State-of-the-Art: Centerline Rumble Strips Usage in the United States

by Daniel E. Karkle , Margaret J. Rys, and Eugene R. Russell

Centerline Rumble Strips (CLRS) are used to avoid cross-over roadway departures, making rural highways safer. The objectives of this study were to obtain nationwide, updated information about states' policies and guidelines for utilization of CLRS and to provide a list of gaps in research along with good practices. Results indicate that 36 states reported the use of CLRS. The total CLRS approximate mileage is 11,333 miles. The predominant CLRS pattern is: milled, length 16", width 7", depth 0.5", spacing 12", continuous. This survey reported that 17 states have written policies or guidelines. A list of good practices used by the states is presented.

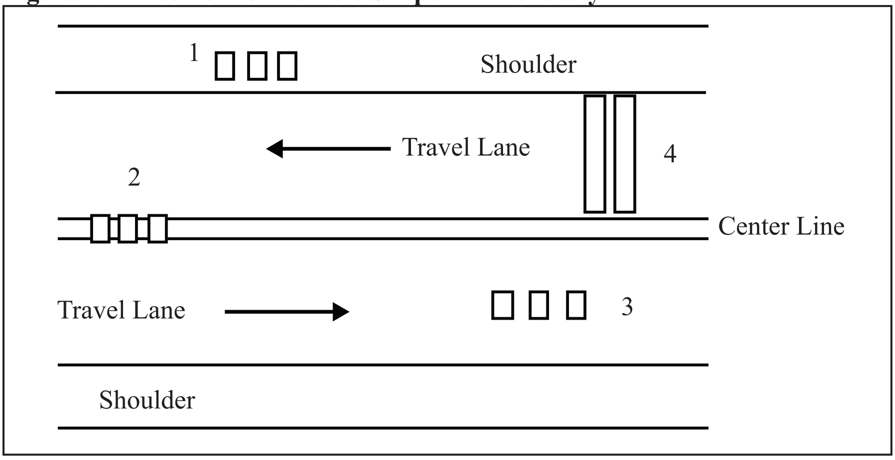
INTRODUCTION

Roadway departure fatalities are a serious problem in the United States. A roadway departure crash is defined as a non-intersection crash which occurs after a vehicle leaves the traveled way, crossing the center line of undivided highways, or crossing an edge line (longitudinal pavement marking located at the edge of the traveled lane and the shoulder) of the roadway. Roadway departures are usually severe and involve run-off-the-road (ROR), sideswipes, and head-on crashes. There are many contributing factors for the occurrence of roadway departures, and the principal of them are driver drowsiness, fatigue, alcohol/drug impairment, and inattention, along with poor visibility caused by inclement weather. Roadway departure crashes account for the majority of rural highway fatalities. According to data from the Fatality Analysis Reporting System (FARS), in 2009 there were 11,185 fatal roadway departure crashes on rural highways, resulting in 23,169 fatalities (NHTSA 2009). Furthermore, roadway departure crashes correspond to approximately 40% of all crashes in the United States, and the estimated annual cost of roadway departure crashes is $100 billion (FWHA 2003).

In order to reduce the number of roadway departure crashes, since 1955, several state departments of transportation have installed rumble strips and other accidents countermeasures on U.S. highways (Carlson and Miles 2003).

Rumble strips are raised or indented patterns utilized to alert drivers that they are moving out of the travel lane. When vehicles' tires pass over the rumble strips, noise and vibration are produced by this contact, which provides motorists with a warning that they are leaving the travel lane. Rumble strips are designed to alert drowsy and inattentive motorists and can generally be classified by their position in relation to the travel lane as: a) shoulder rumble strips (including edgeline rumble strips), b) centerline rumble strips, c) midlane rumble strips, and d) transverse rumble strips. Figure 1 illustrates the position of each type of rumble strips in relation to the travel lane. The commonly referred dimensions of rumble strips are: length, normally defined as the dimension perpendicular to the traffic direction; width, usually defined as the dimension parallel to the traffic direction; depth of height; and spacing, usually measured from center to center of rumble strip patterns. The spacing can be continuous, if the rumble strips are placed with constant spacing along the roadway, or alternatively, if the spacing changes along the roadway (for example: 12 in., followed by 24 in., spacing).

Figure 1: Placement of Rumble Strips in a Roadway



Note: (1) Shoulder Rumble Strips, (2) Centerline Rumble Strips, (3) Midlane Rumble Strips, (4) Transverse Rumble Strips

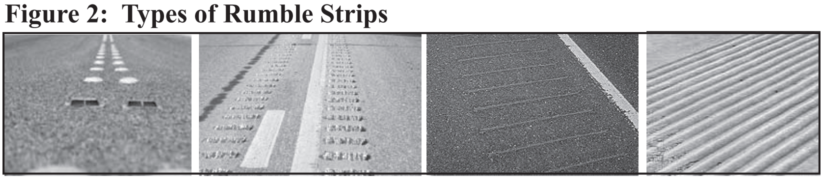
Shoulder rumble strips (SRS) are placed on the shoulders or on the edge line (along the longitudinal pavement marking located at the edge of the travel lane and the shoulder) of the roadway and are a countermeasure for ROR type crashes. On divided highways, SRS may be installed on both the outside and median shoulders. When installed along the edge lines, they are commonly referred to as "rumble stripes" or edgeline rumble strips. The benefits of rumble strips are the greater free space allowed on the shoulders for motorists to perform corrective maneuvers, for other users such as bicyclists to use the shoulders, and that they can be installed on roadways with narrow or nonexistent shoulders. Centerline rumble strips are placed on the center of the roadway and are designed to mitigate cross-over crashes.

Midlane rumble strips is a concept with no actual installations known. Their theoretical placement would be in the center of the travel lane, serving to potentially prevent both cross-over and ROR crashes.

Transverse rumble strips are usually placed across the full width of the travel lanes. They are designed to alert motorists of approaching roundabouts, intersections, and toll plazas.

According to Elefteriaou et al. (2000), there are four types of rumble strips classified by their installation process: a) raised, b) milled, c) rolled, and d) formed, as presented in Figure 2. The milled is the most common type of rumble strip in the United States. They can be installed on new or existing asphalt and Portland cement concrete (PCC) pavements. This type of rumble strip is produced by a machine, which cuts a groove in the pavement. Raised rumble strips are made by adherence of proper material to new or existing pavement surfaces. Formed rumble strips are installed on PCC surfaces by forming grooves or indentations into the concrete during its finishing process. Rolled rumble strips are installed only on asphalt surfaces by a roller that presses grooves into the hot surfaces when the asphalt is being compacted.

Figure 2: Types of Rumble Strips



a) Raised b) Milled c) Rolled d) Formed

Source: Richards and Saito (2005)

Centerline Rumble Strips

This study focuses on the applications of CLRS. Centerline rumble strips are primarily installed on the center line of undivided two-lane highways, and their main purpose is reduction of cross-over crashes, more specifically, head-on and opposite direction sideswipe and front-to-side type crashes, which are usually caused by driver inattention and drowsiness. The data available on the FARS database reveal that in 2009, 56% of the fatal crashes occurred on rural roads. Among these, 74% occurred on undivided two-lane roads, and 20% of these accidents involved two vehicles traveling in opposite directions, totaling 2,579 cross-over fatal crashes per year (NHTSA 2009). CLRS are accepted as a countermeasure that reduces approximately 25% of cross-over crashes, making two-lane rural roads safer. Therefore, the use of them in the United States has increased over the years.

Several authors have reported advantages other than crash reduction in installing CLRS, such as low interference in passing maneuvers, versatile installation conditions, and public approval (Miles et al. 2005; Richards and Saito 2007). Due to their associated low costs of installation and maintenance, CLRS provide high benefit-cost ratios. For instance, Carlson and Miles (2003) reported estimated benefit-cost ratio associated with CLRS in the range of 0.17 to 39.16 (the higher the roadway traffic volume, the greater the benefit), considering five states and assuming cross-over crash reduction of 20%. However, some concerns involving CLRS, such as the levels of exterior noise, potential decreased visibility of the painted strips, potential tendency to speed up pavement deterioration, possibility of causing driver erratic maneuvers, and ice formation in the grooves, have been cited in the current literature (Russell and Rys, 2005). The policies and guidelines for CLRS installation are very distinct among the states using them. A better understanding of good practices and gaps in research about the use of CLRS would contribute to future enhancement of their associated advantages and reduction of their potential weaknesses. For these reasons, the objectives of this study are to obtain nationwide, updated information about states' policies and guidelines for utilization of CLRS and to provide a list of gaps in research along with good practices in the country. It is expected that the information from this study will be useful for planners and policy makers, providing guidance for future applications of CLRS.

LITERATURE REVIEW

This section presents a review of the pertinent studies that focus on the different effects of CLRS and the previous national surveys on CLRS policies. Studies of other types of rumble strips, for example, shoulder rumble strips, are not part of the scope of this work.

Safety Effectiveness of CLRS

There are several published and unpublished studies revealing that CLRS reduces cross-over crashes. Generally, the methods utilized in these studies are the Naïve before-and-after, which just compares the before and after numbers with no adjustments, and the Empirical Bayes method, which uses more sophisticated, state-of-the-art statistics. Some of these studies are summarized in Table 1. The results of these studies are not uniform. The differences in the crash reduction effects may be partially attributed to differences of the CLRS applications, since different patterns of rumble strips have proven to generate different levels of noise and vibration stimuli for drivers. The best pattern and application of CLRS along the roadway can be considered a gap in research since it remains unknown. Chen et al. (2003) claim that the performance of rumble strips should be a function of the difference between noise and vibration stimuli over rumble strips and over smooth pavement conditions (the best pattern would be the one that produces the largest differences). In addition, an increase in order of 9 to 10 dBA (dBA corresponds to the unit of the A-scale on a sound-level meter, which is the scale that best approximates the frequency to which that human ear can respond) in the level of sound is necessary for a person to be alerted by the presence of that sound (Lipscomb

1995, cited by Rys et al. 2008). Therefore, CLRS should raise the levels of sound by at least 10 dBA. Miles and Finley (2007) stated that the "standard" rumble strips dimensions (milled, length equal or greater than 12 in., width of 7 in., depth of 0.5 in., and spacing of 12 to 24 in.) in the United States provide adequate increase in the sound level to alert all drivers, regardless of the speed or the type of pavement.

Table 1: Safety Effectiveness of CLRS

State	Study	Statistical Method	Type of Crash Studied	Crash Reduction
Arizona	AECOM (2008)	Comparison Group	Fatal and serious injury cross-over	61.0%
	Kar and Weeks (2009)	Naïve Before-and-After	Fatal and serious injury cross-over	56.0%
California	Fitspatrick et al. (2000)	Naïve Before-and-After	Fatal head-on	90.0%
			Total head-on	42.0%
	Persaud et al. (2003)	Empirical Bayes	Cross-over	12.0%
			All types	14.0%
Colorado	Outcalt (2001)	Naïve Before-and-After	Head-on	34.0%
			Sideswipe	36.5%
	Persaud et al. (2003)	Empirical Bayes	Cross-over	31.0%
			All types	11.0%
Delaware	Delaware DOT (2003)	Naïve Before-and-After	Head-on	95.0%
			Drove left to the center	60.0%
			PDO	Increase 13%
			Injury	Increase 4%
			All Types	8.0%
	Persaud et al. (2003)	Empirical Bayes	Cross-over	81.0%
			All types	23.0%
Kansas	Karkle et. al (2009)	Naïve Before-and-After	Fatal head-on	80.0%
			Head-on	81.0%
			Sideswipe	78.0%
			Cross-over	80.0%
			Fatal and serious injury cross-over	59.0%
		Empirical Bayes	Cross-over	85.0%
			All types	33.0%
Maine	Unpublished Maine DOT	Naïve Before-and-After	Head-on	91.7%
			ROR	28.9%
Maryland	Persaud et al. (2003)	Empirical Bayes	All types	19.0%
Massachusetts	Noyce and Elango (2004)	Comparison Group	Several	Inconclusive

Table 1: Safety Effectiveness of CLRS (continued)

State	Study	Statistical Method	Type of Crash Studied	Crash Reduction
Minnesota	Persaud et al. (2003)	Empirical Bayes	Cross-over	Increase 12%
			All types	0.0%
	Briese (2006)	Cross-Sectional Comparison	Cross-over	43.0%
			All types	42.0%
			Cross-over - Fatal and severe injury	Increase 13%
			All types - Fatal and severe injury	73.0%
	Knapp and Schmit (2009)	Cross-Sectional Comparison	Cross-over - Fatal and severe injury	47.0%
			All types - Fatal and severe injury	40.0%
	Torbic et. al (2009)	Empirical Bayes	All Types	11.1%
			Fatal and injury	21.8%
			Cross-over	48.9%
			Fatal and injury cross-over	44.7%
Missouri	Unpublished Missouri DOT	Naïve Before-and-After	Head-on	29.0%
			Sideswipe	61.0%
		Empirical Bayes	Head-on	53.0%
			Sideswipe	62.0%
Nebraska	Unpublished Nebraska DOT	Naïve Before-and-After	Cross-over	64.0%
Oregon	Monsere (2002) cited by Russell and Rys (2005)	Naïve Before-and-After	Cross-over	69.5%
		Comparison Group	Cross-over	79.6%
	Persaud et al. (2003)	Empirical Bayes	All Types	46.0%
Pennsylvania	Galenabiewski et al. (2008)	Naïve Before-and-After	Cross-over	48.0%
	Torbic et. al (2009)	Empirical Bayes	All Types	1.6%
			Fatal and injury	6.2%
			Cross-over	25.8%
			Fatal and injury cross-over	44.4%
Washington	Persaud et al. (2003)	Empirical Bayes	Cross-over	21.0%
			All types	25.0%
	Torbic et. al (2009)	Empirical Bayes	All Types	Increase 2.3%
			Fatal and injury	Increase 4.1%
			Cross-over	35.4
			Fatal and injury cross-over	35.4

Pavement Deterioration Due to Water/Ice Accumulation, and Winter Maintenance Issues

Water and ice accumulation in CLRS grooves may or may not cause accelerated pavement degradation. Torbic et al. (2009) claimed that several DOTs' maintenance crews have reported that heavy traffic would speed pavement deterioration due to the presence of rumble strips and that the water and ice accumulated in the grooves would crack the pavement. The authors state that these concerns have not been validated. Moreover, in a survey conducted in 2005, 15 DOTs did not believe that CLRS cause pavement deterioration due to ice or water accumulation in the grooves (Russell and Rys 2005). However, a Virginia inspection on the milled CLRS found that approximately 1% of the strips inspected were deteriorating (Torbic et al. 2009). The reason for the deterioration may be poor pavement conditions before the installation of CLRS, as found by the following studies.

According to Kirk (2008), the Kentucky Transportation Center (KYTC) held a meeting with personnel from the Kentucky DOT to investigate if the joint deterioration found on Daniel Boone Parkway and Mountain Parkway in Kentucky was caused by CLRS. The conclusion was that these roads had poor pavement performance even before the rumble strip installation. In addition, the conclusion was that water and ice accumulation in the centerline rumble strip is a non issue. Another study also suggests that the center joint degradation promoted by CLRS only appears to occur when the pavement condition is not adequate before the CLRS installation (Knapp and Schmit 2009). The same authors also conducted a survey about winter maintenance problems caused by CLRS. Seven of the nine surveyed states indicated that they were not aware of any maintenance problems. Two states responded that the snow/ice in the CLRS may melt and then refreeze at a time when winter maintenance activities are no longer occurring. Minnesota DOT engineers anecdotally noted that more salt appears to be needed along roadway sections with CLRS, which might suggest the need to reconsider CLRS designs and/or winter maintenance practices.

Regarding the effect of CLRS on winter maintenance and operation activities, additional passes of snowplow appeared to be needed in Alaska due to the presence of milled CLRS. However, CLRS may be beneficial because they provide guidance for snowplow drivers (Russell and Rys 2005). In addition, Hirasawa et al. (2005) claimed that the Japanese CLRS pattern produces sufficient warning (sound and vibration) for drivers on slushy winter roads, even when the center line was invisible.

The concerns reviewed in this section can be qualified as gaps in research because there is limited literature about these topics, and a specific scientific investigation is yet to be done in order to prove or disprove any hypothesis. Results available and presented in this section were obtained mainly from questionnaires.

Other Users of the Highways

The noise and vibration caused by CLRS may affect bicyclists, motorcyclists, and residents near highways. The policies on CLRS can play a role to equilibrate the trade-off between safety and other aspects. Three studies are consistent with the conclusion that CLRS did not appear to be a safety hazard to motorcyclists (Miller 2008, Hirasawa et al. 2005, Bucko and Khorashadi 2001). Only one study evaluated the safety effectiveness of CLRS. Miller (2008) investigated 26 of the 29 motorcyclist crashes that occurred in Minnesota after the installation of CLRS and concluded that those crashes were unrelated to CLRS. An estimate of the safety effectiveness of CLRS regarding motorcyclists remains a gap in research.

Three studies concluded that the patterns of rumble strips that produce the greatest levels of noise and vibration for drivers are the least comfortable for bicyclists (Bucko and Khorashadi 2001, Outcalt 2001, and Elefteriadou et al. 2000). In addition, Torbic (2001) concluded that there is a linear relationship between bicyclists' whole-body vibration and comfort. Another study found that the space that drivers leave between their vehicles and bicyclists is greater along roadway sections with CLRS as compared with similar situations without CLRS (Zebauers 2005 cited by Knapp and Schmit 2009).

Several studies have found that rumble strips increase the level of external noise, which may affect roadside residents. Finley and Miles (2007) concluded that pavement type and rumble strip dimensions affect the levels of exterior noise. Karkle et al. (in press) concluded that distance, type of vehicle, and speed of vehicles affect the levels of exterior noise and that at the studied distances up to 150 ft., the noise caused by a 15-passenger van and a sedan hitting CLRS could disturb residents. The authors recommended that a minimum distance from houses and businesses should be considered for installation of CLRS and suggested that 200 ft. of distance from the center of the roadway should be considered as the minimum. Makarla (2009), based on a survey with a limited number of roadside residents, suggests that the respondents were willing to accept the levels of noise generated by the CLRS due to the increase in safety aspects.

The Operational Usage of the Travel Lane by Drivers

CLRS may affect the lateral position, i.e. may cause vehicles to operate closer to the shoulders, the speed at which the drivers travel and other operational aspects. Several studies found that CLRS cause drivers to move to the right, farther away from the center line (Torbic et al. 2009). If installed in conjunction with rumble stripes, drivers appear to position the vehicle closer to the center of lanes at locations with lane widths as narrow as 11 ft. and shoulder widths of 3 ft. (Finley et al. 2008). Moreover, the vehicle travel speed does not appear to be changed much by the presence of CLRS and the passing opportunity maneuvers seems to be unchanged by the presence of CLRS (Miles et al. 2005).

In addition, CLRS may influence other operational aspects, such as: a) the presence of both CLRS and shoulder rumble strips on the same roadway may cause drivers to react to the left after hitting CLRS under drowsiness or inattention condition. (Noyce and Elango [2004]), using a simulated environment, reported that 27% of the participants initially reacted leftward after encountering CLRS; and b) CLRS may affect operational aspects of emergency vehicles. This result was not confirmed in a survey conducted in 2005, which revealed that 17 DOTs had no evidence or opinion of CLRS causing people to react to the left (Russell and Rys 2005).

The Visibility of Pavement Markings

It is controversial how CLRS affect the visibility of pavement markings. According to Bahar and Parkhill (2005), there is a debate whether the degradation of the pavement marking visibility occurs faster if the markings are painted on top of the rumble strips. However, several authors reported that the visibility of pavement markings placed over rumble strips is higher than over smooth pavement, especially during wet-night situations (Torbic et al. 2009). The current belief is that CLRS improve the night visibility of the pavement markings.

METHODOLOGY

A survey was emailed to the 50 state DOTs between April and May 2010, and consisted of 17 questions regarding the following topics: use of CLRS, type of construction and pattern dimensions, total mileage, placement of CLRS in relation to the longitudinal joint and center line, type of CLRS application along the longitudinal roadway, type of pavement and policy on depth and age of pavement, minimum lane and shoulder width requirements for CLRS installation, and concerns from the public about CLRS.

RESULTS AND DISCUSSION

The total response rate of this survey was 60%, or 30 state DOTs. The results are summarized below.

1. *Are there any centerline rumble strips installed on your highways (yes or no)?*

Among the total of 30 respondents, 90% (n=27) answered "Yes" and 10% (n = three) answered "No" to this question.

Combining the information from three previous state-of-the-art studies (Russell and Rys 2005, Richards and Saito 2007, Torbic et al. 2009) with this current survey, the number of state agencies that have at least once reported the use of CLRS is 36.

2. *What is the type of construction used by your agency (milled, rolled, raised, or combination)?*

Among the 27 respondents that have reported the use of CLRS, only one state (Florida) does not use the milled type. Florida has reported the use of only the raised type of CLRS. Two states (Texas and North Carolina) reported the use of a combination, i.e., both raised and milled types. The other 24 states reported the use of the milled type of CLRS.

3. *What are the strip dimensions used by your agency? The length refers as the dimension perpendicular to the center line and spacing is measured from center to center.*

Florida uses a continuous raised pattern with length and width of 2.5 in., height of 0.5 in. and spacing of 30 in.

Among the states that use the milled CLRS type, the dimensions varied as follows:

- Length: the range was 6 to 24 in., with 16 in. the predominant value used by about 42% (n = 11) of the respondents.
- Width: the range was 5 to 9 in., with 7 in. the predominant width used by about 85% (n = 22) of the respondents.
- Depth: the range was 0.375 – 0.625 in., with 0.5 in. the predominant depth used by about 73% (n = 19) of the respondents.
- Spacing: the range was 5 to 48 in., with12 in. the predominant spacing used by about 77% (n = 20) of the respondents.
- Continuous or Alternating: About 65% (n=17) answered continuous, about 19% (n = five) reported the use of alternating pattern, and about 12% of the respondents use both continuous and alternating patterns.
- Class of Highway: the answers for this topic varied. Some of the reported classes of highways were all classes, rural undivided and rural two-lane arterial.

4. *How many miles are there installed by type of highway and dimensions?*

Responses varied from three miles (Delaware) to 3,200 miles (Pennsylvania) as shown in Table 2. The total mileage reported was approximately 11,333. This number does not include the states of Colorado and Texas that did not report the number of CLRS miles installed.

5. *Where are the rumble strips installed in relation to the longitudinal joint and centerline* (*CLRS completely within pavement markings, CLRS extended into the travel lane, CLRS on either side of pavement markings*)?

Among the 27 states using CLRS, about 67% (n=18) answered that CLRS are installed completely within pavement markings. About 45% (n=12) answered CLRS extended into the travel lane and about 15% answered CLRS on either side of pavement markings. Some of the states reported more than one type of CLRS placement.

Table 2: Number of Miles of CLRS per State

State	# Miles	State	# Miles
AK	118	MI	3,000
AR	74	MN	30
AZ	174	MS	400
CO	Unknown	MO	700
DE	3	NE	300
FL	68	NC	32
HI	10	NH	< 100
ID	268.28	OK	9.25
IA	60	OR	93
KS	232	PA	3,200
KY	190	TX	Unknown
LA	408	VA	18.5
MD	412	WA	1,425
ME	7 - 8	**Total**	**Approx. 11,333**

6. *Where are the CLRS installed in relation to longitudinal roadway* (*continuous or specific locations*)?

Among the states using CLRS, about 89% (n=24) install them in a continuous manner. Only 18.5% (n = five) of the states reported the use of CLRS at specific locations such as curves and no passing zones. Some of the states reported both alternatives.

7. *In what type of pavement has your agency installed centerline rumble strips (only asphalt, only concrete, or both)? Do you have any policy regarding depth and age of the pavement?*

About 74% (n=20) of the respondents reported the use of CLRS only on asphalt pavements. About 26% (n = seven) reported the use of CLRS on both asphalt and concrete pavements. The guidelines regarding the age and minimum depth of the pavement for installation of CLRS are summarized in Table 3. Examples of guidelines are given below.

- Kansas: CLRS are installed in asphalt pavement surfaces 1.5 in. or more in depth. Age of pavement is not addressed in the policy. However, they are typically installed as part of resurfacing projects.
- Pennsylvania: CLRS should not be installed on existing concrete pavements with overlay less than 2 ½ in. depth. New pavements (less than one-year-old) should present a minimum 1½ in. depth and existing concrete pavements should not have overlays less than 2.5 in. in depth for installation of CLRS. The pavement should be in sufficiently good condition, as determined by the district, to effectively accept the milling process without deteriorating. Otherwise the pavement needs to be upgraded prior to milling.
- Washington has no specific policy. However, the policy reads: "Ensure that the pavement is structurally adequate to support milled rumble strips. Consult the Region Materials Engineer to verify pavement adequacies."

Table 3: Guidelines Regarding Age and Depth of Pavement

State	Min. Pavement Depth (in.)	Min. Pavement Age (years)
AK	2	No
DE	Requires consultation of pavement management section	
IA	2.5	7
KS	1.5	No
KY	Pavement in good condition	
LA	2	≥ 10
MD	Pavement in good condition	
MI	Engineering judgment	
MN	Engineering judgment	
MS	Considering for new pavement in future	
MO	1.75	New overlays
NE	No	New Pavement
OR	Pavement in good condition	
PA	1.5	Older than 1 year
TX	2	No
WA	Pavement is structurally adequate	

A supplementary question was sent to the seven state DOTs that reported the installation of CLRS on concrete pavement. This question asked the state DOTs about their experience and if they have any center joint deterioration caused by CLRS on concrete pavements. The answers are given below.

- Texas: "I have not heard of any reports of pavement deterioration caused by CLRS. Most of our centerline rumble strips are installed on hot mixed asphaltic surfaces and we have also not had any negative pavement reports."
- Nebraska: "We do not place rumble strips on the joint. We place them on the south side of east-west highways and the east side of north south highways to match our paint striping."
- Iowa: "We have yet to install any on PCC pavement."
- Idaho: "I haven't heard of any deterioration yet, but we are fairly new to the installations. We may know more in a few years."
- Missouri: "To date, I am not aware of joint deterioration due to the CLRS with our concrete pavements. As I indicated previously, we have installed the CLRS more in the last year or two. This may be an issue more after a few years, but currently we do not seem to be having issues."
- Colorado: "I have not seen or heard of any deterioration of the concrete joints, but I have not inspected them for such an occurrence."
- Michigan: "I can tell you that we have very little experience with CLRS on concrete, but what I heard recently from two of our regions is that milling on the CL joint on an old PCC pavement is a bad idea. We will be changing our specifications to reflect that."

8. *Is there a minimum lane width requirement for the installation of centerline rumble strips* (*yes or no, elaborate*)?

About 67% (n=18) of the respondents answered "Yes" to this question and about 33% (n = nine) did not report a lane width requirement. Some states have suggestions or guidelines rather than requirements. Table 4 shows the lane width values reported by the respondents.

Table 4: Minimum Lane Width for Installation of CLRS

State	Min. Lane Width (feet)
AK	Requires Lane + Shoulder ≥ 14
WA	Requires Lane + Shoulder ≥ 12
MI, MO, PA	Require Roadway ≥ 20
DE, MD	Require 10
HI, KY, LA	Require 11
NE	Requires 12
MN	Proposal to Require 12
NC	Suggests 10
IA, TX	Suggest 11
AZ	Suggests 12
OK	Experimented 12

9. *Is there a minimum shoulder width requirement for installation of centerline rumble strips (yes or no, elaborate)?*

About 70% (n=19) answered "No" to this question. About 30% (n = eight) of the respondents have a minimum shoulder width requirement for the installation of CLRS. Some states have a suggested value rather than a requirement. Table 5 shows the shoulder width values reported by the respondents.

Table 5: Minimum Shoulder Width for Installation of CLRS

State	Min. Shoulder Width (feet)
WA	Requires Lane + Shoulder ≥ 12
AK	Requires Lane + Shoulder ≥ 14
KS	Requires 3. Less is allowed to provide continuity
MN	Proposal to require 2
AZ	Suggests 4
MO	Suggests 4
IA	Eng. Judgment
OK	Experimental sites with 8 shoulder

10. *Are there both centerline rumble strips and shoulder rumble strips along the same roadway? (yes or no, number of miles)?*

About 74% of the respondents have installed both CLRS and SRS along the same roadway. The total number of miles reported for this dual application was approximately 1,600. Some states answered "Yes" to this question, but did not report the number of miles. Seven states answered "No" to this question.

11. *Are there both centerline rumble strips and edge line rumble strips (also referred as rumble stripes) along the same roadway (yes or no, number of miles)?*

About 33% (n = nine) of the respondents answered "Yes" to this question. The total number of miles for this type of dual application was 722. The other 18 states answered "No" to this question.

12. *If you have answered yes on the previous question, has your agency installed both centerline rumble strips and edge line rumble strips in sections of highway with narrow (width less than 3 feet) or no shoulder?*

Only three states (MS, OK, and WA) reported that they have installed dual application on sections of highways with narrow or no shoulder. Only Washington reported the number of miles (less than one mile for this case).

13. *Are there other requirements for installation of centerline rumble strips (traffic volume, crash rate, traffic volume, etc)?*

About 52% (n=14) of the respondents have other requirements such as crash rates, minimum AADT, and speed limit for installation of CLRS. For instance, Texas has the following requirements: "Apply CLRS in roadways with high-incidence crash rate with regard to head-on, opposite direction sideswipe and/or single vehicle cross-over crashes as a result of inattentive drivers or impaired visibility of pavement markings during adverse weather; CLRS shall not be milled or rolled into bridge decks; breaks in the CLRS will start at least 50 ft. and no more than 150 ft. prior to each approach for the following instances: bridges, intersections, and driveways with high usage or large trucks; CLRS may be installed along the edge line delineating pavement stripes for two-way left turn lanes (TWLTL). The TWLTL should have at least a 14-ft. width from the outside edges of the solid edge lines, and the CLRS will be reduced to 12 in. in width for each edge line. Consider noise impacts when the installation is near residential areas, schools, and churches. A minimum of 3/18 in. depth of milled CLRS or rolled CLRS may be considered in these areas. Posted speed limit should be greater or equal to 45 mph."

14. *Does your agency have a written policy or guidelines for the installation of centerline rumble strips (yes or no)?*

About 63% (n = 17) of the respondents reported that they have some type of written policy or guidelines for the installation of CLRS. About 37% (n = 10) of the respondents answered "*No"* to this question.

15. *Has your agency performed a before-and-after study to evaluate the effectiveness of centerline rumble strips and/or edge line rumble strips (yes or no)?*

About 52% (n=14) of the respondents reported that they have, at least anecdotally, performed a before-and-after safety evaluation of CLRS. About 48% (n=13) of the respondents answered "No" to this question.

16. *Has your agency received any concerns from the public about vehicles hydroplaning due to the contact with rumble strips?*

Only one state (Kansas) reported that only one person has presented a concern about vehicles hydroplaning after hitting CLRS.

17. *Has your agency received other type of concerns from the public about centerline rumble strips (yes or no, elaborate)?*

About 70% (n=19) of the respondents have received concerns from the public regarding CLRS. The causes of concerns cited were: roadside residents about external noise (n=11), motorcyclists (n=11), bicyclists (n = three), pavement deterioration (n = two), lack of advance signing of treated sections (n = one), and snow and ice removal maintenance issues (n = one). Other eight states did not report any kind of concern received from the public.

Based on the results found in this current survey and in the literature review, it is possible to summarize the gaps in research and good practices involving the use of CLRS. Good practices are given below.

- For enhancing the safety effectiveness of CLRS: adopt a minimum AADT (DOTs responses ranged between 1500 and 3000), a minimum speed (DOTs responses ranged between 40 and 55 mph), a minimum crash rate for the installation of CLRS, a minimum lane width (DOTs responses ranged between 10 and 12 ft.), and a minimum shoulder width (DOTs reported two to four feet). In addition, install CLRS in roadways continuously in no-passing and passing zones, but discontinue the use of CLRS at intersections and at bridge decks, and adopt a pattern that is able to generate approximately 10 dBA above the ambient in-vehicle sound level. The predominant pattern in the country (length=16 in., width=7 in., depth=0.5 in. and spacing=12 in.) has this characteristic (Miles and Finley 2007). Thus, this pattern is recommended.

- To avoid potential pavement deterioration caused by CLRS, good practices include: install CLRS only on new construction or overlays; adopt a minimum pavement depth to install CLRS (DOTs responses ranged between 1.5 and 2.5 in.). Do not install CLRS if the center joint is not in good condition (use engineering judgment).
- A widely applied practice to reduce the impact of CLRS on winter maintenance activities is to avoid the raised type of CLRS in areas where snow is frequent.
- Bicyclists are not expected to hit CLRS very often. However, an intermittent gap in the spacing of CLRS may help bicyclists to cross the travel lane when needed.
- External noise issues may be addressed by the adoption of a minimum distance from houses or businesses to install CLRS. Karkle et al. (in press) recommended 200 ft. of distance, but semi-trucks were not considered in the study.
- To reduce the potential impact of CLRS on vehicles' position on the travel lane, good practices include: adopt a minimum shoulder and lane width for installation of CLRS (DOTs reported lane widths ranging from 10 to 12 ft. and shoulder widths ranging from two to 4 ft.). Utilize CLRS in conjunction with "rumble stripes" when technically feasible, since one study showed that CLRS in conjunction with "rumble stripes" resulted in drivers positioning the vehicle closer to the center of lanes (safer condition) at locations with lane widths as narrow as 11 ft. and shoulder widths of 3 ft. (Finley et al. 2008).
- In order to avoid potential drivers' mistakes on initial reactions after hitting CLRS, when CLRS are installed in conjunction with shoulder rumble strips (SRS) on the same roadway, different patterns of CLRS and SRS should be used.
- Other factors suggested for inclusion in CLRS installation guidance found in the reviewed literature were: type of roadway, location of roadway, local and regional conditions, roadway alignment, consistency within a state, and experience of others (Russell and Rys, 2005). Furthermore, Carlson and Miles (2003) recommended that CRLS may be installed along the edge line delineating pavement stripes for two-way left turn lanes.

The gaps in knowledge associated with CLRS are: to determine the optimum dimensions for CLRS pattern, to determine the effects of CLRS on the visibility of pavement markings, to estimate the safety effectiveness of CLRS regarding motorcyclists, and to verify the effects of CLRS on pavement deterioration rates.

CONCLUSIONS

This paper presented the most recent survey about the DOT policies and practices regarding CLRS. The use of CLRS has grown over the years. In 2005, the total mileage of CLRS installed in the United States was 2,403 miles (Richards and Saito 2007). This current survey found a total mileage of approximately 11,333 miles (not including the states of Texas and Colorado), which represents an increase of about 372% over five years. The state DOTs are in the process of implementing written policies or guidelines for installation of CLRS. In 2006 only seven U.S. states had written policies or guidelines (Torbic et al. 2009). This survey reported that 17 states have written policies or guidelines. According to survey results, the milled type of CLRS construction is the predominant type, and the CLRS predominant pattern dimensions are: length 16 in., width 7 in., depth 0.5 in., spacing 12 in., continuous. This pattern is recommended since it produces sufficient amount of noise to alert drivers. Moreover, the installation of CLRS on only asphalt pavement is predominant. Among the states that use CLRS on concrete pavements, the center joint deterioration appears not to be an important issue. This result is consistent with the literature review. Some previously cited studies have reported that pavement deterioration after the installation of CLRS seems to occur on roads that had poor pavement conditions before the CLRS application. Several state DOTs made the recommendation to investigate the condition of the pavement and to install CLRS only on sections with pavement in good condition.

The combination of CLRS and rumble strips is rarely used on sections of highways with narrow or no shoulder, despite the results that drivers appear to position the vehicle closer to the center of lanes at locations with lane widths as narrow as 11 ft. and shoulder width of 3 ft. (Finley et al. 2008).

The main causes of concerns received from the public regarding CLRS are the external noise produced by them that may disturb roadside residents and from motorcyclists, although some published results from the literature state that CLRS do not have a negative effect on motorcyclists.

Centerline rumble strips are an efficient countermeasure to reduce cross-over crashes. The policies and guidelines for CLRS installation are not very consistent among the states using them. Therefore, a list of good practices was given in this study. It can be useful in providing guidance for future applications of CLRS.

Future research may be performed on the gaps in research topics summarized by this study, which includes: to determine the optimum dimensions for CLRS pattern, to determine the effects of CLRS on the visibility of pavement markings, to estimate the safety effectiveness of CLRS regarding motorcyclists, and to verify the effects of CLRS on pavement deterioration rates.

References

AECOM Transportation. *Safety Enhancement Evaluation of Ground-in Centerline Rumble Strips*. Report to Arizona Department of Transportation, Phoenix, AZ, 2008.

Briese, M. *Safety Effects of Centerline Rumble Strips in Minnesota*. Report Number MN/RC-2008-44, Minnesota Department of Transportation, St. Paul, MN, 2006.

Bahar, G.J. and M. Parkhill. *Synthesis of Practices for the Implementation of Centerline Rumble Strips.* Transportation Association of Canada (TAC), 2005.

Bucko, T.R. and A. Khorashadi. *Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Audible Edge Stripe.* Office of Transportation Safety and Research, California Department of Transportation, 2001.

Carlson, P.J. and J.D. Miles. *Effectiveness of Rumble Strips on Texas Highways: First Year Report*. Report FHWA/TX-05/0-4472-1, Texas Department of Transportation, Austin, TX, 2003.

Delaware Department of Transportation. *Centerline Rumble Strips: The Delaware Experience*. http://www.deldot.gov; accessed in July 2008.

Chen, C., E.O. Darko, and T.N. Richardson. "Optimal Continuous Shoulder Rumble Strips and the Effects on Highway Safety and the Economy." *ITE Journal* 5 (73), (2003): 30-41. http://www.ite.org/itejournal/journalsearch.cfm.

Elefteriadou, L., M. El-Gindy, D. Torbic, P. Garvey, A. Homan, Z. Jiang, B. Pecheux, and R. Tallon. *Bicycle-Tolerable Shoulder Rumble Strip.* The Pennsylvania State University, The Pennsylvania Transportation Institute, Report Number: PTI 2K15, 2000.

Federal Highway Administration. *Rumble Strips.* FHWA Publication No: FHWA-RC-BAL-04-0015, Washington, D.C., 2003.

Finley, M.D. and J.D. Miles. *Exterior Noise Created by Vehicles Traveling over Rumble Strips.* Transportation Research Board 86th Annual Meeting, Transportation Research Board, National Research Council, Washington, D.C., 2007.

Finley, M.D., D.S. Funkhouser, and M.A. Brewer. *Studies to Determine the Operational Effects of Shoulder and Centerline Rumble Strips on Two- Lane Undivided Roadways*. Report 0-5577-1, Texas Department of Transportation, Austin, TX, 2008.

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

Golembiewski, G., R. Haas, B. Katz, and T. Bryer. *Evaluation of the Effectiveness of PennDOT's Low Cost Safety Improvement Program (LCSIP)*. Publication FHWA-PA-2008-16-070308. Pennsylvania Department of Transportation, 2008.

Hirasawa, M., K. Saito, and M. Asano. "Study on Development and Practical Use of Rumble Strips as a New Measure for Highway Safety." *Journal of the Eastern Asia Society for Transportation Studies* (6), (2005): 3697–3712. http://www.easts.info/on-line/journal_06/3697.pdf.

Kar, K. and R.S. Weeks. "The Sound of Safety." *Public Roads* 4 (72), (2009): 10–16.

Karkle, D.E., M.J. Rys, and E.R. Russell. *Evaluation of Centerline Rumble Strips for Prevention of Highway Cross-over Accidents in Kansas.* Proceedings of the 2009 Mid-Continent Transportation Research Symposium, Ames, IA, 2009.

Karkle, D.E., M.J. Rys, and E.R. Russell. "Centerline Rumble Strips: A Study of Exterior Noise." *Journal of Transportation Engineering*. (in press). http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=JTPEXX000001000001000162000001&idtype=cvips&prog=normal

Kirk, A. *Evaluation of the Effectiveness of Pavement Rumble Strips*. Research Report KTC-08-04/SPR319-06-1F, Kentucky Transportation Center, University of Kentucky, Lexington, KY, 2008.

Knapp, K.K. and M. Schmit. *Assessment of Centerline Rumble Strips in Minnesota: Executive Summary and Project Task Summary Attachments*. Center for Excellence in Rural Safety, State and Local Policy Program, Hubert H. Humphrey Institute of Public Affairs, University of Minnesota, Minneapolis, MN, 2009.

Lipscomb, D.M. *Auditory Perceptual Factors Influencing the Ability of Train Horns*. Third International Symposium on Railroad-Highway Grade Crossing Research and Safety, 1995: 195.

Makarla, R. "Evaluation of External Noise Produced by Vehicles Crossing Over Centerline Rumble Strips on Undivided Highways in Kansas." Thesis (M.S.), Kansas State University, 2009.

Miles, J. D., P. J. Carlson, M.P. Pratt, and T.D. Thompson. *Traffic Operational Impacts of Transverse, Centerline, and Edgeline Rumble Strips.* Report No. FHWA/TX-05/0-4472-2. Texas Department of Transportation, 2005.

Miles, J.D. and M.D. Finley. *Evaluation of Factors that Impact the Effectiveness of Rumble Strip Design.* Presented at the 86th Annual Meeting of the Transportation Research Board, Washington D.C., 2007.

Miller, K.W. *Effects of Center-Line Rumble Strips on Non-Conventional Vehicles.* Minnesota Department of Transportation, 2008.

Monsere, C.M. *Preliminary Evaluation of the Safety Effectiveness of Centerline (Median) Rumble Strips in Oregon*. Presented at the Institute of Transportation Engineers Quad Conference, Seattle, WA, 2002.

National Highway Administration (NHTSA). "FARS Database." Accessed January 25, 2011. http://www-fars.nhtsa.dot.gov, 2009.

Noyce, D.A. and V.V. Elango. "Safety Evaluation of Centerline Rumble Strips: Crash and Driver Behavior Analysis." *Transportation Research Record: Journal of the Transportation Research Board* 1862, (2004): 44-53.

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

Persaud, B.N., R.A. Retting, and C. Lyon. *Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads*. Insurance Institute for Highway Safety, Arlington, VA, 2003.

Richards, S.J.N. and M. Saito. "State-of-the-Practice and Issues Surrounding Centerline Rumble Strips." *WIT Transactions on the Built Environment* (94), (2007): 36-45.

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

Rys, M.J., L. Gardner and E.R. Russell. "Evaluation of Football Shaped Rumble Strips Versus Rectangular Rumble Strips." *Journal of the Transportation Research Forum*, 47 (2), (2008): 41-54.

Torbic, D. J. "Comfort and Controllability of Bicycles as a Function of Rumble Strip Design." Dissertation (Ph.D). The Pennsylvania State University, 2001.

Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon. *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*. NCHRP Report 641, Transportation Research Board, National Research Council, Washington, D.C., 2009.

Zebauers, V. *Centerline Rumble Strips Help Cars and Bicyclists*. In the 2005 Annual Meeting and Exhibit Compendium of Technical Papers, Institute of Transportation Engineers, Washington, D.C., 2005.

Daniel E. Karkle *is a Ph.D. student in the Department of Industrial and Manufacturing Systems Engineering at Kansas State University. He received his B.S. degree in civil production engineering in Brazil.*

Margaret J. Rys *is an associate professor in the Department of Industrial and Manufacturing Systems Engineering at Kansas State University. She obtained her integrated B.S/M.S degree from the Technical University of Wroclaw, Poland, in 1979 and M.S. (1986) and Ph.D. (1989) from Kansas State University, all in industrial engineering. She has almost 20 years of experience conducting research and teaching courses in human factors engineering, quality, engineering economy, statistics, and safety. During the past 20 years she has been principal or co-principal investigator on more than 40 projects and authored and co-authored more than 50 journal papers.*

Eugene R. Russell*, PE, is a professor emeritus of civil engineering at Kansas State University and still conducts research on a part-time basis. He has 50 years of transportation and traffic engineering experience, including 42 in academia. He has directed more than 80 research projects covering a wide range of highway engineering and highway safety issues, authored or co-authored more than 100 technical papers, and more than 100 presentations at U.S. and international conferences.*