REPORT 2015 - 07

VERMONT AGENCY OF TRANSPORTATION

Research and Development Section
Research Report

EVALUATION OF THE EFFECTIVENESS OF CENTERLINE RUMBLE STRIPES ON RURAL ROADS

Report 2015 – 07

March 2015

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Reporting on RAC SPR-714

STATE OF VERMONT
AGENCY OF TRANSPORTATION

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
2015-07	- - -	- - -

4. Title and Subtitle EVALUATION OF THE EFFECTIVENESS OF CENTERLINE RUMBLE STRIPES ON RURAL ROADS	5. Report Date MARCH 2015 6. Performing Organization Code
7. Author(s) Wendy M. Ellis	8. Performing Organization Report No. 2015-07
9. Performing Organization Name and Address Vermont Agency of Transportation Materials and Research Section 1 National Life Drive National Life Building Montpelier, VT 05633-5001	10. Work Unit No. 11. Contract or Grant No. RAC SPR-714
12. Sponsoring Agency Name and Address Federal Highway Administration Division Office Federal Building Montpelier, VT 05602	13. Type of Report and Period Covered 2009-2013 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report documents the site characteristics, constructability, summary of audibility testing, and maintenance response of centerline rumble stripes at two locations: US Route 4 in Mendon-Killington and VT Route 105 in Sheldon.

The primary objective of this research initiative was to evaluate the effectiveness of centerline rumble stripes in reducing lane departure crashes and improving the safety of undivided roadways. Ease of installation was documented along with the design of the rumble stripes in conjunction with the adjacent pavement markings. In addition, the long-term performance of rumble stripes is assessed. Criteria included overall durability and wear resistance in new or aged pavement. Differing snowfall environments as well as winter maintenance practices were identified as contributing factors.

Results at the Mendon-Killington location are promising, showing a reduction of crossover crashes and associated injuries. Crossover crashes decreased from an annual average of 12.86 to 7.2, a 44 percent reduction. Injuries decreased from an average of 7.8 to 4, a 48.6 percent decrease. Sheldon saw a slight decrease in the annual average of crossover crashes of 2.63 to 2.25. Due to the small pool of data for evaluation at the site, the data is not statistically significant.

Sound level readings were recorded in the A-weighted decibel scale using a Pass-by evaluation method detailed in this report. All values were under OSHA's Permissible Exposure Limits (PEL) of 90 dBA. The noise levels did not decrease as the rumbles wore down. Readings in Mendon-Killington were approximately 10 dB higher than in Sheldon, possibly due to pavement age and CLRS dimensions. As expected the tandem dump truck produced the largest readings, averaging 89.7 dBA in Mendon-Killington, followed by the pick-up at 84.3 dBA and the passenger car at 81.0 dBA. The same vehicle types in Sheldon produced readings of 80 dBA, 77.5 dBA, and 73 dBA respectively.

The maintenance districts response is positive. Although it is reported that it does take more effort to clear snow from the CLRS, it does help keep drivers off the centerline and in their own lane. District contacts noted that no complaints have been received from area residents regarding noise and although both locations have worn-in, areas still provide the awareness that motorists need if they hit the centerline. No repairs have been required at either location.

17. Key Words	18. Distribution Statement
Centerline Rumble Stripes, Safety	No Restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. Pages	22. Price
- - -	- - -		- - -

Form DOT F1700.7 (8-72) **Reproduction of completed pages authorized**

EXECUTIVE SUMMARY

VTrans is deploying Centerline Rumble Stripes (CLRS) in a concerted effort to improve safety on two-lane bidirectional highways. A CLRS is a semi-circular depression in the pavement on the centerline area. Commonly centerline pavement markings are placed upon or directly adjacent to the rumble stripe. The rumble stripe depth may vary from a quarter inch depth to more than one half inch depth. Patterns for rumple stripes used in VT rely on a 7 inch width semi-circle.

The study found that rumble stripes have different sounds intensities based on pavement type, depth and vehicle type. Rumble stripes have two mechanisms that actively alert a driver to centerline presence – there is an audible sound as the tire strikes the rumble stripes and there is an active vibration in the vehicle steering wheel. The combination of auditory and tactile sensing promotes rapid driver awareness.

Crash analysis from the two sites evaluated demonstrates reduction in the total number of crashes and the proportion associated with centerline crossover events. The post installation data set is not large enough to compare averaging before and after the CLRS, although summation on a rolling four-year period confirms effectiveness. There were decreases in the number of injury events and fatal events after installation. Noise evaluation for the projects suggests that there is not any wear-in reduction in noise level. The increase in sound level was inversely proportional to the vehicle size and base sound level. Passenger cars, which were quietest on pavement, increased the most, while a tandem truck increased the least. The noise data demonstrated that configuration of the rumble stripes could affect noise levels by as much as double from one project to another. Costs associated with the installation of rumble stripes are insignificant when considered against resurfacing costs. Rumble stripes cost less to install than a permanent pavement marking, although they cost more than paint markings designed to last one year.

The response to the rumble stripes in these locations rural and commercial was favorable. Highway operations staff noted that there were some changes needed to clear the rumble stripes. Revisions to salt application rate and position accommodated the needs. Rumble stripes are a low cost, easily created highway technology that yielded measurable safety benefits. Wide spread deployment with attention to the rumble stripe configuration to address noise level is recommended.

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ABSTRACT

This report documents the site characteristics, constructability, summary of audibility testing, and maintenance response of centerline rumble stripes at two locations: US Route 4 in Mendon-Killington and VT Route 105 in Sheldon.

The primary objective of this research initiative was to evaluate the effectiveness of centerline rumble stripes in reducing lane departure crashes and improving the safety of undivided roadways. Ease of installation was documented along with the design of the rumble stripes in conjunction with the adjacent pavement markings. In addition, the long-term performance of rumble stripes is assessed. Criteria included overall durability and wear resistance in new or aged pavement. Differing snowfall environments as well as winter maintenance practices were identified as contributing factors.

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INTRODUCTION

In Vermont, nearly 4,000 crashes have occurred where vehicles have crossed the centerline, resulting in 94 deaths since 2009 (*1*). These types of crashes are not unique to Vermont; they are resulting in many fatalities nationwide. According to the Federal Highway Administration (FHWA,) there has been a downward trend of highway fatalities across the United States. Although this is encouraging, data shows there are still thousands of deaths annually (*2*). Many factors can impact the severity of a crash. These factors include roadway geometry, driver behavior, climatic conditions and vehicle factors. Crossover crashes are largely severe in nature.

In an effort to reduce the total number of crashes, FHWA selected three focus areas including Roadway Departures, Intersection-Related and Pedestrian-Related crashes. The combination of these crash types accounted for 86.2 percent of all crashes in 2010 (*3*). In 2011 the largest percentage of crashes were classified in the roadway departure category. There were 15,307 fatal roadway departure crashes in the United States, resulting in 16,948 deaths, accounting for 51 percent of all fatal crashes that year alone (*4*). FHWA defines a roadway departure crash as, "*A non-intersection crash in which a vehicle crosses an edge line, a centerline, or otherwise leaves the traveled way*." (*2*)

FHWA issued a memorandum, dated July 10, 2008 providing guidance and encouraging highway officials to prioritize safety by incorporating roadway enhancements on every federally funded highway project to address the outstanding number of roadway departure crashes. The memorandum listed several countermeasures to accelerate safety goals one of which was the use of centerline rumble strips or stripes (CLRS) (*5*). Guidelines for the design and installation of this countermeasure were released in Technical Advisory T 5040.40 by FHWA on November 7, 2011. The guidelines characterize CLRS as a countermeasure to assist distracted, drowsy or otherwise inattentive drivers who unintentionally stray over the centerline. The document notes that studies such as NCHRP Report 641 show that CLRS improve the drivers' chances of a quick and safe return to their lane. Because of the increased safety this countermeasure provides, FHWA has recommended that CLRS be installed system-wide (*6*). Many states under the recommendations and guidance of FHWA have chosen to install CLRS on highway improvement projects.

The Vermont Agency of Transportation (VTrans) is considering installing CLRS on every State highway where appropriate. However due to limited local historical data regarding these safety enhancements, installations are limited to certain conditions. An important consideration is balancing safety benefits with environmental impacts from noise.

Installations are considered where the pavement width is 28 feet or greater with a 3-foot shoulder, speed limit is 45 mph or higher, Average Daily Traffic is a minimum of 1,500 vehicles per day, or if crash history indicates a pattern of head-on, sideswipe, or single vehicle crashes. Since 2009, VTrans has installed 114 miles of CLRS along five major routes including US Route 2, US Route 4, US Route 7, VT Route 9 and VT Route 105 (*1*).

Since CLRS are a new concept in Vermont with mixed perception of their worthiness, this research initiative aimed to evaluate the first two installations and their effectiveness in reducing crossover crashes and improving the safety of undivided roadways in association with roadway characteristics. To determine the effectiveness of CLRS in Vermont the evaluation included six components:

1) Survey of States
2) Literature Review
3) Crash Data Analysis
4) Field Data Collection
5) Sound/Noise Level Analysis
6) Cost Effectiveness

SURVEY OF STATES

A survey of states concerning CLRS design, installation and effectiveness was conducted, specifically focusing on states with cold climates. States were asked to share their experiences with rumble stripes to provide any guidance regarding common procedures and practices that may have been helpful in our data collection and organization.

Usage

The following states replied to the survey: Louisiana, Kentucky, Connecticut, California, Hawaii, Maryland, Arkansas, Iowa, Pennsylvania, Texas, Alabama, North Dakota, Michigan, Arizona, Delaware, New Jersey, Virginia, Alaska and Oregon. Out of the twenty-one states that replied, nineteen of them utilize CLRS techniques. Some are still in the experimental stages of use, while others have been implementing them for over twenty years.

Installation

On average, centerline rumble stripes across these states had been observed for ten years. Milled depths varied slightly, but most are ½-inch deep. Alaska, Michigan, Arizona and Iowa's stripes are ⅜-inch and some states allow up to ⅝-inch depth. Half the states accept the technique of installing CLRS over the centerline joint in the pavement. The types of retroreflective markings placed over the milled rumble stripes were not consistent, as they ranged from Methyl Methacrylate (MMA), Waterborne, Thermoplastic and Epoxy.

Noise Levels

Some states have received noise complaints regarding the rumble stripes, but they reported that these complaints are relatively minimal. Overall, the states reported that driver response had been primarily positive for cars, vans and pickup trucks.

Crash Data

Nine of the participating states reported a decreased number of crashes in the areas where they had installed rumble stripes. The remaining states noted they did not have enough data to make their conclusions at the time of the survey.

LITERATURE REVIEW

At the beginning of the project a literature review was conducted to determine details of other studies and if any advancements had been made to design, installation processes, or evaluation methods. Through extensive document review, although CLRS are considered cost effective, further research should be done to obtain specific information pertaining to their effects in Vermont. While installations of CLRS have shown a positive effect in many states, areas such as evaluating the wear from winter maintenance practices, determining sound level effects, and summarizing local crash reductions need more research.

PROJECT LOCATION SUMMARY

Two projects incorporating centerline rumble stripes were included in this research initiative, one on existing pavement as part of a statewide pavement marking restriping project and one on new pavement as part of a paving project. Both projects were programmed for the 2009-construction season by the Traffic Safety and Design Section, however due to scheduling and the American Reinvestment and Recovery Act (ARRA) of 2009, the project incorporating stripes on new pavement was postponed to the 2010 construction season.

Each site was visited prior to construction to establish test site locations and document the condition of the pavement prior to construction. Pavement condition surveys including crack mapping and photographs to document each test site were completed.

Mendon-Killington

In 2009, L&D Safety Markings Corporation applied centerline rumble stripes into existing pavement along US Route 4 starting from mile marker MM 1.650 in Mendon, Vermont and extended easterly to mile marker MM 2.050 in Killington, Vermont for a total of 6.33 miles, as part of the Statewide NHG MARK (203) pavement marking restriping project. According to the project plans, work performed included grinding centerline rumble stripes, new pavement markings including centerlines, edge-lines, lane lines, dashed and dotted acceleration and deceleration lanes, gore markings, ramp edge-lines, stop bars and stop letters, symbols, and crosswalks (*7*).

Prior to installing the CLRS, a total of 101 injuries and 5 fatalities resulted from 208 total crashes from 2002 to 2009 (*9*). The Annual Average Daily Traffic (AADT) averaged 10,675 over this time (*10*).

The dimensions of the CLRS installed at this location were 7 inches x 16 inches and 0.5 inches deep. The detail is shown in Figure 1. They were installed at approximately 1-foot offset from the present location of the centerline. The placement design is shown in Figure 2 and Figure 3.

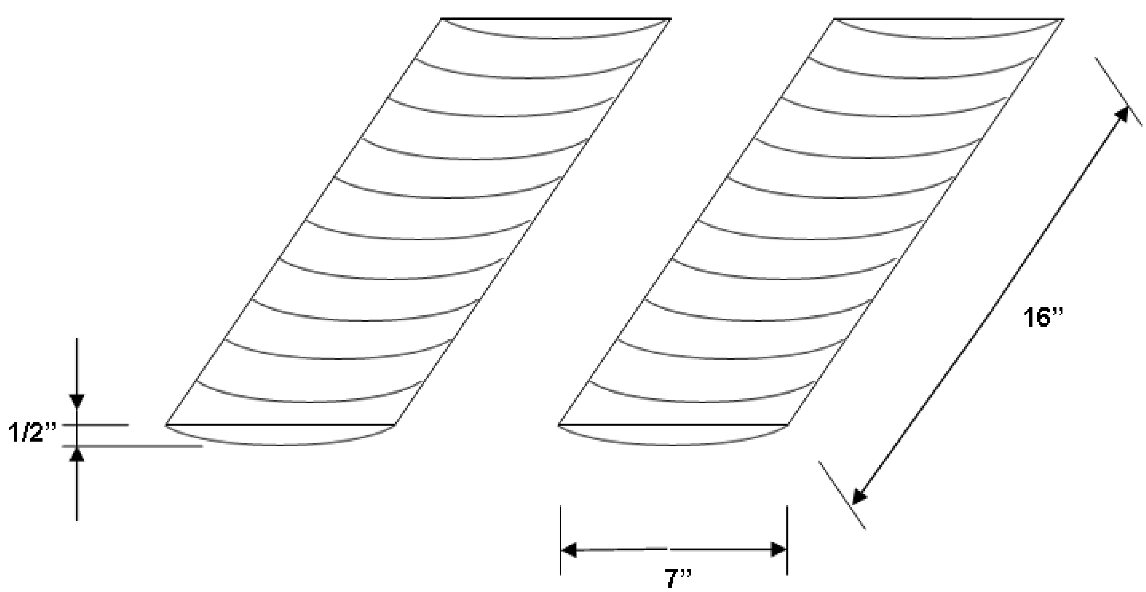

Figure 1: Mendon-Killington CLRS Dimensions.

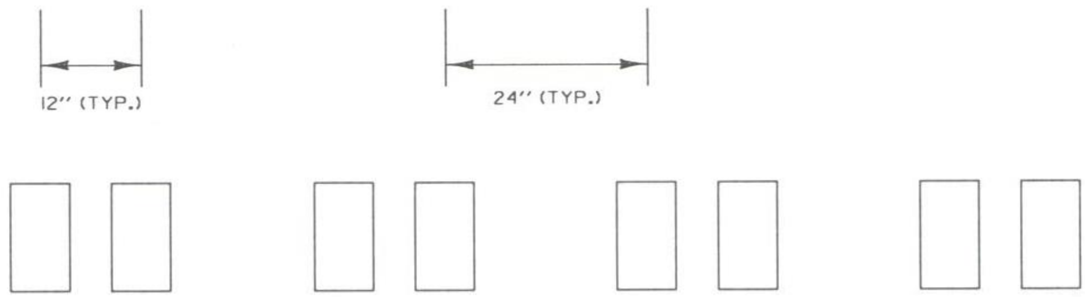

Figure 2: Rumble stripe spacing.

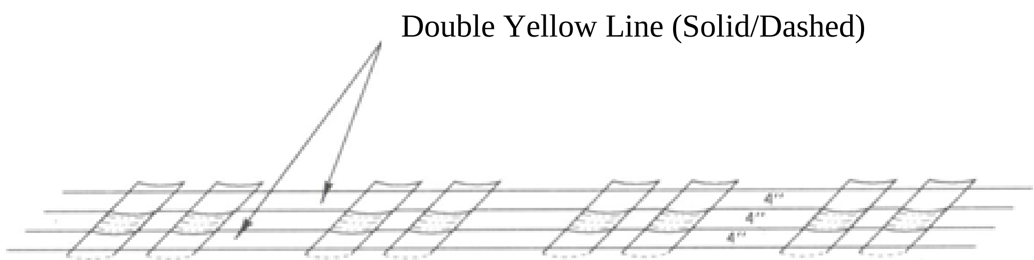

Figure 3: Rumble stripe design.

As per the project plans, waterborne paint was used for pavement markings on the Mendon-Killington project. The plans also called for the CLRS to be installed approximately 1-foot from the existing centerline, breaking where they cross the paving joint. However, during the preconstruction meeting held on August 20, 2009 the Contractor pointed out that it would be unlikely that the milling and striping could be done in one day and there were not any line striping targets specified in the plans. This was concerning because it introduced a safety hazard where the rumble stripes would be without any markings, not alerting motorists to their presence. To solve this issue, representatives from Pavement Management, Traffic Safety and Operations, and Construction concluded that it was best to leave the centerline location "*as is*", and that any milling and restriping would be done directly over the existing lines.

Sheldon

Over the 2010 construction season, L&D Safety Marking Corporation, the pavement marking sub-contractor for Pike Industries installed centerline rumble stripes in the 50 mph speed zones on Vermont Route 105 as part of the Sheldon-Enosburg STP 2714 (1) pavement rehabilitation project. According to the project plans, work performed under this project included resurfacing of the existing highway with a leveling course and new wearing course, new pavement markings, guardrail, signs, grinding centerline rumble stripes, and other incidental items. The paving project began at mile marker MM 2.000 in Sheldon and extended easterly for 9.479 miles, ending at mile marker MM 0.476 in Enosburg. CLRS were installed in Sheldon on approximately 6 miles of the total 9.479 miles paved, excluding residential and lower speed areas (*8*).

Prior to installing the CLRS, a total of 37 injuries and 4 fatalities resulted from 68 total crashes from 2002 to 2010 (*9*). The Annual Average Daily Traffic (AADT) averaged 5,500 over this time (*10*).

The dimensions of the CLRS installed at this location were 7 inches x 12 inches and 0.5 inches deep. The detail is shown in Figure 4. The placement design was the same as constructed along the Mendon-Killington project, shown in Figure 2 and Figure 3.

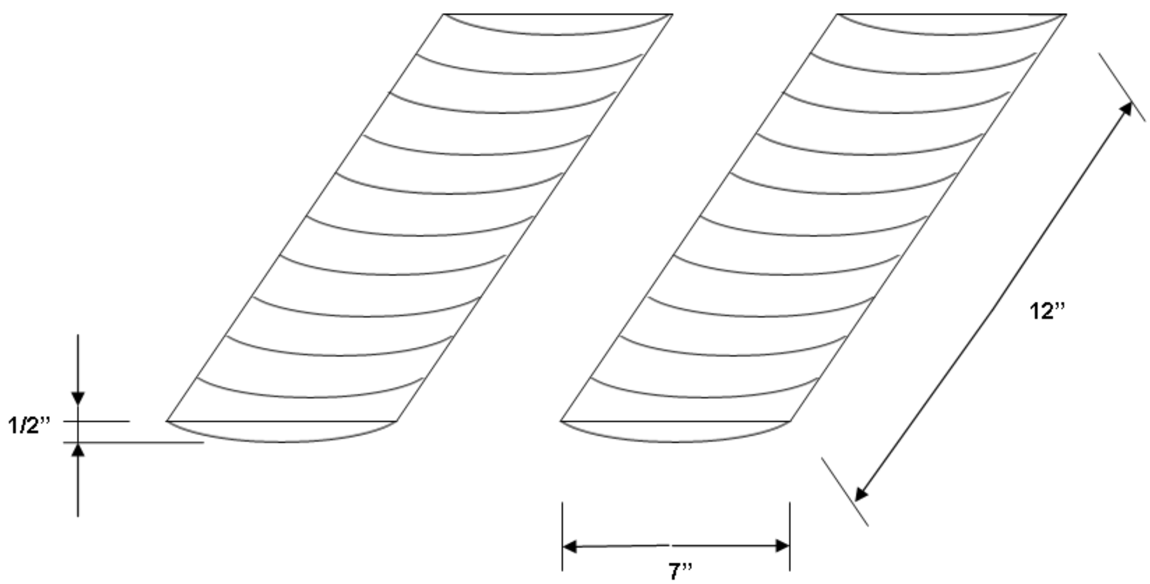

Figure 4: Sheldon CLRS Dimensions.

During the Sheldon-Enosburg pre-construction conference held in the spring of 2010 it was noted that the specified marking to be used was thermoplastic. However, according to the Vermont 2006 Standard Specifications for Constructions, Specification 646.07(c), "*Durable Pavement Markings – Thermoplastic*," shall be applied to the pavement through screed extrusion. Through the process, the bottom of the extrusion shoe is in direct contact with the pavement and the top and other three sides are contained by, or are part of, suitable equipment for maintaining the temperature and controlling the flow of material. The fourth side of the shoe contains the extrusion opening. Due to the application method, depths and spacing of the rumbles, it was uncertain that the markings could be applied properly as per the specification. Instead, polyurea was selected to replace thermoplastic for the centerline marking to eliminate the specification conflict. Pavement Management, Research, Traffic Safety and Design, and the contractor chose the order of proper construction. The recess for the polyurea pavement markings was first completed, followed by milling the rumble stripes, and then the rumble stripes were marked with spray-applied polyurea.

CONSTRUCTION

Mendon-Killington

The entire length of the rumble stripes was completed by Thomas Grinding on Friday, October 9th, 2009, with the milling machine shown in Figure 5 and Figure 6. Weather conditions were overcast and the air temperature was 50ºF. After the milling machine ground the stripes, the stripes were swept by BD Sweeping. All sweeping operations were conducted directly after milling, shown in Figure 7. Figure 8 shows the rumble stripes after milling and sweeping processes finished.

Figure 5: Milling machine.

Figure 6: Milling machine

Figure 7: Street sweeper

Figure 8: Rumble stripes after milling and sweeping.

L&D Safety Markings Corporation completed all pavement marking striping operations on Monday, October 12. According to www.wunderground.com, weather conditions were recorded as clear with a mean temperature of 38ºF; the temperature was approximately 45ºF at noon (*11*). Research personnel were unable to be onsite for striping operations therefore no photographs were taken, however photos were taken at the first site visit following installation (See Figure 9).

Figure 9: Centerline rumble stripes approximately one month after installation in Mendon, VT.

Sheldon

In an attempt to extend the duration for retroreflectivity of the polyurea durable pavement markings, L&D Safety Markings Corporation recessed along the centerline for the pavement markings on Monday, July 12, 2010 and Tuesday, July 13, 2010. The subcontractor then milled the rumbles on Monday, July 19, 2010 from MM 5.200 to 11.015. The rumble stripes were then swept and the subcontractor applied polyurea along the centerline on Wednesday, July 21, 2010. According to www.wunderground.com, weather conditions were recorded as clear with a mean temperature of 70ºF; the temperature was approximately 81ºF at noon (*11*). The centerline rumble stripes are shown in Figure 10.

Figure 10: Centerline rumble stripes immediately after painting in Sheldon, VT.

MAINTENANCE RESPONSE

The maintenance districts in which the two rumble stripe projects were located, District 3 and 8, were contacted throughout the study to gain their feedback regarding the CLRS. Both districts provided positive feedback regarding the CLRS and noted that although it does take longer to clear snow from the CLRS it helps keep drivers off the centerline and in their own lane. Dwight Robtoy, District 8 Transportation Area Maintenance Supervisor stated,

> "*At first I didn't like the CLRS because it was hard to get the snow cleared from the rumbles but since the installation in Sheldon I've seen a decrease in potential accidents along this route and people tend to stay in their own lane* (*12*)."

In some cases, having the CLRS in place has aided in winter maintenance. Bruce Nichols, District 3 General Maintenance Manager noted,

> "*The main reason I like it is during snow storms it has helped me several times find the lane I needed to be in. When a storm is over and we are salting to clean the road up it keeps traffic in their lane to drive in the salt we have already applied which helps the salt work faster* (*13*)."

Both district contacts also noted no receipt of complaints from area residents regarding noise. Although both locations have worn in areas, rumble stripes still provide the awareness that motorists need if they hit the centerline. No repairs have been required at either location.

CRASH DATA ANALYSIS

The 2005 NCHRP Synthesis 339 found that head-on and opposite direction, sideswipe injury crashes were reduced by an estimated 25 percent at sites treated with centerline rumble strips or stripes (*14*). VTrans crash data contains information summarizing each crash including location information, contributing circumstances, type of collision, and the number of injuries and fatalities.

For the purposes of this analysis, VTrans 2002-2014 crash data was utilized to perform a cross-sectional analysis of both sites prior to and following installation of the CLRS. The two CLRS locations do not share common roadway characteristics such as number of lanes, lane widths, CLRS dimensions, climatic regions, and AADT, therefore the sites were analyzed individually because these differences can result in dissimilar driver behavior as well. For each site, various potential explanatory variables for each crash including weather conditions, time of day, time of year, type of crash, and reason for each crash was examined to determine any changes in the number of crashes, injuries, and fatalities before and after the CLRS installations.

It is important to note that these results do not account for the incidents not reported where motorists hit the CLRS and avoided crashing their vehicle. To compare each site equally for before and after installation, the year of which each project was constructed was excluded from individual analysis.

Crash types include Head On, Opposite Direction Side Swipe, Same Direction Side Swipe, Single Vehicle Crash, Rear End, Broadside and Other. For this analysis all crashes where the vehicle causing the crash crossed into the wrong lane of traffic regardless of type of crash was included in the head on crash total for each year.

Mendon-Killington

Crash Reduction

A total of 189 crashes were reported along US Route 4 in Mendon-Killington prior to the installation of CLRS in the 9 years from 2002 to 2008. Head on crashes, including other types of crashes where vehicles crossed into the wrong lane of traffic accounted for 90 of the 189 total crashes during this period, equaling 47.6 percent. After installation, a total of 77 crashes occurred in the five years between 2010 and 2014. Of these, head on collisions totaled 36, resulting in less than a 1 percent proportional reduction of head on crashes. Although this percentage is not promising, it is important to note that the average overall crash total and head on crash total per year both decreased. Head on crashes decreased from 12.86 to 7.20 crashes per year. These were reductions in annual rates of head-on crashes by 46 percent and overall crashes by 43 percent.

Table 1 summarizes the annual number of crashes and percentage of head on and wrong lane collisions along US Route 4 in Mendon-Killington.

Total Crossover Crashes

Figure 11 shows the number of crossover crashes per year both before and after the CLRS were installed. Although the crash total in 2011 was similar to totals reported prior to the installation of the CLRS, there is a downward trend of crashes of this type in all other years following installation.

Annual Crash Rate

The AADT and total number of crashes reported were utilized to calculate the probability of a crash occurring along the stretch of roadway per 1 million vehicles. First, the annual traffic was calculated using the AADT for each individual year. The traffic count totaled 27,521,000 vehicles from 2002 to 2008. The total number of crashes during this time was 191. This equals a crash rate of 6.94 crashes per 1 million vehicles. After the CLRS were installed, there were 17,045,500 vehicles and 92 crashes, equaling 5.4 crashes per 1 million vehicles, a 22 percent reduction in total crashes. Figure 12 shows the average crash rate per 1 million vehicles for both before and after the CLRS installation.

Table 1: Percentage of Head On/Wrong Lane Crashes in Mendon-Killington from 2002 to 2014.

Year	Head On/Wrong Lane	Other	Overall Total	% of Head On/Wrong Lane Crashes
2002	8	9	17	47.1%
2003	11	19	30	36.7%
2004	10	13	23	43.5%
2005	19	18	37	51.4%
2006	13	18	31	41.9%
2007	15	18	33	45.5%
2008	14	4	18	77.8%
Total	**90**	**99**	**189**	**47.6%**
Avg. per Year	**12.86**	**14.14**	**27.00**	
2010	7	9	16	43.8%
2011	12	10	22	54.5%
2012	5	8	13	38.5%
2013	7	5	12	58.3%
2014	5	9	14	35.7%
Total	36	41	77	46.8%
Avg. per Year	**7.20**	**8.20**	**15.40**	

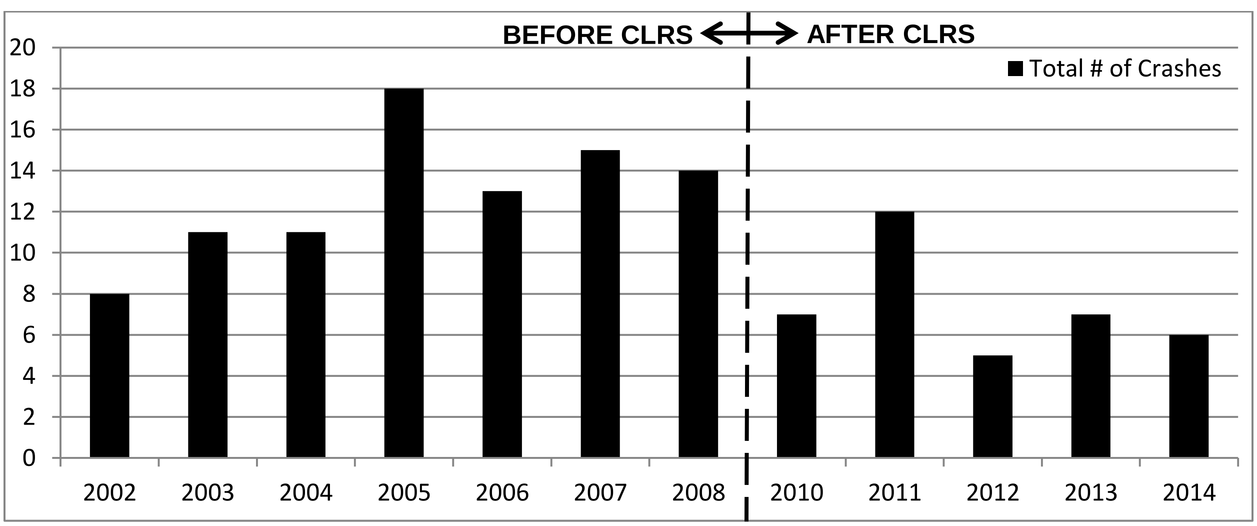

Figure 11: Total number of crossover crashes in Mendon-Killington from 2002-2014.

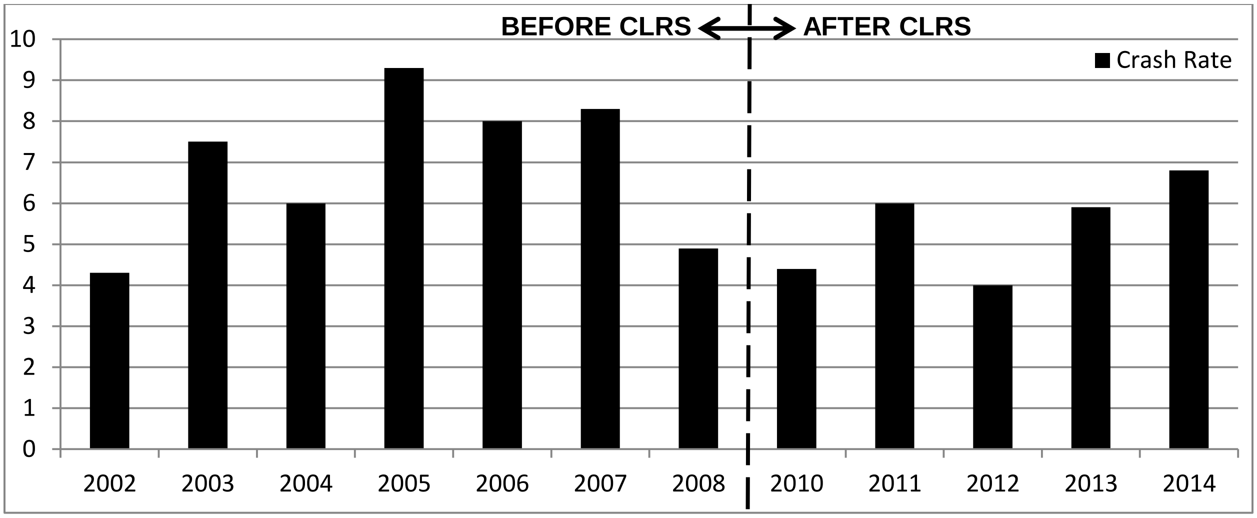

Figure 12: Annual crash rate (Number of all crashes per 1 million vehicles) in Mendon-Killington from 2002 to 2014.

<u>Reported Injury Analysis</u>

Prior to the CLRS installation there were 62 total injuries resulting from crossover crashes from 2002 to 2008, averaging 7.78 injuries per year. After the installation, there were 20 injuries from 2010 to 2014, averaging 4 injuries per year, a reduction of 48.57 percent. Figure 13 shows the number of injuries per year from 2002 to 2014. Fatalities are far less common than injuries at the site, two prior the CLRS and one after.

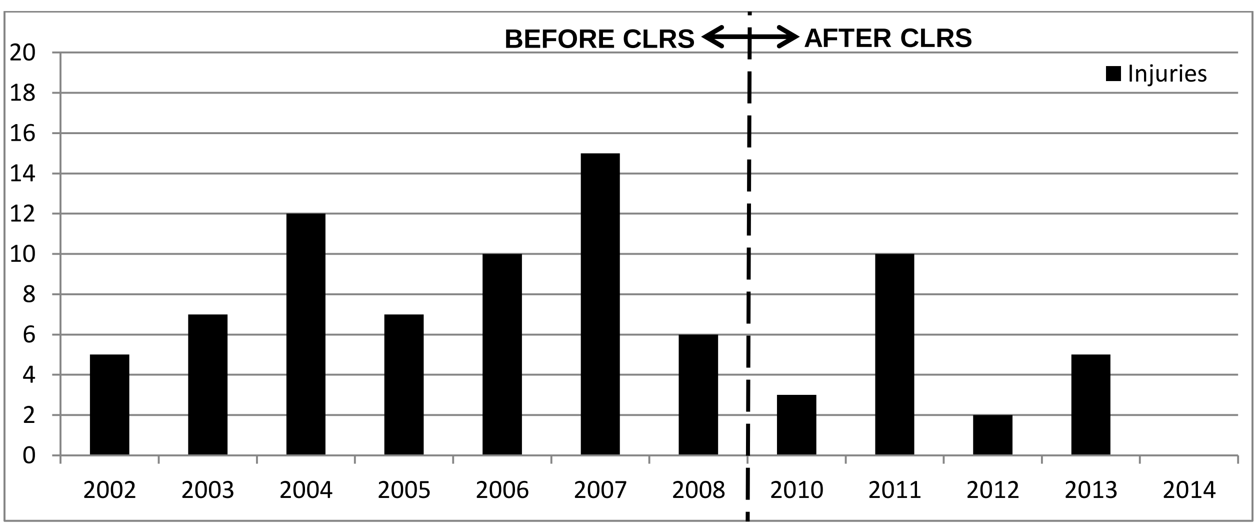

Figure 13: Total number of crossover crash injuries in Mendon-Killington from 2002 to 2014.

Sheldon

A total of 65 crashes were reported along VT Route 105 in Sheldon prior to the installation of CLRS from 2002 to 2009. Head on crashes, including other types of crashes where vehicles crossed into the wrong lane of traffic accounted for 21 of the 65 total crashes during this period, equaling 32.3 percent prior to the CLRS installation. After installation a total of 41 crashes occurred. Of these, head on collisions totaled nine, resulting in a 10.3 percent reduction of head on crashes of the overall total. Although this percentage is more promising than in Mendon-Killington, it is important to note the head on crash average per year decreased from 2.63 to 2.25 crashes per year while the average overall crashes per year increased from 8.13 to 10.25. The low AADT and small crash totals makes it difficult to assess the effectiveness of the CLRS because of the limited number of crashes; single incidents are skewing the dataset. Specifically, there were only nine head on crashes following installation of the CLRS at this site; however, in 2012 and 2013 there were none.

Table 2 summarizes the annual number of crashes and percentage of head on and wrong lane collisions along VT Route 105 in Sheldon.

Table 2: Percentage of Head On/Wrong Lane Crashes in Sheldon from 2002 to 2014.

Year	Head On/Wrong Lane	Other	Total	% of Head On/Wrong Lane Crashes
2002	5	7	12	41.7%
2003	2	5	7	28.6%
2004	3	15	18	16.7%
2005	5	3	8	62.5%
2006	3	6	9	33.3%
2007	0	1	1	0.0%
2008	2	5	7	28.6%
2009	1	2	3	33.3%
Total	**21**	**3**	**65**	**32.3%**
Avg. per Year	**2.63**	**5.50**	**8.13**	
2011	5	11	16	31.3%
2012	0	2	2	0.0%
2013	0	12	12	0.0%
2014	4	7	11	36.4%
Total	9	0	41	22.0%
Avg. per Year	**2.25**	**8.00**	**10.25**	

Total Crossover Crashes

Figure 14 shows the number of crossover crashes per year both before and after the CLRS were installed. Although 2011 and 2014 totals are equal to or more than some of the years prior to the CLRS installation, the totals are less than five per year across the board. Again, with so few incidents there is no statistical significance to this data set.

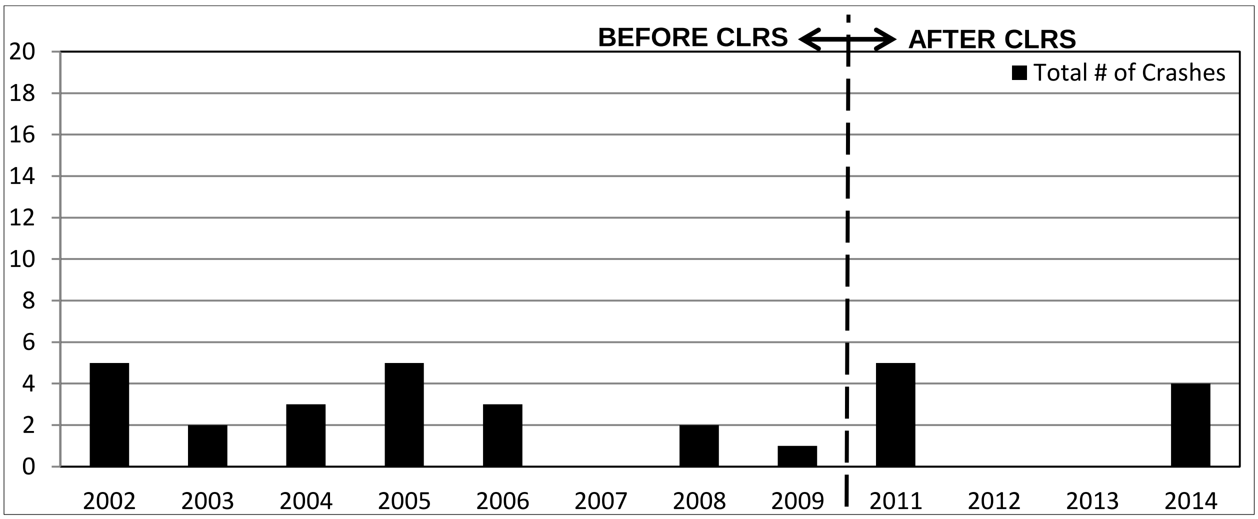

Figure 14: Total number of crossover crashes in Sheldon from 2002-2014.

Annual Crash Rate

The annual crash rate was calculated in the same manner as Mendon-Killington. The traffic count totaled 19,856,000 vehicles from 2002 to 2009. The total number of crashes during this time was 72. This equals a crash rate of 3.63 crashes per 1 million vehicles. After the CLRS were installed, there were 7,811,000 vehicles and 41 crashes, equaling 5.25 crashes per 1 million vehicles, a 31 percent increase in total crashes. While the total annual crash rate increased, crossover crashes decreased on average from 2.65 crashes per year before to 2.25 per year after. Although there were limited incidents at this location the average crash per year decrease is promising. Figure 15 shows the average crash rate per 1 million vehicles for both before and after the CLRS installation.

Reported Injury Analysis

Prior to the CLRS installation there were 14 total injuries resulting from crossover crashes from 2002 to 2009, averaging 1.75 injuries per year. After the installation, there were 12 injuries from 2011 to 2014, averaging 3 injuries per year, an increase of 71.43 percent. Figure 16 shows the number of injuries per year from 2002 to 2014. Fatalities are far less common than injuries at the site, two prior the CLRS and one after. There were four fatalities prior to the installation of the CLRS and none reported afterward.

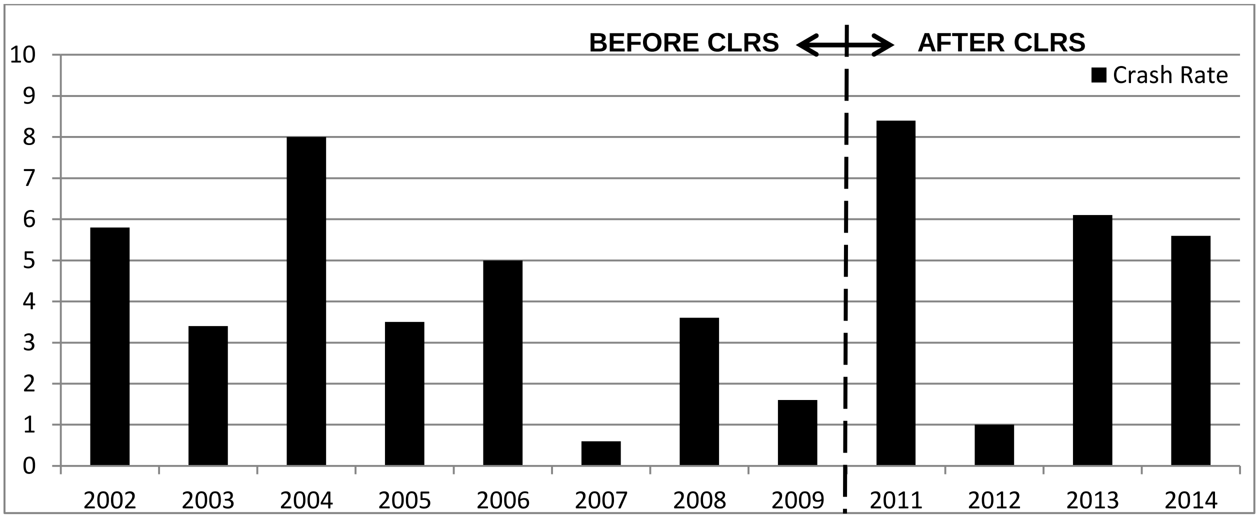

Figure 15: Annual crash rate (Number of crashes per 1 million vehicles) in Sheldon from 2002 to 2014.

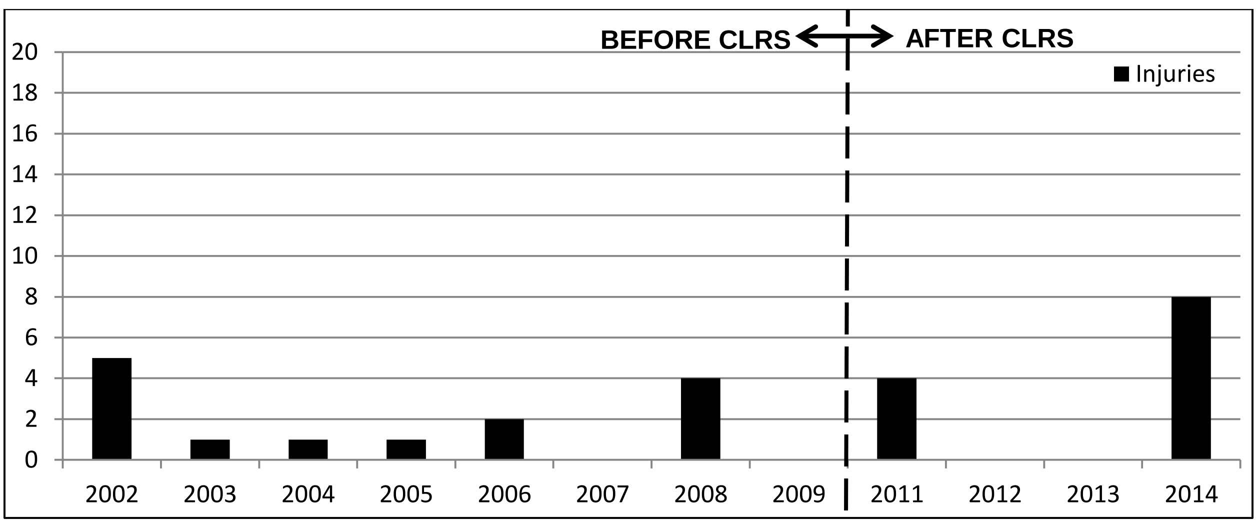

Figure 16: Total number of crossover crash injuries in Sheldon from 2002 to 2014.

SOUND/NOISE LEVEL ANALYSIS

Background

Noise is a form of energy that is transmitted through the air as pressure waves that can be harmful to the human ear depending on the intensity and duration of noise exposure (*15*). Sound intensity is defined as the sound power that passes perpendicularly through a surface divided by the area of the surface. Intensity levels are measured using the decibel (dB) scale (*16*). Intensity and distance is referred to as an inverse square relationship. If a sound is 10 times more intense, it is reported as 10 dB higher, which is perceived as twice as loud. If it is 100 times more intense, it is reported as 20 dB higher. If the distance from the sound source is doubled then the intensity is quartered. More simply, the closer the sound source the larger the intensity and less harmful to one's ear (*17*).

To measure sound there are A-, B- and C-weighted sound level scales, which were designed to approximate the equal-loudness contours at low, medium, and high sound pressure levels. The A-weighted scale measures low sound pressure levels and most closely matches the perception of loudness by the human ear. Values reported with this scale uses dBA for units. The B- and C-weighted scales measures medium and high sound pressure levels respectively. Sometimes the B- and C-weighted scales are used in conjunction with the A-weighted scale to determine the frequency level of a sound (*18*).

The Occupational Safety & Health Administration (OSHA) has implemented Permissible Exposure Limits (PEL) including time weighted averages (TWA) to control and minimize occupational noise induced hearing loss. The PEL for an 8-hour workday for all workers is 90 dBA. The standard uses a 5-dBA exchange rate where if a noise level increases by 5 dBA then the exposure limit time is halved (*19*). OSHA notes that the PEL to continuous steady-state noise is limited to a maximum of 115 dBA and an impulsive or impact noise should not exceed 140 dB peak sound pressure level (*20*). The smallest sound intensity that the human ear can detect is known as the threshold of hearing, equal to 0 db (*16*). The National Institute on Deafness and Other Communication Disorders (NIDCD) (*21*) and the Center for Hearing and Communication (CHC) (22) have identified the noise levels of common sounds. Some of these are included in the Table 3.

In FHWA Technical Advisory T 5040.40 dated November 7, 2011, FHWA identified potential adverse effects of installing centerline rumble stripes including: increased maintenance due to premature pavement joint deterioration and noise to adjacent residents. The memo recommends that state agencies modify the design and placement of CLRS to balance between motorist safety and noise effects to area residents. They further suggest that regarding placement, CLRS should be installed in passing zones and to place gaps in the rumbles in the vicinity of intersections and driveways, areas where the CLRS would be crossed by left-turning traffic (*23*).

Table 3: Common Sound Comparison.

Sound	Noise Level (dB)
Jet Engines	140
Stock Car Races	130
Threshold of pain begins.	**125**
Ambulance Siren	120
Chain Saw	120
Threshold of sensation begins.	**120**
Car Horn	110
Motorcycle	110
Baby Crying	110
Snowmobile	105
Snowblower	105
Regular exposure to sound over 100 dB of more than 1 minute risks permanent hearing loss.	**100**
Newspaper Press	97
Electric Drill	95
Lawnmower	90
Level at which risk of hearing damage begins.	**90**
Noisy Restaurant	85
Diesel Truck (40mph, 50 ft)	84
Avg. City Traffic	80
Toilet	80
Washing Machine	78
Freeway Traffic	70
Vacuum Cleaner	70
Hair Dryer	60-95
Sewing Machine	60
Comfortable hearing levels end.	**60**
Electric Toothbrush	55
Rainfall	50
Refrigerator	50
Quiet Office/Library	40
Soft Whisper	30
Rustling Leaves	20
Threshold of hearing.	**0**

dB Range detected from CLRS (Lawnmower 90 through Hair Dryer 60-95)

Data Collection Design

To measure the noise pollution at the sites, a Pass-by Method that was developed based on two studies described in the NCHRP Report 630 entitled, "*Measuring Tire-Pavement Noise at the Source*" (*24*) and a study conducted by Colorado DOT on, "*Tire/Pavement Noise*" (*25*) were reviewed. A variant of these methods was used for this study.

For the study, measurements were collected approximately one month after installation and then annually for three years. Two people with sound level meters were positioned at 25 feet and 50 feet perpendicularly from the rumble stripes. Three vehicles types were used for the experiment: a District tandem plow truck, a pick-up truck and a passenger car. To determine any possible variables, the tire size, type, pressure, tread depth, vehicle make, model, vehicle weight, and photographs were recorded. Each vehicle travelled on the rumble stripes at three different speeds: 30, 40 and 50 mph. Four trials were conducted at each speed with each vehicle. One of the four trials was conducted on standard pavement (no rumble stripe contact) to determine the difference in sound levels between the two. The sound meters used in this study was a non-digital, B&K (Bruel & Kiaer) Sound-Level Meter, Model # 2205 and a RadioShack, Digital Sound-Level Meter, Model # 33-2055. All data was measured in the A-weighted scale and reported in decibels.

Analysis

Both sites were analyzed using the same metrics and share commonalities even though the two CLRS locations do not have common roadway characteristics such as number of lanes, lane widths, CLRS dimensions, climatic regions and AADT. Observations are summarized below:

- All measurements were below the 90 dBA OSHA PEL.
- Loudest sound levels for all vehicle types were recorded while vehicles were travelling 50 mph.
- The rumble stripe pavement showed wear at the final site visits, however they still created audible and tactile awareness when driven on at both locations.
- Mendon-Killington was louder for all vehicles by approximately 10 dB, which equals a sound level that is perceived to be twice as loud as the values measured in Sheldon.
- One cause of concern is the potential noise level increase that the CLRS may produce when driven on compared to traffic driving on the adjacent pavement without rumbles. This evaluation produced an average increase in noise of 5.3 dBA in Mendon-Killington and 2.0 dBA in Sheldon. The differences recorded in noise increases could be due to:
  1) Pavement age; the CLRS in Sheldon were installed on new asphalt where the CLRS in Mendon-Killington was installed on asphalt that was 8 years old or

2) Dimensions were different; the depth and width were the same but the transverse length was 12 inches in Sheldon and 16 inches in Mendon-Killington.

Although these are noticeable increases in sound, they are not substantial increases where they would become harmful to one's hearing.

- The tandem dump truck produced the loudest values at both locations, followed by the pick-up and then the passenger car. One may anticipate that the tandem dump truck would produce much larger values however due to position of the rear tires and width of rumbles at both locations the tires do not hit the rumbles in the same manner as the passenger car or pick-up truck. The loudest measured values in both sites for all vehicles are shown in Table 4.
- Values were consistent over the course of the evaluation and for the most part did not decrease with age as anticipated due to pavement wear and deterioration. Values are shown in Figure 17 and Figure 18, averaged for all vehicle types for each year.

Table 4: Loudest Measured Individual Values (dB).

Vehicle	Mendon-Killington	Sheldon
Car	81	73
Pick-up Truck	84.3	77.5
Tandem Dump Truck	89.7	80

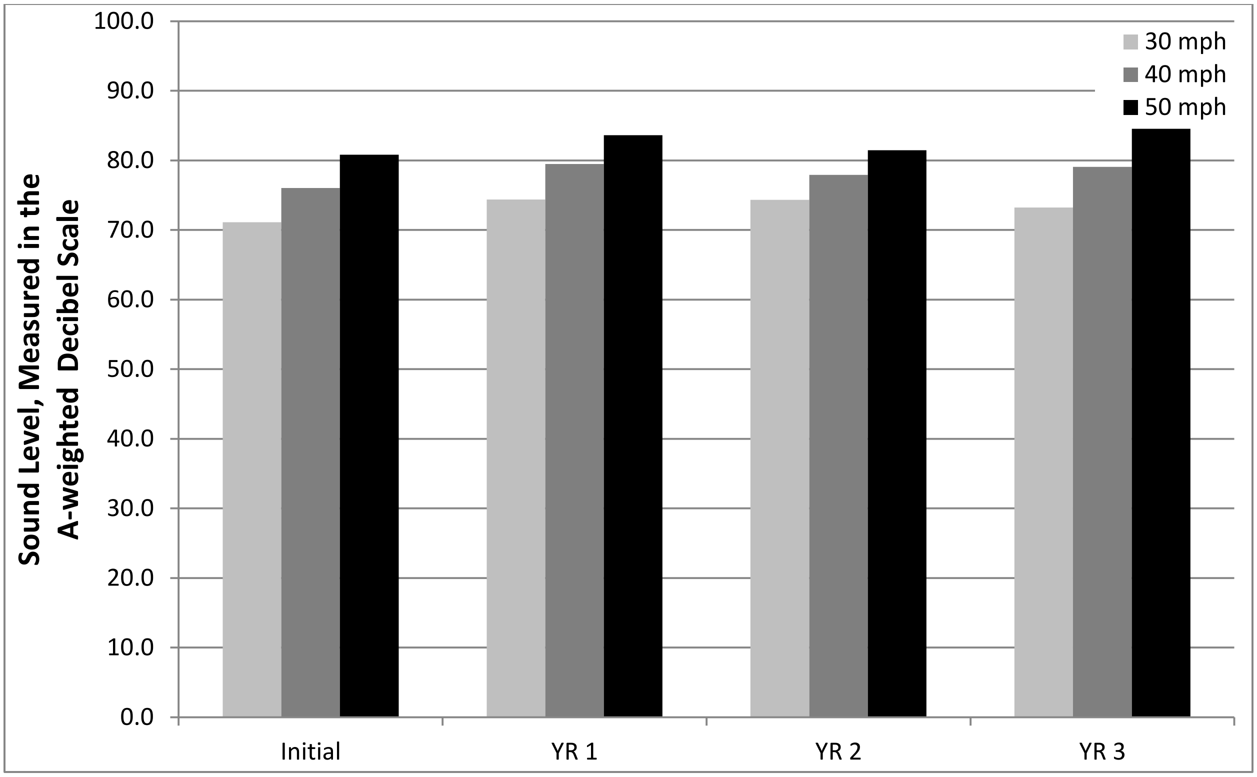

Figure 17: Mendon-Killington Average Sound Measurements (dBA).

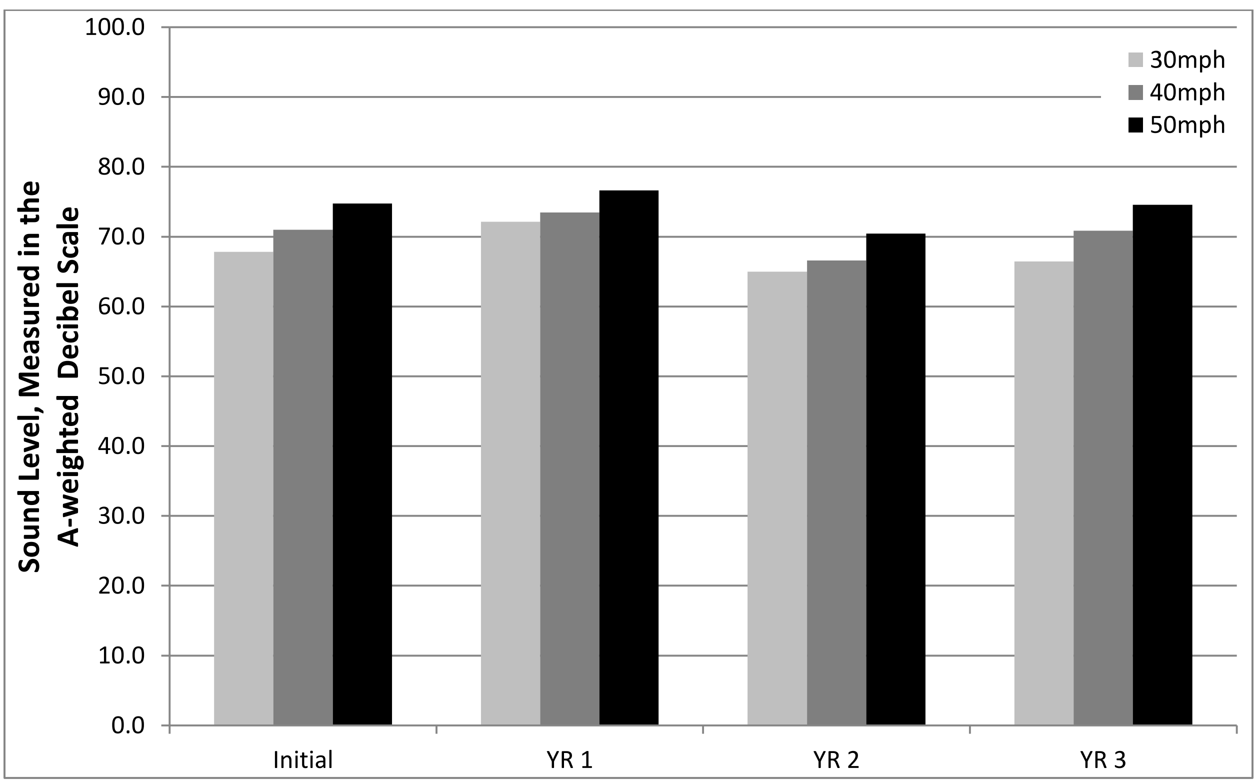

Figure 18: Sheldon Average Sound Measurements (dBA).

PROJECT COSTS

VTrans does not differentiate between milled rumble stripes located on the shoulder and those located on the centerline for the purposes of historical unit price. For these projects the cost to mill the rumbles per linear foot of roadway for Mendon-Killington was $0.38 and Sheldon was $0.25. In comparison, the average unit price per linear foot for all installed milled rumbles both shoulder and centerline in 2014 was $0.22.

It is difficult to compare the pavement-marking portion of CLRS because marking-binder costs can vary greatly depending on the marking type. In Mendon-Killington, the unit price per linear foot for the waterborne permanent pavement markings was $0.06. The average cost to install markings of this type in 2014 was the same, $0.06. For the recessed Polyurea pavement markings installed in Sheldon, the cost was $1.25 per linear foot. This marking type is much more expensive because it is considered a durable marking type, meant for permanent applications and expected to last much up to three times longer with higher retroreflectivity than waterborne paint. In 2014, the average unit price per linear foot to install recessed Polyurea was $1.01.

SUMMARY AND RECOMMENDATIONS

Studies have shown that incorporating centerline rumble stripes (CLRS) along rural routes is a cost effective safety measure. Since 2009, VTrans has installed CLRS on 114 miles along five major routes including US Route 2, US Route 4, US Route 7, VT Route 9 and VT Route 105 (*1*). The first two installations were included in this study and were located in the towns of Mendon and Killington. These installations were along US Route 4 from mile marker MM 1.650 in Mendon to MM 2.050 in Killington (October 2009) and in the town of Sheldon along VT Route 105 in 50 mph zones from mile marker MM 2.000 to MM 9.479 for a total of approximately 6 miles.

This study evaluated the CLRS effectiveness in reducing lane departure crashes and improving the safety of undivided roadways. In addition, a sound analysis was conducted and the overall durability and resistance to wear characteristics of the centerline rumble stripes were examined in terms of preexisting pavement and climatic conditions as well as winter maintenance practices. Ease of installation was documented along with the design of the rumble stripes in conjunction with the adjacent pavement markings.

Over the evaluation period, crash data showed that in Mendon-Killington the average head-on crash rate decreased from 12.86 to 7.25 crashes per year while the overall crashes decreased from 27 to 15.4 per year. Based on AADT, there were 6.94 crashes per 1 million vehicles before installation and decreased to 5.4 crashes per 1 million after installation resulting in a 22 percent reduction. A significant reduction by 48.6 percent of injuries was reported at the site averaging 7.8 per year before installation and 4 per year afterward. The same results were not reported at the Sheldon location due to a significantly lower crash rate making individual crashes weigh higher in the overall total. Although overall crashes increased from 8.13 per year before installation to 10.25 per year afterward, head on crashes were reduced slightly from 2.63 per year before to 2.25 per year afterward.

A Pass-by Method was used to measure noise pollution at both sites where two people with sound level meters were positioned at 25 feet and 50 feet from the rumble stripes. Three vehicles were used for the experiment: a District tandem plow truck, a pick-up truck and a passenger car. To determine any possible variables, the tire size, type, pressure, tread depth, vehicle make, model, vehicle weight, and photographs were recorded. Each vehicle travelled on the rumble stripes at three different speeds: 30, 40 and 50 mph. Four trials were conducted at each speed with each vehicle. One of the four trials was conducted on bare pavement (no rumble stripe contact) to determine the difference in sound levels between the two. All measurements were recorded in the A-weighted scale, which is most like the human ear in terms of perceived loudness. All values were under OSHA's Permissible Exposure Limits (PEL) of 90 dBA. The noise levels did not decrease as the CLRS wore down. Readings in Mendon-Killington were approximately 10 dB higher than in Sheldon, possibly due to pavement age and CLRS dimensions. As expected the tandem dump truck produced the largest readings, averaging 89.7 dBA in Mendon-Killington, followed by the pick-up at 84.3 dBA and the passenger car at 81.0 dBA. The same vehicle types in Sheldon produced readings of 80 dBA, 77.5 dBA, and 73 dBA respectively.

The maintenance districts response is positive. Although it is reported that it does take more effort to clear snow from the CLRS, it does help keep drivers off the centerline and in their own lane. District contacts noted that no complaints have been received from area residents regarding noise and although both locations have worn in areas still provide the awareness that motorists need if they hit the centerline. No repairs have been required at either location.

Overall, the CLRS installations in Mendon-Killington and Sheldon have proved to be successful in terms of reducing crashes and injuries and having acceptable noise levels that is not harmful to area residents or motorists. It is recommended that VTrans include them on additional projects in areas that would benefit from a low cost safety treatment.

IMPLEMENTATION STRATEGY

VTrans published Highway Safety & Design Engineering Instructions (HSDEI) #14-101 regarding Guidelines for Milled Centerline Rumble Stripes on September 8, 2014 to provide guidance to designers. The document outlines criteria and design guidance for when CLRS should be considered on projects: (*26*)

Installation Criteria:

- Combined travel lane and shoulder width is 14 feet or greater in each direction.
- Speed limit is 45 mph or higher.
- AADT is 1,500 or greater.
- Pavement condition is new or good with no paving/overlay projects anticipated within three years following CLRS installation.
- When the above conditions are not met but crash history warrants a corrective safety measure.

Design Guidance:

- CLRS should be the same width as the double yellow centerline (12 inches for 4-inch lines and 18 inches for 6-inch lines).
- CLRS should be a ⅜-inch deep, 7-inch long rumble with either a 12-inch or 18-inch width.
- The groove pattern shall be two grooves at 12 inches on center with 24 inches spacing between pairs.
- CLRS should be continuous through passing zones.
- CLRS should be discontinued where or at:
  - Centerline breaks are provided (i.e. intersections).
  - Residences within 100 feet of the centerline to mitigate noise.
  - Breaks total a length greater than 50 percent of the total length within a half mile section.
  - The minimum length of rumble segments is less than 500 feet.
  - Raised medians are provided.
  - Two way left turn lanes are provided.
  - Closely space commercial drives with high volume of turning traffic.
  - Bridges where the curb to curb width is less than 28 feet.
  - Bridges or concrete roadways with less than a 2.5-inch bituminous pavement overlay.

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