis).

Alerting the Driver

Shoulder rumble strips and edge-line rumble strips are designed to produce an auditory and/or vibratory alert when a vehicle begins to depart the roadway or lane of travel.

Noise Levels

Factors inside the vehicle, such as the sound system or engine noise, may diminish the impact of noise generated when the vehicle travels over rumble strips. Several studies have investigated the amount in decibels (dB) that noise levels need to increase to successfully alert a driver, but the thresholds are not well established (Watts 1977).

One study found that a noise increase of 6 dB inside the vehicle clearly alerts the driver of a vehicle leaving the road. Rumble strips that were 1/2 inch deep increased the inside-vehicle sound level by at least 6 dB for different tested vehicle types, except for dump trucks (Outcalt 2001).

An earlier study found that rumble strips generally produced a 7 dB increase over normal driving noise inside the vehicle at frequencies between 50 and 160 hertz (Hz). However, while noise level within the car was shown to vary by type of rumble strip, outside noise created by the strips did not vary between different rumble strip designs and configurations (Higgins and Barbel 1984).

Vibrations

Studies have focused on determining rumble strip design types and dimensions to achieve optimum vibration levels in different types of vehicles.

When a vehicle's tires pass over rumble strips, vertical and lateral accelerations are transferred through the vehicle, causing the seat and steering column to vibrate and alert the driver. The rumble strip dimensions must be wide and deep enough to generate vibrations sufficient to alert heavy-vehicle drivers, but not so violent as to cause compact-vehicle drivers to lose control (Morena 2003).

Comparisons of milled-in and rolled-in shoulder rumble strips show a considerable difference in vibration. A tire-drop study conducted at 112 locations in Virginia found that milled-in shoulder rumble strips/stripes produced 12.5 time more vibrational stimulus and 3.35 times more auditory stimulus than rolled-in shoulder rumble strips. The study also suggested that rolled-in shoulder rumble strips had very little effect on heavy vehicles (Chen 1994).

A similar study in Colorado evaluated vibration levels in the steering column and floor of four different types of vehicles, ranging from a station wagon to an unloaded dump truck, driven at 55 or 65 mph, over either 2 inch or 7 inch wide, milled-in rumble strips. The wider milled-in rumble strips provided greater vibration in both the floor and steering column (Outcalt 2001).

Another study in Kansas found no change in vibration levels generated by square-shaped, milled-in shoulder rumble strips and football-shaped, milled-in shoulder rumble strips in numerous test-runs involving various-sized vehicles (Gardner et al. 2006).

Crash Reduction

Several studies have compared safety data preceding and following the deployment of shoulder rumble strips or edge-line rumble strips.

Fatal and Injury Crash Reduction

A recent Missouri Smooth Roads Initiative (SRI) study, which included 61 sites and more than 320.5 miles of both shoulder rumble strips and edge-line rumble strips, found that the SRI program, overall, showed a statistically-significant 8 percent decrease in fatal and disabling-injury crashes and a statistically-significant 6 percent decrease in fatal and all-injury crashes for one year after installation (Potts et al. 2008).

A study encompassing 1,125 kilometers of state highways in Connecticut with milled-in shoulder rumble strips found that installing the rumble strips reduced single-vehicle 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).

Likewise, the New York State Department of Transportation (NYSDOT) and New York State Thruway Authority 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 (NYSDOT 1997).

A study in Mississippi found that installation of edge-line rumble strips on a two-lane roadway resulted in a 25 percent reduction in right-side ROR crashes (ATSSA 2006). Another study in Texas found a 46.7 percent reduction in shoulder encroachments after installation of edge-line rumble strips (Miles et al. 2005).

Cost Effectiveness

In a review of several state reports about the cost effectiveness of shoulder rumble strips, the FHWA Turner-Fairbank Highway Research Center found benefit-cost ratios as high as 182:1 from the New York State Thruway Authority and as low as 30:1 from the Nevada Department of Transportation (FHWA 1991).

For example, in an extensive analysis of the Missouri SRI that accounted for crash frequency per mile, traffic growth, reduction in crashes due to rumble strips, crash cost, service life, installation cost, and minimum attractive rate of return, researchers found that most types of rumble strips have a high cost-benefit ratio.

Using \$38.33 per 100 feet as the estimated cost of installing shoulder rumble strips or edge-line rumble strips, the benefit-cost ratios listed in Table 3.3 were calculated.

As shown in Table 3.3, resurfaced urban multi-lane divided highways with shoulder rumble strips yielded the highest benefit-cost ratio. The value 27.3 indicates that \$1 invested in these roadway improvements would result in a benefit of \$27.30 over a five-year period.

Table 3.3. Benefit-cost ratios for shoulder, edge-line rumble strips/strips for Missouri’s SRI projects (Potts et al. 2008)

SRI Treatment	Roadway Classification	Benefit-Cost Ratio
Resurfacing with wider markings and edge-line rumble strips	Rural freeways	4.8
	Rural multilane divided highways	6.2
	Urban freeways	15.2
Resurfacing with wider markings and shoulder rumble strips	Rural freeways	8.5
	Urban freeways	20
	Urban multilane divided highways	27.3

Guidance in Neighboring States

Many state transportation agencies implement shoulder rumble strips and/or edge-line rumble strips. State guidelines vary due to different climates, road designs, and/or maintenance practices.

A survey of shoulder rumble strip and edge-line rumble stripe practices was distributed to each state on the National State Engineers Listserv in 2009. Respondents from states adjacent to Iowa provided the summaries of their respective guidelines, listed in Table 3.4 (updated since 2009, wherever possible).

Iowa DOT Guidance

The Iowa DOT has policy and design guidelines for shoulder rumble strips. The photos in Figures 3.8 and 3.9 are from Section 3C-5 “Milled Rumble Strips” of the Design Manual. The shoulder rumble strip policy follows the Iowa DOT’s paved shoulder policy. Other special circumstances involving noise, bicycles, volume, etc. are addressed in the Iowa DOT’s paved shoulder policy.

The second photo (Figure 3.9) shows a gapped pattern for use on highways where bicyclists are permitted, allowing for them to cross over in the gaps.

Table 3.4 2009 Summary of shoulder rumble strip and edge-line rumble stripe practices for neighboring states*

Minnesota	Minnesota currently has no state guidance for installing shoulder rumble strips. However, Mn/DOT had contracted with the University of Minnesota to help establish guidelines. Shoulder rumble strips are placed on all highways and identified state highways with high single-vehicle run-off-road crash rates.
Wisconsin	The Wisconsin Department of Transportation specifies design guidelines for shoulder rumble strips in its <i>Facilities Development Manual</i> . The manual states that rumble strips shall be installed on paved shoulders on both sides of freeways and expressways except on tapers to right or left turning lanes, along turn curves, across side road intersections, or across commercial driveways. The guidelines also suggest providing space between the rumble strip and the edge of the paved shoulder so slow moving vehicles traveling on the shoulder can straddle the rumble strip and reduce damage to the rumble strips.
Illinois	Illinois is drafting a roadway departure plan as part of the Illinois Comprehensive Highway Safety Plan. The Illinois Department of Transportation's <i>Bureau of Design and Environment Manual</i> states that shoulder rumble strips shall be installed on Interstates and other freeways built to Interstate standards and on all rural expressways with a greater than 50 mph posted speed limit. The manual also recommends that shoulder rumble strips be installed along all highways that are high-accident locations as identified by the Division of Traffic Safety. The standard design type used in Illinois is milled-in shoulder rumble strips, and formed-in rumble strips are allowed for PCC shoulders. Special consideration is recommended for facilities where bicyclists are permitted and where shoulder widths are less than 6 feet.
Missouri	The Missouri Department of Transportation includes guidelines in its <i>Engineering Policy Guide</i> for the installation of milled-in shoulder edge line rumble strips on every state route (roadways that carry 80 percent of the traffic in the state), every shoulder that is at least 2 feet wide, and every roadway with speeds greater than 50 mph. Four-inch high-reflectivity paint is applied over the rumble strips to provide greater nighttime visibility.
Nebraska	The Nebraska Department of Roads specifies in its <i>Roadway Design Manual</i> that shoulder rumble strips shall be constructed for all Interstate and expressway projects and rural high-speed highways (with posted speed limits greater than 45 mph), whether new construction or resurfacing.
South Dakota	South Dakota is currently updating the state policy on shoulder and centerline rumble strips.
Kansas	Kansas requires that milled-in shoulder rumble strips be installed on rural highways that have 8 to 10 foot paved shoulders, leaving a 3 foot minimum paved area for bicyclists. Milled-in shoulder rumble strips are also required for median shoulders 6 feet wide or greater. Rumble strips are required for all reconstruction and new construction projects on all roadways.

* Information gathered in 2009 unless updates readily available (see related References)



Figure 3.7. Milled shoulder rumble strips (Iowa DOT)



Figure 3.8. Gapped shoulder rumble strip pattern provides bicyclists with crossover spaces (Iowa DOT)

Current Iowa Practice for Shoulder Rumble Strips

Current Iowa DOT practice is to place either continuous or gapped 12 inch milled-in shoulder rumble strips 6 inches from the edge line on state highways as follows:

- Install continuous shoulder rumble strips on both the inside and outside shoulders on Interstates when placing full-width (10 foot right side, 6 foot left side) paved shoulders
- Install continuous shoulder rumble strips on the inside shoulders of expressways
- Install gapped shoulder rumble strips on the outside shoulders of expressways
- Install continuous or gapped shoulder rumble strips if a 4 foot or greater paved shoulder is present

Installation options vary according to specific highway situations: on state highways with less than 4 foot paved shoulders and high SVROR crash history, consider installing continuous or gapped shoulder rumble strips.

Figures 3.10 through 3.12 show three shoulder rumble strip installations in Iowa.

Figure 3.13 shows page 1 of the Iowa DOT design details for milled shoulder rumble strips.



Figure 3.9. Gapped milled-in rumble strips on a state highway with 4 foot paved shoulders



Figure 3.10. Continuous milled-in shoulder rumble strips on Iowa two-lane roadway with 2 foot paved shoulders



Figure 3.11. Formed-in PCC shoulder rumble strips on an Iowa highway

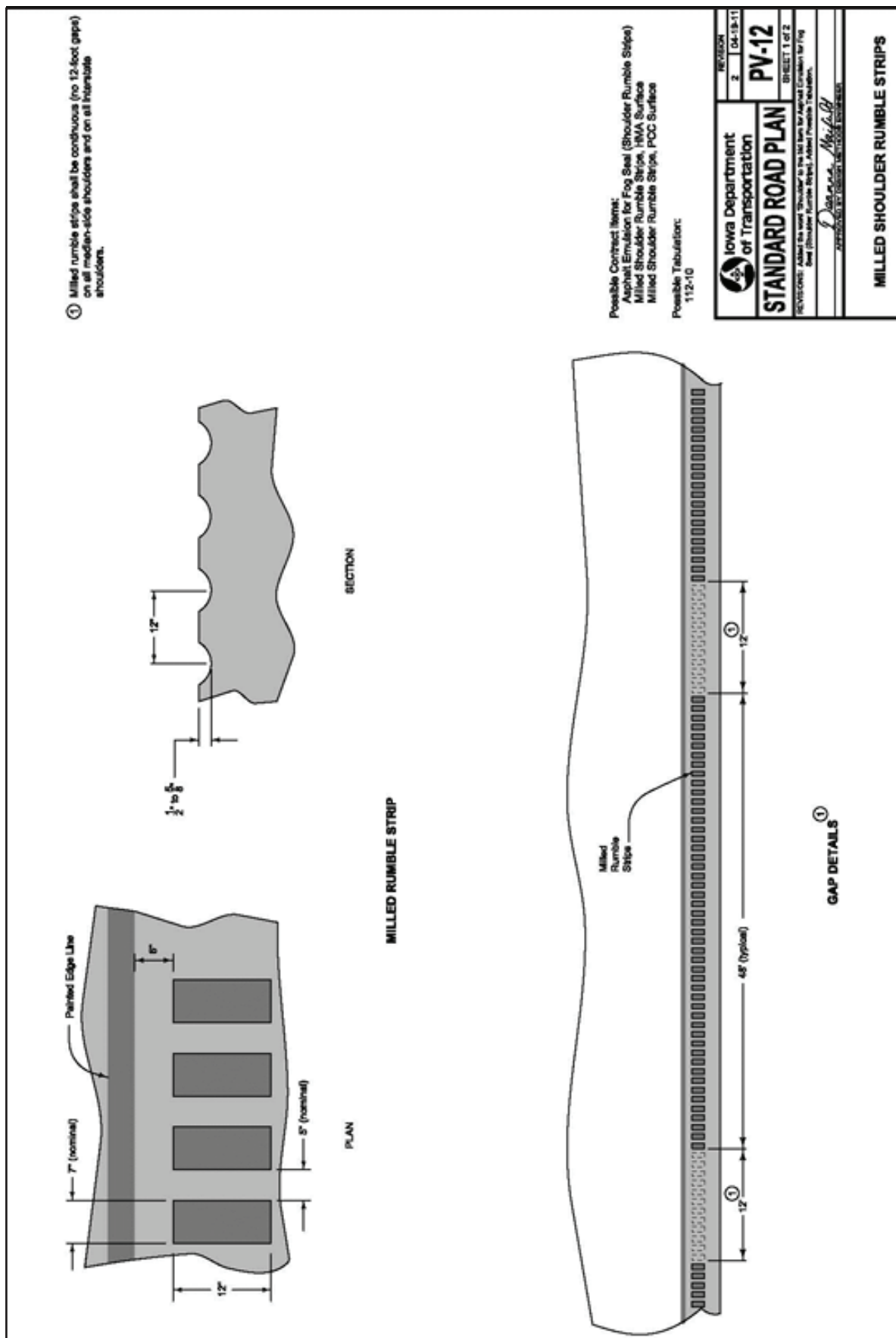


Figure 3.12. Current Iowa DOT standard plan and detail for milled shoulder rumble strips

Proposed Design Changes

Based on research, including an interim version of this report chapter and the changes proposed in it, the Iowa DOT Office of Design updated the policy and standard road plan for milled shoulder rumble strips (as referenced earlier in this section) in 2010.

Proposed Policy Guidance

The research team recommends that the Iowa DOT clearly implement the following policy guidance on shoulder rumble strips:

- Install shoulder rumble strips on all state-level primary roadways with paved shoulders.
- Install rumble strips on all identified 5 percent corridors, regardless of location.
- As appropriate, on other than state highways with a combined lane and shoulder width equal to or less than 30 feet, consider installing gapped shoulder rumble strips and paint the edge line into the rumble strip.

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Figure 3.13 Gapped milled-in shoulder rumble stripes on US Highway 34 near Creston, Iowa (Roche 2011)

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Chapter 4:

Centerline Rumble Strips

Centerline Rumble Strips At a Glance

- Centerline rumble strips (CLRS) are short transverse grooves that are placed along the centerline of a two- or four-lane undivided roadway
 - The treatment produces noise and vibration when a vehicle's tires cross the grooves in the roadway
 - CLRS have an expected crash reduction factor of 14 percent for all crashes, and 55 percent for head-on crashes
 - CLRS can easily be installed on new, existing, or reconstructed asphalt or concrete pavements, depending on the installation technique
-

General Description

Centerline rumble strips (CLRS) are transverse grooves that are placed along the centerline of a two- or four-lane undivided roadway as illustrated in Figure 4.1.

These treatments can be installed on new, existing, or reconstructed asphalt or PCC pavements. Figure 4.2 illustrates a CLRS application on a two- or four-lane roadway.



Figure 4.1. Continuous milled-in centerline rumble strips and edge line rumble strips on US Highway 34 near Creston, Iowa (Roche 2011)

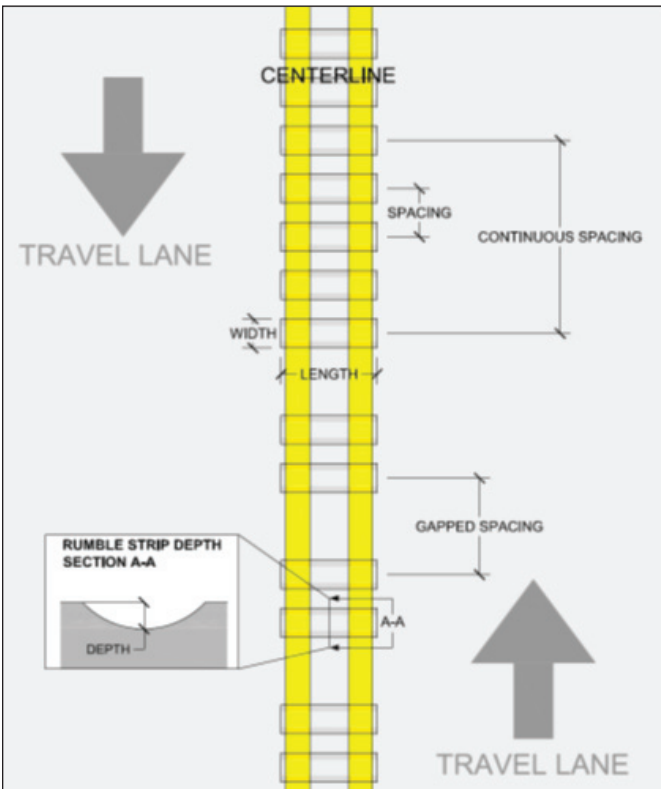


Figure 4.2. Characteristics of centerline rumble strips

Similar to shoulder rumble strips, CLRS provide a tactile and audible alert to drivers that the vehicle is crossing the centerline and that corrective action is needed. (The chapter on Shoulder Rumble Strips contains information about the vibratory and auditory levels produced by these treatments.)

Due to their ease of installation and maintenance, CLRS have been found to be useful for reducing the number of cross-centerline multi-vehicle crashes at a relatively low cost. Additionally, multiple research studies by state agencies have reported a high cost-benefit ratio for CLRS (DeIDOT 2007, WSDOT 2005, Chen and Cottrell for VDOT 2007, Potts et al. for MoDOT 2008).

Table 4.1 provides definitions of terms typically used to describe the placement and features of CLRS (as shown in Figure 4.2).

Installation Locations

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 eventually install CLRS on all rural two- or four-lane undivided roadways. In addition, 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 (Russel 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

Table 4.1. CLRS characteristic definitions

Design	Physical dimensions of the individual rumble strip, such as length, width, depth, and shape
Pattern	Physical layout of the rumble strips, such as distance between strips (gapped or continuous) or single- or double-strip arrangement
Width	Rumble strip dimension parallel to the centerline
Length	Rumble strip dimension perpendicular to centerline
Spacing	Distance between rumble strips, typically measured from center to center
Continuous Spacing	Arrangement in which the CLRS are installed in a continuous pattern with equal spacing between rumble strips
Gapped Spacing	Arrangement in which the CLRS are installed in sets of two with a gap spacing of one rumble strip
Depth	Depth of the center of the rumble strips within the pavement

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.

Maintenance and Installation Concerns

Two concerns regarding the installation and maintenance of CLRS have been noted. The first concern was identified during a survey of states described in NCHRP Synthesis 339, “Centerline Rumble Strips.” Because milled-in CLRS on concrete roadways are often placed adjacent to or close to a pavement joint, milling grooves into the concrete surface may lead to deterioration of the pavement and reduced pavement marking visibility over time (Russell and Rys 2005).

A second concern is the installation of CLRS on two-lane roadways with cross slopes that meet at a crown. This crown is usually made of 2 percent cross slopes on each side of the roadway that together result in a triangular shape. Because the rumble strip blade is a flat surface, the installer is sometimes forced to follow a path on either side of the actual centerline of the road.

In an evaluation of 5,000 miles of CLRS, the Michigan Department of Transportation (MDOT) found that, when rumble strips coincide with the crown of the pavement, the cutting machine either travels on the left or right side of the center of the roadway and produces an uneven cut, as illustrated in Figure 4.3.

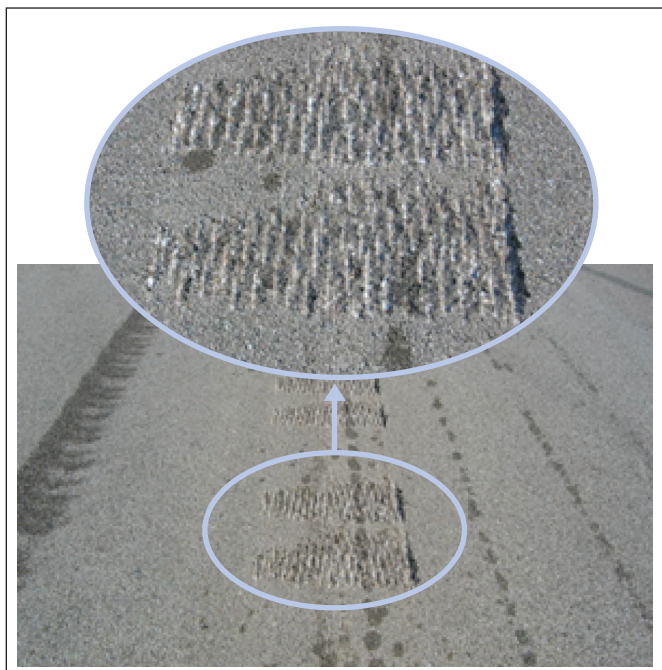


Figure 4.3. Uneven CLRS milling (Michigan DOT 2009)

To counteract the uneven CLRS that MDOT observed, MDOT developed a cut with a variation in depth, and a modification was made to the cutting equipment. For the new cutting equipment, the depths on the outside edge of the rumble strip are much shallower than at the center of the rumble strip, where the two cross slopes meet. This alteration is illustrated in Figure 4.4.

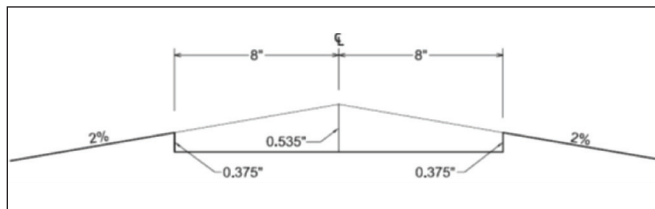


Figure 4.4. Michigan DOT CLRS profile dimensions (2009)

Rumble Strip Designs and Patterns

Design Type

The CLRS design type refers to the device width, depth, shape, spacing, and pattern. As shown in Figures 4.5 through 4.10, various designs have been developed, including continuous or alternating patterns and milled-in rumble strips between 4 and 18 inches long. Generally, rumble strip installations are consistent along sections of a roadway and are typically consistent throughout the state, depending on the installer and state transportation agency.

Commonly, rumble strips are 0.5 inches deep and are spaced 12 inches from center to center. The length of the rumble strip (from 4 to 18 inches) also varies 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.

Installation Inside the Centerline

One of the most common types of CLRS installation involves placing the centerline within the CLRS, as shown in Figures 4.5 and 4.6. By installing CLRS to fall within the centerline pavement marking, the centerline’s paint beads and CLRS, together, can enhance the centerline pavement markings at night and during rain storms, providing greater visibility to the driver.

Advantages:

- Enhances the centerline pavement markings during nighttime and poor visibility conditions
- Does not reduce the travel lane width

Disadvantages:

- Milled-in CLRS may fall on the roadway pavement joint
- Debris, water, or ice may collect in the centerline
- Vehicles may wear down pavement markings over time
- Depending on the crown of the roadway, the CLRS may not be milled in evenly



Figure 4.5. 6 inch CLRS in Arizona (Kar and Weeks 2009)



Figure 4.6. 18 inch CLRS in Iowa (Iowa DOT)

Installation Outside the Centerline

To keep the centerline pavement markings free of debris, prevent wear from vehicles traveling over the CLRS, and avoid placing rumble strips along the center joint of PCC roadways, NCHRP Synthesis 339 suggests installing the CLRS outside of the centerline pavement marking (Russell and Rys 2005). Several states, including Minnesota, Wisconsin, and North Carolina, follow this practice. Figures 4.7 and 4.8 illustrate rumble strip placement adjacent to the centerline pavement markings.

Advantages:

- Keeps debris and ice buildup away from the centerline pavement marking and joint
- Provides even CLRS by milling on the side slope

Disadvantages:

- Reduces the effective travel lane width
- Can increase outside noise because vehicles have a greater chance of driving over the CLRS
- Can increase in the installation costs, depending on the pattern used



Figure 4.7. CLRS outside of pavement markings in North Carolina (Troy 2007)



Figure 4.8. Continuous CLRS in Wisconsin on Highway 142 (Dulaski and Noyce 2006)

Pattern Type

Just as CLRS can differ by design, these devices can also differ by pattern. Continuous or alternating CLRS are the two most-common patterns evaluated by researchers as shown in Figures 4.9 and 4.10.

For either of these patterns, rumble strips may be milled-in adjacent to or on top of the centerline pavement markings and are typically 4 to 18 inches in length, 7 inches wide, and 12 inches apart, from center to center.

Alternatively, some state agencies install continuous rumble strips with the same design in an alternating pattern to differentiate the vibration and auditory signal of CLRS from that of shoulder rumble strips/strips as shown in Figure 4.8. Another alternating pattern is used in Michigan, where every third milled-in rumble strip is skipped as shown in Figure 4.10.



Figure 4.9. Continuous centerline rumble stripes (Stein and Neuman 2007)



Figure 4.10. Alternating CLRS (Michigan DOT 2009)

A literature review identified few documented efforts to study the effectiveness of various CLRS patterns. One notable study was conducted as part of NCHRP Synthesis 339, “Centerline Rumble Strips.” Authors Russell and Rys investigated CLRS patterns on eight miles of Kansas Interstate (2005). The study investigated 12 patterns differentiated by lengths ranging from 5 to 16 inches; an on-center spacing of 12 inches, 14 inches, or a combination of the two; and continuous and alternating patterns (See Figures 4.11 and 4.12).

In NCHRP Synthesis 339, the CLRS were initially milled-in on the right shoulder, and seven test vehicles were used to record steering wheel vibrations and interior noise nearest to the driver’s ear.

After first testing the 12 patterns as a shoulder application, two patterns were selected for installation and testing as CLRS on a rural freeway:

- 12 inches long with continuous 12 inch on-center spacing
- 12 inches long with alternating 12 inch and 24 inch on-center spacing

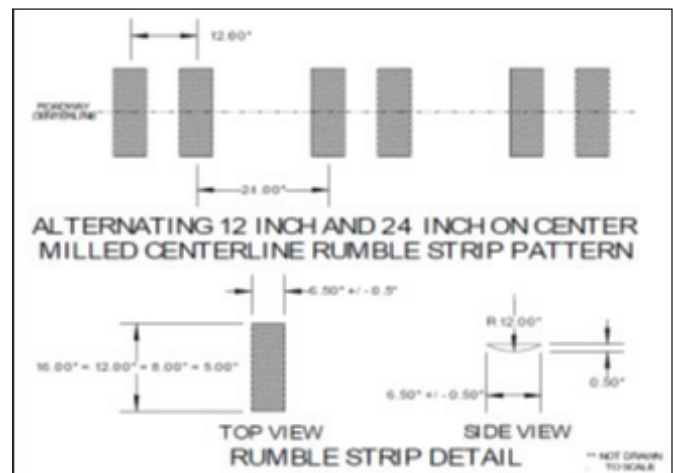


Figure 4.11. Kansas alternating CLRS

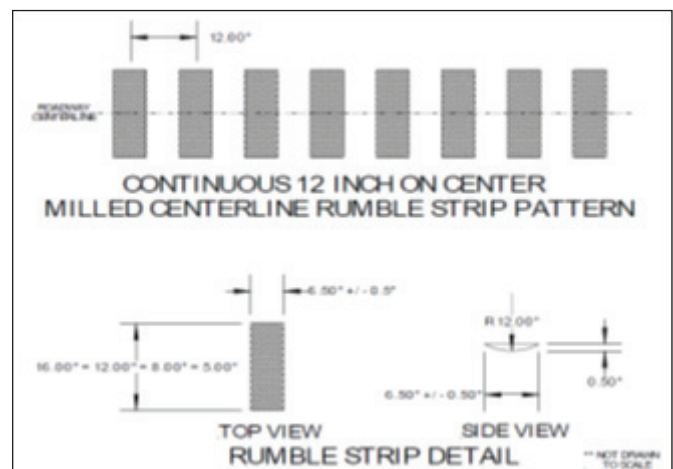


Figure 4.12. Kansas continuous CLRS

Both patterns were placed in 2003 on a 15 mile segment in rural areas in Kansas. The researchers found that the alternating pattern produced higher average vibration levels than the continuous pattern in four of the six vehicles tested. In addition, the researchers felt that both CLRS patterns (continuous and alternating) were effective in alerting a driver when the vehicle crossed the centerline (or deviated from their lane).

Raised Pavement Markings

CLRS may also include raised pavement markings (RPMs). RPMs are durable reflective or non-reflective markers used to provide lane guidance (3M 2009). These devices also provide a tactile warning when a driver deviates from their lane. Examples of raised pavement markers, which can vary in dimensions and application procedures, are illustrated in Figures 4.13 and 4.14. Both reflective and non-reflective RPMs are found mainly in southern states, including Arizona, California, Florida, Nevada, and Texas (Institute of Transportation Studies 1999).

A Caltrans study reported in NCHRP 440 described the effectiveness of a circular type of RPM called Botts' Dots on a 23.5 mile long roadway segment (See Figure 4.14). The results of the two-year before and a two-and-a-half year after study showed that the number of accidents on the studied roadway was reduced from 4.5 per month to 1.9 per month (Fitzpatrick et al. 2000). However, the effectiveness of the raised pavement markers may differ in locations where snow plow operations can abrade or remove the pavement markers from the roadway (Russell and Rys 2005).

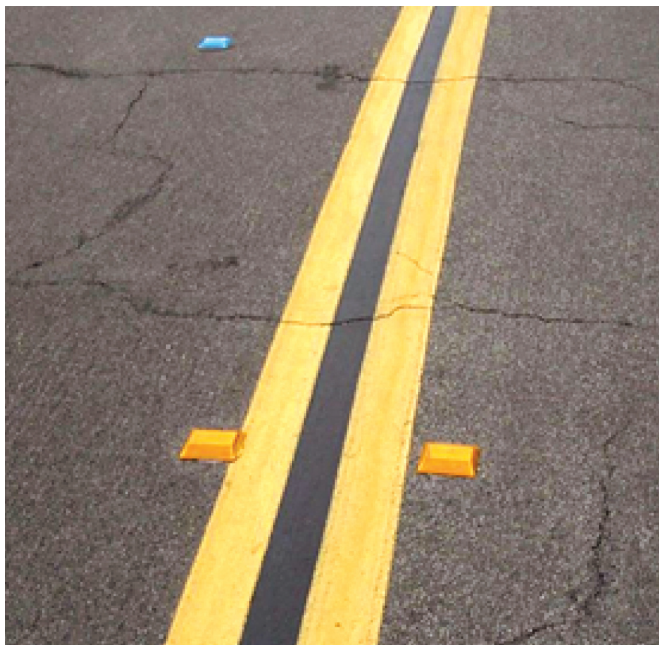


Figure 4.13. Raised centerline pavement markers (Intransition 2007)



Figure 4.14. Caltrans raised pavement markers, "Botts' Dots"

Combination of Treatments

Some states also use a combination of CLRS treatments, depending on the centerline pavement marking used. Figure 4.15 shows a treatment used in Washington on a two-lane roadway.

The painted at-grade median is wider than a traditionally painted centerline. Typically, this would be found close to a left turning lane or, as in this case, a wide roadway cross-section. The treatment includes a combination of 16 inch milled-in rumble strips, thermoplastic raised centerline pavement markings, and reflective raised pavement markings located within the travel lane.



Figure 4.15. Painted median CLRS with raised thermoplastic edge line rumble strips and raised pavement marking lane guidance (Gray Notebook 2008)

Performance/Research Verification

Several studies have shown that CLRS are an inexpensive countermeasure that can be used to alert drivers as they begin to cross the centerline. Given that only a limited number of published studies to date have evaluated the effectiveness of CLRS, they are still considered a “tried” countermeasure in many research publications (Neuman et al. 2003).

Crash Reduction

Based on documented research findings, the FHWA has found that agencies installing CLRS can expect a 14 percent reduction in all crashes and a 55 percent reduction in head-on crashes (FHWA 2008). In addition, the Insurance Institute for Highway Safety (IIHS) has reported that CLRS have led to an overall decrease of 15 percent for all injury crashes and a 25 percent reduction in frontal and opposing-direction sideswipe crashes (Persaud et al. 2004).

To analyze the effectiveness of CLRS, several studies have compared safety data for periods preceding and following the deployment of CLRS.

A before and after study conducted by Persaud et al. investigated the effectiveness of CLRS on more than 210 miles of rural undivided two-lane roads in seven states, including California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington (2004). Data included in the model consisted of annual average daily traffic (AADT), crashes, and roadway geometric data. An empirical Bayes 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.

In a similar, but more geographically-focused study, Kar and Weeks evaluated CLRS installed in 2002 at 14 northern Arizona locations that included arterials, minor arterials, and collectors (2009). The authors selected locations where the Arizona Department of Transportation (ADOT) wanted to reduce cross-centerline crashes. 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 Department of Transportation (CDOT) investigated the effectiveness of 17 miles of 12 inch long CLRS (Outcalt 2001). Four years of before-and-after data were compared, and the authors found a 34 percent

decrease in head-on crashes and a 36.5 percent decrease in opposing-direction 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 (Gray Notebook 2008). The data indicated the following:

- 28 percent reduction in all fatal and serious injury collisions
- 26 percent reduction in all cross-centerline collisions
- 50 percent reduction in fatal and serious injuries resulting from cross-centerline collisions

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 A 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 and a 9 percent increase in AADT for the studied segments.

In studies that focused on the effectiveness of CLRS alone, a recent study of the Missouri Smooth Roads Initiative (SRI) investigated six sites and 24.8 miles of centerline and edge line milled-in rumble strips as a combination. The investigators found that the SRI program overall showed a statistically significant 8 percent decrease in fatal and disabling injury crashes and a statistically-significant 6 percent decrease in fatal and all-injury crashes for one year after installation. For the six sites with centerline and edge line milled-in rumble strips, the data showed a 74.5 percent decrease in fatal-and-disabling-injury crashes and a 35.5 percent decrease in fatal and all-injury crashes. Standard errors of 18.2 and 14.5, respectively, were found (Potts et al. 2008).

Lane-Keeping Position

In addition to crash data analyses, several studies have evaluated the impact of CLRS on lane-keeping, or the ability of drivers to maintain their vehicle lateral position within a lane. Lane keeping is used as a crash surrogate with the assumption that treatments resulting in better lane keeping will also decrease lane departures and, subsequently, crashes. Lane-keeping is usually measured by a vehicle's lateral placement within the lane.

Lateral position is defined as the location of the vehicle's longitudinal axis relative to a longitudinal road reference point or centerline (Porter et al. 2004). By measuring lateral position, researchers can determine where the vehicle travels within the lane and whether the tactile and audible alerts that the CLRS (as well as shoulder rumble strips) issue to the driver are an effective countermeasure for deterring centerline encroachment.

On a 15 mile segment of rural two-lane highway west of Waco, Texas, where CLRS had been installed, Pratt et al. investigated the effects of both edge-line rumble strips and CLRS on passing maneuvers and vehicle lateral placement (2006). Passing maneuvers were observed using four concealed video cameras mounted on a test vehicle. Results showed that the presence of CLRS had no impact on how vehicles passed the test vehicle or the number of times the test vehicle was passed. Vehicle lateral displacement was measured using pneumatic traffic counters in a Z configuration on the same segment of highway. Results showed that CLRS had a positive impact on vehicle lateral placement by increasing vehicle separation from the CLRS.

In a study of CLRS alone, Porter et al. investigated the impacts of CLRS on vehicle lateral placement on rural two-lane roads in Pennsylvania (2004). A before-and-after study was performed using electric switches at four locations on tangent segments. Three of the four sites had 12 foot wide travel lanes, and the fourth site had 11 foot wide travel lanes. Two of the four locations were control sites, and data were collected a brief period before and four months after installation. Results after the installation of CLRS showed that vehicles that traveled in the 12 foot wide lanes moved away from the CLRS by 7.5 inches, while vehicles traveling in the 11 foot wide lanes moved away from the CLRS by 9 inches.

On a rural two-lane highway segment outside of St. Cloud, Minnesota, Briese also studied the effects of CLRS on vehicle lateral displacement (2006). An analysis of observations indicated no differences in vehicle lateral displacement after the installation of CLRS.

Cost Effectiveness

WSDOT has found the cost-benefit ratio for CLRS to be 60:1 (Gray Notebook 2008).

Besides evaluating the benefit-cost ratio of CLRS, the Virginia Department of Transportation (VDOT) estimated the device crash reduction factor. During a system-wide analysis supporting the creation of CLRS implementation guidelines, Chen and Cottrell investigated several high-crash roadway segments, including an 8.66 mile long segment on Route 1 in a northern

Virginia district (2006). This route was considered by VDOT to have one of the highest recorded cross-centerline crash rates (based on three years of data): 4.73 crashes per mile. After installation of CLRS, VDOT estimated the crash reduction factor to be 20 percent and estimated the cost-benefit ratio to be 7.6 (Chen and Cottrell 2005).

Motorcycle Accommodations

Along with the passenger cars and heavy vehicles using two-lane roadways, motorcycles are becoming more prevalent. In 2006, nearly 146,000 motorcycles were registered in Iowa (Gkritza et al. 2010).

Motorcycle interest groups initially expressed concerns about motorcyclists' ability to maintain their balance while passing other vehicles when CLRS are present (Miller 2008). Although the effectiveness of this technique has not been quantified, some agencies addressed these concerns by providing advance notice when rumble strips are present.

For example, Chatham County, Georgia, requires temporary advance warning signs, as shown in Figure 4.16. Typically, these signs are maintained for 10 to 12 months after CLRS installation to alert motorcyclists and the general public of the countermeasure. The Michigan Motorcycle Safety Action Plan specifies that similar signage is required for CLRS (MDOT 2006).



Figure 4.16. CLRS advance warning (Chatham County, Georgia Signs 2009)

San Diego County has actually used CLRS as a traffic-calming measure aimed at discouraging vehicles, primarily motorcyclists, from traveling across the centerline or cutting across the centerline in a horizontal curve (2007).

Miller has investigated whether CLRS have contributed to motorcycle accidents by endangering the riders and whether CLRS negatively affected rider behavior (2008). Miller’s research team first investigated crash data from 1999 to 2006 on rural two-lane roadways in Minnesota and identified crashes that occurred in the presence of CLRS. During this period, 9,845 motorcycle-related crashes occurred. Of these, 29 involved the presence of CLRS, and none of the crash records mentioned the CLRS as a contributing factor.

Next, video field data were collected for 44 hours to observe rider behavior in the presence of CLRS. Miller observed no change in rider behavior or near-miss crashes at the study site.

Finally, researchers had 32 motorcyclists riding various motorcycle designs evaluate rumble strips on a closed course. The research team found that riders had no difficulty passing over the rumble strips and made no adjustments to throttle, braking, or steering during the simulated passing operations.

CLRS Design and Placement Guidelines in Neighboring States

Many transportation agencies implement CLRS and state guidelines often vary due to differing climates, road designs, and/or maintenance practices. To determine the CLRS design and placement guidelines used by different states, a survey was distributed via the National Safety Engineers Listserv to states adjacent to Iowa in 2009. Several representatives from state transportation agencies responded, and additional information was obtained from a review of state transportation agency websites.

The information gathered about agency design and placement typically includes safety considerations (such as crash risk) defined by individual jurisdictions (See Table 4.2). Note that the thresholds for tolerable risks are not consistent across jurisdictions.

Table 4.2 Summary of centerline rumble strip installation guidelines for states adjacent to Iowa*

Minnesota	Has recently released a draft technical memorandum that indicates CLRS shall be placed on all rural highway construction and maintenance pavement projects where the speed limit is 50 mph or greater.
Wisconsin	Installs CLRS. The University of Wisconsin-Madison is currently developing standardized guidance on the placement and design of shoulder rumble strip and CLRS installations.
Illinois	Considers the use of CLRS on two-lane highways experimental and has limited device use to locations with curves. Currently, CLRS are recommended to extend through the super-elevation transition of the curve. The rumble strips are similar to the design used by the Missouri Department of Transportation (MoDOT): 16 inches long by 7 inches wide with a 5 inch gap spacing between strips and every third rumble strip omitted, so that a different pattern results than that used for shoulder rumble strips.
Missouri	Specifies that “all two-lane major roads with new pavement will have centerline rumble strips unless the posted speed limit is less than 50 mph.” In addition, CLRS are installed on major two-lane and minor roadways with a cross-centerline crash history. CLRS are not recommended on roadways with a roadway width of 20 feet or less. CLRS should only be applied on the mandated roadway segments when the pavement thickness is at least 1.75 inches, and rumble strips cannot be placed on any joints. In terms of design, CLRS are 12 inches wide and installed in a gapped pattern, except in passing lanes, where two sets of rumble strips are recommended (See Figures 4.17 and 4.18).
Nebraska	Is establishing a plan with the Nebraska Department of Roads (NDOR) to install milled-in CLRS on two-lane roads where a history of cross-centerline crashes has been identified. Tests performed by NDOR have confirmed device effectiveness, and standard drawings were created that specify a standard length of 12 inches in either a square or football-shaped pattern (See Figure 4.20).
South Dakota	Installs CLRS on roadway segments with a history of cross-centerline crashes. As of 2009, only one location in South Dakota, a one mile long section of US 14A with curves, has CLRS.
Kansas	Provides general inspection guidance. The Kansas 2007 state policy also allows the use of milled-in continuous CLRS on all reconstruction, new construction, and overlay projects that are five miles or more in length. The policy indicates that “centerline rumble strips may be used on two-lane, Class Band C, rural highways with asphalt pavement surfaces 1.5 inches or more in depth and having a paved shoulder width of at least 3 feet.” To provide continuity between different roadway segments, CLRS may also be used at highway locations where the shoulder width changes. An engineering study is recommended for segments that do not meet these criteria.

* Information gathered in 2009 unless updates readily available (see related References)

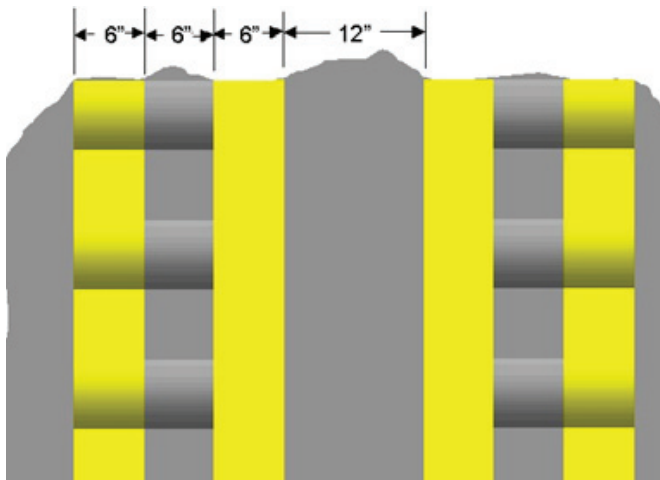


Figure 4.17. Missouri DOT passing lane CLRS marking detail

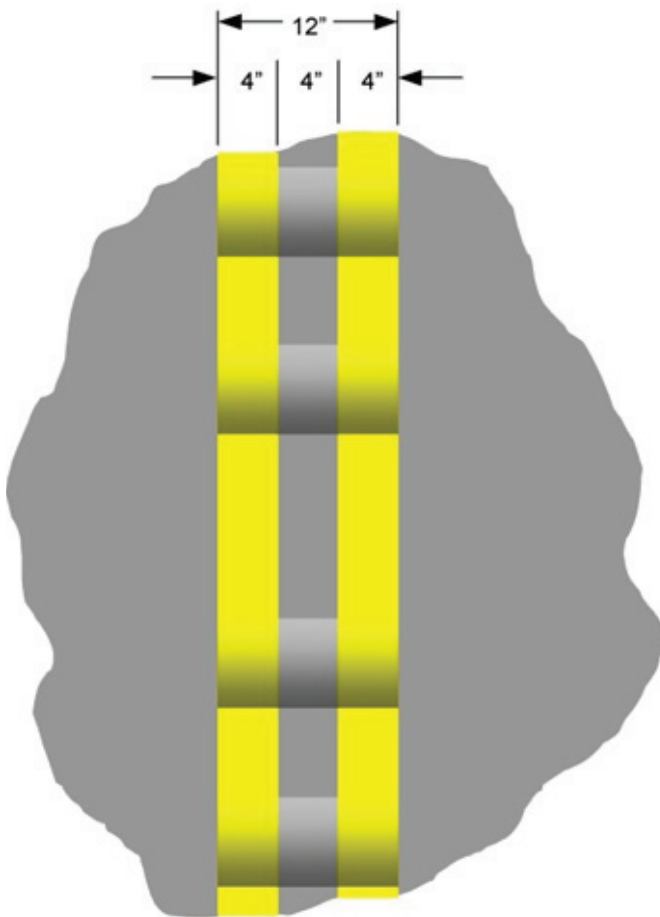


Figure 4.18. Missouri DOT CLRS marking for two-lane roadway

Iowa DOT Guidance

The first three CLRS installations in Iowa were on US 34, US 52, and US 61. Based on research, including an interim version of this report chapter and changes proposed in it, the Iowa DOT Office of Design updated the policy and standard road plan for CLRS in 2010.

Current Policy Guidance for Centerline Rumble Strips

Iowa DOT policy guidelines (2010) indicate, to qualify for milled CLRS, a project must meet one of these conditions:

- Two-lane primary road with ADT greater than 3,000 and 2 foot or wider shoulders and 11 foot or wider lanes
- Identified as 5 percent cross centerline crash corridor with 2 foot or wider shoulders and at least 11 foot lane widths, as they are resurfaced

Installation of both CLRS and edge-line shoulder rumble stripes (described in the previous chapter) are recommended to reduce SVROR crashes and CLRS are recommended in locations with a high number of cross-centerline multiple-vehicle crashes. Figure 4.19 is a photo from the 2010 Design Manual.

Current Design Guidance for Centerline Rumble Strips

The first page of the current Iowa DOT standard design for CLRS is shown in Figure 4.21.



Figure 4.19. Gapped milled centerline rumble stripe pattern (Iowa DOT)

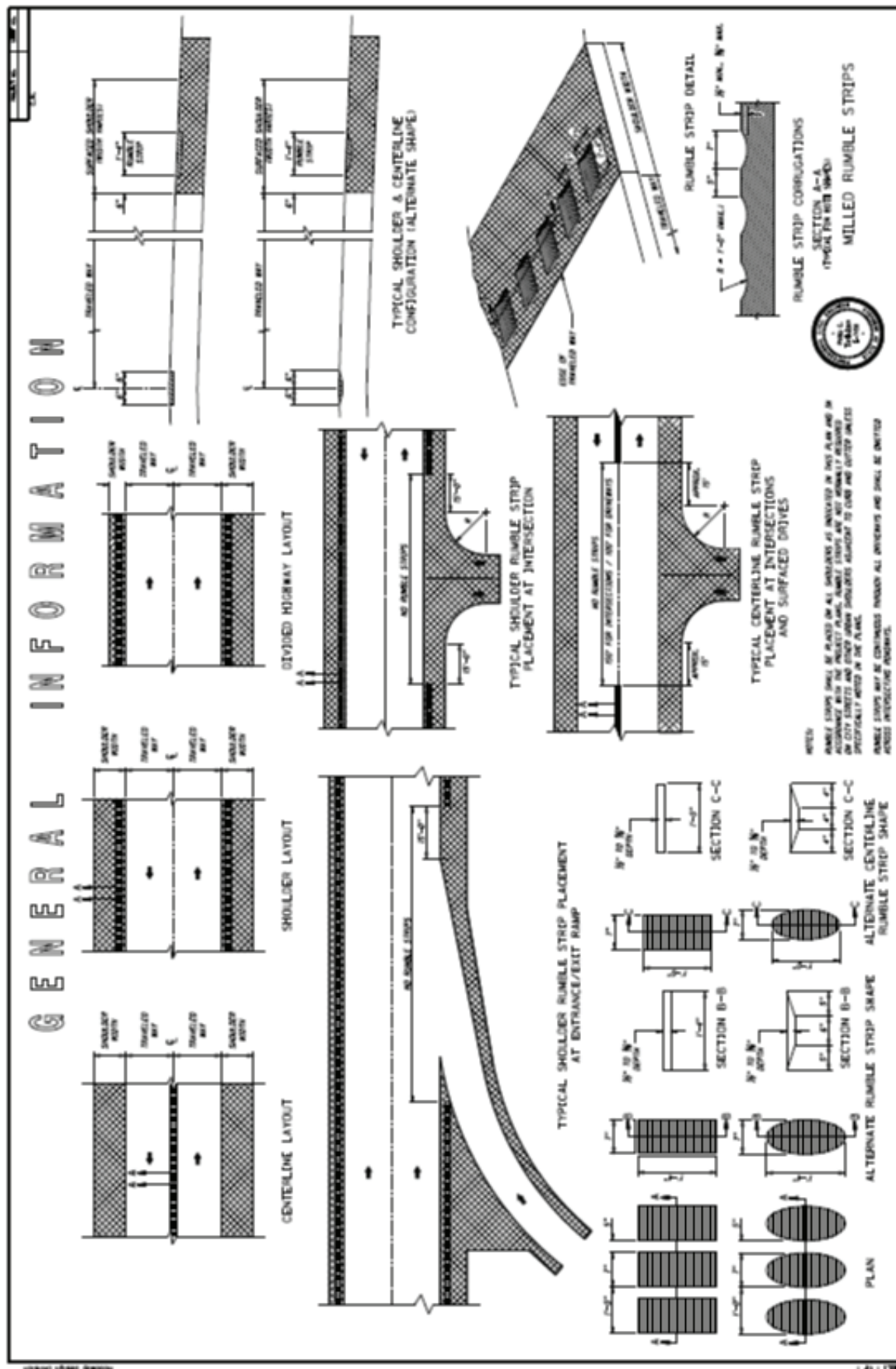


Figure 4.20. Nebraska Department of Roads standard rumble strip plan

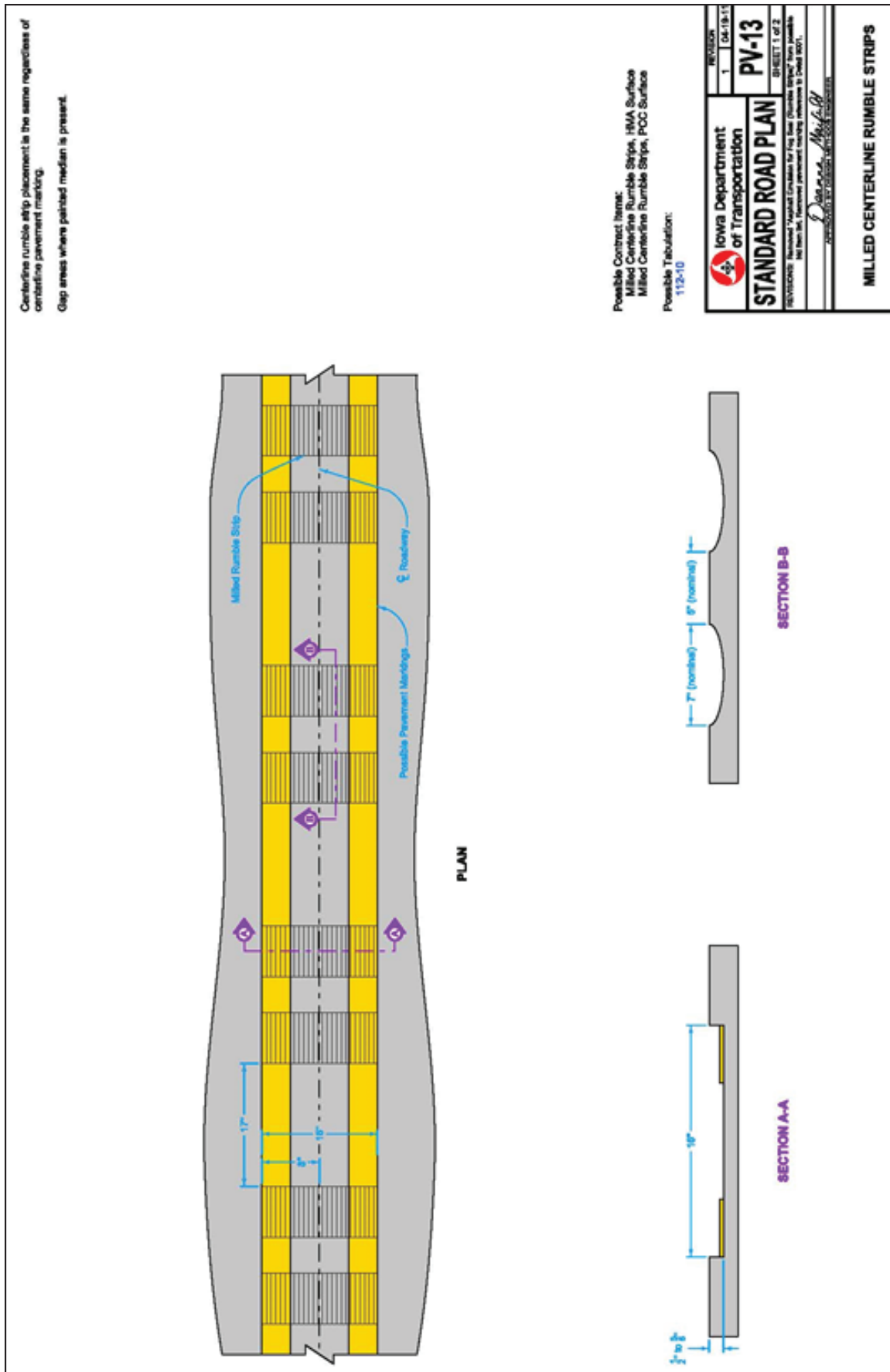


Figure 4.21. Current Iowa DOT CLRS design standards

Proposed Policy Guidance Changes

These are the recommended policy guidance changes for CLRS at this time:

- Install CLRS on all identified 5 percent corridors as the corridors are resurfaced.
- Retrofit CLRS on all identified 5 percent corridors resurfaced in the past five years.
- Once installed, these lane departure countermeasures should be maintained, unless specifically found to not be effective.

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Chapter 5:

High-Tension Median Cable Barriers

High-Tension Median Cable Barriers At a Glance

- High-tension median cable barriers are parallel wire cables supported by breakaway posts
 - These barriers are designed to prevent vehicles that depart the roadway from crossing the median into oncoming traffic
 - According to the FHWA, high-tension cable barriers are effective in reducing the number of head-on crashes and studies show they're effective at reducing fatal and major injury crashes
 - High-tension cable barriers are relatively inexpensive and have a high benefit-cost ratio
-

General Description

High-tension median cable barriers typically consist of three or four parallel wire cables supported by breakaway posts and anchored to the ground at the ends. The resulting barrier system is easy to install and can be indefinite in length (See Figure 5.1). In most cases, however, the span of the cable barrier is limited to allow for emergency vehicle access points and roadway structures.

High-tension cable barriers are designed to prevent a vehicle that departs the roadway from crossing the median into oncoming traffic. These barriers can be used on both sloped and level terrain and can deflect up to 10 feet when impacted. In this way, the barriers can minimize the potential for head-on crashes and, depending on the barrier location, also minimize the potential for roll-over and other types of crashes that occur on depressed medians.

Figure 5.2 shows the results of a collision between a high-speed vehicle and a cable median barrier. The barrier system may be able to withstand multiple crashes before maintenance or section replacement is required, depending on the cable barrier design and the type of vehicle crashes.



Figure 5.1. High-tension cable median barriers on Interstate 35 between Ames and Ankeny, Iowa



Figure 5.2. Prevented cross-median crash by a cable median barrier (Washington State DOT)

Advantages/Disadvantages

NCHRP publication 244, “Guardrail and Median Barrier Crashworthiness: A Synthesis of Highway Practice” (Ray and McGinnis 1997), lists the following advantages and disadvantages associated with high-tension cable median barriers:

Advantages

- Installation is less expensive than for other barrier systems
- Forces acting on the vehicle occupants during a crash are lower than the forces generated by impacts with other barrier types
- Cable barriers perform well in crash tests, resisting up to 2,000 kg or roughly 4,400 lbs
- The system is aesthetically pleasing
- Sight distance problems are minimized

Disadvantages

- In a typical crash, barrier damage is greater than for other systems
- Damaged barrier sections must be repaired or replaced quickly because the barrier may be ineffective during down time
- A minimum clear space is required for cable deflection behind the barrier when the barrier is struck by a vehicle
- Periodic retensioning of cables may be required, even if the barrier is not hit by vehicles
- May pose some risk for highway workers maintaining the systems

Design Variations/Types

Roadway cable barriers have been used for more than 80 years. In 1960, a New York design for low-tension cable barriers, which became the generic US design, used three spring-tensioned cables attached to poles using a J-bracket.

In the 1990s, several private manufacturers began developing high-tension versions of the low-tension cable barrier system. A high-tension barrier system consists of breakaway posts throughout the system and either prefabricated or poured-in-place concrete anchors on both ends.

The three or four cables are tightened to a specific tension, ranging between 2,000 and 9,000 pounds, depending on climate, system length, and manufacturer (McDonald and Batiste 2007). This high tension provides an additional

measure of safety that low-tension cable barriers lack: vehicles can be captured with a deflection from 6.6 feet to 9.2 feet (AASHTO 2006).

In addition, the tension in the system should keep the cables from falling to the ground, even with several posts missing. This can result in the barrier withstanding additional impacts, before repairs take place.

The breakaway support post cross sections can be shaped in a C, I, circular, or rectangular form. The posts are inserted into various foundation types, depending on the soil conditions. Because the system is in tension, the length of the barrier can be indefinite. However, many states end the barrier at emergency vehicle access points or at structures such as tunnels and bridges.

Manufacturers of High-Tension Cable Median Barriers

Several private companies manufacture high-tension cable median barriers. All of these barriers must meet a set of guidelines described in NCHRP Report 350, “Recommended Procedures for the Safety Performance Evaluation of Highway Features,” and must then be accepted by the FHWA for use on the National Highway System (Ross et al. 1993). NCHRP 350 specifies ways to evaluate safety hardware, including the components of various high-tension cable barriers, according to three general criteria shown in Table 5.1

Table 5.1. Ways to evaluate high-tension cable barriers (Ross et al. 1993)

Criteria	Description
Structural Adequacy	The system must contain and redirect the vehicle with no under-riding, over-riding, or penetration
Occupant Risk	Fragments of the system cannot penetrate the passenger compartment, the vehicle must remain upright during and after the collision, and the passenger must not undergo excessive impact of deceleration
Vehicle Trajectory	After the impact, the vehicle should not intrude into adjacent traffic lanes, nor should it exit the system at an angle greater than 60 percent of the entry angle

Test Levels

Under the conditions identified in NCHRP 350, a number of high-tension cable median barriers have been successfully tested at different NCHRP test levels, including test level 3 (TL-3) and test level 4 (TL-4). TL-3 involves a 2,000 kg

pickup truck impacting the barrier at 62.14 mph (100 km/hr) at a 25 degree angle. TL-4 involves an 8,000 kg single-unit truck impacting the barrier at 49.7 mph (80 km/hr) at a 15 degree angle (Ross et al. 1993). Generally, manufacturers have two different cable barrier designs to meet each of the test levels.

In a scanning tour of Midwestern states, University of Illinois researchers identified several common high-tension cable barrier systems. These systems are illustrated in Figures 3.3 through 3.7. (See their websites for additional information.) Note that, in addition to these systems, many other products have been accepted by the FHWA (Medina and Benekohal 2006, Alberson 2006).

Brifen USA

<http://www.brifenusa.com>



Figure 5.3. Brifen Wire Rope Safety Fence (WRSF) (Alberson 2006)

Trinity Highway Products

<http://www.highwayguardrail.com>



Figure 5.4. Trinity Highway Products Cable Safety System (CASS™) (Alberson 2006)

Blue Systems AB

<http://www.bluesystems.se>



Figure 5.5. Blue Systems SAFENCE (Alberson 2006)

Gibraltar Cable Barrier Systems

<http://www.gibraltartx.com>



Figure 5.6. Gibraltar Cable Barrier Systems three cable system (Alberson 2006)

Nucor Steel Marion, Inc.

<http://www.nucorhighway.com>



Figure 5.7. NU-CABLE™ TL-3 (Nucor Steel Marion 2009)

Installation

For agencies that choose to install high-tension cable median barriers, two important considerations can influence device effectiveness and maintenance needs: barrier location and weed mitigation

Barrier Location

To prevent cross-median crashes using high-tension cable median barriers, two of the most critical aspects to consider are the median geometry and the placement of the cable barrier system within the median.

For median geometry, both depressed medians and steep back slopes can create especially dangerous safety problems for oncoming vehicles when out-of-control vehicles travel through the median. Researchers at the University of Nebraska's Midwest Roadside Safety Facility have noted that median geometry affects cross-median crash frequency. This is especially the case when depressed highway medians with steep foreslopes allow encroaching vehicles to become airborne and grant the driver little opportunity to take corrective action (Sicking et al. 2008).

In addition, as part of NCHRP Synthesis 318 "Safe and Quick Clearance of Traffic Incidents," researchers found that medians with steep back slopes forced vehicles to climb up the back slope rather than steer back toward the center of the median (Ross 1989).

Therefore, cable barrier placement is critical to stopping a vehicle that encroaches into the median. The Missouri Department of Transportation (MoDOT) (2007) recommends two locations in which a high-tension cable barrier could be most effective. As shown in Figure 5.8, the most effective locations are either at the bottom of the median ditch or on the foreslope closer to the oncoming traffic's travel lane.

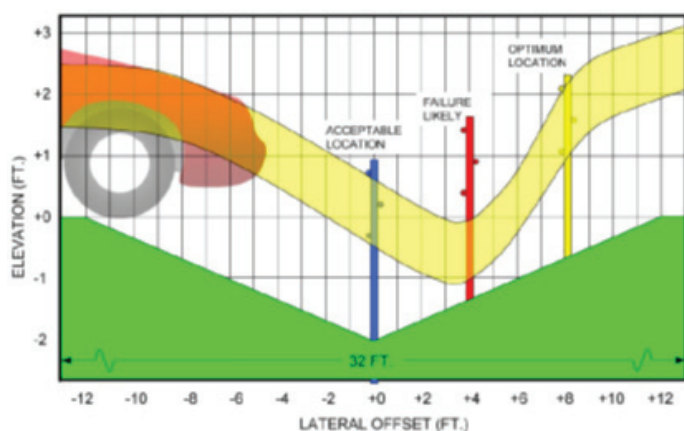


Figure 5.8. Cable barrier offset for medians wider than 30 feet (Missouri DOT 2007)

High-tension cable barriers located too close to the vehicle's own travel lane might be considered an obstacle for drivers.

The Wisconsin Department of Transportation (WisDOT) conducted a survey of state DOTs regarding their use of cable barrier systems. Results of this survey show that 76 percent of 22 states with high-tension cable barriers use the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (RDG) for guidance (CTC 2007). The RDG explains how the proximity of a median barrier to the roadway could be perceived as an obstacle. However it also states, "for long, continuous runs of railing, [the offset distance] is not so critical... As long as the barrier is located beyond the perceived shoulder of the roadway, it will have minimum impact on driver speed or lane position" (AASHTO 2006).

Weed Mitigation

Because high-tension cable median barriers are typically located within the median, agencies commonly report problems with managing vegetation in the median. A report prepared for WisDOT on the state of the practice of weed mitigation found that most state agencies install a narrow "mow strip" underneath the cable barrier (CTC 2007). As illustrated in Figure 5.9, this strip runs the length of the cable barrier and is between 3 and 5 feet wide. The strip is composed of material such as gravel, asphalt, concrete, or a composite. The strip's purpose is to reduce the need for herbicides or hand mowing in the vicinity of the cable barrier.



Figure 5.9. Mow strip for cable guardrails (WeedEnd®)

Median Cable Barriers in Other States

Using a survey of state departments of transportation (DOTs) conducted through the Newmark Structural Engineering Laboratory (NSEL) listserv, the WisDOT study also described several state guidelines for cable barrier placement, weed control, and related considerations (CTC 2007). A summary of these guidelines is presented in Table 5.2.

Table 5.2. State guidance on high-tension median cable barrier placement and mowing strip strategies

State	Barrier Lateral Placement and Mowing Strip Strategies
Missouri	Placing on 6:1 slope paving 3.5 inches of asphalt cement concrete > 4 foot downslope from shoulder edge, 8 feet from travelled way Overall hits about the same when down the middle or up near the shoulder Some bounce back observed
Florida	One installation (6 miles) at 12 foot from edge of lane, at shoulder break point Up to 6:1 slope, asphalt mow strip 2 inches thick, 3 feet wide One installation (23 miles) at 17 feet from edge of lane, 5 foot down 6:1 slope
California	Minimum distance 10 feet from traveled way with 30:1 taper
Michigan	Minimum 12 feet from edge of lane
Illinois	Have installations 8 feet from lane edge, at edge of shoulder Have installations at 15 feet from edge of shoulder without mow strip on 6:1 Have installations at 12 feet+ within thin hot-mix asphalt mow strip
Utah	12 foot minimum from edge of lane, 8 foot minimum from ditch bottom, 8:1 or flatter slope 4 foot wide 6 inch deep compact base mow strip
Texas	12 foot minimum from edge of shoulder Concrete riprap mowing strip (mostly) 1 foot minimum from ditch bottom, 6:1 or flatter slope Initial installations at 8 feet, but they were getting too many nuisance hits
Minnesota	Currently 2 foot downslope from shoulder point of inflection for slope 4:1 to 6:1, 4 foot downslope from shoulder point of inflection for slope 6:1 or less
Kentucky	Installing at least 8 feet from traveled way and at least 10 feet from ditch bottom Some have concrete mow strips, some have gravel strips, some are in granular shoulder, and some have no mow strip
Wisconsin	No set installation location

Motorcycle Accommodations

Many motorcycle interest groups see high-tension cable median barriers as a hazard to riders who become involved in crashes on high-speed roadways. Currently, no research reports adequately address the specific risks faced by motorcyclists involved in crashes with cable median barriers (Candappa et al. 2005). NCHRP 22-26, "Factors Related to Serious Injury and Fatal Motorcycle Crashes with Traffic Barriers," is currently studying the issue. Results of this research are expected to be released sometime in 2012.

Performance/Research Verification

Today, more than 25 states have installed more than 3,000 miles of both low- and high-tension cable barriers (Alberson 2006). Although only a few studies have evaluated the effectiveness of cable median barrier systems, the results have generally been positive.

Crash Reduction

According to the FHWA, high-tension cable barriers are effective in reducing the number of head-on crashes. A crash reduction factor of 29 has been reported for multilane divided highways, and a crash reduction factor of 92 has been reported for rural highways (Bahar et al. 2001).

One study conducted in Oregon found that cable barriers installed in 1996 along 14.5 kilometers of roadway reduced the roadway fatality crash rate from 0.6 per year to 0 per year, while the major injury crash rate increased from 0.7 to 3.8 per year. These findings were based on a comparison of two years of after data and nine years of before data. The study also found that during the two-year after period, two of the 53 vehicles that impacted the barriers went under the cable (Sposito and Johnston 1998).

Using a similar type of before-after comparison, University of North Carolina researchers compared three years of before data to four years of after data to measure the effectiveness of a 13.7 kilometer segment of cable barrier in North Carolina. The cable barrier segment data were also compared to data from the state's entire Interstate system. The results of the statistical models showed a decrease in fatal and major injury crashes and an increase in other less-severe crashes. The researchers also concluded that the overall crash severity index dropped sharply after the cable barrier installation (Hunter et al. 2000).

WSDOT has also found that cable median barriers lead to less-severe injuries than other barrier types. In an internal review of 11,457 median barrier collisions from 1999 to 2004, researchers found that occupants of vehicles that struck a cable barrier were less likely to be killed or injured than those in vehicles that struck a concrete barrier (Neuman et al. 2008). Another WSDOT investigation of the effectiveness of cable barrier systems used a before-and-after study to measure the change in crash rates along 135 miles of roadway where cable barrier systems were installed. The results showed an 80 percent reduction in fatal crashes and a 75 percent reduction in disabling crashes after the installation of the cable barrier system (MacDonald and Batiste 2007).

Benefit-Cost Ratios

High-tension cable barriers are relatively inexpensive and have a high benefit-cost ratio. Washington has found a typical installation to cost \$44,000 per mile (Milton et al. 2004) and McClanahan et al. (2003) found an overall societal benefit based on crash data to be \$420,000 per mile annually. Even more savings could be accrued if highway crews developed a system and skills to repair the barriers more efficiently (Milton 2004).

While high-tension cable median barrier systems have relatively low installation costs, their maintenance costs depend on the number of vehicle impacts borne by the barrier system. A high frequency of such collisions can lead to high maintenance or replacement costs. However, agencies have found that cable median barriers have paid for themselves, in that the number of lives saved outweighed the maintenance costs.

The North Carolina Department of Transportation (NCDOT) found its low-tension cable median barrier program provided the state with a cost savings of \$290 million between 1999 and 2003 after 96 lives were saved (Strasburg and Crawley 2005). WSDOT found benefit-cost ratios between 0.6 and 5.5, depending on the median width, with a median width of 30 to 40 feet having the highest benefit-cost ratio (Milton 2004).

However, researchers at the Texas Transportation Institute (TTI) argue that finding a realistic benefit-cost ratio for high-tension cable barriers may be difficult at present. The researchers state that variables such as traffic composition, whether a mow strip is needed, barrier placement, and roadway geometry have significant safety and cost implications that have not yet been measured definitively (Miaou et al. 2005). The variability of these factors makes it difficult to estimate benefit-cost ratios with accuracy.

Iowa DOT Guidance

Current Practice for High-Tension Cable Median Barriers

The Iowa DOT uses high-tension cable median barriers as one countermeasure to address cross-median crashes on high-speed divided highways. Installation locations are determined based on crash history, site characteristics, and installation costs.

As part of the Iowa Comprehensive Highway Safety Plan (CHSP), the Iowa DOT has identified the top 5 percent of the state's high-speed highway segments that have the most severe safety problems based on several safety-related factors. Figure 5.10 is an example showing the highway segments with the highest density of multiple-vehicle cross-median crashes, based on CHSP criteria.

As of February 2011, the Iowa DOT places median cable barriers a minimum of 12 feet from the travel lane wherever possible. In addition, high-tension cable barriers are placed on federal and state highways to protect median obstacles, such as bridge piers and changeable message signs.

Proposed Policy Guidance

The Iowa DOT CHSP approach to identifying high-crash locations and placing high-tension cable median barriers has proven to be an objective and quantifiable strategy to be adopted more widely for other areas across the state.

It is recommended that the Iowa DOT also implement the following policy guidance changes:

- As part of the 5 percent program, continue to analyze identified divided highway segments that have high rates of cross-median crashes.
- Install high-tension cable median barriers on identified 5 percent divided highway segments with high rates of cross-median crashes.
- Give priority to the segments with the highest traffic volumes.

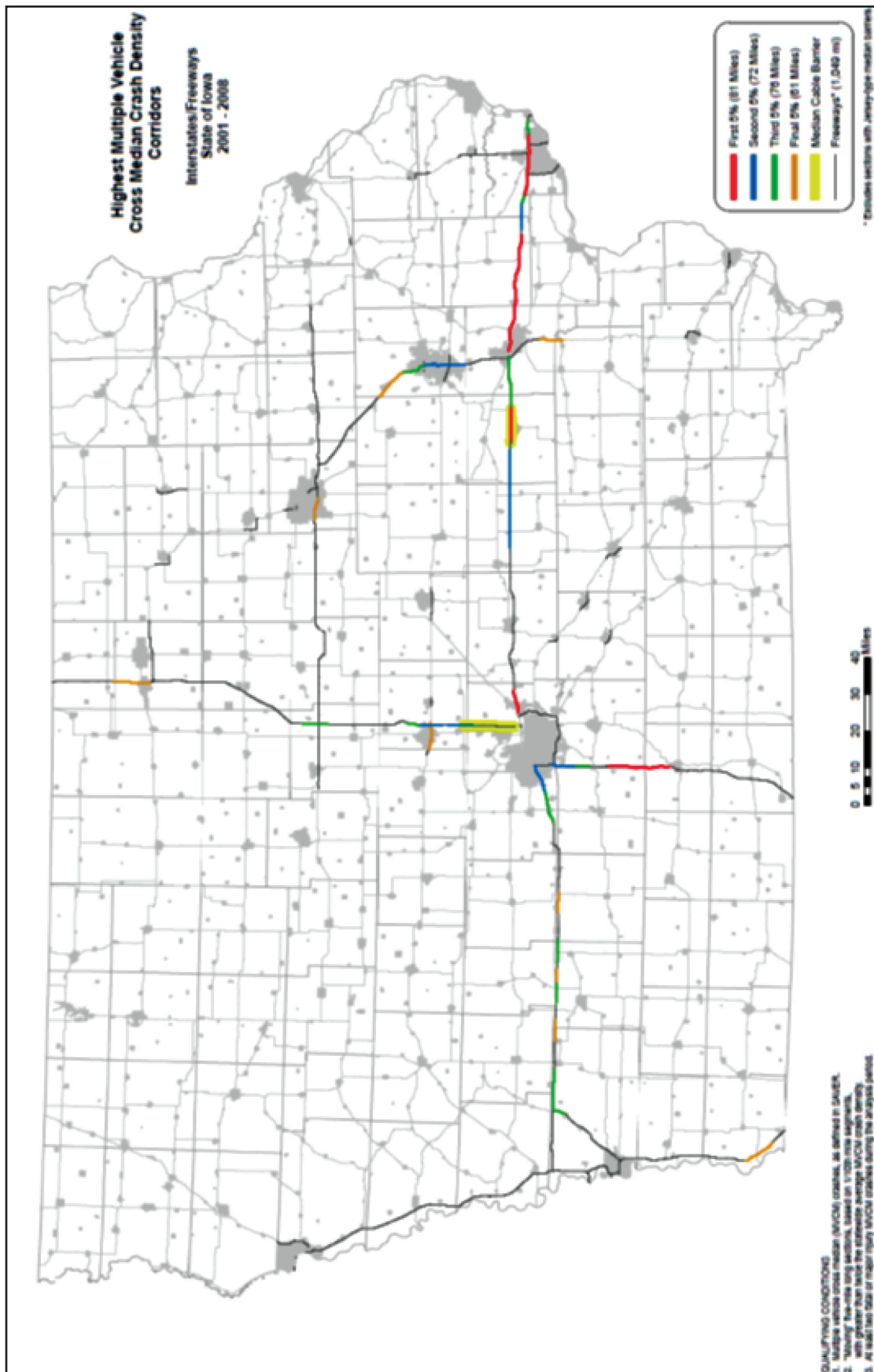


Figure 5.10. 2001-2008 Highway segments with highest multiple-vehicle cross-median crash density (in top 5 percent increments) and segments with median cable barriers highlighted in yellow

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Chapter 6:

Horizontal Curve Countermeasures

Horizontal Curve Countermeasures At a Glance

- Curves have about three times the crash rate of tangent sections
 - AASHTO reports that 76 percent of curve-related fatal crashes are single vehicles leaving the roadway and either striking a fixed object or overturning, and another 11 percent of curve-related crashes are head-on collisions
 - A multitude of engineering treatments, which don't require major redesign or reconstruction, have been utilized to reduce speed and crashes on horizontal curves
 - Information about the effectiveness of each treatment is included in this chapter
-

Background

The FHWA (2009) estimates that 58 percent of roadway fatalities are due to lane departures and 40 percent of fatalities are SVROR crashes. Horizontal curves have been correlated with crash occurrence in a number of studies. Curves have about three times the crash rate of tangent sections (Torbic et al. 2004). AASHTO (2008) reports that 76 percent of curve-related fatal crashes are single vehicles leaving the roadway and either striking a fixed object or overturning. Another 11 percent of curve-related crashes are head-on collisions.

Torbic et al. (2004) report that around 25 percent of the nation's fatal crashes occurred on sharp horizontal curves, mostly on two-lane rural highways (See Figure 6.1). Iowa crash data for 2001 to 2005 indicate that 12 percent of all fatal crashes and 15 percent of all major injury crashes in Iowa occurred on curves; 14 percent of all urban fatal crashes and 11 percent of all urban major-injury crashes occurred on curves; and 11 percent of all rural fatal crashes and 19 percent of all rural major-injury crashes occurred on curves.

Specific curve characteristics have been correlated to crash frequency and severity, including radius, degree of curve, length of curve, type of curve transition, lane and shoulder widths, preceding tangent length, and required speed reduction from the posted to advisory speed. Luediger et al. (1988) and Council (1998) found that crash rates increase as the degree of curve increases, even when traffic warning devices are used to warn drivers of the curve. Miaou and Lum (1993) found that truck crash involvement increased as horizontal curvature increased, depending on the length of the curve.



Figure 6.1. Rural two-lane horizontal curve in Ohio

Mohamedshah et al. (1993) found a negative correlation between crashes and degree of curve for two-lane roadways. Council (1998) also found that the presence of spirals on horizontal curves reduced crash probability on level terrain, but did not find the same effect for hilly or mountainous terrain. Vogt and Bared (1998) evaluated two-lane rural road segments in Minnesota and Washington (state) using Highway Safety Information System (HSIS) data, and found a positive correlation between injury crashes and degree of horizontal curve. Shankar et al. (1998) evaluated divided state highways without median barriers in Washington and found a relationship between the number of horizontal curves per kilometer and median cross-over crashes. Zegeer et al. (1992) evaluated 10,900 horizontal curves on two-lane roads in Washington using a weighted linear regression model. They found that crash likelihood increases as the degree and length of curve increases. Alternatively, Deng et al. (2006) evaluated head-on crashes on two-lane roads in Connecticut for 720 segments using an ordered probit model. They included geometric characteristics in the analysis, but did not find that presence of horizontal or vertical curves were significant.

Bonneson et al. (2007) developed a relationship between injury and fatal crashes and curve radius. They compared injury, fatal, and property-damage-only (PDO) crashes and the results of both models are shown in Figure 6.2. As illustrated, the crash rate increases exponentially when the horizontal curve radius is less than 1,000 feet.

Along with horizontal curve radii, the vehicle speed reduction required from the posted speed limit to the advisory speed required to traverse a curve has an impact on frequency and severity of crashes on curves.

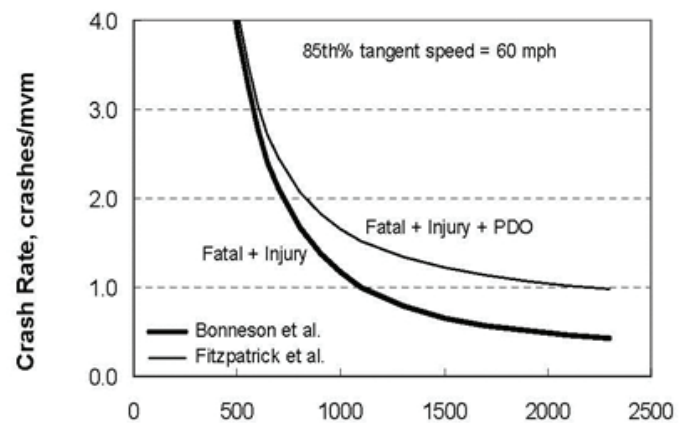


Figure 6.2. Crash rate as a function of radius (Bonneson et al. 2007)

Abrupt changes in operating speed, resulting from changes in horizontal alignment, are suggested to be a major cause of crashes on rural two-lane roadways (Luediger et al. 1988). Higher crash rates are experienced on horizontal curves that require greater speed reductions (Anderson et al. 1999). This finding is also supported by Fink and Krammes (1995), who indicate that curves requiring no speed reduction did not have significantly different mean crash rates from their preceding roadway tangents.

Countermeasures

A multitude of engineering countermeasures have been utilized to reduce speed and crashes on horizontal curves and are described in this chapter. Treatments that include major redesign or reconstruction have not been included. Information about each treatment is provided, along with information about effectiveness. The Manual on Uniform Traffic Control Devices (MUTCD) and applicable state or county guidelines should be consulted before application of any countermeasure. Some treatments may be listed as experimental and would require MUTCD approval.

Curve Warning Signs

The MUTCD includes a variety of warning signs that can be used prior to a horizontal curve to alert the driver of a sudden change in alignment, so they can adjust accordingly. A study conducted by Hammer (1989) evaluated the effectiveness of minor improvements on California roadways. At horizontal curves, crashes were reduced 18 percent when advance curve warning signs were installed and 22 percent when speed advisory signs were installed.

Charlton and Baas (2006) studied the effectiveness of warning signs on driver behavior in the Waikato District of New Zealand. Nine signs were tested, one of which was specifically for curves. Speeds were also measured upstream and downstream of each sign and compared before and after installation of the warning signs. The curve sign was a combination of a curve sign and a chevron sign, displaying the speed limit, and implementation of the signs were found to reduce mean speeds by about 2 mph.

Other studies suggest that use of curve warning signs is not effective. This could be due to misapplication or inconsistent use. Bonneson et al. (2007a and 2007b) noted that many communities use curve warning signs and speed reduction plaques inconsistently. Ritchie (1972) investigated driver's speeds through horizontal curves as a function of the curve signs and advisory speeds. The researchers concluded that advance warning signs may have given drivers more con-

fidence about the upcoming curve and, as a result, drivers increased their speeds and lateral acceleration. Finally, Zwahlen (1983) concluded that speed advisory signs are not more effective at reducing speeds than curve warning signs alone.

Chevron Alignment Sign

Background

Chevron alignment signs are common roadway delineators located at horizontal curves or at sudden changes in roadway alignment, which provide additional emphasis and guidance for drivers (Migletz et al. 1994). Guidance on placement of chevrons is provided in the MUTCD. Examples of chevrons on rural curves are illustrated in Figures 6.3 and 6.4.



Figure 6.3. Chevrons located on an Ohio rural two-lane curve



Figure 6.4. Chevrons with reflective post on a rural two-lane road in Ohio

Effectiveness

Lyles and Taylor (2006) conducted a literature review of the effectiveness of chevrons and post-mounted delineators (PMDs), which are retroreflective devices located serially at the side of a roadway to indicate alignment. (Each delineator consists of a flat reflecting surface, typically a vertical rectangle, mounted on a supporting post.) They concluded the following about the impact of chevrons:

- Drivers have been noted to shift away from chevrons as they negotiate curves—toward the centerline on curves to the left and away from it on curves to the right.
- Several studies noted that average (day and night) speeds increased when chevrons were added.
- Crash reductions have been noted on curves marked with chevrons where standard curve-related signs have not been effective.
- While chevrons provide additional guidance for the driver, it may not be more than PMDs or raised pavement markers.
- Chevrons have more effect at night, on sharper (greater than seven-degree) curves, and when used in conjunction with edge lines.

Zador et al. (1987) evaluated the effectiveness of chevrons, PMDs, and raised pavement markers in reducing speed and placement of vehicles traveling on curves. Forty-six sites in Georgia and five sites in New Mexico, including several control sites, were selected. Speed and lateral placement data were collected at each curve and the authors report that:

- When chevrons were used at night, vehicles moved away from the centerline; they moved further away from the centerline when raised pavement markings were used.
- Vehicle speed and placement variability were slightly reduced with the use of chevrons and raised pavement markings.

A study to determine driver preference and effectiveness of PMDs and chevrons, in conjunction with roadway edge lines, was performed by TTI in 2009. Chrysler et al. investigated driver response using closed course driving with instrumented vehicle data collection to analyze driver response. The study found that with chevrons, drivers moved away from the centerline by 10 to 20 inches, centerline encroachments decreased by 88 to 93 percent, the variability in lateral lane positions decreased by 40 percent, and vehicle speeds decreased between 1.4 to 2.2 miles per hour (mph).

A study conducted by Jennings and Demetsky (1983) investigated the effectiveness of chevrons along several rural Virginia curves with ADT between 1,000 and 3,000 vpd. The researchers found chevrons reduced the overall speed and speed variance. In addition, the researchers recommended that chevrons be installed on curves greater than 7 degrees.

Roadside Post-Mounted Delineators

Description

Roadside PMDs are used by a number of agencies to highlight the edge of the roadway and provide guidance at critical geometric changes in the roadway. PMDs usually have some type of reflector treatment, as illustrated in Figures 6.5 and 6.6.

Effectiveness

Lyles and Taylor (2006) conducted a literature review of the effectiveness of chevrons and PMDs and concluded the following about the impact of post mounted delineators:



Figure 6.5. Flexi-Guide post-mounted delineators (Pexco)



Figure 6.6. Post-mounted delineators in Captiva, Florida

- Similar to chevrons, drivers tend to shift away from PMDs or away from the edge of the road toward the centerline.
- Day and nighttime speeds tend to increase when PMDs are used.
- PMDs have been shown to reduce variance in lateral placement.
- PMDs should only be placed on the outside of the curve and could be confusing if placed otherwise.
- PMDs have more effect when used with freshly-painted centerlines.

As noted in the section on chevrons, Zador et al. (1987) evaluated the effectiveness of chevrons, PMDs, and raised pavement markers. For PMDs, they found that vehicles tended to move toward the centerline.

NCHRP 440: Accident Mitigation Guide for Congested Rural Two-Lane Highways, summarized studies which indicate that rural roadways with PMDs, in addition to the presence or absence of edge lines, have a lower crash rate than roadways without PMDs. The report further states PMDs are justified for roadways with ADT exceeding 1,000 vehicles per day (Fitzpatrick et al. 2000). Several research studies have found that PMDs reduced rural crash rates on sharp curves during darkness (Taylor et al. 1972). McGee and Hanscom (2006) reported that the Ohio DOT (ODOT) found a 15 percent reduction of SVROR crashes at horizontal curves with PMDs.

Bali et al. (1978) conducted a study investigating crash data at 500 sites in 10 states on rural highways at tangent and curved segments. Although the model did not fully explain the crash variance between the types of delineation, the researchers concluded that rural highways with PMDs had lower crash rates than highways without PMDs.

A study conducted by Kallberg (1993) in Finland evaluated the effectiveness of PMDs on 20 rural 80 km/hr and 100 km/hr roadways with hills, curves, and straight tangents. Using collected speed and four years of before data and two years of after data, a naïve analysis showed an increase in speed in darkness and crashes increased by 40 to 60 percent on the studied segments.

In a study to determine driver preference and effectiveness, PMDs and chevrons, in conjunction with roadway edge lines, was performed by Chrysler et al. (2009). The researchers investigated driver response using closed-course driving with instrumented vehicle data collection to analyze driver response. The researchers found that with PMDs, drivers moved away from the centerline by 7 to 20 inches, centerline encroachments decreased by 78 percent, the variability in lateral lane positions decreased by 38 percent, and neither PMD type decreased vehicle speeds.

Raised Pavement Markers

Background

Raised pavement markers (RPMs) are durable reflective or non-reflective markers used to provide lane guidance (3M 2009). RPMs also provide a tactile warning when a driver deviates from the lane. Typical RPMs are shown in Figure 6.7. RPMs that are recessed into the pavement at a rural horizontal curve in Arizona are shown in Figure 6.8.

Both reflective and non-reflective RPMs are usually limited to southern states, given some concern about durability of the markers during winter snow maintenance (Institute of Transportation Studies 1999). The effectiveness of RPMs may differ in locations where snow plow operations can abrade or remove the pavement markers from the roadways (Russell and Rys 2005).



Figure 6.7. Typical raised pavement markers in the center of a curve in Washington



Figure 6.8. Raised pavement markers recessed into the pavement in rural Arizona

Effectiveness

Lyles and Taylor (2006) summarized the available literature on the effectiveness of chevrons and PMDs and concluded the following about the impact of RPMs:

- RPMs are more effective at reducing crashes at high-crash locations than elsewhere, although general reduction was not noted.
- RPMs tend to have more effect during the night than the day.
- RPMs had more effect on lateral placement over and above freshly-painted centerlines over time.
- The variability of speed and lateral placement was decreased with RPMs.
- There was some evidence that RPMs had greater effect than PMDs and chevrons.
- As noted in the section on chevrons, Zador et al. (1987) evaluated the effectiveness of chevrons, PMDs, and RPMs in reducing speed and placement of vehicles traveling on curves. The researchers found the following about RPMs:
- When chevrons were used at night, vehicles moved away from the centerline; they moved further away from the centerline when RPMs were used.
- Vehicle speed and placement variability were slightly reduced with the use of chevrons and RPMs.

A study conducted by Zador et al. (1982) investigated the effectiveness of recessed pavement markers installed on the centerlines of 700 two-lane horizontal curves in Georgia that were in excess of six degrees. Two years of before-crash data and five years of after-crash data were used with night and daytime crashes being separated. The study found the installation of the pavement markers reduced nighttime crashes by 22 percent and SVROR crashes by 12 percent.

Dynamic Curve Warning Systems

Background

A dynamic curve warning system is a supplemental sign used to get driver attention in advance of a curve. These devices, located prior to a horizontal curve, are intended to target drivers to lower their speed limit before entering the curve. The dynamic warning system can either be a simple flashing beacon or a variable message sign, using either inductive loops or a k-band radar device to capture approach vehicle speed. Different messages have been displayed, including warning messages and display of the driver's speed. Two examples of dynamic warning systems on rural two-lane horizontal curves are illustrated in Figure 6.9.



Figure 6.9. Speed-activated signs in Ohio and Florida (top: Hawkins, InTrans)

Effectiveness

Research studies performed both inside and outside the US have showed a positive impact from dynamic curve warning systems.

A study conducted by Preston and Schoenecker (2000) investigated the relationship between vehicle speed entering the curve and successfully navigating through a rural curve, radius of 819 feet, with the aid of a dynamic curve warning sign. Four days of speed data were collected and the researchers found a relationship between entering speed and the probability of successfully navigating the curve. In addition, the research found the dynamic curve warning sign was most effective for vehicles entering the curve 20 mph over the posted advisory speed.

Another study by Tribbett et al. (2000) investigated the effectiveness of dynamic curve warning systems on five rural curves in California through observing the overall speed reduction of vehicles prior to the study curves. The researchers found a significant truck speed reduction on three of the five curves and significant passenger vehicle speeds at two of the five curves (Tribbett et al. 2000 and Torbic et al. 2004).

Bertini et al. (2006) studied the effectiveness of a dynamic curve warning system on the change in mean speed and change in speed distribution. The system was tested on northbound and southbound I-5 in Myrtle Creek, Oregon. The overhead freeway dynamic curve warning system is illustrated in Figure 6.10.

Data were collected during seven different time periods with four periods prior to installation and three periods after installation. Results show statistically-significant reductions



Figure 6.10. Overhead dynamic curve warning sign in Oregon (Bertini 2006)

(based on a 95 percent confidence interval) in mean speed. Maximum actual reductions were 2.6 mph for passenger vehicles and 1.9 mph for commercial vehicles. Speed -distribution curves were lower and were statistically significant based on a 95 percent confidence level using the chi-square test.

Another type of vehicle-activated sign, which displayed a standard curve sign when the driver was above the speed limit, was tested in the United Kingdom. Winnett and Wheeler (2000) studied the effects of vehicle-activated signs on driver speed, number of accidents resulting in injury, and driver reactions to the signs. The study was completed on two-lane (A-, B- and C-class) roads in Norfolk, Wiltshire, West Sussex, and Kent. Before and after data were taken for a minimum of seven days at each site, with after-data being taken one month after installation and then either one or three years later. Data collected were speed and, if in operation for more than one year, accident data. Results showed that mean speed decreased by 2.1 and 6.9 mph at one month after installation of the signs. Crashes decreased by 54 percent at the Norfolk bend site and 100 percent at the Wiltshire bend site.

High-Friction Surface Treatment

Background

High-friction surface treatments increase the coefficient of friction between the roadway and vehicle wheels to keep a vehicle on the roadway. A high-friction surfacing system consists of a combination of resins and polymers (usually urethane, silicon, or epoxy) with a binder that's topped with a natural or synthetic hard aggregate. The rougher texture and greater surface area of the system increase the pavement friction (Julian and Moler 2008). An applied high-friction surface treatment is illustrated in Figure 6.11. (And, friction treatments are typically available in multiple colors.)

Effectiveness

Limited research was found on high-surface friction treatment use on horizontal curves; however, freeway ramp curves are similar in geometric attributes to horizontal curves. Julian and Moler (2008) report 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.

Reddy et al. (2008) studied the effectiveness of a high friction-surface treatment that the Florida Department of Transportation (FDOT) used on an on-ramp to I-75 northbound from East Royal Palm Boulevard, seen in Figure 6.12. They used a before and after study to examine friction factor, crash frequency, vehicle speeds, and shoulder encroachment.



Figure 6.11: A high-friction surface treatment (Julian and Moler 2008)



Figure 6.12: High-friction surface application area of I-75 northbound on-ramp from East Royal Palm Boulevard in Florida (Reddy et al. 2008)

They first studied the change in friction factor using skid tests. Results from the skid tests showed an increase in friction number (FN) at 40 mph from 35 to 104. Next crash frequency was studied by examining crash data from 4.3 years before and 12 months after the installation of the treatment. A decrease in crash averages from 2.54 per year to 2 per year after the installation were found. Not enough data were collected to determine if this change was statistically significant.

They also used five before and nine after spot speed studies using a radar gun to measure the change in average speeds both before and after. Data were collected at various times of the day and in both wet and dry conditions. It was found that with the treatment, mean speeds decreased by about 6

mph in dry conditions and 3 mph in wet conditions; also, the deviation and variance of speeds decreased after implementation. They found that speeds decreased by 2.62 mph for wet conditions and 3.72 mph for dry conditions. They also found that the proportion of speed limit violations (over 25 mph) decreased significantly with the use of the treatment in both wet and dry conditions.

Another study evaluated shoulder encroachment due to application of a high-friction treatment. The number of vehicles that crossed the pavement edge line was collected and they found a statistically significant decrease in shoulder encroachment using a Z-test (Reddy et al. 2008)

Julian and Moler (2008) mention a program by the NYSDOT that investigated sites around the state with identified low pavement friction. The state treated 36 identified sites with new overlay and microsurfacing (high-friction surfacing) between 1995 and 1997. The NYSDOT found a reduction in wet-road crashes by 50 percent and total crashes by 20 percent.

Wider Edge Lines

Background

Wider pavement markings have been used to improve the visibility and conspicuity of the centerline, lane line, or edge line stripping (Ray et al. 2008). In rural horizontal curve applications, white edge lines have been widened from a typical width of 4 inches to 6 or 8 inches.

NCHRP Report 440, "Accident Mitigation Guide for Congested Rural Two-Lane Highways" recommends that 8 inch wide edge lines are only used on roadways that have 12 foot wide lanes, unpaved shoulders, and an ADT of 2,000 to 5,000 vehicles per day (Fitzpatrick et al. 2000 and Neuman et al. 2003). However, this report also states that edge line widening is not recommended for rural two-lane roads with the following conditions (Fitzpatrick et al. 2000):

- 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

Effectiveness

Donnell et al. (2006) studied the effects of using a wider (8 inch) edge line on horizontal curves along rural two-lane Pennsylvania highways as illustrated in Figures 6.13 and 6.14. Data were collected at eight sites: four treatment sites had the



Figure 6.13. Before wider edge line treatment (Donnell 2006)



Figure 6.14. After 8 inch edge line treatment (Donnell 2006)

8 inch edge line and four comparison sites had the 4 inch edge line. Vehicle lateral position and speed were evaluated. They found no significant reduction in speed or encroachment due to the placement of the wide edge lines.

Likewise, research performed by Cottrell (1987) in Virginia evaluated the effect of 8 inch wide edge lines on ROR and associated crashes on three two-lane rural road sections, which

were 60.7 miles long. A before and after comparison test was performed analyzing three years of before and two years of after crash data. The conclusions was that the wider edge lines had no significant affect at reducing the number of crashes.

Hall (1987) recommended Arizona discontinue the practice of installing 8 inch wide edge lines after an analysis of 530 miles of rural two-lane highways with unusually high ROR crash rates, finding the treatment didn't have a significant effectiveness in crash reduction.

In addition, Hughes et al. (1984) investigated the crash reduction on two-lane rural roads in Ohio, Maine, and Texas with an ADT between 5,000 and 10,000 vehicles per day. Based on available crash data, they found 8 inch edge lines compared to 4 inch edge lines did not reduce crash frequency.

However, an unpublished research study stated that the NYSDOT found curves on rural roads showed a higher crash reduction with new 8 inch edge lines compared to curves with 4 inch edge lines. This study also mentions a 10 percent decrease in total crashes, a 15 percent decrease in major injury crashes, and a 17 percent decrease in fixed object crashes (Neuman et al. 2003 and McGee and Hanscom 2006).

Transverse Pavement Marking Bars

Background

Transverse pavement marking bars, sometimes referred to as peripheral transverse bars, transverse strips, or optical bars, are pavement markings placed perpendicular to the flow of traffic. Transverse pavement marking bars give the perception to drivers that the vehicle is speeding up and that the lane is becoming narrower (Agent 1980).

Performance/Research Verification

Shinar et al. (1980) evaluated the pavement marking pattern shown in Figure 6.15. The researchers placed this pattern across both lanes of traffic 318 feet (97 meters) prior to the horizontal curve and ending at the center of the curve. They found that the 85th percentile speed decreased by 6 mph (9.5 km/hr).



Figure 6.15. Wundt-Herring pavement marking layout (Shinar et al. 1980 and Godley 1999)

Several research studies have investigated varying sizes and patterns of transverse pavement marking bars and shown 85th percentile speed reductions between 0 and 6 mph (Shinar et al. 1980, Gawron and Ranney 1990, and Koziol and Mengert 1977).

Griffin and Reinhart (1996) conducted a comprehensive study that investigated previous research (performed between 1970 and 1990) on the effectiveness of transverse bars located prior to changes in roadway geometry including: approaches to roundabouts, stop-controlled intersections, prior to interstate work zones, and rural highways. The comprehensive study included the following general conclusions of sites with transverse bars:

- Speeds were reduced by 1 to 2 mph
- 85th percentile speeds were reduced by up to 15 mph at locations
- Crash reduction occurred at sites where transverse bars were located
- Speed reductions occurred during the day rather than at night

Hallmark et al. (2007) evaluated transverse bars as entrance treatments to rural communities. These bars are 12 inches (parallel to lane line by 18 inches perpendicular to lane line, as shown in Figure 6.16. They found a 1 to 2 mile reduction in 85th percentile speed.

The bars for this type of marking 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 (Hancock and Riessman 2004).

Mn/DOT also experimented with converging thermo-plastic broken chevrons known as "Tiger Tails" to reduce vehicle speeds prior to a rural work zone. A stretch of I-90 in Minnesota with the treatment is illustrated in Figure 6.17.

Briese found through a before and after speed analysis that the Tiger Tails were not effective in reducing vehicle speeds and, in some cases, found vehicle's speed increased during the treatment (Briese 2003).

Katz et al. (2006) studied the effects of transverse speed bars on vehicle speeds at two rural horizontal curves and a highway exit ramp in New York, Texas, and Mississippi. Data were collected upstream of the curve and at the point of tangency (PT) of the curve at each site. An Analysis of VAriance (ANOVA) test was performed to compare the mean difference between both data collection points at the 0.50 level. They found the optical speed bars were effective in reducing speeds, but that the type of driver, traffic composition, and degree of curvature might have an impact on overall effectiveness.



Figure 6.16. Transverse pavement markings as a rural gateway traffic calming treatment (Hallmark et al. 2007)



Figure 6.17. Mn/DOT "Tiger Tails" broken chevron pattern (Briese 2003)

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. Three patterns were used in this study, including a leading pattern, primary pattern, and work zone pattern. Leading up to the deceleration area (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 three patterns used in this study are illustrated in Figure 6.18.

The researchers found that use of the 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) investigated transverse pavement marking bars at a rural highway site in New Brunswick, Canada. The authors did not specify the design characteristics of their study. A simple before and after speed study was conducted with results shown in Table 6.1

Hildebrand et al. concluded that the mean and 85th percentile speeds were reduced (statistically significant) by 2.1 mph (3.4 km/hr) and 2.4 mph (3.8 km/hr) and the greatest reduction in speed occurred during the nighttime observations. Furthermore, they also concluded that the transverse bars provided an increased level of safety during the night

conditions due to the high retroreflective capabilities of the pavement markings (Hildebrand et al. 2003).

Agent (1980) found transverse pavement markings prior to a sharp horizontal curve in Kentucky had a benefit-cost ratio of 45.9 due to the number of crashes prevented.

Pavement Legends

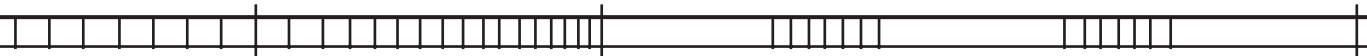
Background

Pavement legends consist of pavement markings in advance of curves or intersections to provide additional information, such as the words SLOW or CURVE leading into a curve or an arrow at an intersection detailing which movements lanes permit. These pavement legends are useful, because they provide easily seen and understood information within the driver’s line of sight (McGee and Hanscom 2006).

Effectiveness

Retting and Farmer (1998) investigated the effectiveness of installing the word SLOW with a left-turn arrow and an 18 inch wide line at a rural two-lane Virginia site with a sudden left turn or near 90 degree curve, as seen in Figure 6.19. The treatment was installed 220 feet prior to the curve and the word, arrow, and line consisted of white thermoplastic and reflective glass beads.

A before and after speed study with a control site was performed and they found vehicle speeds reduced from 34.3 to 33.2 mph, representing a 3 percent speed reduction. However,



Graduated Spacings With Leading Pattern and Intermittent Work Zone Pattern

Figure 6.18. Leading, primary, and work zone bar pattern (Meyer 1999)

Table 6.1. Summary of speed bar effect on speed, pace, and standard deviation (Hildebrand et al. 2003)

Site	Mean (km/hr)	85th Percentile (km/hr)	Percent in Pace (%)	Standard Deviation (km/hr)
Rte 1 - Musquash Day # 1	-2.4	-3.2	-5.0%	-0.24*
Rte 1 - Musquash Day # 2	+0.6	-0.5	+3.0%	-1.55*
Rte 1 - Musquash Night # 1	-7.7*	-7.4	+9.0%	-1.44*
Rte 1 - Musquash Night # 2	-4.0	-3.9	+3.5%	-0.53*
Average	-3.4 km/hr*	-3.8 km/hr*	+2.6%	-0.94 km/hr*

*Statistically significant at 5 percent significance level

the researchers noted that the upstream and control site saw an increase in speeds during the same study period.

Chrysler and Schrock (2005) also examined the effectiveness of pavement markings consisting of words and symbols on reducing speeds for rural highway curves. They tested four different markings including transverse lines, the message CURVE AHEAD, the message CURVE 55 MPH on a rural curve, and a curve symbol plus 50 MPH on an urban curve (See Figure 6.20).



Figure 6.19. Test site pavement markings (Retting and Farmer 1998)



Figure 6.20. CURVE AHEAD in Texas (Chrysler and Schrock 2005)

Each of the markings was applied to the roadway with the majority being applied 400 feet after the standard curve warning sign. Text was about 8 feet tall. Using a before and after speed study, where they only looked at vehicles with 5 seconds or more headway, they examined the change in mean speeds. Results showed that the CURVE plus advisory speed limit seemed to get the greatest reductions in speed at about 4 mph, which was not statistically significant. The CURVE AHEAD markings did not see a change in driver behavior, while the curve symbol and 50 MPH urban marking saw a 10 percent decreases in speed (Chrysler and Schrock 2005).

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