GEORGIA DOT RESEARCH PROJECT 12-12

FINAL REPORT

CENTERLINE RUMBLE STRIPS SAFETY AND MAINTENANCE IMPACTS

OFFICE OF RESEARCH
15 KENNEDY DRIVE
FOREST PARK, GA 30297-2534

Technical Report Documentation Page

1. Report No.: FHWA-GA-14-1212	2. Government Accession No.:	3. Recipient's Catalog No.:	
4. Title and Subtitle: Centerline Rumble Strips Safety And Maintenance Impacts		5. Report Date: September 2014	
		6. Performing Organization Code:	
7. Author(s): Angshuman Guin, Ph.D., Michael P. Hunter, Ph.D., Michael O. Rodgers, Ph.D., Jerome Sin		8. Performing Organization Report No. 12-12	
9. Performing Organization Name and Address: Georgia Tech Research Corporation School of Civil and Environ. Engineering 790 Atlantic Drive Atlanta, GA 30332-0355		10. Work Unit No.:	
		11. Contract or Grant No.:	
12. Sponsoring Organization Name and Address: Georgia Department of Transportation, Office of Research; 15 Kennedy Drive; Forest Park, GA 30297-2534		13. Type of Report & Period Covered: Final; June 2012 – May 2014	
		14. Sponsoring Agency Code:	
15. Supplementary Notes: Prepared in cooperation with the US Department of Transportation, Federal Highway Administration			
16. Abstract: Soon after implementation of centerline rumble strips in Georgia around 2005-2006, GDOT observed pavement distress and deterioration at one of the centerline rumble strips sites. As no definitive correlation has been drawn between centerline rumble strips and pavement deterioration, a literature review and a survey were conducted to investigate this issue. Of the 28 state DOTs that responded, 10 state DOTs indicated that they encountered adverse effects associated with centerline rumble strips. Of the 10 state DOTs, five identified accelerated pavement deterioration as an issue, three identified pavement failure as an issue, seven identified noise as an issue. However, as state DOTs recognize the benefits of centerline rumble strips, nearly every state DOT surveyed (27 out of 28) is currently planning or constructing centerline rumble strips despite the possibility of adverse effects. In addition, the literature review and survey results reveal that any adverse effects of centerline rumble strips appear to arise on a case-by-case basis rather than appearing as a systematic issue. Thus, the recommendation for GDOT is that it should continue its centerline rumble strips program with several considerations and amendments to existing design policies: the pavement on which the centerline rumble strips will be installed, the strength of the longitudinal joint, and effects to nearby residents.			
17. Key Words Centerline rumble strips, accelerated pavement deterioration, pavement failure, survey,		18. Distribution Statement	
19. Security Class (This Report): Unclassified	20. Security Class (This Page): Unclassified	21. No of Pages 40	22. Price

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

GDOT Research Project No. 12-12

Centerline Rumble Strips Safety Impact Evaluation

Final Report

CENTERLINE RUMBLE STRIPS SAFETY AND MAINTENANCE IMPACTS

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June, 2014

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CLRS	Centerline Rumble Strips
dB	Decibels
DOT	Department of Transportation
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
HMA	Hot mix asphalt
Mph	miles per hour
WSDOT	Washington State DOT

EXECUTIVE SUMMARY

Within the last decade, centerline rumble strips have become increasingly prevalent as a countermeasure for cross-over the centerline crashes on undivided roadways throughout the United States. In 2005, the Georgia Department of Transportation (GDOT) initiated a plan to address safety issues through engineering related solutions, known as the Safety Action Plan. Part of the plan was the implementation of centerline rumble strips in rural locations across Georgia in 2005 and 2006. However, soon after implementation, GDOT experienced pavement distress and deterioration at one of the centerline rumble strips sites. At the time, over 150-miles of centerline rumble strips have been installed at 10 different sites throughout the state. As no definitive correlation has been drawn between centerline rumble strips and pavement deterioration, a literature review and a survey were conducted to investigate this issue.

The primary focus of this investigation was the development and sending of a survey to obtain updated information and the nationwide perspective regarding centerline rumble strips from state DOTs around the United States. Contact persons were drawn from both a recent survey regarding centerline rumble strips and state DOT websites. In total, 28 state DOTs have responded to the survey; the literature review revealed that 41 states have implemented centerline rumble strips on their roadways. Within the survey, there were two primary topics: adverse effects due to centerline rumble strips experienced by each state DOT and the current status of centerline rumble strips within each state DOT. The adverse effects to be investigated in the survey were determined from GDOT's experience with centerline rumble strips and anecdotal evidence from the literature review:

- Accelerated pavement deterioration (e.g., increased cracking)
- Pavement failure (e.g., section loss)
- Decreased visibility of paint striping (e.g., obscured by accumulated sand, decreased retro-reflectivity)
- Residential issues (e.g., excessive noise)
- Other adverse issues not listed above

The survey was designed to dynamically direct a respondent through the survey based on the respondent's prior responses. The survey was emailed to each contact on September 16, 2013 with a specified closing date of October 4, 2013. During the three weeks in which the survey was open, new contact information was added as initial contacts responded with information of persons who were better qualified to respond.

Of the 28 state DOTs that responded, 10 state DOTs indicated that they encountered adverse effects associated with centerline rumble strips. Of the 10 state DOTs, five identified accelerated pavement

deterioration as an issue. Four of the five state DOTs suspected the age of the roadway to be a cause of this issue; two suspected the method of pavement design; one suspected the method of centerline rumble strips installation. In response, some state DOTs reinstalled the centerline rumble strips; one state DOT in particular changed their centerline rumble strips design to include two rows of rumble strips that straddle the centerline joint.

Out of the same set of 10 state DOTs, three identified pavement failure as an issue. Two of the three state DOTs suspected the age of roadway to be a cause of this issue. In response to this issue, all of the state DOTs resurfaced the roadway, while two of the three state DOTs reinstalled centerline rumble strips after resurfacing.

Again out, of the same set of 10 state DOTs, seven identified noise as an issue. In another question aimed at all state DOTs, 16 of the 28 state DOTs indicated noise as a reservation regarding future centerline rumble strips installation. Responses to this issue ranged from improved education to affected residents regarding the safety benefits of rumble strips, to verification that the centerline rumble strips installation was not too deep or improperly placed, or simply waiting for complaints to subside.

Overall, despite reservations regarding centerline rumble strips, 27 of the 28 responding state DOTs indicated they are currently considering, planning, or constructing additional centerline rumble strips; the remaining respondent was not certain of their state DOT's future position on centerline rumble strips. Ultimately, several state DOTs acknowledged that their installations of centerline rumble strips were implemented within the past five years which is potentially not sufficient time for issues to arise.

As a part of this study, the investigators, in cooperation with GDOT personnel, conducted a limited forensic evaluation of the pavement failure associated with the centerline rumble strip installation along SR-369 near Gainesville, GA. As a result of this investigation, it was found that the likely cause of this pavement failure was a pre-existing pavement construction defect (missing bituminous tack coat) along the longitudinal joint exacerbated by the milling of the rumble strips and/or heavy truck traffic. While there is no direct evidence, it is believed to be unlikely that milling the centerline rumble strips into sound pavement would have resulted in the observed pavement failure.

As state DOTs recognize the benefits of centerline rumble strips, nearly every state DOT surveyed is currently planning or constructing centerline rumble strips despite the possibility of adverse effects. In addition, the literature review and survey results reveal that any adverse effects of centerline rumble strips appear to arise on a case-by-case basis rather than appearing as a systematic issue. Thus, the recommendation for GDOT is that it should continue its centerline rumble strips program with several

considerations and amendments to existing design policies: the pavement on which the centerline rumble strips will be installed, the strength of the longitudinal joint, and effects to nearby residents.

ACKNOWLEDGMENTS

The authors of this report wish to thank the Georgia Department of Transportation for its support and assistance throughout this effort, in particular the efforts of Yusuf Ahmed, Binh Bui, David Jared, and E. David Adams.

1.0 INTRODUCTION

First proposed nearly two decades ago, centerline rumble strips have become increasingly prevalent throughout the United States, growing from several 15-mile sections in 2000 to around 2,400-miles in 2005 to well over 11,000-miles by 2011 (*8, 19*). Operating similarly to the more familiar shoulder rumble strips, centerline rumble strips alert motorists that they are inadvertently crossing the centerline through auditory, tactile, and visual stimuli (*27*). Motivated by reported crash reductions in other states of as much as 21% in head-on and opposite-direction sideswipe crashes and a 25% reduction in injuries, the Georgia Department of Transportation (GDOT) installed more than 150-miles of centerline rumble strips (CLRS) during 2005 and 2006 (*30*) on a variety of rural roadways. These installations were a part of GDOT's Safety Action Plan that was designed to reduce the total number of crashes by 2% annually and ultimately meet AASHTO's goal of a fatality rate of 1.0 per 100 million vehicle-miles-traveled and were overseen by the GDOT Division of Operations in collaboration with the Office of Maintenance either as stand-alone projects or part of ongoing resurfacing projects (*30*).

Soon after implementation, GDOT began receiving reports of pavement deterioration at sites with centerline rumble strips and consequently suspended the centerline rumble strips program until the underlying issues could be identified and resolved. This research study was initiated to investigate this issue and identify any other potential adverse effects of centerline rumble strips that might impact future installations of centerline rumble strips in Georgia. This study addressed these issues through three primary means: 1) a literature review of current practices and issues with centerline rumble strips; 2) a survey of state DOT's to identify their current practices and their experiences with centerline rumble strip installations and 3) a limited forensic investigation as to the factors likely responsible for pavement deterioration at one of the Georgia CLRS installation sites. The results from each of these efforts are presented in this report.

2.0 REVIEW OF CURRENT PRACTICE

A number of studies have shown that centerline rumble strips can have significant effects on decreasing crashes and serve as an effective countermeasure for lane departure related crashes (see for example (*21*)). Section 2 of this report focuses on a review of current practices for use and installation of centerline rumble strips in the United States. A review of reported adverse impacts of the installation of centerline rumble strips is given in Section 3.

2.1 Background of Centerline Rumble Strips

The most common method of keeping drivers in their designated lanes is through painted road markings. However, the effectiveness of this method is limited by the attentiveness of drivers and prevailing environmental conditions (*26*). As a supplemental treatment to assist in lane control, right shoulder rumble strips were introduced in 1955 along the New Jersey Turnpike (*3*). These rumble strips were designed to provide the motorist with a combination of auditory and tactile stimuli when the vehicle had departed the travel lane and the vehicles' tires passed over the rumble strips. If this departure was inadvertent, these stimuli informed the motorist of the need to maneuver their vehicle in order to avoid a potential crash (*21*). By the 1960's, shoulder rumble strips began appearing in many other states and have since become common along the shoulders of freeways and principal arterials throughout the nation due to their proven effectiveness in alerting drivers of departures from the roadway due to drowsiness, fatigue, or inattentiveness (*3*).

Lane departures can, of course, also occur along the centerline of the roadway and represents a major crash risk. These centerline crossings can result in a head-on collision, sideswipe collision with a vehicle traveling the opposite direction, or opposite-side roadway departure. Limited access or divided highways often seek to control these departures by physical measures such as wide medians or barriers that separate opposing traffic. However rural roads, especially two-lane highways, generally lack such physical barriers and therefore have a risk of centerline crossings due to a failure in lane keeping. Several factors may amplify this risk: poor environmental conditions, driver inattention, driver fatigue, or traveling at speeds not intended for the roadway. Though these factors can be partially mitigated by engineering improvements such as roadway widening or the installation of a median barrier, such improvements are often costly (*21*). Centerline rumble strips seek to ameliorate these risks in much the same way as their shoulder counterparts. Whether there are raised bumps or grooved indentations in the roadway, the striking of a vehicle's tires with these surfaces produces noise that provides the motorist with an auditory and tactile

warning that they are leaving the travel lane. The primary differences between centerline and shoulder rumble strips are in their placement and crash types that they aim to address.

While still much less common than shoulder types, the use of centerline rumble strips has increased significantly since the 1990s. Early surveys in 2000 indicated that about 20 states and at least one Canadian province had experimented with or implemented centerline rumble strips ranging from a few miles up to 15-miles (*26*). By 2003, many additional centerline rumble strips had been installed on an experimental basis (*21*). Examples of these installations included:

- A 2.9-miles section of centerline rumble strips installed in 1994 in Delaware (*4*)
- A 17-miles section of centerline rumble strips installed along a winding two-lane mountain highway in 1996 in Colorado (*20*)
- 100-miles of centerline rumble strips installed statewide in Washington (*19*)

Today, many states are still performing studies on the effectiveness of centerline rumble strips, and as of 2011, there have been over 11,300 miles installed around the country (*11*).

2.2 Crash Statistics

Many of these centerline rumble strips were implemented as a response to the serious problem of roadway departure fatalities. As noted by Russell and Rys in 2005: "Crashes that qualify as centerline rumble strips correctable are any cross-centerline (cross-over) crash that begins with a vehicle encroaching on the opposing lane, excluding any crash that began by running off the road to the right and overcorrecting and any crash that began by a vehicle going out of control owing to water, ice snow, etc., before crossing the centerline (*26*)." As few studies existed on the effectiveness and safety impact of centerline rumble strips at the time, several transportation agencies opted to evaluate the effectiveness of centerline rumble strips relevant to their geographic location and conditions.

2.2.1 Roadway Environment

In comparing urban roadways to rural roadways, though urban roadways experience a higher rate of motor vehicle crashes, fatal crashes are more likely to occur on rural roadways (*21*). While rural roads account for 40% of all vehicular travel, they account for 60% of all fatalities (*26*). These statistics have not changed much over time. A 2001 report found that 60% of fatal crashes occurred on rural roads; a 2009 study found that 56% of fatal crashes occurred on rural roads. Furthermore, the fatality rate per 100 million vehicle-miles-traveled was 2.7 times higher on rural roads than on urban roads. These nationwide statistics were echoed in Georgia and other southeastern states, as detailed in Table 1 (*38*, *39*).

Table 1: Rural Versus Urban Fatalities in the Southeast for 2010 (*38*)

State	Rural Fatalities		Urban Fatalities	
	Number	Percent	Number	Percent
Alabama	496	58	281	33
Georgia	659	51	625	49
Mississippi	507	72	193	28
Tennessee	577	58	412	42

Data also revealed that 74% of fatal crashes on rural roads were on two-lane roads; 20% of these involved two vehicles travelling in opposite directions (*11*). Lastly, a total of 83% of two-lane undivided road crashes occurred on rural roads (*17*). Compared to urban roads, rural roads generally have higher traffic speeds, lower rates of seatbelt use, and longer emergency response times (*21*).

2.2.2 Crash Type

Several studies have evaluated the type of crashes addressed with centerline rumble strips, focusing specifically on cross-over crashes in the form of head-on crashes and opposite-direction sideswipe crashes. Data from the 1999 Fatality Analysis Reporting System (FARS) revealed that 18% of non-intersection fatal crashes were a result of two vehicles colliding head-on (*17*). This was the same for 1997 and 1998 data and remained consistent throughout the 2000s (e.g. the rate was 20% in 2009 (*11*)). In terms of roadway environment, 75% of head-on crashes occurred on rural roads. Though the high percentage of head-on crashes on undivided, two-lane, two-way roads may suggest failed passing maneuvers, the majority of fatal head-on crashes occurred in non-passing zones (*17*). In accounting for other cross-over crashes, opposite-direction sideswipe crashes accounted for approximately 27% of fatal crashes on rural, two-way, two-lane roads (*33*).

2.2.3 Crash Locations

Which side of the road vehicles left the roadway during lane departure incidents is also of interest. In a study conducted in Michigan, 47% of crash vehicles were observed to have departed the travel lane to the left, while 53% departed the roadway to the right (*16*). In another study conducted in Texas, 47.3% of all crashes on two-way, two-lane roads involved crossing the centerline, with 41.5% of all crashes on these roads ran off the road to the far left side (*14*).

2.2.4 Causal Factors

A number of factors can cause motorists to leave the travel lane and cross the centerline or run off the road. Of inadvertent causal factors, motorist inattention was the most common. Studies cite that up to 86% of fatal head-on crashes on two-lane highways were a result of the driver being inattentive or asleep

(*9*). In a 2006 study undertaken by the state of Kentucky, driver inattention was the most frequently cited factor, contributing to over 41% of all crashes (*12*). Other causes, such as fatigue, accounted for 5% of all crashes. Another study from Texas confirmed driver inattention as the most frequently cited factor to run-off-the-road crashes, at 24.1% of all crashes. The second most common cause was falling asleep or driver fatigue, at 12.4%. In cases of driver inattention, common distractions cited included reaching for a cell phone or adjusting the audio system. Ultimately, most crashes have multiple contributing factors (*14*).

2.2.5 Roadway Geometry

In comparing crash rates of tangent sections to horizontal curve sections, tangent sections experience around 65% of all fatal crashes, while horizontal curve sections experience around 35% of all fatal crashes (*40*). However, though there may be more incidents on tangent sections, this characteristic has not been determined to be a statistically significant variable in the context of centerline rumble strips and the type of crashes it addresses. Head-on crashes and opposite-direction sideswipe crashes experienced a reduction of 47% on tangent sections and 49% on horizontal curve sections, concluding that the safety effectiveness of centerline rumble strips is the same for both types of roadway geometry (*40*).

2.3 Properties of Centerline Rumble Strips

Although the design of centerline rumble strips is relatively consistent across the nation, placement and construction techniques vary widely from agency to agency (*12*) and there exists no uniform national definition or policy regarding the form, dimensions, and placement of centerline rumble strips (*26*).

2.3.1 Forms of Rumble Strips

Installation of rumble strips as a countermeasure can be accomplished in a variety of ways. Rumble strips may be installed in at least four different locations along the roadway; these are, from most prevalent to least prevalent: the shoulder, the centerline, across the roadway (transverse), and down the middle of the travel lane (midline) (*11*). Shoulder and centerline rumble strips cover their respective areas as discussed previously. Transverse rumble strips incorporate rumbles that are placed across the full width of the travel lanes. These are typically designed to alert motorists of approaching changes in the roadway, such as roundabouts, intersections, and toll plazas (*40*). Midline rumble strips, still in the theoretical stage, targets cross-over and run-off-the-road crashes, mitigating travel lane departures by placing rumbles along the center of the travel lane (*11*, *15*). As of 2011, no transportation agencies had installed this form, potentially due to negative reactions by motorcyclists and bicyclists who view this as dangerous, as many riders frequently cross the center of the travel lanes in the course of normal travel (*15*).

The actual rumble strips themselves predominantly come in four types: raised, milled-in, rolled, and formed; these are illustrated respectively in Figure 1 (*23*, *25*). By far the most common form of centerline rumble strips is the milled-in rumble strips (*26)*.

Figure 1: Forms of Centerline Rumble Strips; from left to right: Raised, Milled-In, Rolled, Formed (*23*)

Milled-in Rumble Strips

Milled-in rumble strips, also known as ground-in rumble strips, are cut into the road surface by a machine with a cutting head (*5*). These grinding machines can grind up to 1.25-mph, and carves out regular indentations on roadway independent of the roadway age (*20*). The repetitive milling of the roadway creates smooth, uniform, and consistent grooves in the pavement surface in one of two shapes: football shaped or rectangular shaped (Figure 2). In terms of safety benefits, no statistical differences between the two shapes have been found (*29*).

Figure 2: Patterns of Milled-in Centerline Rumble Strips, from left to right: Football-shaped, Rectangular-shaped (*29*)

Due to the nature of the installation, milled-in rumble strips can be installed on new or existing asphalt and Portland cement concrete surfaces. Cut into the pavement, milled-in rumble strips have not been shown to negatively impact the structure of the roadway, although there are concerns. However, some disadvantages are that milled-in rumble strips tend to be more expensive to implement than other types of rumble strips, are non-reflective in nature, and when driven over, tend to produce greater noise levels (*5*, *29*).

Formed Rumble Strips or Rolled Rumble Strips

Formed rumble strips consist of V-shaped or rounded grooves pressed into concrete as they are being constructed during the compaction phase of road construction or reconstruction. Similarly, rolled rumble strips consist of rounded grooves pressed into hot asphalt by a roller with a steel pipe welded to the drum, creating depressions as it passes over the asphalt (*25*). While this type leads to less noise and is less expensive than other types of rumble strips, formed and rolled rumble strips can only be done during construction or reconstruction, which hinders extensive application (*5*).

Raised Rumble Strips

Raised rumble strips are raised, narrow, and rounded or rectangular markers that are attached to new or existing pavements. As these rumble strips are affixed to the roadway surface, raised rumble strips can come in several materials, including asphalt, rubber-like material, and plastic. Some advantages include improved retro-reflectivity, as materials such as glass beads can be embedded in the composition to enable greater visibility at night for drivers. In addition, raised rumble strips can be applied to the roadway at any time. However, there have been concerns of raised rumble strips, particularly in areas with wintry weather as snowplows may inadvertently remove them. Furthermore, raised rumble strips tend to be costlier than other types of rumble strips (*5*).

2.3.2 Application of Centerline Rumble Strips

The applications and physical properties of centerline rumble strips range widely from one jurisdiction to the next. This section touches upon the dimensions, placement, and design considerations of various types of centerline rumble strips.

2.3.2.1 Installation Properties

Typical Dimensions

As dimensions are not standardized, state transportation agencies have developed their own policies regarding dimensions. Some typical dimensions of milled-in rumble strips type, expressed in length (dimension perpendicular to the centerline), width (dimension parallel to the centerline), and spacing (space between the center of an indentation to the next) are listed in Table 2.

Table 2: Common Milled-in Centerline Rumble Strips Dimensions (*11*)

Dimension	Range (inches)		Most Common (inches)
Length	6	25	16
Width	5	9	7
Depth	0.375	0.625	0.5
Spacing	5	48	12

Lateral Placement

Though centerline rumble strips are always installed at the centerline, the actual installation locations may vary. While predominantly installed within the pavement markings that constitute the centerline, centerline rumble strips can be placed in a variety of places around the centerline (*11*, *40*). Some example placements are illustrated in Figure 3.

Figure 3: Examples of Different Lateral Placements of Centerline Rumble Strips; from left to right: Within Pavement Markings, Extended into Travel Lane, on Either Side of Pavement Markings (*40*)

Facility Type

The types of roadway centerline rumble strips are installed on vary from agency to agency. These facility types include: urban multi-lane undivided highways, urban two-lane roads, rural multi-lane undivided highways, and rural two-lane roads; most state transportation agencies install on rural two-lane roads. Agencies may or may not have a lane width requirement (*40*). For installations where there are more than two lanes, some agencies widen the centerline rumble strip length (*1*). In terms of pavement type, the majority of agencies have only installed centerline rumble strips on asphalt; other agencies have installed on both asphalt and concrete (*11*).

Dual Application

In terms of application with respect to other types of rumble strips, the majority of states with centerline rumble strips had both centerline rumble strips and shoulder rumble strips installed on the same stretch of roadway, while a handful of states had both centerline rumble strips and edge line rumble strips

on the same roadway. Furthermore, three states had both centerline rumble strips and edge line rumble strips in sections of roadway with a narrow shoulder of less than three feet or no shoulder (*11*). All in all, the decision to install multiple applications of rumble strips on the same stretch of roadway was up to the agency, with some agencies reporting that existing shoulder rumble strips does not influence the site selection process for centerline rumble strips (*1*).

2.3.2.2 Design Policies and Considerations

As of 2011, nearly two-third of states with centerline rumble strips have some sort of written policies or guidelines for centerline rumble strips installation; the depth of these guidelines varies from state to state. Two-thirds of states with policies had a lane width requirement for installation; one-third of states with policies had a minimum shoulder width requirement, and roughly half of states with policies had other requirements such as minimum crash rates, AADT, or speed limits for installation (*11*). For example, California requires the occurrence of fatal crashes to justify centerline rumble strips installation, while Washington State gives investment priority to roadways with AADT of less than 8,000, combined lane and shoulder width of 12 to 17 feet, and posted speeds between 45 and 55 mph (*12*, *19*).

Design considerations for centerline rumble strips installation also vary. Some examples regarding design considerations include installations in passing zones, horizontal curves, and places with existing rumble strips. In a 2011 survey, about one-fifth of state transportation agencies with centerline rumble strips intentionally installed them at specific locations such as at curves and no passing zones (*11*). Other agencies recommended changes in centerline rumble strips' depth depending on the location, such as shallower milled-in cuts on curves based on the assumption that motorcycles pass over them (*8*).

2.4 Benefits of Centerline Rumble Strips

The literature indicates that centerline rumble strips are a low-cost and effective countermeasure for mitigating cross-over crashes (see for example (*26*)). The effectiveness is accomplished and exemplified in several ways.

2.4.1 Noise

The noise produced by centerline rumble strips is an auditory stimulus for the motorist. In a study conducted regarding the human perception of changes in sound level, it was concluded that sounds must rise at least 10 dB above the sound of the environment for the user to become alerted to the presence of that sound (*13*). As the noise within a car driving on rumble strips is at least 15 dB higher than the normal ambient noise when driving, rumbles strips are effective at alerting the motorist. In addition, there is a

positive correlation between rumble strip depth and sound levels, and between speed and sound levels, as seen in Figure 4 (*8*).

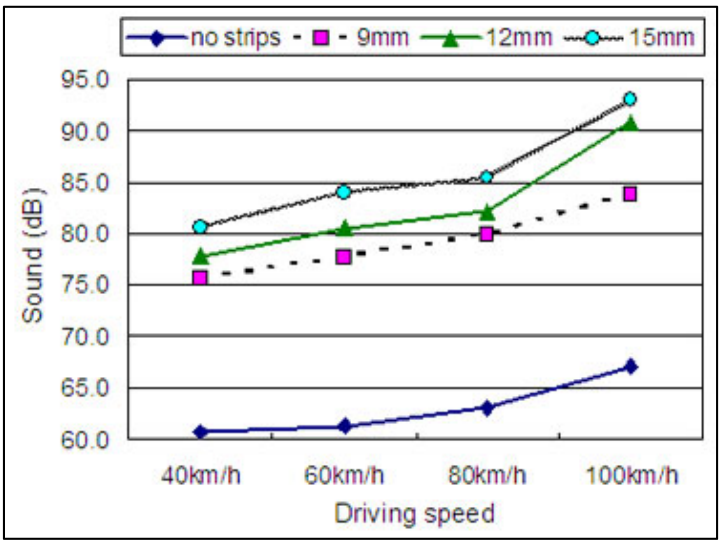

Figure 4: Average Sound Heard by Motorists Driving on Rumble Strips at Various Speeds (*8*)

In terms of rumble strips placement, a study conducted in Kansas revealed that continuous rumble strips with a spacing of 12-inches produced the highest average decibel levels, followed by the alternating 12-inches and 24-inches spacing; the continuous 24-inches spacing pattern produced the lowest average decibel levels. These results were consistent across different vehicle types and sizes. Thus, additional relationships are hypothesized, including a positive correlation between densities of rumble strips indentations and average sound levels (*28*).

2.4.2 Vibration

A secondary purpose of centerline rumble strips is to provide tactile stimulus to the motorist. From a study in Japan, researchers discovered that the vibration in a car driving on rumble strips tend to be at least 10 dB higher than driving on the regular road. In addition, they discovered that there is a positive correlation between the rumble strip depth and the vibration level; these findings are shown in Figure 5 (*8*).

As of 2009, however, there has yet to be research in determining the minimum level of vibration stimuli required to alert the motorist (*40*).

2.4.3 Additional Benefits

Centerline rumble strips have multiple other benefits, including improved safety in low visibility driving conditions. A public opinion survey produced an overwhelming response that centerline rumble strips aid in poor visibility conditions, particularly for large truck drivers (*23*). Similarly, centerline rumble

strips were appreciated by drivers in areas with wintry weather (*3*, *10*). In Alaska and Minnesota, centerline rumble strips have made motorists aware of the centerline when the roads were covered in snow. In addition, the distance required for breaking decreases with the depth of the rumble strips due to its uneven surface in areas with wintry weather (*8*).

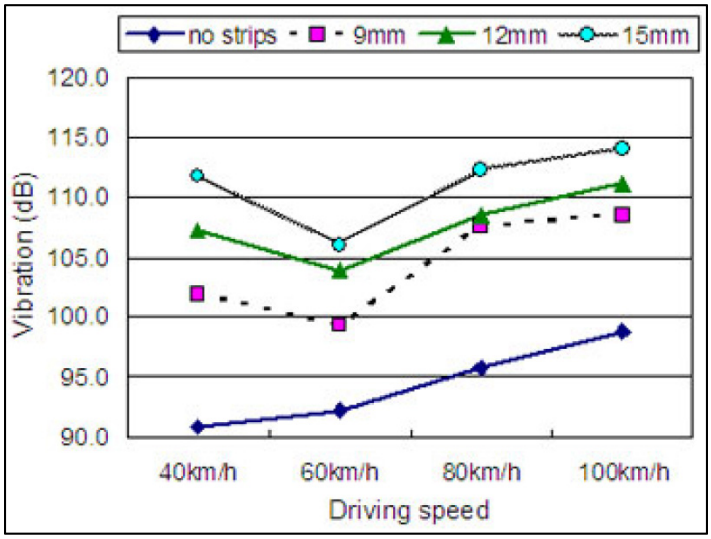

Figure 5: Average Vibration Experienced by Motorists Driving on Rumble Strips at Various Speeds (*8*)

2.4.4 Low Associated Treatment Costs

Centerline rumble strips are a fairly inexpensive safety countermeasure to implement. The price per linear foot ranged from $0.18 per linear foot in Minnesota (*2*) to $0.87 per linear foot in Colorado (*20*). In Kansas, the price per linear foot varied between $0.08 and $0.26 (*27*), while in Delaware, the costs ranged from $0.20 to $0.60 per linear foot, excluding traffic control costs (*4*). Several factors contribute to the variability of the cost. These factors include: the dimensions of the pattern (longer strips and deeper cuts require more time to mill); the type of roadway surface (e.g. concrete vs. asphalt); traffic volume (impacting traffic control costs) and overall size of installation, as larger projects tend to have lower average costs (*27*).

Centerline rumble strips installations typically exhibit high benefit to cost ratios. In a study examining roadways with centerline rumble strips, all but two of 20 locations studied exhibited a benefit-cost ratio of greater than 1 with ratios ranging from 1.89 to 39.16 (*3*). Consistent with this research, a Delaware three year before and after naïve analysis produced a 110:1 benefit-cost ratio (*4*).

3.0 REVIEW OF ADVERSE IMPACTS

The majority of adverse issues regarding centerline rumble strips were in the form of anecdotal evidence. These reported issues included excessive external noise, adverse effects to motorcyclists and bicyclists, pavement deterioration, lack of advanced signing of treated sections, and snow or ice removal maintenance issues (*26*). These issues can be broken down into two categories: weather related and non-weather related.

3.1 Weather Related Concerns

From the anecdotal evidence, it is hypothesized that there is a relationship between the presence of centerline rumble strips and adverse effects on the pavement on which centerline rumble strips are installed. Furthermore, uncertainty exists regarding the effects of inclement weather on the performance and effectiveness of centerline rumble strips (*11*).

3.1.1 Wintry Inclement Weather

In snowy and icy inclement weather, agencies in regions with wintry weather such as the Alaska DOT have noted that snow or ice occasionally compacted into their rumble strips and persisted for a short time after a storm. However, in most cases, traffic eventually clears it. When traffic does not clear it, additional passes of the snowplow were needed (*26)*. Unlike Alaska, other agencies have had issues in snowy and icy inclement weather (*11*). According to Oregon's maintenance crews, their shoulder rumble strips would fill with water, and upon encountering cold weather, would freeze to become a "trench of ice" (*7*).

In other cases, it was not the weather that affected the strips but rather the operations occurring during the winter season that led to the deterioration of the rumble strips and the surrounding pavement. One issue was experienced by maintenance crews in New Hampshire, where rumble strips damage occurred due to the chains fitted on snowplows. When the snowplows inadvertently drove over the shoulder rumble strips, the rumble strips tore the tire chains; at the same time the chains damaged the rumble strips. In response, New Hampshire offset all new shoulder rumble strips farther from the travel lane in order to aid the snow plow wheels from inadvertently driving in the shoulder rumble strips (*7*). On the other hand, while snowplow blades cause little or no damage to milled rumble strips, it is suggested to place them at least 8-inches off of the travel lane in order to minimize contact with snowplows (*5*). Aside from issues with their chains, snowplow blades were found to scrape raised rumble strips off the pavement surface; therefore, raised rumble strips were typically restricted to regions that do not need to worry about snow removal (*36*).

A second case revealed that the sand applied during snowstorms in Colorado adversely affected rumble strips. Though the sand did not completely obscure the centerline rumble strips, it blocked part of the paint stripe at the bottom of the grooves. Over time, the pavement marking on the pavement concurrent with centerline rumble strips wore off quicker than areas without these installations (*20*). A similar situation occurred due to the application of other snow removal and anti-freezing agents which were caught in the grooves. In New Hampshire, the collection of winter maintenance debris often not only blocked, but expedited the deterioration of portions of the pavement marking. This ultimately reduced the retro-reflectivity on centerline and edge line rumble strips. In addition to reduced visibility, during night time, the normally solid lines looked like dashed lines, contributing to reduced driver safety (*8*). On the opposite spectrum, Minnesota said that more salt may be needed along sections with centerline rumble strips; here the presence of salt is an acceptable alternative to the presence of ice (*11*). Lastly, Oregon experienced issues with sand in that the maintenance crew had a difficult time cleaning the rumble strips of sand from sanding activities after the winter season (*7*).

Yet, other cases reveal that most debris and water was unable to linger long due to the air turbulence of traffic, particularly from large trucks. Therefore, freezing of pooled water was not found to be a major cause of pavement deterioration (*7)*. Similarly, as air movement caused by passing traffic rapidly dries residual water in the grooves, there was no indication of asphalt deterioration caused by the presence of wintry weather (*20*). Lastly, issues of ice accumulation in centerline rumble strips were determined to be a "non-issue" in a study performed by the Kentucky Transportation Center (*12*). This was consistent with the conclusion that the issues of snow, ice, or winter maintenance activities have not had a documented effect on the level of sound generated by the rumble strips. In any case, the benefits were determined to outweigh the disadvantages of installing shoulder rumble strips or centerline rumble strips in areas that receive snowy and icy inclement weather (*20*).

3.1.2 Wet Inclement Weather

Other weather related concerns include concerns that may arise due to wet weather conditions. In wet inclement weather, there have been theories that the water pooling in the rumble strips may potentially accelerate pavement deterioration due to the increased surface area of exposed pavement (*41*). From a NCHRP survey, 15 of 24 responding agencies responded that water accumulation had no effect on pavement deterioration; seven replied that they did not know, and two replied that there was an effect. In the states that indicated an effect, there was not a clear reason for pavement deterioration aside from speculation (*26*). However, it was believed that the situation of standing water in milled-in rumble strips is worsened with a smaller cross slope. One route in New Mexico had rumble strips installed on the roadway next to a narrow median and was noted to have an issue with standing water, which led to concerns about

hydroplaning or icing. However, there have been several publications that express the opposite viewpoint. One discussion indicated that in order to generate enough force to pull the water out of the rumble strips, a combination of a significant volume of trucks and high speeds of passing traffic must exist (*7*). According to a FHWA Technical Advisory on shoulder and edge line rumble strips, traffic flow near rumble strips was satisfactory in keeping water from accumulating and retaining in the strips (*34*). Nonetheless, agencies have noted that pooling or standing water has led to no reduction in effectiveness of the rumble strips (*1*).

Where there are deterioration concerns, there are a number of remedies that can be applied. Though most remedies were not created only for pavements with rumble strips, many can provide enhanced benefits to these pavements (*41*). For example, an asphalt fog seal can be placed over milled-in rumble strips to reduce its exposure to the elements (*35*).

3.1.3 Freeze-Thaw Cycles

Other possible weather related issues may arise due to freeze-thaw cycles of water collecting in the grooves, which may be exacerbated in pavements with rumble strips due to the increase of surface area (*7*). Field tests, however, refute this hypothesis, instead revealing that the vibration and action of wheels passing over and near rumble strips knock debris, ice, and water out of the grooves. However, the long term effects of freeze-thaw cycles have not been investigated (*3*).

3.2 Non-Weather Related Concerns

While weather may exacerbate issues relating to centerline rumble strips, the mere presence of centerline rumble strips has raised concerns regarding adverse effects on the roadway, driver behavior, and levels of noise.

3.2.1 Pavement Deterioration

Several papers and agencies have expressed concerns about pavement deterioration and its related maintenance issues. In one instance, the Kentucky Transportation Center held a meeting with maintenance personnel from three different districts within Kentucky to specifically address maintenance issues. It was found that pavement deterioration existed along the centerline joint on two of the three studied highways; the roadway material was not specified. However, it was concluded that the deterioration occurred due to a combination of poor pavement performance and subsequent retrofit application of rumble strips (*12*).

In regard to concrete pavement deterioration, the majority of state DOTs have not installed centerline rumble strips on concrete pavement as of 2011. Of the state DOTs that have experience in this area, several have suggestions in place for future installations. Nebraska DOT advises not to place the centerline rumble strips on the roadway joint, but rather on the south side of the striping on east-west

highways, and the east side of north-south highways. Michigan DOT does not have much experience of centerline rumble strips on concrete, but officials in several regions within the state advise against milling on the centerline joint of old Portland cement concrete. Still other DOTs, including Texas DOT, Idaho DOT, Missouri DOT, and Colorado DOT, with the disclaimer that the installations were too new and that any deterioration may become evident with the passage of time, stated that they were not aware of deterioration on concrete joints. Nonetheless, several state DOTs have policies regarding the depth and age of potential roadways on which to install centerline rumble strips; these are shown in Table 1 (*11*).

Table 3: Sample of State Centerline Rumble Strips Policies (*11*)

State	Min. Pavement Depth (inches)	Min. Pavement Age (years)
Alaska	2	None
Delaware	Requires consultation of pavement management section	
Iowa	2.5	7
Kansas	1.5	None
Kentucky	Pavement in good condition	
Louisiana	2	$\geq$ 10
Maryland	Pavement in good condition	
Michigan	Engineering judgment	
Minnesota	Engineering judgment	
Mississippi	Considering for new pavement in future	
Missouri	1.75	New overlays
Nebraska	None	New pavement
Oregon	Pavement in good condition	
Pennsylvania	1.5	> 1
Texas	2	None
Washington	Pavement is structurally adequate	

In a study conducted in Hokkaido, Japan by the Civil Engineering Research Institute for Cold Region, researchers have noted that spalling began to occur around the fourth year after centerline rumble strips installation, sometimes exposing the pavement joint. This relationship to centerline rumble strips is unclear however, and was ultimately attributed to the thinness of the pavement overlay. Where the pavement overlay was not the issue, researchers have suggested that spalling can be reduced and water penetration can be prevented by sealing the joint with the thermoplastic material used for the centerline marking (*8*).

In Washington State, most milled-in rumble strips have not adversely affected the surrounding pavement. However, there have been instances where milled-in rumble strips have been associated with accelerated pavement deterioration, leading to continuous ruts and large areas of pavement delamination. The Washington State DOT (WSDOT) hypothesis was similar to aforementioned cases: poor pavement existed prior to centerline rumble strips installation where significant pavement deterioration was observed. This was found in two types of pavement: bituminous surface treatment pavement and hot mix asphalt pavement with low density, particularly along longitudinal joints. WSDOT's response was that rumble strips installations should be limited to roadways with adequate pavement structure and thickness and avoided on open-graded pavements. In addition, WSDOT noted that it may be necessary to remove and inlay existing rumble strips prior to any resurfacing projects. Similar with other agencies, WSDOT's design manual suggests that roadway pavements should be structurally adequate to support milled-in rumble strips (*6*).

3.2.2 Roadway Visibility

As centerline rumble strips are often installed along the centerline, there is a concern for the potential of decreased visibility of the centerline striping (*11*). While night visibility may be improved due to the reflection of light from vehicles' headlights onto the far-side of the grooves of milled-in rumble strips, daytime visibility could be adversely affected. In addition, the nature of milled-in centerline rumble strips allows the accumulation of debris, such as salt and sand, in the grooves (*18*). This is potentially a problem in states that experience wintry weather and require salt or sand treatments; though the debris does not completely fill the grooves, it obscures part of the paint striping at the bottom, leading to reduced visibility of the paint markings during the day and making the solid lines look like dashed lines (*18*, *20*). Nonetheless, it was found that passing traffic typically cleared the grooves of debris (*20*).

3.3 General Public Concerns

In addition to pavement related concerns, centerline rumble strips have been a source of issues for members of the general public, including motorists who travel on roadways with centerline rumble strips and residents who live near these roadways.

3.3.1 Motorcyclists and Bicyclists

The primary concern regarding cyclists is the perception of danger when riding over the grooves of rumble strips. Two experiments regarding motorcyclists and bicyclists and rumble strips were conducted in Hokkaido, Japan, in 2002 and 2003. Through video recording and analysis, no dangerous driving or riding was identifiable. However, a questionnaire revealed that some drivers and riders felt unsafe when

riding over grooves around 0.59-inches (15-mm) deep. In Hokkaido, a rumble strips depth of 0.472-inches (12-mm) was adopted in response (*8*).

On the contrary, studies performed in the United States discovered that test track riders did not consider rumble strips to be a hazard. One study, performed by Kansas State University, evaluated cyclists' response by riding motorcycles over centerline rumble strips in Colorado and test sections in Kansas. The conclusion of the study was that centerline rumble strips did not pose a safety problem (*22*). A second study, based on a test track in Minnesota, found no evidence that centerline rumble strips were a hazard to 2- or 3-wheeled cycles. In fact, there was no recorded change in throttle, braking, or steering when driving over the strips and no evidence to indicate stability problems. Though a minority of riders considered the rumble strips to be a nuisance, most riders were neutral towards centerline rumble strips. Despite potential concerns, this study revealed that changes in the dimensions of rumble strips or additional signage were not justified. Rather, it was recommended that new cyclists become aware of the rumble strips early in their experience to ensure that they will be not alarmed at their first encounter (*15*).

3.3.2 Levels of Exterior Noise

The impacts of noise is a common source of complaint from residents near roadways with centerline rumble strips in addition to the effects noise may have on protected wildlife species (*37*). Though the noise produced by rumble strips is only intermittent and typically caused by errant vehicles, transportation agencies continue to receive complaints from nearby residents. As mentioned in previous sections, greater groove depth and width increases interior noise and vibration. Therefore, while any deepening or widening of the grooves would directly benefit the motorist, these changes come at an expense to the surrounding environment. In one instance, a shoulder rumble strips installation was heard over 250-feet away at a noise level above 80 dB (*26*). In another instance, a centerline rumble strips installation on U.S. Forest Service land in Colorado led to complaints regarding noise (*20*). Lastly, in Connecticut, the local transportation agency removed their installation of centerline rumble strips in response to complaints of excessive noise from nearby residents (*18*).

As a result, some agencies have factored the issue of noise into their centerline rumble strips design policies, recommending that minimum distances of centerline rumble strips installations from houses and businesses should be considered (*11*). These minimum distances range from 200-feet to 650-feet away from the center of the highway (*1*, *11*). On the contrary, though centerline rumble strips raised the noise level, some property owners concluded that its presence made driving safer and suggested they are willing to accept the levels of noise (*11*, *18*).

3.3.3 Driver Behavior

Though the presence of centerline rumble strips is to act as a countermeasure for drivers who may inadvertently cross the centerline, it has been hypothesized that the presence of the centerline rumble strips may negatively influence the lateral position of drivers, causing motorists to operate closer to shoulders and leading them to make erratic maneuvers (*11*). This can be attributed to motorists' dislike of the sound and vibration of rumble strips, or that rumble strips may damage to their vehicles (*5*).

Another unintended consequence of centerline rumble strips is driver unfamiliarity, especially in combination with drowsiness or inattention. This unfamiliarity has led nearly one-third of motorists to make an initial leftward correction of the vehicle upon encountering centerline rumble strips. This reaction occurred in approximately one-fifth of the time on tangent roadway segments to over one-third of the time on curved roadway segments. It is theorized that drivers react this way due to familiarity with shoulder rumble strips (*18*).

A third example of driver behavior modification is that while the centerline rumble strips prevents collisions where it is installed, the problem of head-on collisions still exists and may simply be transferred to areas without centerline rumble strips further down the roadway (*4*).

4.0 SURVEY DESIGN

The primary focus of the electronic survey portion of this study was to identify any adverse effects state DOTs may have experienced from centerline rumble strips, their response to these effects and any policies or procedures that they may have developed based on their experiences. In addition to investigating potential adverse effects of centerline rumble strips, the survey also sought to establish the current status of centerline rumble strips around the country. These objectives were accomplished through questions concerning the prevalence of centerline rumble strips within each state agency's jurisdiction, methods of centerline rumble strips installation, and the future of each agencies centerline rumble strips program. In addition, there were questions related to the type of roadway and the environments in which centerline rumble strips were installed. The non-maintenance related responses are listed along with the entire survey results in the Appendix. Because not every state DOT has centerline rumble strips, or has encountered issues with centerline rumble strips, the survey was designed so that only questions relevant to the particular state DOT were presented to the responder.

The survey was divided into seven categories (see Appendix). Each category enabled the responding agency to provide information about themselves and the current and future status of centerline rumble strips within their state. The seven categories were:

- Contact Information
- Centerline Rumble Strips Introduction
- Centerline Rumble Strips Installation Reasoning
- Centerline Rumble Strips Installation Detail
- Centerline Rumble Strips Issues
    - Accelerated Pavement Deterioration
    - Pavement Failure
    - Decreased Visibility of Paint Striping
    - Residential Related Issues
    - Other Issues
- Conclusions
- Thank You and Further Contacts

The survey was designed to dynamically direct a respondent through the survey based on the respondent's prior responses. If the respondent stated their state did not have centerline rumble strips installations, the survey would jump from Centerline Rumble Strips Introduction to Conclusions. Similarly, if the respondent

stated their state DOT encountered Centerline Rumble Strips Issues, the survey would take the respondent through the appropriate issues questions.

In order to investigate any potential adverse effects of centerline rumble strips, this survey was developed and coded into a commercial survey platform (SurveyMonkey®). Links to the survey were sent out to contacts identified within each State DOT via email. As no central list of contact persons specializing in centerline rumble strips for each state DOT was available, the survey contacts list was built in two steps. The first step utilized a list of contacts available online from a recent survey regarding centerline rumble strips (*24*). This contact list highlighted whether or not the state DOT responded to the survey. If the state DOT did not respond to the survey, contacts representing each state were found by searching various state DOT agencies' websites for persons specializing in safety, maintenance, or operations. If no contact could be found, a form was submitted to the agency requesting for a contact with centerline rumble strips experience to assist in this survey. Upon compilation of the contacts list, the survey link was emailed to each contact on September 16, 2013 with a specified closing date of October 4, 2013. During the three weeks in which the survey was open, new contact information was added as initial contacts responded with information of persons who were more qualified or in a better position to respond to the survey questions.

As of the initial deadline of October 5, 2013, twenty-four surveys had been completed. The deadline was then extended to October 19, 2013 and an additional reminder to the non-responsive contacts was sent. By the second deadline, four more surveys had been completed. Due to time constraints, the survey deadline was not extended further. However, as the survey is still open to responses.

5.0 SURVEY RESULTS

This survey sought to investigate potential adverse effects of centerline rumble strips by allowing respondents representing state DOTs to choose any of four preselected suspected issues and/or submit their own issues. In addition, this survey aimed to determine the current and future status of centerline rumble strips within each state DOT. The four preselected issues were chosen based on issues identified in the literature review detailed in Section 3. These issues were:

- Accelerated pavement deterioration (e.g., increased cracking)
- Pavement failure (e.g., section loss)
- Decreased visibility of paint striping (e.g., obscured by accumulated sand, decreased retro-reflectivity)
- Residential issues (e.g., excessive noise)
- Other adverse issues not listed above

Of the 28 state DOTs that responded, 10 state DOTs mentioned that they have experienced adverse issues associated with centerline rumble strips; the other 18 state DOTs did not mention experience with any issues. Figure 6 illustrates the state DOTs that responded to the survey (blue), which of the responding state DOTs that experienced adverse effects (red dashes), and which state DOTs have centerline rumble strips according to previous literature and surveys (blue stripes) (*11, 31, 36*).

5.1 Accelerated Pavement Deterioration

Accelerated pavement deterioration is indicated by a higher rate of deterioration on roadways with centerline rumble strips than on roadways without centerline rumble strips. This could be characterized by an increase in cracking, trenching, or rutting of the pavement surface. Of the 10 state DOTs that indicated experiencing adverse effects, five stated that accelerated pavement deterioration may have occurred due to centerline rumble strips; the extensiveness of this issue ranged from rare to occasional. The five state DOTs that have experienced this issue are Illinois, Iowa, Nebraska, Nevada, and Washington. The majority of these issues occurred on asphalt roadway, with one occurrence on concrete roadway (Nebraska) and one on bituminous surface treated roadways with low AADTs (Washington). In addition, some state DOTs had an issue with centerline joint deterioration due to flawed construction processes, where centerline rumble strips may or may not have been the primary contributor to this issue. Lastly, some state DOTs have concerns regarding accelerated pavement deterioration due to water ponding in the centerline rumble strips grooves and additional freeze/thaw stress on the joint. However, evidence of the issue was not documented.

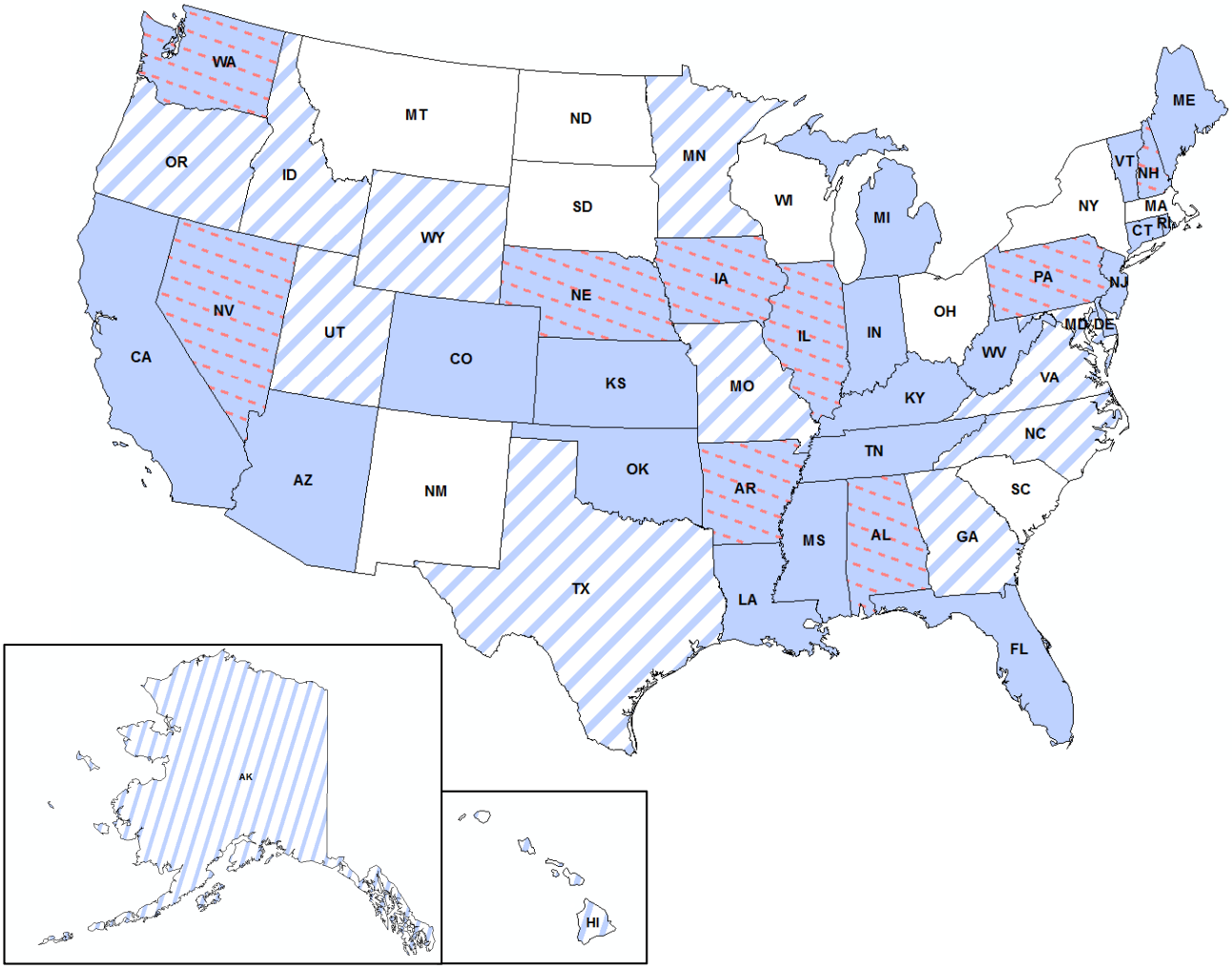

Figure 6: Survey Responses

Blue – Received Response and CLRS Presence

Blue Hatch – CLRS Presence (*11*, *31*, *36*)

Red Dashes – Experienced Adverse Issues due to CLRS

The responses to accelerated pavement deterioration varied from state DOT to state DOT, with some state DOTs responding in several ways. State DOT responses to accelerated pavement deterioration questions are detailed in Table 4.

Table 4: State DOT Reponses to Accelerated Pavement Deterioration Questions

State DOT	Suspected Cause of Accelerated Pavement Deterioration	Response to Accelerated Pavement Deterioration	Additional Details
Illinois	- Age of roadway	- No action taken	The failures this agency has seen have occurred on pavements which were several years old when the centerline rumble strips were milled in. This agency has not seen issues with centerline rumble strips installed into new pavements. However, all of these installations were fairly recent. This agency does have concerns with water ponding in the grooves and placing additional freeze/thaw stress on the joint. It will be watching this closely.
Iowa	- Age of roadway - Method of pavement design - This agency has general issues with centerline joint deterioration that is generally held as a flaw in its construction process.	- Uncertain - Centerline joint repair and reinstallation of rumbles	
Nebraska	- Age of roadway - Environmental conditions - Most damage is caused by milling rumble strips into older pavement, which leads to raveling and joint damage in hot mix asphalt and joint spalling in Portland cement concrete. There was one hot mix asphalt project that the mill head damaged the surface by peeling out the pavement in the heat of summer (100+ °F)	- Increased maintenance response - Resurfaced roadway and reinstalled centerline rumble strips	This agency currently uses dual, 8-inch rumble strips that straddle the centerline joint (2-inches on each side, 4-inches total between strips). The close proximity to the joint is a contributing factor to the damage. However, this agency is reluctant to change the design to introduce narrower rumble strip with additional width between the dual strips due to limited research.

Table 4 Continued on Next Page

Table 4 Continued

State DOT	Suspected Cause of Accelerated Pavement Deterioration	Response to Accelerated Pavement Deterioration	Additional Details
Nevada	- Age of roadway - Environmental conditions	- Uncertain	
Washington	- Method of CLRS installation - Uncertain at this time - Several issues appear to partly contribute to this problem. This agency's issues were primarily related to recessed pavement markers used in conjunction with milled-in rumble strips. This agency is seeing some "trenching" along the centerline rumble strips installations. Installation error in some cases with raised pavement markers being ground through rumbles or vice versa. Other issues may relate to asphalt binders and environmental conditions.	- Increased maintenance response - Resurfaced roadway and reinstalled CLRS - Resurfaced roadway and did not reinstall CLRS	

As Nebraska DOT indicated that their centerline rumble strips design policy has been revised, the respective respondent was contacted regarding the reasoning behind the change. Through a follow-up email, the respondent explained that achieving proper density at the centerline joint during hot mix asphalt concrete (HMA) pavement construction or resurfacing has always been a challenge as it results in a joint that is weaker than the rest of the pavement. In addition to newly resurfaced projects, there have been cases of existing milled-in rumble strips in HMA pavement that exhibited distresses. It has been hypothesized that grinding rumble strips into a typically weak area of the pavement that may or may not have existing distresses may exacerbate the problem of accelerated deterioration. Lastly, there have been cases of spalling in older concrete pavements due to grinding rumble strips into this type of pavement. Therefore, Nebraska DOT has since changed their design policy to a dual rumble strip design in an attempt to minimize damage to the centerline joint as explained in Table 4. Though this has not eliminated the problem, the design change has lessened the severity. While a narrower rumble strip with additional width between the dual strips may further minimize the problem and improve constructability, Nebraska DOT has been reluctant to further revise the design policy due to a lack of research on the effectiveness of such a design.

5.2 Pavement Failure

Pavement failure is characterized by section loss, which is exhibited by pavement falling apart or crumbling away at the centerline rumble strips; three state DOTs have experienced this issue: Nebraska, New Hampshire, and Washington. The respondents representing Nebraska and New Hampshire indicated that this issue was experienced on asphalt roadway, while in Washington this issue was present on bituminous surface treatments. State DOT responses to pavement failure related questions are detailed in Table 5.

Similar to the issue of accelerated pavement deterioration, pavement failure was typically thought to be attributed to the old age of the roadways on which the centerline rumble strips were installed, environmental conditions, the method of centerline rumble strips installation, or the method of pavement construction. Lastly, the agencies' responses to the issue of pavement failure included the increasing maintenance responses, resurfacing the roadway and reinstallation of centerline rumble strips, or resurfacing the roadway without the reinstallation of centerline rumble strips.

5.3 Other Issues

As stated in the literature review, the adverse effect of noise has been a common cause of concern of centerline rumble strips. Seven of the 10 state DOTs that experienced issues explicitly stated noise concerns as an issue, with extensiveness ranging from rare to occasional. Six of these seven state DOTs experienced noise issues from centerline rumble strips installed on asphalt pavement; Iowa experienced issues on bituminous surface treatment. Possible reasons for noise concerns include an increase of traffic volume and the presence of centerline rumble strips in passing zones or rural residential areas.

Table 5: State DOT Responses to Pavement Failure Questions

State DOT	Suspected Cause of Accelerated Pavement Deterioration	Response to Accelerated Pavement Deterioration	Additional Details
Nebraska	- Age of roadway - Environmental conditions - Method of centerline rumble strips installation	- Increased maintenance response - Resurfaced roadway and reinstalled centerline rumble strips	
New Hampshire	- Age of roadway	- Resurfaced roadway and reinstalled centerline rumble strips	There was a crash history on a segment of roadway in this agency but resurfacing dollars were not immediately available. The centerline rumble strips were milled in and the centerline joint broke apart. This agency is currently specifying joint adhesive during the paving process.
Washington	- Method of pavement design or construction	- Resurfaced roadway and did not reinstall centerline rumble strips	

Table 6: State DOT Reponses to Residential Issues Questions

State DOT	Suspected Cause of Residential Issues	Response to Residential Issues
Arkansas	- The presence of rumble strips in rural residential areas	- No action taken
Iowa	- Newness of rumble strips in the environment is the most frequent issue; calls subside in 2-3 months post installation.	- No action taken
Michigan	- Noise from vehicles passing in locations with centerline rumble strips	- No action taken - Refined installation policy to identify "suburban" locations where population was greater than in typical rural areas - Noise issues arise occasionally. We verify the installation is to our standard. If too deep or installed in locations that will be hit inadvertently (other than in passing zones) we have made adjustments.
Nebraska	- A few noise complaints would be reported regardless of pavement condition, type, etc.	- Explained to concerned parties safety benefits of rumble strips
Nevada	- Increased traffic volume	- No action taken
Pennsylvania	- Noise complaints	- Depending on the situation, sometimes breaks were placed in the pattern or left alone
Washington	- Most often in passing areas or horizontal curves	- Exterior and interior vehicle noise studies to examine possibilities for restriping, removing, and re-milling of CLRS

5.4 Future of Centerline Rumble Strips

Whether or not a state DOT experienced issues, most state DOTs have some reservations regarding the installation of additional centerline rumble strips. These results are summarized in Figure 7. These issues include increased maintenance requirements associated with centerline rumble strips, potential adverse effects to cyclists, adverse effects on driver behavior by causing motorists to keep a distance from the centerline and drive closer to the shoulder, and excessive noise produced when a vehicle drives over the rumble strips. Specific reservations regarding centerline rumble strips installation by state DOT are detailed in Table 7.

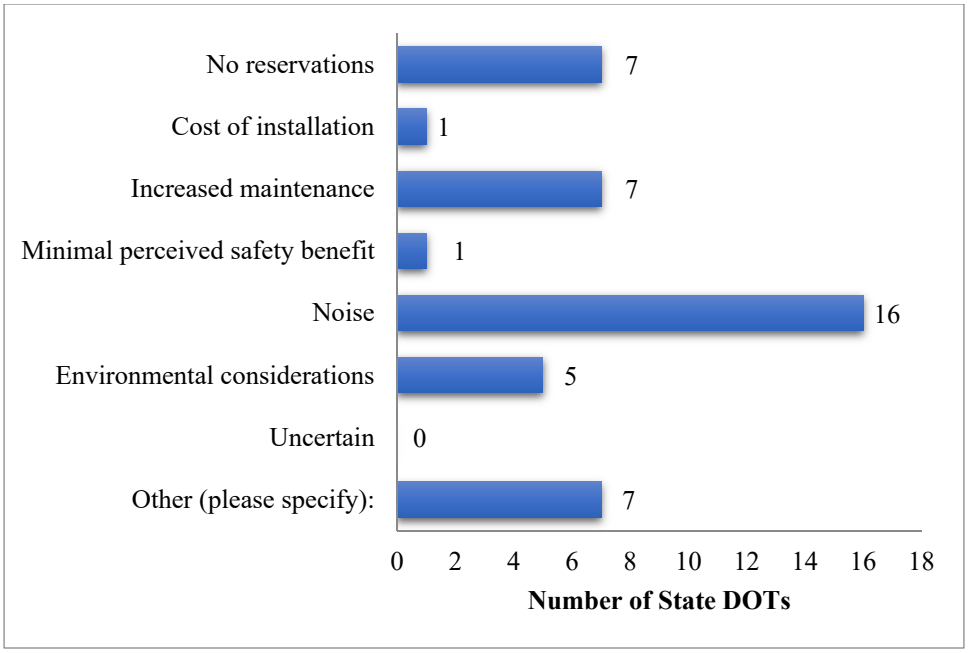

Figure 7: Reservations Regarding Centerline Rumble Strips Installation

Table 7: Reservations Regarding Centerline Rumble Strips Installation by State DOT

State DOT	Reservations Regarding CLRS Installation	Additional Details Provided by Respondents ("Other")
Alabama	- Environmental conditions	
Arizona	- Noise	Small diameter tire vibration during passing, particularly from motorcycles.
Arkansas	- Noise	
California	- Noise	There have not been significant maintenance issues with rumble strips installations. Noise is a concern and California DOT's policy guidance encourages installations which have breaks where autos make turning movements. Efforts are underway to test alternative depths and grind patterns to minimize audible noise outside the vehicle.
Colorado	- Noise	
Connecticut	- Noise	
Delaware	- Noise	
Florida	- Cost of installation	
Illinois	- Increased maintenance - Environmental conditions	
Indiana	- Increased maintenance - Noise	

Table 7 Continued on Next Page

Table 7 Continued

State DOT	Reservations Regarding CLRS Installation	Additional Details Provided by Respondents ("Other")
Iowa	- Increased maintenance - Minimal perceived safety benefit - Noise - Environmental conditions	
Kansas	- No reservations	
Kentucky	- No reservations	
Louisiana	- No reservations	
Maine	- Noise	
Michigan	- No reservations - Noise	
Mississippi	- Increased maintenance	
Nebraska	- Increased maintenance - Environmental conditions	
Nevada	- No reservations - Noise	
New Jersey	- No reservations	
New Hampshire	- No reservations	
Oklahoma	- Increased maintenance	Main concern for the Oklahoma DOT is the effect of the centerline rumble strips on asphalt pavement. Since the longitudinal joint is located in center of the pavement, the concern is the effect milling has on the joint.
Pennsylvania	- Noise	
Rhode Island	- Noise	
Tennessee	- Noise	Tennessee DOT has three concerns: - Forcing cars to the outside of the lane - The combination of centerline and edgeline rumbles - Overall complaints
Vermont	- Noise	Vermont DOT has not had huge concerns about the longevity of the pavement but noise has been the overwhelming source of issues on their current installations.
Washington	- Noise	With the exception of exterior noise issues and the few pavement issues, Washington state DOT has experienced that CLRS are a proven and effective low cost device to significantly cut ROTR collisions.
West Virginia		Potential increase in rate of pavement deterioration

Despite reservations, nearly every responding state DOT was either currently constructing centerline rumble strips or planning additional centerline rumble strips as summarized in Figure 8 and detailed in Table 8.

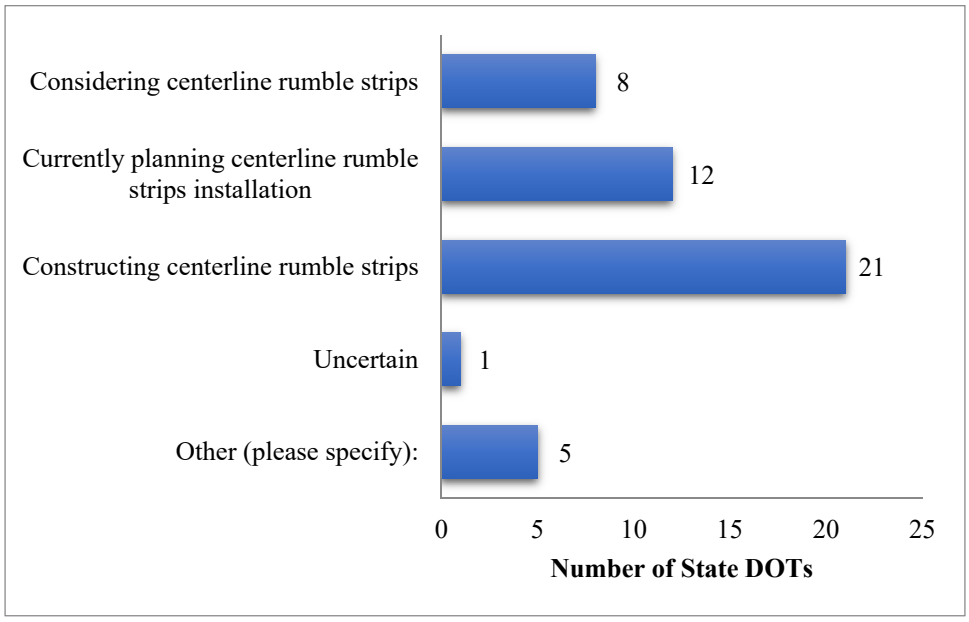

Figure 8: Future of Centerline Rumble Strips Program

Table 8: Position on Centerline Rumble Strips by State DOT

State DOT	Position on CLRS	Additional Details Provided by Respondents ("Other")
Alabama	- Considering additional CLRS - Planning CLRS installation - Constructing CLRS	Developing a design for use in Alabama that reduces the concern of water ponding and freezing.
Arizona	- Constructing CLRS	
Arkansas	- Planning CLRS installation	
California	- Constructing CLRS	
Colorado	- Constructing CLRS	
Connecticut	- Planning CLRS installation	Connecticut DOT has just completed the design of a project that will install centerline rumble strips at five locations on state roads
Delaware	- Constructing CLRS	
Florida	- Considering CLRS	
Illinois	- Considering additional CLRS - Planning CLRS installation - Constructing CLRS	
Indiana	- Constructing CLRS	
Iowa	- Considering additional CLRS - Planning CLRS installation - Constructing CLRS	
Kansas	- Constructing CLRS	
Kentucky	- Constructing CLRS	
Louisiana	- Constructing CLRS	
Maine	- Constructing CLRS	
Michigan	- Constructing CLRS	
Mississippi		Centerline rumble strips are considered in high cross-over or run-off-the-road to the left crash locations on a case by case basis.
Nebraska	- Planning CLRS installation - Constructing CLRS	
Nevada	- Constructing CLRS	
New Jersey	- Considering CLRS - Planning CLRS installation - Constructing CLRS	
New Hampshire	- Considering additional CLRS - Planning CLRS installation - Constructing CLRS	
Oklahoma	- Uncertain	

Table 8 Continued on Next Page

Table 8 Continued

State DOT	Position on CLRS	Additional Details Provided by Respondents ("Other")
Pennsylvania	- Considering additional CLRS - Planning CLRS installation	
Rhode Island	- Constructing CLRS	
Tennessee	- Considering CLRS - Planning CLRS installation	
Vermont	- Planning CLRS installation - Constructing CLRS	Vermont DOT is planning to use centerline rumble strips on a more systemic basis across its state highway network
Washington	- Planning CLRS installation - Constructing CLRS	
West Virginia	- Constructing CLRS	West Virginia DOT is trying to be selective and use centerline rumble strips where it will get the most benefit. Though West Virginia DOT has only placed centerline rumble strips for two years, it is pleased with its use so far.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the results of the literature review and survey as well as presenting the results of a brief forensic evaluation of the pavement failure along SR-369 in north Georgia at the location of a CLRS installation and recommendations for additional study.

6.1 Literature Review

With over 150-miles of centerline rumble strips on roadways throughout the state, Georgia has joined the ranks of states which utilize centerline rumble strips as a countermeasure to cross-centerline crashes, including head-on and opposite-direction sideswipe collisions. A number of factors can lead to the aforementioned crash types, the most common being inattentive or sleeping drivers, which accounted for 86% of fatal head-on crashes on two-lane highways. This statistic, coupled with characteristics of rural roads such as higher traffic speeds, lower rates of seatbelt use, and longer emergency response times, necessitates countermeasures such as centerline rumble strips. Though centerline rumble strips may be constructed in several forms, the majority of installations are of the milled-in type, as this type is cost effective and can be readily implemented on existing roadways. Furthermore, centerline rumble strips can be constructed directly on the centerline, extended into the travel lane, or on either side of the centerline pavement markings. In addition to preventing these crash types, centerline rumble strips may have the added benefits of improving safety in low visibility driving conditions, especially in areas with wintry weather or when the roadway markings are obscured.

There has been anecdotal evidence of adverse effects due to centerline rumble strips, including excessive external noise, accelerated pavement deterioration, or snow or ice removal issues. However, with the exception of noise, most adverse effects were not a major cause of concern. In the case of accelerated pavement deterioration, various studies suspect poor pavement prior to centerline rumble strips installation; for snow or ice removal issues, it was found that passing traffic generated enough force to pull debris, snow, or standing water from the grooves of the centerline rumble strips. Lastly, with the exception of select cases, the issue of noise has been addressed through changes to design policies and increased awareness of the benefits of centerline rumble strips to affected residents.

6.2 Survey

In order to investigate adverse effects of centerline rumble strips, a survey was developed and sent to the 50 state DOTs around the country with responses received from 28. The results of this survey indicated that most state DOTs were in favor of centerline rumble strips and were continuing to invest in

the implementation of centerline rumble strips. 10 out of the 28 state DOTs that responded indicated encountering adverse effects of centerline rumble strips. In agreement with the findings from the literature review, respondents attributed much of the increased maintenance to poor initial roadway conditions prior to centerline rumble strips installation.

In regards to specific issues, seven of the 28 state DOTs that responded to this survey experienced issues relating to the pavement on which centerline rumble strips were installed. Though these state DOTs suspected multiple causes for pavement related issues, common suspected causes were the age of the roadway or the method in which the roadway was paved. Secondly, while the frequency in which these issues occurred was not quantified, a common response to pavement related issues was to resurface the roadway and reinstall centerline rumble strips. Only WSDOT included the answer of "resurfaced the roadway and did not reinstall centerline rumble strips." However, WSDOT also responded with "increased maintenance response" and "resurfaced the roadway and reinstalled centerline rumble strips." Though pavement issues were cited by multiple state DOTs, the responses and suspected causes varied on a case-by-case basis. Therefore, future follow-up discussions with the respective state DOTs may be required to determine whether others have experienced similar issues faced by GDOT. One other specific issue encountered by many of the state DOTs was the issue of excessive noise from centerline rumble strips. 16 of the 28 state DOTs indicated noise as one of the reservations regarding future centerline rumble strips installation. As of 2014, only one state DOT has indicated that centerline rumble strips were removed solely due to noise complaints. Most other state DOTs responded to this issue by improving communication with local residents or simply waiting for complaints to subside. Lastly, several state DOTs noted that their installations of centerline rumble strips were implemented within the past five years and therefore have not had sufficient time for issues to arise.

6.3 Field Forensic Evaluation

As a part of this study the investigators, in cooperation with GDOT personnel, conducted a limited forensic evaluation of the pavement failure associated with the centerline rumble strip installation along SR-369 near Gainesville, GA. Three short sections of pavement were examined over an approximately one quarter mile interval. Each of the segments showed a dominant seam crack associated with centerline and an approximately two-foot wide band of associated fatigue cracks to either side. In the most severe areas, the surface (wear) layer was broken into approximately 10 cm (4 in) square segments that could be removed by hand. Approximately 10% of broken pavement segments were missing.

Four samples of the broken segments were removed by hand and examined as well as the underlying base layer. Both field observations and subsequent laboratory examination of the samples

showed each to be a full two-inch depth and failed to find any traces of a tack coat between the base of the sample and the underlying pavement. Based on these observations, it was hypothesized that the most likely cause of this pavement failure was a pre-existing pavement construction defect (missing bituminous tack coat) along the longitudinal joint exacerbated by the milling of the rumble strips and/or heavy truck traffic. Since each of these samples was collected near the pavement seam, the most likely explanation for the absence of the tack coat was that in the previous pavement overlay, the tack coat was improperly overlapped near the seam.

While these hypotheses are consistent with the field observations, additional testing and analysis will be required to establish to a high degree of certainty that this was the failure mechanism. Nevertheless, it seems highly likely that the pavement in this area was at least partially compromised before the milling of the centerline rumble strips. Further, while there is no direct evidence, it is believed to be unlikely that milling the centerline rumble strips into sound pavement would have resulted in the observed pavement failure.

6.4 Recommendations

As state DOTs recognize the benefits of centerline rumble strips, nearly every state DOT is currently planning or constructing centerline rumble strips despite the possibility of adverse effects. In addition, the literature review and survey results reveal, any adverse effects of centerline rumble strips appear to arise on a case-by-case basis rather than show up as a systematic issue. Thus, it is recommended that GDOT continue its centerline rumble strips program with several considerations and amendments to existing design policies regarding the pavement on which the centerline rumble strips will be installed, the strength of the longitudinal joint, and the effects of CLRS on nearby residents. In terms of the roadway health, the roadway should be verified to have been constructed or rehabilitated properly in order to minimize accelerated deterioration. Similarly, the strength of the longitudinal joint should be verified; if this is an issue, dual centerline rumble strips straddling the centerline joint such as those constructed in Nebraska should be considered. Lastly, as noise has been an issue encountered by many state DOTs, several design considerations should be taken into account. First, a minimum distance of the respective roadway to residents' homes should be taken into consideration. Second, the benefits and reasons for installing centerline rumble strips on the respective roadway should be publicized to residents living near the affected roadway. Third, the installation of centerline rumble strips in passing zones, horizontal curves, and driveway or plaza entrances should be examined on a case-by-case basis.

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A. APPENDIX: SURVEY AND RESPONSES

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Introduction

As a part of this study, a survey of all 50 state Departments of Transportation was conducted to determine the policies, procedures, and experiences, if any, that the various states had with the application of centerline rumble strips. Of special interest to this survey was to establish the prevalence of any perceived pavement maintenance issues similar to those associated with Georgia's application. The survey shown below was sent to representatives of all 50 state transportation DOTs in September, 2013. The individual state contacts were determined by various means including personal contacts, state DOT websites, contact forms and directories. This survey was conducted electronically using the Survey Monkey® website (https://www.surveymonkey.com/) and was sent to the various contacts via e-mail. If the contact did not respond within the month, a reminder e-mail was sent. As of March, 2014, contacts from 28 state DOTs had responded to the survey. These states are:

Alabama	Iowa	New Hampshire
Arizona	Kansas	Oklahoma
Arkansas	Kentucky	Pennsylvania
California	Louisiana	Rhode Island
Colorado	Maine	Tennessee
Connecticut	Michigan	Vermont
Delaware	Mississippi	Washington
Florida	Nebraska	West Virginia
Illinois	Nevada	
Indiana	New Jersey	

A text copy of this electronic survey is given below and a summary of the responses are given in the boxes below each question.

Survey

Contact Information

The Georgia Institute of Technology in Atlanta, GA, working in association with the Georgia Department of Transportation (GDOT), is investigating pavement failure along the centerline joint at several centerline rumble strip sites in the state of Georgia. As part of this investigation we are seeking to determine whether other transportation agencies have also experienced issues with roadways on which centerline rumble strips have been installed and any mitigation measures that may have been implemented.

To help obtain this information, we hope you will be willing to complete the attached survey, or if you are not the correct person to complete this survey, to direct us to the correct contact. The survey should take no more than 15 minutes.

The results of this survey will be used by Georgia Tech researchers and GDOT. You will have the opportunity to receive a final copy of this report.

Your participation and expertise are invaluable and we sincerely thank you for your time and responses. If you have any questions, please do not hesitate to email michael.hunter@ce.gatech.edu or jerome.sin@gatech.edu.

Note: Questions with an asterisk (*) require answers.

1. Contact Information:
    - Name:
    - Title:
    - Email:
    - Phone:
    - Agency/Organization:
2. What is your area of expertise?
   Please select all that apply.
    - Engineering
    - Maintenance
    - Safety
    - Other (please specify):

3. Mailing address:
4. Do you know other individuals within your agency with centerline rumble strips expertise? If so, please provide their contact information:

Table A- 1: Respondent's Area of Expertise

What is your area of expertise?		
Answer Options	Response Percent	Response Count
Engineering	89.3%	25
Maintenance	10.7%	3
Safety	42.9%	12
Other (please specify):	10.7%	3
Responses		28

Other (please specify):

- Construction, troubleshooting, pavement evaluations, distress surveys
- Materials
- Pavements and hot mix asphalt materials

For confirmation, this is an installation of centerline rumble strips (source: http://safety.fhwa.dot.gov/):

Figure A - 1: Centerline Rumble Strip Example

Centerline Rumble Strips Introduction

5. How prevalent are centerline rumble strips installation in your agency's jurisdiction? *Please select one.*
    - None
    - Rare
    - Occasional
    - Frequent
    - Extensive
    - Uncertain

Table A- 2: Prevalence of Centerline Rumble Strips in Respondent's Agency

How prevalent are centerline rumble strips installation in your agency's jurisdiction?		
Answer Options	Response Percent	Response Count
None	0.0%	0
Rare	32.1%	9
Occasional	32.1%	9
Frequent	17.9%	5
Extensive	17.9%	5
Uncertain	0.0%	0
Responses		28

Centerline Rumble Strips Installation Reasoning

6. Please identify any causal factors your agency is addressing with centerline rumble strips: *Please select all that apply.*
    - ☐ Inattentive or distracted driving
    - ☐ Drowsy driving
    - ☐ Noticeability of centerline in inclement weather conditions
    - ☐ Noticeability of centerline in changes to roadway geometry (e.g. horizontal curvature)

- High benefit to cost ratio
- Test trial / study / evaluation
- Encouragement from FHWA
- Uncertain
- Other (please specify):

Table A- 3: Causal Factors Addressed by Centerline Rumble Strips

Please identify any causal factors your agency is addressing with centerline rumble strips:		
Answer Options	Response Percent	Response Count
Inattentive or distracted driving	85.7%	24
Drowsy driving	82.1%	23
Noticeability of centerline in inclement weather conditions	42.9%	12
Noticeability of centerline in changes to roadway geometry (e.g., horizontal curvature)	28.6%	8
High benefit to cost ratio	50.0%	14
Test trial / study / evaluation	39.3%	11
Encouragement from FHWA	25.0%	7
Uncertain	3.6%	1
Other (please specify):	14.3%	4

Other (please specify):

- Volume thresholds are part of the criteria for this transportation agency. It is generally held that there is not a lower cost alternative for preventing cross-centerline lane departure crashes, and is justified to address the random occurrence of this type of crash.
- Lane departures.
- This agency has been trying to address areas where there are high accident rates and the likelihood of vehicles crossing centerline is more prominent and leading to accidents. This agency's terrain is varied with low lying areas along rivers and high, hilly, mountainous terrain, both of which are subject to limited visibility due to heavy fog conditions and/or limited sight distance. The installation of centerline rumble strips has helped with driver awareness as vehicles navigate these locations.
- This agency was an early adopter of centerline rumble strips; centerline rumble strips have proven to be a cost effective tool.

7. Please identify any crash types your agency is addressing with centerline rumble strips:
   Please select all that apply.
   - ☐ Front-end/head-on collisions
   - ☐ Opposite-direction side-swipe collisions
   - ☐ Left-side run-off-the-road collisions
   - ☐ None of the above
   - ☐ Uncertain
   - ☐ Other (please specify):

Table A- 4: Crash Types Addressed by Centerline Rumble Strips

Please identify any crash types your agency is addressing with centerline rumble strips:		
Answer Options	Response Percent	Response Count
Front-end / head-on collisions	92.9%	26
Opposite-direction side-swipe collisions	82.1%	23
Left-side run-off-the-road collisions	60.7%	17
None of the above	0.0%	0
Uncertain	3.6%	1
Other (please specify);	3.6%	1

Other (please specify):

- Systematic approach to improve safety.

Centerline Rumble Strips Installation Details

8. What method(s) does your agency utilize to install centerline rumble strips?
   Please select all that apply.
   - ☐ Milled-in (cut into asphalt)
   - ☐ Formed (pressed into concrete)
   - ☐ Rolled (pressed into hot asphalt)
   - ☐ Uncertain
   - ☐ Other (please specify):

Table A- 5: Methods Used to Install Centerline Rumble Strips

What method(s) does your agency utilize to install centerline rumble strips?		
Answer Options	Response Percent	Response Count
Milled-in (cut into asphalt)	100.0%	28
Formed (pressed into concrete)	3.6%	1
Rolled (pressed into hot asphalt)	3.6%	1
Uncertain	0.0%	0
Other (please specify):	7.1%	2

Other (please specify):

- Milled-in into concrete as well.
- Previously used rolled but not any longer.

9. Of the above choices, which, if any, is the predominant installation method of your agency? *Please select one.*
    - Milled-in
    - Formed
    - Rolled
    - No predominant installation method
    - Uncertain
    - Other (please specify):

Table A- 6: Predominant Installation Method of Centerline Rumble Strips

Of the above choices, which, if any, is the predominant installation method of your agency?		
Answer Options	Response Percent	Response Count
Milled-in (cut into asphalt)	96.4%	27
Formed (pressed into concrete)	0.0%	0
Rolled (pressed into hot asphalt)	0.0%	0
No predominant installation method	3.6%	1
Uncertain	0.0%	0
Other (please specify):	0.0%	0

10. On what type of roadway(s) are your agency's centerline rumble strips installed?

Please select all that apply.

- ☐ Rural
- ☐ Urban
- ☐ Uncertain
- ☐ Other (please specify):

Table A- 7: Roadway Types of Centerline Rumble Strips Installation

On what type of roadway(s) are your agency's centerline rumble strips installed?		
Answer Options	Response Percent	Response Count
Rural	96.4%	27
Urban	17.9%	5
Uncertain	0.0%	0
Other (please specify):	10.7%	3

Other (please specify):

- Iowa: This agency has installed centerline rumble strips outside of incorporated city limits.
- Louisiana: This agency is installing centerline rumble strips on roadways with speed limits of 50 mph or greater. If the roadway is in an urbanized area, centerline rumble strips are only placed based on crash analyses.
- Vermont: This agency has published guidelines that direct the installation towards areas that are not built up and have lower housing densities.

11. Does your agency have specifications for centerline rumble strips design and/or placement?

Please select one.

- Agency has specifications
- Agency does not have specifications
- Uncertain if agency has specifications

Table A- 8: Existence of Specifications for Centerline Rumble Strips Design/Placement

Does your agency have specifications for centerline rumble strips design and/or placement?		
Answer Options	Response Percent	Response Count
Agency has specifications	89.3%	25
Agency does not have specifications	10.7%	3
Uncertain if agency has specifications	0.0%	0

Centerline Rumble Strips Issues

12. Has your agency had issues with centerline rumble strips such as (but not limited to):

    Please select one.

    - Accelerated pavement deterioration (e.g. increased cracking)
    - Pavement failure (e.g. section loss)
    - Decreased visibility of paint striping (e.g. sand, decreased retro-reflectivity)
    - Residential issues (e.g. excessive noise)
    - Other adverse issues not listed above

    - Yes
    - No, please skip to question 30.
    - Uncertain

Table A- 9: Presence of Issues Associated with Centerline Rumble Strips

Has your agency had issues with centerline rumble strips such as (but not limited to): - Accelerated pavement deterioration (e.g., increased cracking) - Pavement failure (e.g., section loss) - Decreased visibility of paint striping (e.g., sand, decreased retro-reflectivity) - Residential issues (e.g., excessive noise) - Other adverse issues not listed above		
Answer Options	Response Percent	Response Count
Yes	35.7%	10
No	32.1%	9
Uncertain	32.1%	9

Issue 1: _____

13. Has your agency had issues with **Issue 1** on roadways with centerline rumble strips?

    Please select one.

    - Yes
    - No
    - Uncertain

14. How extensive is **Issue 1** on roadways with centerline rumble strips?

    Please select one.

    - Rare
    - Occasional
    - Frequent
    - Extensive
    - Uncertain

15. On what type of pavement has **Issue 1** occurred?

    Please select all that apply.

    - ☐ Asphalt
    - ☐ Concrete
    - ☐ Uncertain
    - ☐ Other (please specify):

16. What cause(s) has your agency determined for **Issue 1**?

    Please select all that apply.

    - ☐ Age of roadway
    - ☐ Environmental conditions (e.g. freeze/thaw cycle, water ponding, etc.)
    - ☐ Method of centerline rumble strips installation
    - ☐ Method of pavement design or construction
    - ☐ Increased traffic volume
    - ☐ Uncertain at this time

17. What was your agency's response to **Issue 1**? (please select all that apply)
    - Increased maintenance response
    - Resurfaced roadway and reinstalled centerline rumble strips
    - Resurfaced roadway and did not reinstall centerline rumble strips
    - No action taken
    - Uncertain
    - Other (please specify):
18. Please share any additional details you wish to provide regarding **Issue 1:**

Issue 2: _____

19. Has your agency had issues with **Issue 2** on roadways with centerline rumble strips?

    Please select one.
    - Yes
    - No
    - Uncertain
20. How extensive is **Issue 2** on roadways with centerline rumble strips?

    Please select one.
    - Rare
    - Occasional
    - Frequent
    - Extensive
    - Uncertain
21. On what type of pavement has **Issue 2** occurred?

    Please select all that apply.
    - ☐ Asphalt
    - ☐ Concrete
    - ☐ Uncertain
    - ☐ Other (please specify):

22. What cause(s) has your agency determined for **Issue 2**?

    Please select all that apply.

    - ☐ Age of roadway
    - ☐ Environmental conditions (e.g. freeze/thaw cycle, water ponding, etc.)
    - ☐ Method of centerline rumble strips installation
    - ☐ Method of pavement design or construction
    - ☐ Increased traffic volume
    - ☐ Uncertain at this time

23. What was your agency's response to **Issue 2**? (please select all that apply)

    - Increased maintenance response
    - Resurfaced roadway and reinstalled centerline rumble strips
    - Resurfaced roadway and did not reinstall centerline rumble strips
    - No action taken
    - Uncertain
    - Other (please specify):

Please share any additional details you wish to provide regarding **Issue 2:**

Issue 3: _____

24. Has your agency had issues with **Issue 3** on roadways with centerline rumble strips?

    Please select one.

    - Yes
    - No
    - Uncertain

25. How extensive is **Issue 3** on roadways with centerline rumble strips?

    Please select one.

    - Rare
    - Occasional
    - Frequent
    - Extensive
    - Uncertain

26. On what type of pavement has **Issue 3** occurred?

    Please select all that apply.

    - ☐ Asphalt
    - ☐ Concrete
    - ☐ Uncertain
    - ☐ Other (please specify):

27. What cause(s) has your agency determined for **Issue 3**?

    Please select all that apply.

    - ☐ Age of roadway
    - ☐ Environmental conditions (e.g. freeze/thaw cycle, water ponding, etc.)
    - ☐ Method of centerline rumble strips installation
    - ☐ Method of pavement design or construction
    - ☐ Increased traffic volume
    - ☐ Uncertain at this time

28. What was your agency's response to **Issue 3**? (please select all that apply)

    - Increased maintenance response
    - Resurfaced roadway and reinstalled centerline rumble strips
    - Resurfaced roadway and did not reinstall centerline rumble strips
    - No action taken
    - Uncertain
    - Other (please specify):

Please share any additional details you wish to provide regarding **Issue 3:**

Responses to *Issues Identified* Questions:

Accelerated Pavement Deterioration

Table A- 10: Extensiveness of Accelerated Pavement Deterioration

How extensive is accelerated pavement deterioration?		
Answer Options	Response Percent	Response Count
Rare	20.0%	1
Occasional	60.0%	3
Frequent	0.0%	0
Extensive	0.0%	0
Uncertain	20.0%	1

Table A- 11: Pavement Type on Which Accelerated Pavement Deterioration Occurred

On what type of pavement has accelerated pavement deterioration occurred?		
Answer Options	Response Percent	Response Count
Asphalt	80.0%	4
Concrete	20.0%	1
Uncertain	0.0%	0
Other (please specify)	40.0%	2

Other (please specify):

- Asphalt with chip seal
- Bituminous surface treatment routes with AADTs below 5,000

Table A- 12: Causes Agency Has Determined for Accelerated Pavement Deterioration

What causes has your agency determined for accelerated pavement deterioration?		
Answer Options	Response Percent	Response Count
Age of roadway	80.0%	4
Environmental conditions	40.0%	2
Method of CLRS installation	20.0%	1
Method of pavement design	20.0%	1
Increased traffic volume	0.0%	0
Uncertain at this time	20.0%	1
Other (please specify):	60.0%	3

Other (please specify):

- Iowa: This agency has general issues with centerline joint deterioration that is generally held as a flaw in its construction process
- Nebraska: Most damage is caused by milling rumble strips into an older pavement, which leads to raveling and joint damage in hot mix asphalt and joint spalling in Portland cement concrete. There was one hot mix asphalt project that the mill head damaged the surface by peeling out the pavement in the heat of summer (100+ °F).
- Washington: Several issues appear to partly contribute to this problem. This agency's issues were primarily related to recessed pavement markers used in conjunction with milled-in rumble strips. This agency is seeing some "trenching" along the centerline rumble strips installations. Installation error in some cases with raised pavement markers being ground through rumbles or vice versa. Other issues may relate to asphalt binders and environmental conditions.

Table A- 13: Agency's Response to Accelerated Pavement Deterioration

What was your agency's response to accelerated pavement deterioration?		
Answer Options	Response Percent	Response Count
Increased maintenance response	40.0%	2
Resurfaced roadway and reinstalled CLRS	40.0%	2
Resurfaced roadway and did not reinstall CLRS	20.0%	1
No action taken	20.0%	1
Uncertain	40.0%	2
Other (please specify):	20.0%	1

Other (please specify):

- Centerline joint repair and reinstallation of centerline rumble strips.

Please share any additional issues you wish to provide regarding accelerated pavement deterioration.

- Illinois: The failures this agency has seen have occurred on pavements which were several years old when the centerline rumble strips were milled in. This agency has not seen issues with centerline rumble strips installed into new pavements. However, all of these installations were fairly recent. This agency does have concerns with water ponding in the grooves and placing additional freeze/thaw stress on the joint. It will be watching this closely.
- Nebraska: This agency currently uses dual, 8-inch rumble strips that straddle the centerline joint (2-inches on each side, 4-inches total between strips). The close proximity to the joint is a contributing factor to the damage. However, this agency is reluctant to change the design due to limited research.

Pavement Failure

Table A- 14: Presence of Pavement Failure Issues

Has your agency had issues with pavement failure?		
Answer Options	Response Percent	Response Count
Yes	30.0%	3
No	70.0%	7
Uncertain	10.0%	1

Table A- 15: Extensiveness of Pavement Failure

How extensive is pavement failure?		
Answer Options	Response Percent	Response Count
Rare	100.0%	3
Occasional	0.0%	0
Frequent	0.0%	0
Extensive	0.0%	0
Uncertain	0.0%	0

Table A- 16: Pavement Type on Which Pavement Failure Occurred

On what type of pavement has pavement failure occurred?		
Answer Options	Response Percent	Response Count
Asphalt	66.7%	2
Concrete	0.0%	0
Uncertain	0.0%	0
Other (please specify)	33.3%	1

Other (please specify):

- Washington: Multiple lifts of bituminous surface treatment and milled through roadbed at a few locations on a single mountainous recreational route.

Table A- 17: Causes Agency Has Determined for Pavement Failure

What causes has your agency determined for pavement failure?		
Answer Options	Response Percent	Response Count
Age of roadway	66.7%	2
Environmental conditions	33.3%	1
Method of CLRS installation	33.3%	1
Method of pavement design	33.3%	1
Increased traffic volume	0.0%	0
Uncertain at this time	0.0%	0
Other (please specify):	0.0%	0

Table A- 18: Agency's Response to Pavement Failure

What was your agency’s response to accelerated pavement deterioration?		
Answer Options	Response Percent	Response Count
Increased maintenance response	33.3%	1
Resurfaced roadway and reinstalled CLRS	66.7%	2
Resurfaced roadway and did not reinstall CLRS	33.3%	1
No action taken	0.0%	0
Uncertain	0.0%	0
Other (please specify):	0.0%	0

Please share any additional issues you wish to provide regarding pavement failure.

- New Hampshire: There was a crash history on a segment of roadway in this agency but resurfacing dollars were not immediately available. The centerline rumble strips were milled in and the centerline joint broke apart. This agency is currently specifying joint adhesive during the paving process.

Decreased Visibility of Paint Striping

Table A- 19: Presence of Decreased Visibility of Paint Striping

Has your agency had issues with decreased visibility of paint striping?		
Answer Options	Response Percent	Response Count
Yes	10.0%	1
No	90.0%	9
Uncertain	10.0%	1

Table A- 20: Extensiveness of Decreased Visibility of Paint Striping

How extensive is decreased visibility of paint striping?		
Answer Options	Response Percent	Response Count
Rare	100.0%	1
Occasional	0.0%	0
Frequent	0.0%	0
Extensive	0.0%	0
Uncertain	0.0%	0

Table A- 21: Pavement Type on Which Decreased Visibility of Paint Striping Occurred

On what type of pavement has decreased visibility of paint striping occurred?		
Answer Options	Response Percent	Response Count
Asphalt	100.0%	1
Concrete	0.0%	0
Uncertain	0.0%	0
Other (please specify)	0.0%	0

Table A- 22: Causes Agency Has Determined for Decreased Visibility of Paint Striping

What causes has your agency determined for decreased visibility of paint striping?		
Answer Options	Response Percent	Response Count
Age of roadway	100.0%	1
Environmental conditions	0.0%	0
Method of CLRS installation	0.0%	0
Method of pavement design	0.0%	0
Increased traffic volume	0.0%	0
Uncertain at this time	0.0%	0
Other (please specify):	0.0%	0

Table A- 23: Agency's Response to Decreased Visibility of Paint Striping

What was your agency’s response to decreased visibility of paint striping?		
Answer Options	Response Percent	Response Count
Increased maintenance response	100.0%	1
Resurfaced roadway and reinstalled CLRS	0.0%	0
Resurfaced roadway and did not reinstall CLRS	0.0%	0
No action taken	0.0%	0
Uncertain	0.0%	0
Other (please specify):	0.0%	0

Residential Issues

Table A- 24: Presence of Residential Issues

Has your agency had residential issues?		
Answer Options	Response Percent	Response Count
Yes	70.0%	7
No	20.0%	2
Uncertain	10.0%	1

Table A- 25: Extensiveness of Residential Issues

How extensive are residential issues?		
Answer Options	Response Percent	Response Count
Rare	28.6%	2
Occasional	71.4%	5
Frequent	0.0%	0
Extensive	0.0%	0
Uncertain	0.0%	0

Table A- 26: Pavement Type on Which Residential Issues Occurred

On what type of pavement has residential issues occurred?		
Answer Options	Response Percent	Response Count
Asphalt	85.7%	6
Concrete	0.0%	0
Uncertain	14.3%	1
Other (please specify)	14.3%	1

Other (please specify):

- Bituminous surface treated roadways.

Table A- 27: Causes Agency Has Determined for Residential Issues

What causes has your agency determined for residential issues?		
Answer Options	Response Percent	Response Count
Age of roadway	0.0%	0
Environmental conditions	0.0%	0
Method of CLRS installation	0.0%	0
Method of pavement design	0.0%	0
Increased traffic volume	14.3%	1
Uncertain at this time	14.3%	1
Other (please specify):	85.7%	6

Other (please specify):

- Arkansas: The presence of rumble strips in rural residential areas.
- Iowa: The newness of the rumble strips in an environment is the most frequent issue. Calls of complaints subside in 2-3 months after installation.
- Nebraska: A few noise complaints would be reported regardless of pavement condition, type, etc.
- Michigan: Noise from vehicles passing in locations with centerline rumble strips.
- Pennsylvania: Noise complaints.
- Washington: Most often in passing areas or horizontal curves.

Table A- 28: Agency's Response to Residential Issues

What was your agency's response to residential issues?		
Answer Options	Response Percent	Response Count
Increased maintenance response	0.0%	0
Resurfaced roadway and reinstalled CLRS	0.0%	0
Resurfaced roadway and did not reinstall CLRS	0.0%	0
No action taken	57.1%	4
Uncertain	0.0%	0
Other (please specify):	57.1%	4

Other (please specify):

- Michigan: Refined installation policy to identify "suburban" locations where the population was greater than typical rural areas.
- Nebraska: Explained to the concerned parties the safety benefits of centerline rumble strips.
- Pennsylvania: Depending on the situation, sometimes breaks were placed in the pattern or left alone.
- Washington: Exterior and interior vehicle noise studies; examined possibilities for restriping, removing, and re-milling centerline rumble strips.

Please share any additional issues you wish to provide regarding residential issues.

- Michigan: Noise issues arise occasionally. This agency verifies the installation is to its standard. If the centerline rumble strips are too deep or installed in locations that will be hit inadvertently (other than in passing zones), this agency has made adjustments.

Other Adverse Issues

Table A- 29: Presence of Additional Adverse Issues

Has your agency had issues with other adverse issues?		
Answer Options	Response Percent	Response Count
Yes	10.0%	1
No	90.0%	9
Uncertain	10.0%	1

This was an open-ended question. One agency, Alabama, remarked that it had issues regarding the shying away of motorists from the centerline on rural routes due to centerline rumble strips, which resulted in pavement edge and shoulder damage.

Table A- 30: Extensiveness of Driving Behavior Change

How extensive is driving behavior change?		
Answer Options	Response Percent	Response Count
Rare	0.0%	0
Occasional	0.0%	0
Frequent	100.0%	1
Extensive	0.0%	0
Uncertain	0.0%	0

Table A- 31: Pavement Type on Which Driving Behavior Change Occurred

On what type of pavement has driving behavior change occurred?		
Answer Options	Response Percent	Response Count
Asphalt	100.0%	1
Concrete	0.0%	0
Uncertain	0.0%	0
Other (please specify)	0.0%	0

Table A- 32: Causes Agency Has Determined for Driving Behavior Change

What causes has your agency determined for driving behavior change?		
Answer Options	Response Percent	Response Count
Age of roadway	0.0%	0
Environmental conditions	0.0%	0
Method of CLRS installation	0.0%	0
Method of pavement design	0.0%	0
Increased traffic volume	100.0%	1
Uncertain at this time	0.0%	0
Other (please specify):	100.0%	1

Other (please specify):

- Lane width.

Table A- 33: Agency's Response to Driving Behavior Change

What was your agency's response to driving behavior change?		
Answer Options	Response Percent	Response Count
Increased maintenance response	0.0%	0
Resurfaced roadway and reinstalled CLRS	0.0%	0
Resurfaced roadway and did not reinstall CLRS	0.0%	0
No action taken	0.0%	0
Uncertain	0.0%	0
Other (please specify):	100.0%	1

Other (please specify):

- Widened shoulder.

End Responses to *Issues Identified* Questions

Conclusions

29. What is the future of your agency's centerline rumble strips program?

    Please select all that apply.

    - ☐ Considering additional centerline rumble strips
    - ☐ Currently planning additional centerline rumble strips
    - ☐ Constructing centerline rumble strips
    - ☐ Continued upkeep of installed centerline rumble strips
    - ☐ Uncertain
    - ☐ Other (please specify):

Table A- 34: Future of Agency's Centerline Rumble Strips Program

What is the future of your agency's centerline rumble strips program?		
Answer Options	Response Percent	Response Count
Considering additional centerline rumble strips	28.6%	8
Currently planning additional centerline rumble strips installation	42.9%	12
Constructing centerline rumble strips	75.0%	21
Continued upkeep of installed centerline rumble strips	25.0%	7
Uncertain	3.6%	1
Other (please specify):	17.9%	5

Other (please specify);

- This agency is developing a design for use that reduces the concern of water ponding and freezing.
- This agency is planning to use centerline rumble strips on a more systematic basis across its state highway network.
- This agency is trying to be selective and using centerline rumble strips where they would get the most benefit. It is concerned about the potential for increase in rate of pavement deterioration. However, this agency has taken great steps to improve its longitudinal joint density so it hopes it does not see advanced deterioration. This agency has only placed centerline rumble strips for two years, so it does not have enough time to fully answer this. However, this agency is pleased with the use so far.
- Centerline rumble strips are considered in high cross-over or run-off-the-road to the left crash locations on a case by case basis.
- This agency has just completed design of a project that will install centerline rumble strips at five locations on state roads beginning in the spring of 2013. Up until now, there have not been additional installations.

30. What reservations does your agency have in installing additional centerline rumble strips? *Please select all that apply.*

- ☐ No reservations
- ☐ Cost of installation
- ☐ Increased maintenance
- ☐ Minimal perceived safety benefit
- ☐ Noise
- ☐ Environmental considerations (e.g. water ponding)
- ☐ Uncertain
- ☐ Other (please specify):

Table A- 35: Reservations in Installing Centerline Rumble Strips

What reservations does your agency have in installing additional centerline rumble strips?		
Answer Options	Response Percent	Response Count
No reservations	25.0%	7
Cost of installation	3.6%	1
Increased maintenance	25.0%	7
Minimal perceived safety benefit	3.6%	1
Noise	57.1%	16
Environmental considerations (e.g., water ponding)	17.9%	5
Uncertain	0.0%	0
Other (please specify)	25.0%	7

Other (please specify)

- Centerline rumble strips force cars to the outside of the lane
- The combination of centerline and edgeline rumble strips
- Overall complaints
- This agency has not had huge concerns about the longevity of the pavement but noise has been the overwhelming source of issues on its current installations.
- Potential increase in rate of pavement deterioration.
- Small diameter tire vibration during passing.
- Adverse effects towards motorcyclists.
- The main concern for this agency is the effect of centerline rumble strips on asphalt pavement. Since the longitudinal joint is located in the center of the pavement, its concern is the effect of milling at the joint.
- There have not been significant maintenance issues with rumble trips installation with this agency. Noise is a concern and this agency's policy guidance encourages installations which have breaks where automobiles make turning movements. Efforts are underway to test alternative depths and grind patterns to minimize audible noise outside the vehicle.

31. What studies has your agency conducted that involves centerline rumble strips?

Please select all that apply.

- ☐ Safety
- ☐ Maintenance
- ☐ Our agency has not conducted any studies on centerline rumble strips
- ☐ Uncertain

Table A- 36: Studies Agency has Conducted Involving Centerline Rumble Strips

What studies has your agencies conducted that involve centerline rumble strips?		
Answer Options	Response Percent	Response Count
Safety	50.0%	14
Maintenance	17.9%	5
Our agency has not conducted any studies on centerline rumble strips	35.7%	10
Uncertain	10.7%	3

32. Please leave any additional comments you or your agency has regarding centerline rumble strips:

Additional Comments

- California: This agency, as an early adopter of centerline rumble strips, presented data from its installations to a study by the Insurance Institute for Highway Safety.
- Connecticut: Centerline rumble strips were installed on a 0.6-mile section of a route in 1999 but were removed in 2000 due to noise complaints. This agency has not installed centerline rumble strips on state roads since then. This agency will have additional installations beginning in 2014.
- Louisiana: This agency has some concern with milling over joints. No definite conclusion on whether or not it speeds deterioration. Glad to see this is being investigated.
- Oklahoma: This agency is observing the maintenance issue and effect, if any, on kits experimental project locations.
- Mississippi: An independent organization is currently studying this agency's centerline rumble strips program, which were mostly installed after the awarding of a Rural Safety Innovation Program Grant.
- New Jersey: Currently this agency has constructed centerline rumble strips at two specific locations that were targeted for their use. It is in the process of developing standards which include details, specifications and design guidance for their use. This agency expects this to be in place in the fall of 2013. At that time, centerline rumble strips will be specified as a standard on all construction projects with particular roadway characteristics. The questions answered in this survey were based on this agency's current very limited use of centerline rumble strips at only two locations. Any information received relative to pavement performance will be forwarded to our Pavement Management Bureau identified earlier.
- Vermont: This agency's oldest centerline rumble strips have not been in place for too long so it does not have long term experience with pavement distress. This agency did look at crash reduction in the corridors where they have been installed.
- West Virginia: This agency has only placed centerline rumble strips over the past two to three years. Responses have been positive from motorists and internal personnel. It has definitely forced drivers to not cross over the centerline as often as they normally would. Evaluation is still on going.

Thank You

33. May we contact you for additional information or questions regarding your answers?

Please select one.

- Yes
- No
- No, please contact this individual (name, title, e-mail, phone number):

Table A- 37: Opportunity for Additional Information Regarding Centerline Rumble Strips

May we contact you for additional information or questions regarding your answers?		
Answer Options	Response Percent	Response Count
Yes	96.4%	27
No	0.0%	0
No, please contact this individual	3.6%	1

34. Would you like to receive a copy of the final report or are you interested in receiving further information?

Please select one.

- Yes
- No

Table A- 38: Desire for Respondent to Receive a Copy of This Report

Would you like to receive a copy of the final report or are you interested in receiving further information?		
Answer Options	Response Percent	Response Count
Yes	96.4%	27
No	3.4%	1