Research Report

Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety

by

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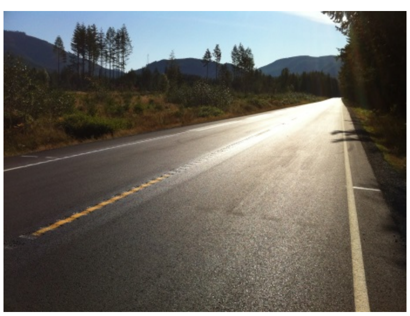

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15. SUPPLEMENTARY NOTES This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		
16. ABSTRACT Noise from vehicles passing over rumble strips is a major source of complaints from residents living adjacent to highways in Washington state. This project evaluated wayside noise levels from various centerline rumble strip designs to determine overall sound levels and 1/3-octave band frequencies. Results suggest that some designs have lower exterior sound levels and sufficient interior sound levels. However, the effects of specific design variables on exterior noise levels were inconclusive and suggest that interactions among variables contribute to exterior sound levels.		
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Introduction

Rumble strips are an effective countermeasure for keeping vehicles on the roadway and reducing the frequency of crashes. Drivers are alerted by the noise and vibration within the vehicle caused by the car's tires rolling over the uneven rumble strip surface. While the in-cabin noise and vibration from rumble strips are intentional and necessary for the rumble strip to be effective, the noise can also be heard outside the cabin, where there is no direct safety benefit. This "exterior rumble strip noise" is a source of disturbance and has been the cause of complaints from roadside residents.

In light of such complaints, the primary objective of this research was to identify centerline rumble strip (CLRS) designs that can maintain the effectiveness of the Washington State Department of Transportation's (WSDOT) standard rumble strips while reducing disturbances at adjacent properties from external rumble strip noise. To achieve that research objective, the following steps were taken:.

1. Evaluate existing research on rumble strip noise.
2. Measure sound levels from current WSDOT rumble strips designs.
3. Identify the rumble strip design patterns that exhibit the least external noise while maintaining effective performance.

Additional rumble strip design challenges are described in depth as part of National Cooperative Highway Research Program (NCHRP) Report 641: *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips* (Torbic et al., 2009).

Background

Introduction to Rumble Strips

Rumble strips consist of texture added to a road centerline or shoulder that is meant to alert unfocused, inattentive, or fatigued drivers that their vehicle has left the travel lane (Figure 1). Rumble strips have proved to be cost effective for reducing the frequency of collisions, and state departments of transportation and local agencies are expanding their use of center line and shoulder rumble strips, particularly on undivided rural highways.

Figure 1: Milled centerline rumble strip (CLRS).

Rumble strips are typically ground into the roadway along the center line, or either just outside or directly beneath the outside lane fog line (Figure 2). Various construction methods and materials are used, including button, rolled, formed, and profiled rumble strips, but ground or milled rumble strips are most commonly used (Federal Highway Administration, 2011). Their popularity is due in part to ground and their being the only designs proven to generate sufficient noise and vibration to be heard and felt in commercial vehicles (Finley and Miles, 2007).

Figure 2: Grinding CLRS on SR 97

This research focused on centerline rumble strips (CLRS), but the results should be generally transferable to shoulder rumble strip (SRS) designs. WSDOT allows only a tight range of depth in its current standard centerline rumble strip designs; however, numerous design variations have been, and continue to be, installed across the state. All the designs currently used meet or exceed modeled safety criteria, but the resulting external rumble strip noise from the various designs has been unmeasured.

How Rumble Strips Work

As vehicles pass over rumble strips, they produce interior noise and generate physical vibration in the vehicle cabin. To be effective, rumble strips must generate sufficient interior noise and vibration to re-focus the driver without being so loud or agitating that they trigger an undesirable surprise response.

While there is some uncertainty about the stimuli levels necessary to alert inattentive drivers, NCHRP 641: *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips* provides recommendations based on the research to date. Recommendations are that to be effective, rumble strips should produce a sound level increase of 10 to 15 A-weighted decibels (dBA) above in-cabin levels while the vehicle is in the travel lane. However, NCHRP Report 641 suggests that in-cabin sound level increases may be reduced to about 6 to 12 dBA when roadways are adjacent to residential land uses (Torbic et al., 2009).

Where and When Rumble Strips Are Used

Center line rumble strips (CLRS) are used to reduce the frequency of lane departure collisions and are an important tool for reducing cross-centerline collisions on undivided roadways. Rumble strips tend to be more cost effective on lower volume roadways and are used primarily on rural roadways with speeds of greater than 35 mph, lane widths of 12 ft. or greater, and total paved roadway widths of at least 24 ft. (Federal Highway Administration, 2011).

A March 2011 WSDOT study (Olson, 2011) found that centerline rumble strips were highly effective across the state highway network, and most effective on roadways where the average annual daily traffic (AADT) was less than 8,000, the combined paved lane and shoulder width was 12 to 17 ft., and the posted speed was 45 to 55 mph.

Section 1600.07(1)(c) of the WSDOT Design Manual (Washington State Department of Transportation, 2012) states that they are installed with no differentiation between areas where passing is permitted and passing is not allowed. More specifically, centerline rumble strips are recommended under the following conditions:

- Engineering analysis indicates a history of crossover collisions that are considered correctable by centerline rumble strips, given the frequency of collisions with contributing circumstances, including inattention, driver fatigue or sleeping at the wheel, or driving over the centerline or on the wrong side of the road.

- They are most appropriate on rural roads but may also be appropriate for some urban roads. Specific urban concerns are noise in densely populated areas, frequent rumble strip interruptions to accommodate left-turning vehicles, and reduced effectiveness at speeds below 35 mph.
- The pavement is structurally adequate to support milled rumble strips.
- The combined lane and shoulder widths in either direction are more than 12 ft. Drivers tend to avoid driving on centerline rumble strips by moving right, which makes a combination of centerline and shoulder rumble strips inappropriate for narrow lane widths.
- No two-way left turn lanes.

For run off the roadway to the right (ROTRR) collisions, shoulder rumble strips (SRS) may be used to reduce collision frequency. However, the use of SRS on undivided roadways is more constrained by policies than the use of CLRS, and therefore, SRS use is more limited. For example, the application of SRS must take into consideration collision experience, shoulder construction and width, and stakeholder involvement, including concurrence from the bicycle community. The WSDOT Design Manual provides additional information and design considerations for both types of rumble strips (Washington State Department of Transportation, 2012).

Unlike guard rail and cable barrier devices that prevent drivers from leaving the roadway and striking a hazard greater than the barrier, rumble strips only alert errant drivers that they are leaving the traveled lane. Rumble strips are not used in place of a physical barrier device, but the two are often used in combination.

Why Rumble Strip Noise Information Is Needed

In recent years, the number of public complaints about external rumble strip noise has increased. WSDOT has received complaints from residents throughout the state on both sides of the Cascade Range. Complaints are generally from suburban, semi-rural, and rural residents and focus on sleep disruption. These locations typically have lower nighttime background sound levels than urban areas, which can make rumble strip noise more disruptive because if they are run over, the relative change in sound levels is greater.

Three characteristics of rumble strip noise make it generally more disruptive than standard traffic noise.

- *Sporadic occurrence*—Standard traffic noise is dominated by the sound of tires on pavement, as well as the vehicle drivetrain and exhaust. It is fairly consistent by time of day and day of week, which helps nearby residents adjust to associated traffic noise patterns. In contrast, rumble strip noise has no pattern, and the timing and frequency of the noise are impossible to predict.
- *Low frequency*—Low frequency sounds travel farther than higher frequency sounds, so they can affect more people, and they can be more annoying to the average person than standard traffic noise sound frequencies between 500 Hz and 5 kHz. For residences very close to the roadway, the frequencies may be low enough to be perceived as vibration.

- *Low Tone*—Standard traffic noise comprises a number of audible sound frequencies that have similar levels. Noise from rumble strips is less widespread across the frequency spectrum and can be dominated by a narrow band of low frequency sound.

It is possible that a rumble strip design that produces the loudest sound level, measured by the peak level, may not be as disruptive as a design that produces a lower overall sound level but with more energy at lower frequencies. Therefore, data on both the overall sound levels and frequencies are needed to understand the characteristics of external rumble strip sound from various rumble strip designs.

For this report, sound levels are reported as A-weighted decibels (dBA). A-weighting is a filtering process that more accurately reflects how sound is heard by the human ear.

What WSDOT Hopes to Achieve with This Research

The primary research objective was to identify rumble strip designs that will provide the same safety benefits as WSDOT's standard rumble strip design while also reducing external rumble strip noise disturbance at adjacent properties.

The project combined field measurements and a literature review to determine whether currently available rumble strip designs would reduce the noise heard by roadside residents and still be effective. The intent was to recommend a standard rumble strip design for CLRS that may be transferable to SRS. If a preferred rumble strip design could be identified, WSDOT Standard Plans and Design Manual would be updated to incorporate the new information.

What Was Not Measured

This report does not include information on background sound levels with no traffic or on pass-by sound levels with traffic only in the traveled lane. Instead, this project focused on comparing relative external sound levels among CLRS designs in recognition of the fact that final design decisions are made on the basis of individual project circumstance.

Given the narrow focus, tire-pavement noise levels from the pavement alone were not evaluated. The measurement methodology was used to record only the vehicle passing over the rumble strip and was based on maximum sound levels that inevitably resulted from the tire-rumble strip interaction. Pavement type might have played a greater role in measuring average sound levels or for measurements that mixed rumble strip driving with driving in the traveled lane. Furthermore, all of the measured pavements shared characteristics similar to those of dense-graded hot mix asphalt constructed within the past seven years, which was determined on the basis of on-board sound intensity measurements.

Measurements were not collected in the vehicle cabin because vehicle characteristics and condition produce significant differences in sound and vibration levels in the cabin. Also, in-cabin sound and vibration are the factors that determine the effectiveness of rumble strip designs. This project was focused on the effects of rumble strips on people outside the vehicle rather than inside. References to safety in this report are included only to highlight that all current WSDOT rumble strip designs are within the acceptable sound level range for warning drivers, per FHWA and other published findings.

Staff and funding limitations prevented collection of measurements at multiple locations that shared the same set of design characteristics (depth, width, length, and spacing). Instead, each measurement location represented a different CLRS design, except for two measurements of CLRS built according to WSDOT Standard Plans. The sample size for each unique design was too small to be statistically significant but sufficient to be informative for no cost/low-cost decisions based on the measured results.

The report includes a brief discussion about how the location of rumble strips can reduce the effect of external rumble strip noise on adjacent residents, but it does not provide recommendations for where rumble strips should be used because the placement decision process was beyond the scope of this effort.

Study Methodology

The following are the steps taken to accomplish the project:

1. Previous research was evaluated to determine the current state of practice and understanding regarding external rumble strip noise. The review gathered rumble strip designs used in other U.S. states and internationally and then compared them to current WSDOT designs. The review also provided information about external and internal noise characteristics of these rumble strip designs for WSDOT to consider.
2. Current WSDOT rumble strip designs and practices were reviewed.
3. Measurements were collected from seven different rumble strips designs at nine locations in Washington state. These measurements were intended to help WSDOT determine which current designs produced the lowest external noise.

4. Options for updating WSDOT rumble strip designs were chosen for consideration.

Literature Review

Most research on rumble strip noise has focused on noise levels within the vehicle cabin to ensure that drivers are sufficiently alerted. There have been limited efforts to balance this issue with noise audible to roadside residents. Nevertheless, two recent reports summarized the results of related work and were used as the primary background references for this report:

- Torbic, D.J., et al., 2009. *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, National Cooperative Highway Research Program, Transportation Research Board, Washington D. C. http://www.TRB.org.
- Caltrans, 2012. *Traffic Noise Generated by Rumble Strips*.

NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips

NCHRP Report 641 (2009) developed guidelines for designing and applying shoulder and centerline rumble strips to ensure they will be an effective motor vehicle crash reduction measure while minimizing adverse effects for motorcyclists, bicyclists, and nearby residents. Included in the report were recommendations for the in-cabin sound and vibration levels necessary for satisfactory performance, a discussion of the effects of external rumble strip noise on nearby residents, examples of state efforts to address complaints about rumble strip noise, and a spreadsheet comparing the noise levels associated with various milled rumble strip designs.

Torbic et al. examined the lowest level of stimuli required to alert an inattentive or drowsy driver, providing equations for determining rumble strip dimensions for a range of operating conditions. The report recommends a strip pattern that produces an in-cabin sound level increase of 10 to 15 dBA on typical rural roadways, and 6 to 12 dBA near residential or urban areas.

The report cites results from a survey of residents living near CLRS installations. The majority of respondents reported the external noise “acceptable” or “tolerable” and believed that the safety benefits to drivers outweighed the additional external noise. However, studies have shown that noise impacts from rumble strips are more tolerable when the rumble strips terminate 656 feet before a residential or urban area. The noise generated from rumble strips is said to be negligible at a distance of 1,640 feet, but some residents still claimed to hear noise from the rumble strips up to 1.2 miles away.

The authors provided examples of efforts states have taken to address complaints about rumble strip noise from nearby residents, including the following:

- Increasing the offset of (shoulder) rumble strips from the edge-line to reduce the frequency of vehicle contact
- Terminating rumble strips before/after a residential area
- Removing rumble strips near noise sensitive properties, such as homes
- Constructing noise barriers.

The research concluded that increasing groove depth, length, and/or width can increase interior noise and vibration.

The WSDOT Design Office developed a Microsoft Excel workbook-based tool, based on NCHRP 641, Sec 9, "Optimum Dimensions for Rumble Strips," to calculate sound level increases inside the vehicle on the basis of rumble strip dimensions.

Traffic Noise Generated by Rumble Strips

The 2012 report from the California Department of Transportation (Caltrans) summarized existing information on the internal and external noise levels produced by vehicles traveling over rumble strips. The report included a literature search and a summary of responses from representatives of state departments of transportation, the USDOT, and consulting firms about their experiences with various rumble strip designs.

The report confirmed that transportation agencies have conducted little research to measure exterior or interior noise levels for standard rumble strips or alternative rumble strip designs. The report noted that as of 2009, no agency had reported developing a useful rumble strip design to reduce exterior noise, and states reported generally handling rumble strip noise complaints by removing the rumble strips, persuading residents of their benefits, or limiting their use near residential areas.

Additional conclusions in the 2012 report included the following:

- Milled rumble strips increase external noise levels by 5 to 19 dBA and increase in-cabin noise levels by 5 to 15 decibels. Wider grooves produce higher noise levels.
- Sinusoidal rumble strips are 3 to 7 decibels quieter inside the vehicle than rectangular strips and increase external noise levels by only 0.5 to 1 dBA.
- A 2004 European Commission report suggested that thermoplastic rumble strips could increase external sound levels by as little as 4 dBA.

- Alternative rumble strip designs used in the United Kingdom, such as Rippleprint and Rumblewave, are said to generate little or no external noise while producing adequate interior noise (Caltrans 2012). However, these designs have a different primary function than rumble strip used in the U.S.

A survey of state DOT work to address rumble strip noise was also included:

- A Michigan DOT study showed that edge line rumble strips increased external sound levels by 16 dBA at 95 ft. for a car driving 70 mph. The average maximum sound level measured was approximately 87.5 dBA.
- A separate project using a Ford F-350 driving 55 mph measured 25 dBA external noise level increases at 50 feet from the centerline rumble strip. Measured maximum external sound levels were approximately 80 dBA.

Gaps in the research include the following:

- There is still little research on noise levels for rumble strips, especially for alternative designs such as sinusoidal and thermoplastic rumble strips.
- We were unable to reach an appropriate contact at Delaware DOT, which is making use of thermoplastic rumble strips.

Additional Sources

Centerline Rumble Strips: Study of External Noise

A study by Karkle et al. (2011) measured maximum sound levels (L_{max}) from rectangular and football shaped center line rumble strips at 15, 30, and 45 meters from the roadway center line and compared those sound levels to measurements of the same vehicles traveling on the smooth roadway. The rumble strip patterns are shown in Figure 3. A passenger car and van were compared traveling at 40 mph and 60 mph.

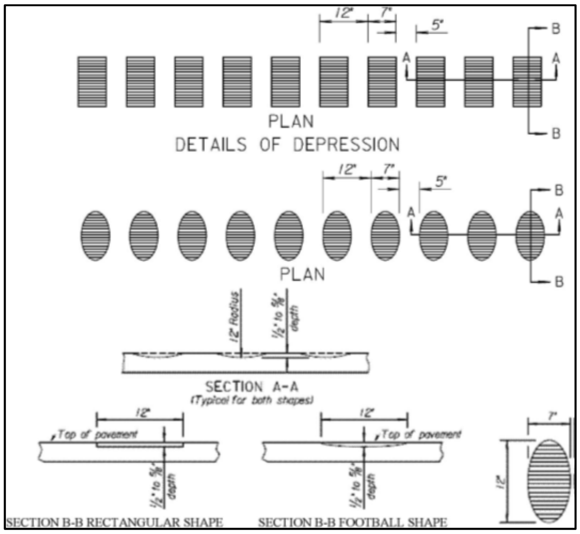


Figure 3: Dimensions of CLRS patterns compared

The following conclusions were drawn from the author's data:

- At 65 mph, rumble strip noise was at least 10 dBA higher than the sound of the vehicle driving on "smooth" pavement.
- No significant sound level difference was found between rectangular (standard) and football-shaped rumble strips.
- At all measured distances, the sound of one car passing over the rumble strips was about 5 dBA lower than the sound of one semi-truck passing on smooth pavement.
- As measurement distance moving away from the source doubled, e.g., 15 m to 30 m, sound levels decreased by approximately 6 dBA. This is consistent with attenuation from a point source, unlike standard traffic ("line source"), which attenuates at 3 dBA with each doubling of distance.

Evaluation of Factors that Impact the Effectiveness of Rumble Strip Design

Finley et al. (2007) reported the following:

- Regarding rumble strip dimensions (e.g., width, spacing, length, and depth/height): "Each dimension plays a specific role in generating sound when traversed by vehicle tires, and the current standard rumble strip design is the only one proven to provide adequate increases in sound to alert all drivers." "Current standard" refers to 12–in. length, 7-in. width, 0.5-in. depth, and 12-in. to -24-in. spacing.
- "Only the milled rumble strip applications 12 inches or wider provided enough sound increase to alert drivers of commercial vehicles."

Low Noise Rumble Strips on Roads— A Pilot Study

Kragh et al. (2007) found the following:

- Rectangular indentations gave rise to significantly higher noise levels (3 to 7 dB higher) than the rumble strips with a sinusoidal profile, as well as significantly higher noise levels (2 to 5 dB higher) than the "cylinder segment" strip" used more commonly in the U.S., including in Washington state. (See examples in Figure 4.)

Rumble Strip Designs

States use various rumble strips, depending on project circumstances and pavement types. While variables such as rumble strip groove pattern, depth, width, shape, and spacing also change by state, the majority of rumble strips in the U.S. are rectangular, approximately 9 to 12 in. long, 5 to 8 in. wide, and ¼ - ¾ in. deep. See Figure 5 for graphical definitions of common rumble strip terms. Cylinder and sinusoidal, or "football," shaped rumble strips have been tested in Europe (Kragh, 2007), along with new trademarked designs such as Rippleprint and Rumblewave (Caltrans, 2012) [1]. No information on experience with these patented designs in the U.S. was available.

WSDOT uses a milled cylinder segment design, and measurement locations on SR 202 and SR 203 were built according to WSDOT Standard Plans: 12 in. long, 6 in. wide, and $^{1}/_{2}$ - $^{5}/_{8}$ in. deep (see Figure 6).

[1] The Rippleprint and Rumblewave designs used in the United Kingdom have been designed for traffic calming, unlike in the U.S., where rumble strips are used primarily as a lane departure warning system. These designs have additional constraints in that they are several feet wide and cannot be laid around corners.

Figure 4: From left to right: European “sinus,” rectangular (Kragh, 2007), and WSDOT cylinder design.

The FHWA has issued a Technical Advisory on Center Line Rumble Strips (T 5040.40, Revision 1) that focuses on the recommended placement of rumbles strips but does not recommend a particular design[i]. FHWA recognizes four types of rumble strips that differ in installation process, size and shape, and the amount of noise they produce (Federal Highway Administration).

1. Milled – different dimensions, a groove is installed by cutting into the pavement
2. Rolled – a roller makes rounded or v-shaped grooves by pressing into hot asphalt
3. Formed – similar to rolled installation, but forms press into the curing concrete
4. Raised – rounded or rectangular markers adhere to the pavement surface

For milled rumble strips, wider and deeper cuts typically generate higher levels of vibration and noise for all types of vehicles because of tire drop; however, tire drop depends on tire properties, vehicle speed, and spacing of the cuts/grooves.

Rumble Strip Designs Currently Used in Washington State

WSDOT first installed center line rumble strips on SR 522 near Maltby in 1995 (Olson, 2011). As of 2010, WSDOT had constructed approximately 1,800 miles of center line rumble strips and 275 miles of shoulder rumble strips using a range of designs on projects throughout the state. In 2002, WSDOT also installed approximately one mile of white plastic strips on the shoulders of SR 509 (MP 13.15 to 14.19). Hundreds of additional lane-miles of roadway have been identified as areas that would benefit from the installation of rumble strips.

The majority of WSDOT rumble strips employ an aggressive pattern to ensure sufficient noise inside the cabin to re-focus the driver's attention. Table 1 describes the full range of centerline rumble strip designs currently installed on WSDOT-maintained roadways in comparison to the designs outlined in the WSDOT Standard Plans and the range of designs evaluated in NCHRP Report 641. The current centerline rumble strip Standard Plan design is shown in Figure 6.

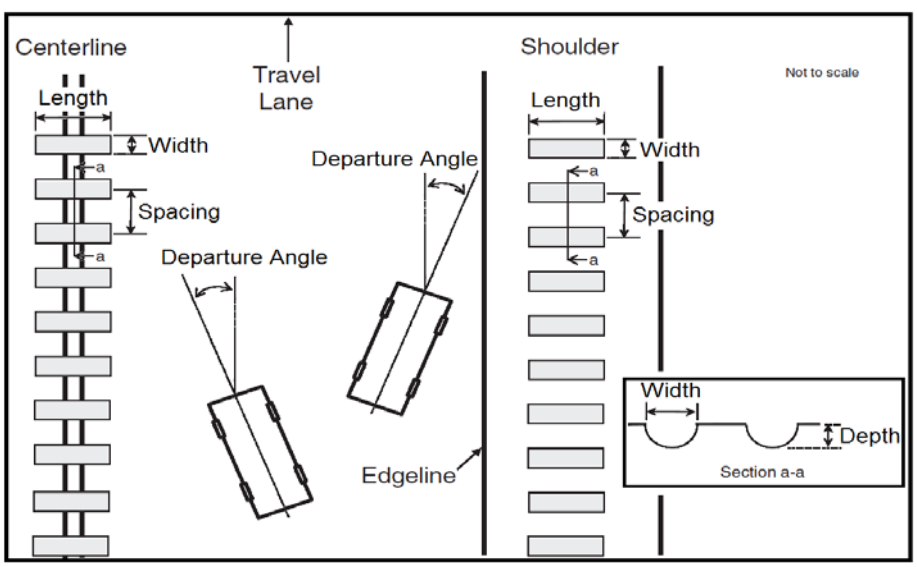


Figure 5: Rumble strip design "descriptors" (WSDOT Design Office)

Table 1: Range of installed rumble strips, current standard plan, and designs evaluated in NCHRP 641

	Groove Length	Groove Depth	Groove Spacing	Groove Width
Washington State (in use)	6 - 12	0.375 - 0.625	12 - 24	3.75 - 6.9
WSDOT Standard Plan (2012)	12	0.5 - 0.625	12	6.5 - 7.5
Evaluated in NCHRP Report 641	6 - 12	0.25 - 0.625	12 - 24	4.88 - 7.65

All dimensions in inches
There may be examples of unintentionally deeper groove depth in the field.

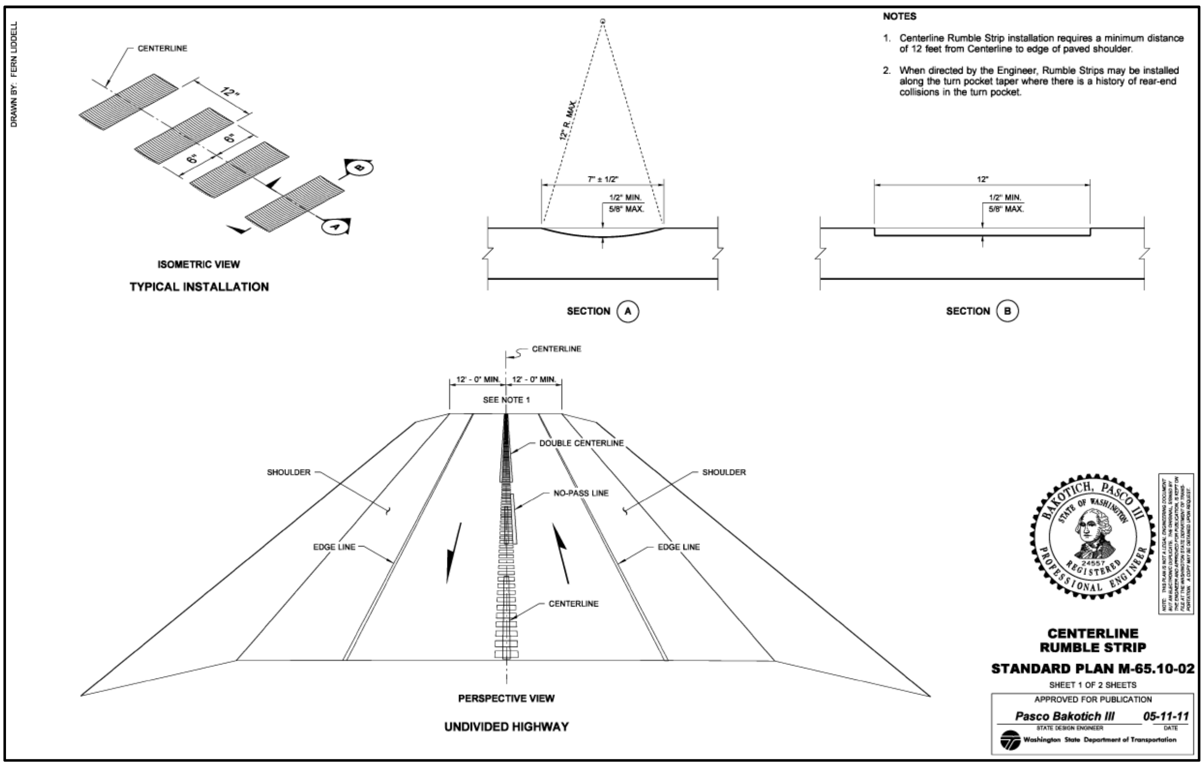


Figure 6: WSDOT's Standard plan for centerline rumble strips (August 6, 2012, page 557)

The Locations Used to Evaluate External Rumble Strip Noise

Nine measurement locations were selected throughout Washington state to represent the range of milled CLRS designs currently used (see Figure 7). Each of the selected locations had a unique set of design characteristics, which are described in Table 2.

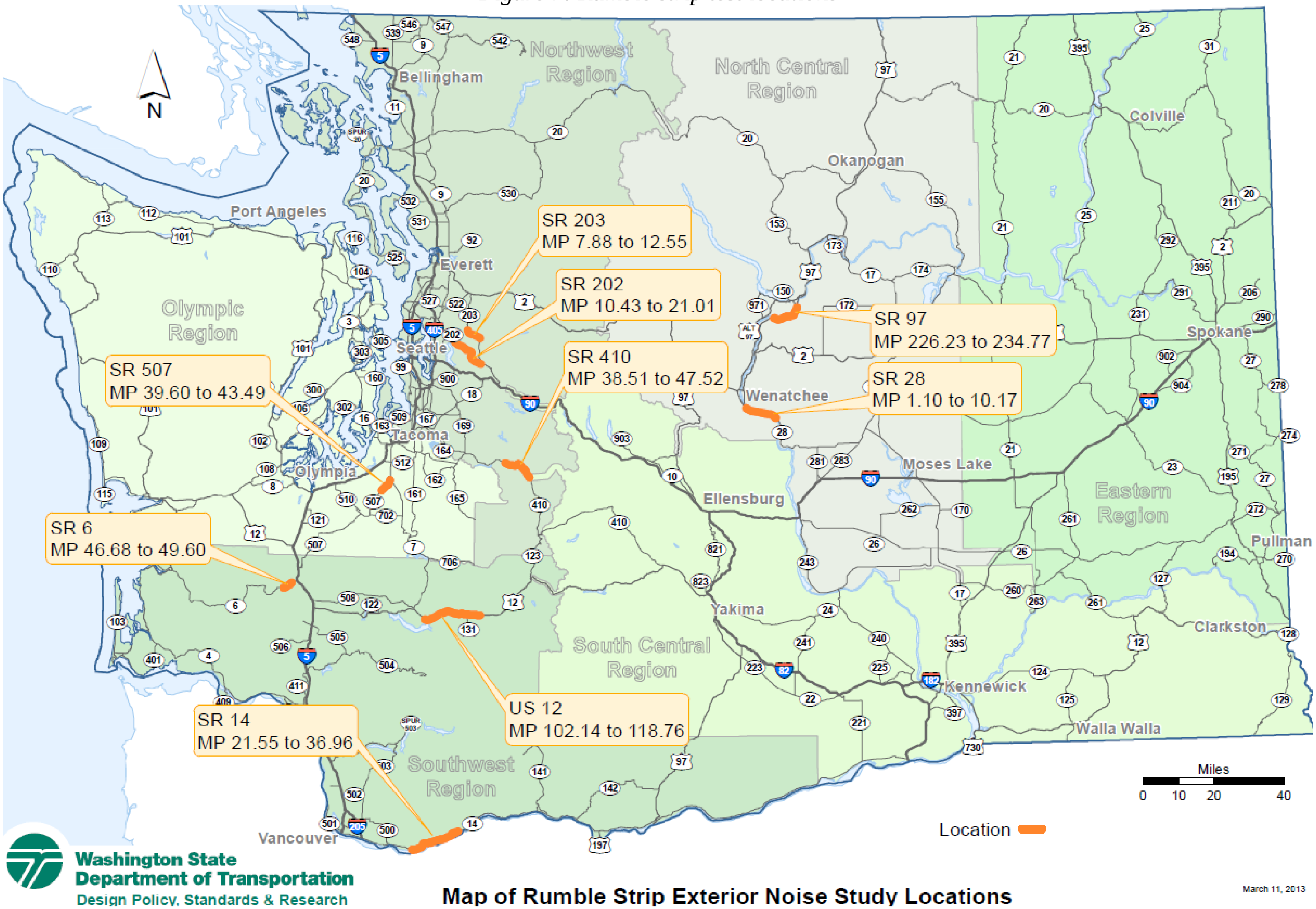
Width, length, and spacing were verified in the field. Field measurements for depth were attempted but proved difficult to verify with the available equipment (a ruler).

Table 2: Representative centerline rumble strip measurement locations

SR	Begin MP	End MP	Depth	Width	Length	Spacing	Contract Number	Install Date*	Rumble Strip Type	Sound Level Measured?
6	46.68	49.60	0.50	6.90	8.00	12.00	6944	Dec-05	Center	Yes
12	102.14	118.76	0.50	6.90	12.00	24.00	8135	Jan-12	Center	Yes
14	21.55	36.96	0.50	6.90	10.00	12.00	6875	Jun-05	Center	Yes
28	1.10	10.17	0.375	6.00	12.00	12.00	7958	Oct-10	Center	Yes
97	226.23	234.77	0.375	6.00	8.00	18.00	Region	Apr-12	Center	Yes
202	10.43	21.01	0.50	6.00	12.00	12.00	7793	Aug-09	Center	Yes
203	7.88	12.55	0.50	6.00	12.00	12.00	7856	Jun-12	Center	Yes
410	38.51	47.52	0.375	6.00	8.00	12.00	8116	Nov-11	Center	Yes
507	39.60	43.49	0.375	6.00	12.00	12.00	7243	Jul-07	Center	Yes

** Or date contract physically completed.*
Width, Length, and Spacing dimensions in inches

Figure 7: Rumble strip test locations



Rumble Strip Noise Measurements

Measurement Equipment

Testers drove a 2010 Ford Escape hybrid that had all-season light SUV/crossover tires (Michelin Latitude Tour) with a new tire tread depth of 12.5/32nds of an inch (see Figure 8). The tires had been driven approximately 20,000 miles at the time of the measurements. As in NCHRP 641, only this passenger vehicle was used, since passenger cars and light trucks are involved in the majority of crashes that are affected by CLRS (Torbic et al., 2009).

Figure 8: 2010 Ford Escape hybrid used for rumble strip measurements; and vehicle tire tread

Two Larson Davis Sound Track LxT1 sound level meters were used to measure sound levels. The meters conform to ANSI S1.4-1985, S1.43-1997 (R 2002), S1.25-1991 (r 2007), and S1.11-2004. The meters were calibrated before and after measurements at each location by using a Bruel and Kjaer Type 4231 calibrator that conforms to ANSI S1.40-1984 (Figure 9).

Figure 9: Verifying calibration of Type 1 sound level meters before measurements.

Measurement Methodology

The researchers used a sound level collection methodology consistent with the American Association of State Highway and Transportation Officials (AASHTO) provisional specification TP 98-13: *Determining the Influence of Road Surfaces on Vehicle Noises Using the Statistical Isolated Pass-By (SIP) Method*. "This test method describes a procedure for measuring the influence of road surfaces on highway traffic noise. The SIP Method provides a quantitative measure of the sound pressure level at locations adjacent to a roadway." (AASHTO, 2014)

Measurements for this project were consistent with the measurement equipment, selection of test sites, traffic conditions, meteorological conditions, and microphone positions described in the TP 98 test procedure (Figure 10). However, unlike the SIP method, the rumble strip results were compared to one another instead of being compared to a reference noise curve.

All test locations were located either in rural areas with no development or areas with low density residential development. The sites were selected to ensure that no other major noise sources could affect the measurement results.

Figure 10: Sound level meters at a test site on US 12

Microphone Position

As shown in Figure 10, two primary microphone positions were used to record simultaneous 10-second measurements:

- 25 feet from the center of the near travel lane and 5 feet above the center lane surface
- 50 feet from the center of the near travel lane and 12 feet above the center lane surface.

The microphone farthest from the road (at 50 feet) was placed 12 feet above the lane surface to reduce the effects of ground surfaces on sound propagation (i.e., “ground effects”).

Measurement Duration

Ten-second measurements were collected as the test vehicle passed the microphone approximately 5 seconds into the measurement period.

Rumble Strip Contact

The test vehicle traveled with two tires on the rumble strip for the full measurement duration.

Vehicle Test Speed

The test vehicle was traveling at 60 mph to ensure consistency between measurements. 60 mph was higher than the posted speed in some locations.

Traffic

Measurements were considered valid if the test vehicle was isolated and clearly the dominant noise source.

Near Lane and Far Lane

Measurements were collected from the test vehicle passing in the near lane and far lane relative to the sound level meter. All facilities were undivided highways with one lane in either direction. Near lane measurements tended to be quieter because the vehicle shielded the microphone from the tires passing over the rumble strip.

Numbers of Measurements

The numbers of simultaneous measurements at each location were between 3 and 10 (6 to 20 total measurements). Numbers varied by test section because of variables that included staff time constraints, prevalence of other traffic, and weather conditions.

Rumble Strip Measurements

Measurements were collected at nine locations throughout the state, as shown in Figure 7. Measurements focused on milled center line rumble strips because these are the most common type of rumble strips used in Washington state. Table 1 describes the range of designs currently used in Washington state. Locations were selected to represent the full range of current WSDOT CLRS designs.

Measurements were evaluated for overall maximum sound level (L_{max}) and by 1/3-octave band frequency to determine whether there were tonal components to the rumble strip designs. Frequency was measured by using a 1/- octave band filter. When sound energy is spread across the audible spectrum (approximately 400 Hz – 5,000 Hz), it is typically considered to be less annoying than when energy is focused at a particular frequency or narrow band of frequencies.

The limited sample size for some of the CLRS designs may have affected the significance of the results. However, the smallest sample sizes were on SR 410 and US 12, and these locations also had the smallest amount of variation between measurements, ranging from 1 to 3 dBA, respectively. At all the other locations, at least five measurements were taken for each condition (vehicles traveling in the near and far lanes with microphones at 25 feet and 50 feet from the center of the near lane).

Summary of Measurement Results

Measurement results were arithmetically averaged on the basis of microphone position and whether the vehicle was traveling in the near or far lane relative to the microphone. All test sections were two lane, undivided highways. Generally, near-lane measurements were quieter because the vehicle shielded the sound from the microphone

(Figure 11). Sound at the microphone farther back at 50 feet was usually quieter than at the microphone at 25 feet because sound energy attenuates over distance.

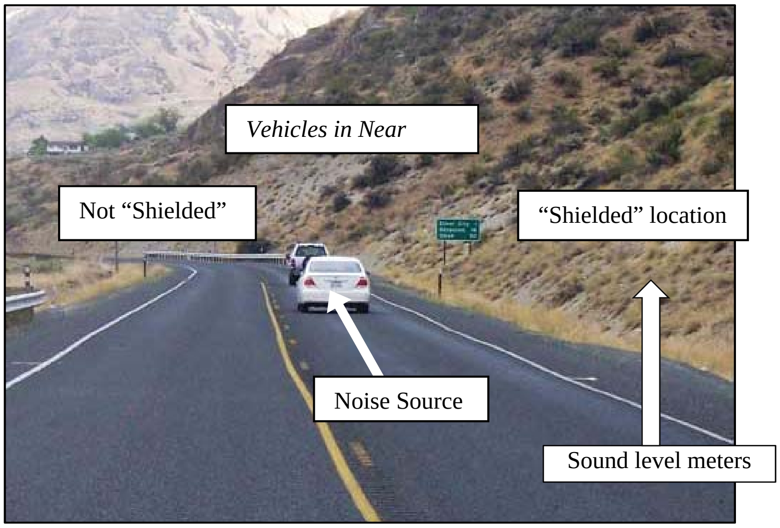


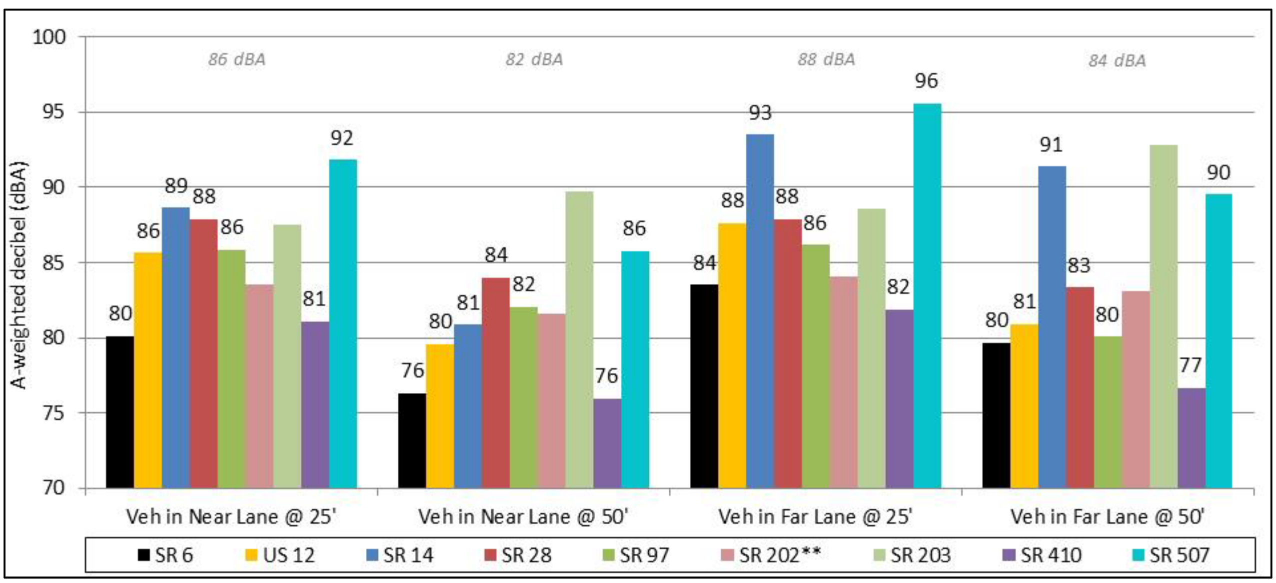
Figure 11: Example of “shielded” sound level meter location

A summary of results is described in Table 3 and Figure 12. The measurements revealed significant differences in external rumble strip noise levels among the various designs. For example, average sound levels on SR 6 were 10-\ to 12 dBA lower than levels on SR 507, depending on the distance from the roadway.

Table 3: Dimensions of measured rumble strip designs and average maximum sound levels (1 = Quiet)

SR	Design Dimensions (in.)				Vehicle Passing in Near Lane (L_{max} dBA)		Vehicle Passing in Far Lane (L_{max} dBA)		Rank Order: Quiet to Loud (25' far lane)
	Depth	Width	Length	Spacing	25'	50'	25'	50'	
SR 6	0.5	6.9	8	12	80	76	84	80	2
US 12	0.5	6.9	12	24	86	80	88	81	5
SR 14	0.5	6.9	10	12	89	81	93	91	8
SR 28	0.375	6.0	12	12	88	84	88	83	6
SR 97	0.375	6.0	8	18	86	82	86	80	4
SR 202	0.5	6.0	12	12	84	82	84	83	3
SR 203	0.5	6.0	12	12	88	90	89	93	7
SR 410	0.375	6.0	8	12	81	76	82	77	1
SR 507	0.375	6.0	12	12	92	86	96	90	9

Note: SR 202 and SR 203 were based on WSDOT Standard Plans that allow a depth of 1/2-5/8.



Mean sound level for all section combined shown above each location/mic combination.

Figure 12: Average maximum sound levels for a single vehicle (L_{max})

Frequency Spectrum: Vehicle Passing in the Far Lane

Overall sound levels were measured along with frequency characteristics by using a 1/3-octave band A-weighted filter. In Figure 13,, the measurement results from the test vehicle passing in the near and far lanes on SR 12 a) demonstrate the similar frequency trend for both conditions and b) highlight the relative difference in sound levels. While there was sound variation among locations, the results were generally consistent. Specific results for each measurement location are included in Appendix A.

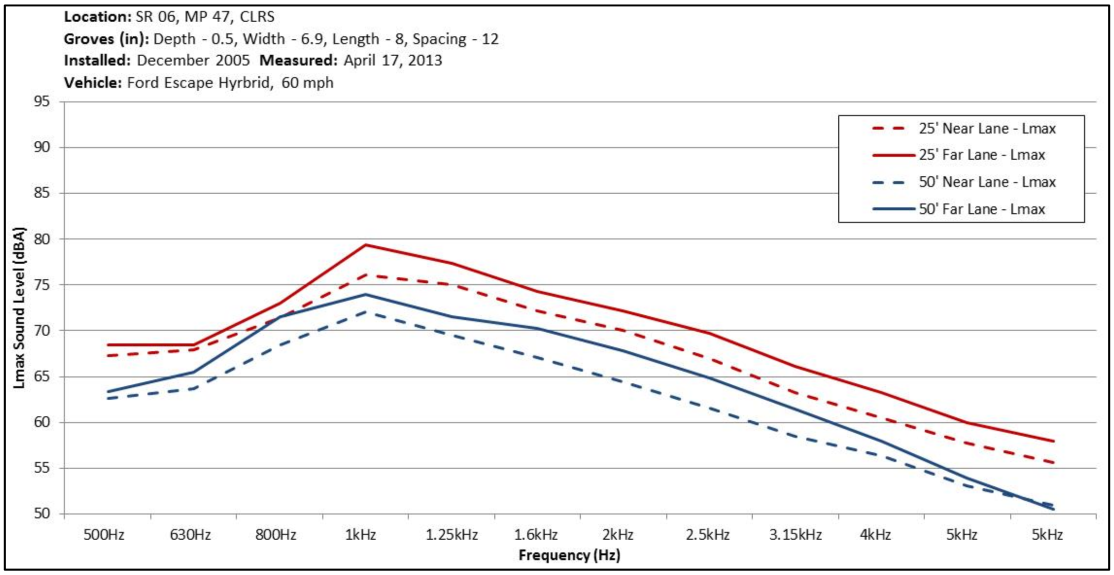


Figure 13: Example of 1/3-octave band measurement results from SR 06

Both the overall sound levels and sound levels at individual frequencies were higher when the vehicle passed in the far lane. Therefore, the following analysis focuses on frequency measurements for the far lane conditions at both microphone positions to highlight the differences among rumble strip designs. Figure 14 and Figure 15 show how, at the near microphone position, the dominant frequency was 800 Hertz (Hz) for all but the strips at SR 97 and SR 507, where 1000 Hz and 630 Hz dominated, respectively. On SR 507, the 630 Hz band continued to dominate even at 50 feet, whereas on SR 97, the peak was 800 Hz at 50 feet. Since overall sound levels on SR 97 were significantly higher than levels at the SR 6 and SR 410 sites, which had the lowest overall sound levels of any measured designs, the slight difference in dominant frequency was not explored further.

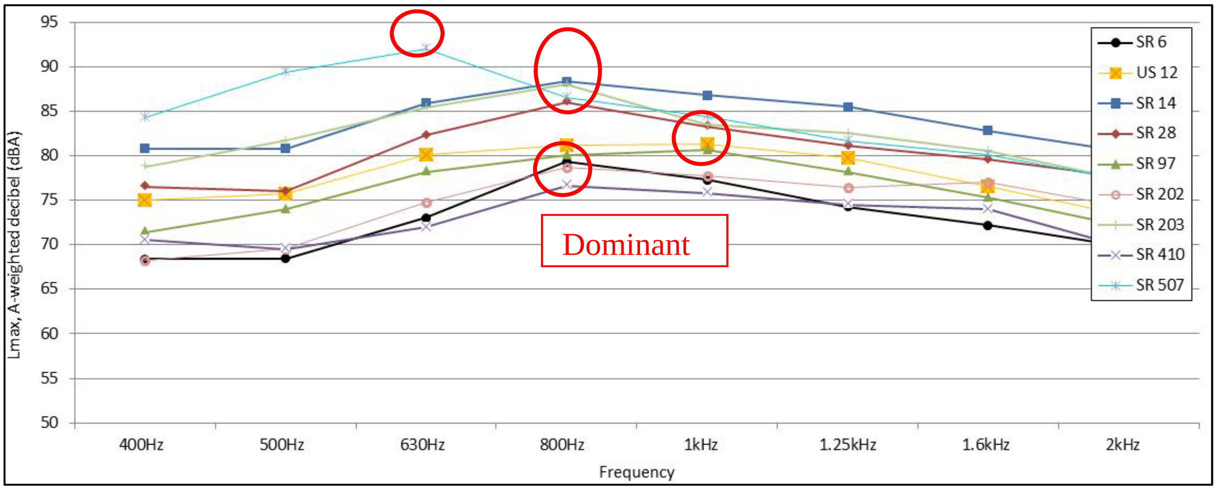


Figure 14: Frequency spectrum for a vehicle passing in the far lane at the 25-foot measurement location

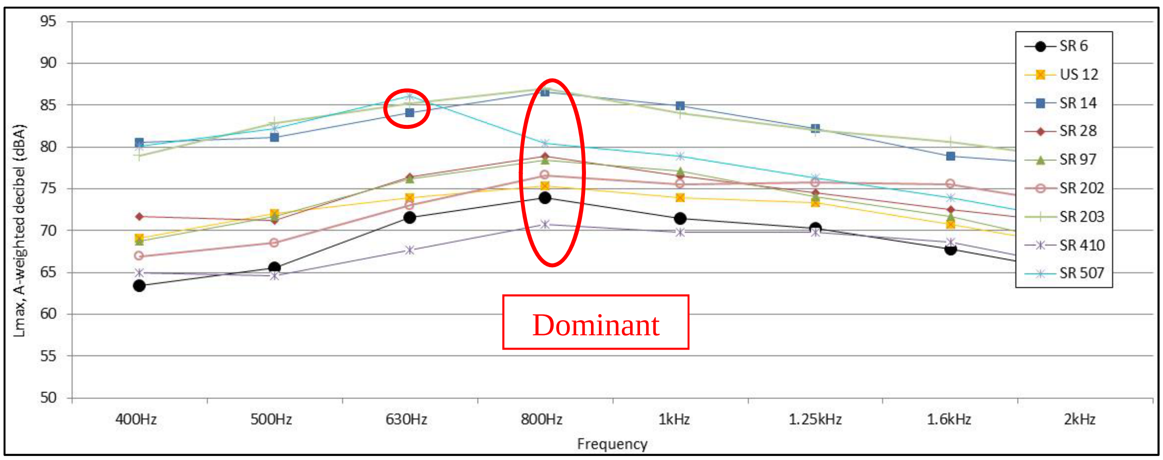


Figure 15: Frequency spectrum for a vehicle passing in the far lane at the 50-foot measurement location

Also notable was how the 800-Hz frequency stood out on SR 507 and SR 28, where it was 3 to 6 dBA higher than adjacent frequency bands at 600 Hz and 1000 Hz. The SR 507 and SR 28 locations shared the same design characteristics (depth, width, length, and spacing). Isolated frequencies are more likely to cause annoyance, especially at lower frequencies that travel farther than "spikes" at the high end of the audible frequency range. However, neither the SR 507 nor SR 28 designs are recommended because of their substantially higher overall sound levels, so the frequency elements were not explored further. These designs had the highest overall measured sound levels and tonal components, so they are considered to have the greatest potential to disturb nearby residents of any measured CLRS. See the full comparison in Table 4.

Table 4: Comparison of average overall L_{max} levels to highest frequency L_{max}

SR	Avg. Lmax (dBA)	Highest Frequency	Lmax (dBA)	Diff in Lmax (dBA)	Avg. Lmax (dBA)	Highest Frequency	Lmax (dBA)	
SR 6	84	800 Hz	79	5	80	800 Hz	74	6
US 12	88	800 Hz	81	7	81	800 Hz	75	6
SR 14	93	800 Hz	88	5	91	800 Hz	87	4
SR 28	88	800 Hz	86	2	83	800 Hz	79	4
SR 97	86	1000 Hz	81	5	80	800 Hz	78	2
SR 202	85	800 Hz	79	6	83	800 Hz	77	6
SR 203	92	800 Hz	88	4	92	800 Hz	87	5
SR 410	82	800 Hz	77	5	77	800 Hz	71	6
SR 507	96	630 Hz	92	4	90	630 Hz	86	4

Variability within Test Sections

Appendix A shows the results of all the measurements for frequencies of 500 Hz to 5 kHz, in addition to the average maximum values (L_{max}) described above. Evaluation of the results showed a large amount of variation among the individual measurements. The difference for L_{max} values among measurements within the same test section ranged from 1 dBA on SR 410 to 11 dBA on SR 14. SR 14 had the highest variation and largest standard deviation of any section. Table 5 compares the minimum and maximum measured values within each test section and describes the amount of variation among measurements. The final column compares results to the ranking based on the average

L_{max} value for each test section described in Table 3. While there was some variation, the following are general results for exterior noise levels from the measured CLRS's:

- Lowest Noise: SR 410, SR 6, and SR 202
- Moderate Noise: US 12, SR 28 and SR 97
- Highest Noise: SR 14, SR 203, and SR 507.

Table 5: Comparison of L_{max} values, variation, and averaged results for 25-ft; far lane measurements

SR	Min. Measured Value		Max. Measured Value		Avg. of Measured Values		Variation between Measures (L_{max})	
	L_{max} (dBA)	Rank Order	L_{max} (dBA)	Rank Order	L_{max} (dBA)	Rank Order	Range (dBA)	Standard Deviation (dBA)
SR 6	81	3	85	2	84	2	3	1
US 12	86	6	90	5	88	5	5	2
SR 14	87	7	98	9	93	8	11	5
SR 28	85	5	94	6	88	6	8	2
SR 97	82	4	88	4	86	4	6	2
SR 202	81	1	86	3	84	3	5	2
SR 203	90	8	94	7	92	7	4	2
SR 410	81	2	83	1	82	1	1	1
SR 507	93	9	98	8	96	9	4	2

1 = lowest or "quietest" value

Comparison to Interior Sound Levels

NCHRP Report 641 evaluated interior sound levels to determine whether rumble strip designs produced sufficient interior noise levels to safely alert the driver. Table 5 compares the measured exterior sound levels to NCHRP interior sound levels with qualitative descriptors form the WSDOT Design Office tool. Interior sound levels are reported as the difference between background levels inside the cabin while the vehicle is driving in the travel lane and noise levels in the cabin while the vehicle is traveling over the rumble strip. NCHRP 641 qualitative noise descriptors are as described below. :All the measured designs achieved at least NCHRP's "target noise level":

- Target Noise Level (+ 6 - 11 dBA)

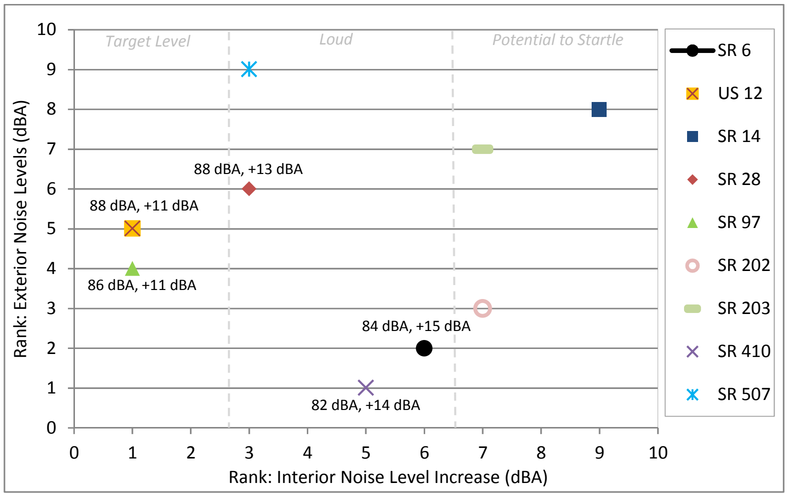
- Loud (+ 11-14 dBA)
- Potential to Startle (+ >15 dBA).

Because the vehicle was on the CLRS for the full measurement period, Table 6 assumes a minimum departure angle of 1 degree. Lower departure angles result in higher sound levels inside the vehicle. Figure 16 compares the interior sound level increases to the measured exterior sound levels. All of the measured CLRS designs met the performance thresholds identified in NCHRP Report 641 of at least 6 dBA and other generally accepted increases of 10 dBA or more.

Table 6: Comparison of interior and exterior noise levels from CLRS designs

SR	Design Dimensions (in.)				NCHRP 641: Interior Sound Increase above Background Levels*			Avg. Exterior Measured Values	
	Depth	Width	Length	Spacing	L_{max} (dBA)	Descriptor	Rank Order	L_{max} (dBA)	Rank Order
SR 6	0.5	6.9	8	12	15	Loud	6	84	2
US 12	0.5	6.9	12	24	11	Target Level	1	88	5
SR 14	0.5	6.9	10	12	16	Potential to Startle	9	93	8
SR 28	0.375	6.0	12	12	13	Loud	3	88	6
SR 97	0.375	6.0	8	18	11	Target Level	1	86	4
SR 202	0.5	6.0	12	12	15	Potential to Startle	7	84	3
SR 203	0.5	6.0	12	12	15	Potential to Startle	7	92	7
SR 410	0.375	6.0	8	12	14	Loud	5	82	1
SR 507	0.375	6.0	12	12	13	Loud	3	96	9

**Assumes a 1-degree departure angle, which results in the highest sound level predictions. Estimates based on 60 mph*



"Target Level," "Loud," and "Potential to Startle" are for interior noise levels based on NCHRP 641. Noise levels are listed with the highest performing sections for exterior levels and interior noise level increases, respectively.

Figure 16: Comparison of rank order for interior and exterior noise levels

Conclusions

The primary research objective was to identify centerline rumble strip (CLRS) designs that can perform similar to the WSDOT standard rumble strip design while reducing external rumble strip noise disturbances at adjacent properties.

Sound Level Results

To determine the acoustic performance of the tested CLRS, sound level measurements were collected at nine locations with varying CLRS designs. Exterior noise levels, including 1/3-octave band frequencies, and interior noise levels were evaluated along with measurement variability.

Exterior Sound Levels

- When vehicles pass over CLRS, overall exterior sound levels (i.e., sound energy) are the major contributor to roadside annoyance.
- SR 410 had the lowest measured overall sound level at the roadside, followed by SR 6 and SR 202.

1/3 Octave Band Frequencies

- Isolated frequencies can also contribute to annoyance associated with noise, especially at lower frequencies that travel farther than "spikes" at the high end of the audible frequency range.
- The SR 410, SR 6, and SR 202 designs all shared an 800-Hz dominant frequency, exhibiting the same general characteristic as a majority of the other measured designs.

Measurement Variability within Test Sections

- The range of measured sound levels and the standard deviation for each section were evaluated to give insight into the consistency of the design throughout the test section. Variation ranged from 1 to 11 dBA, with standard deviations ranging from 1 to 5.
- SR 410, SR 6, and SR 202 had the lowest minimum and maximum Lmax values, consistent with the overall sound levels results. SR 410 and SR 6 had the most consistent results.

Location	Rank: Overall Sound Level	Range: Min –Max Lmax (dBA)	Standard Deviation (dBA)
SR 410	1	1	1
SR 6	2	3	1
SR 202	3	5	2

Interior Sound Levels

- Interior levels identify which CLRS designs increase in-cabin sound levels enough to promote safety but not enough to cause a startle response. This acceptable range is generally considered to be between 6 to 15 dBA, with a preference for levels nearer the maximum.
- CLRS designs are predicted to increase in-cabin sound levels on SR 410 by 14 dBA and on SR 6 by 11 dBA. These increases are qualitatively considered to be "loud" per NCHRP report 641. SR 202 is predicted to increase sound levels by at least 15 dBA, which is considered to have the "potential to startle" the driver.
- Measurements suggested no obvious connection between interior and exterior sound levels (see Table 6).

Overall

- SR 410 and SR 6 are considered the highest performing of the measured sections because they shared the following characteristics:
  - Lowest overall sound levels
  - No 1/3-octave band "spikes"
  - Tightest range of measured results and lowest standard deviations among samples
  - Within the acceptable range for interior sound levels.
- SR 202 was also a higher performer but is not grouped with SR 410 and SR 6 because it had higher overall exterior sound levels, and interior levels have the "potential to startle."

Sound Levels and CLRS Designs

The results suggested that some CLRS designs can have lower exterior sound levels and sufficient interior sound levels. However, the effects of specific design variables on exterior noise levels were inconclusive, and suggested that interactions among variables contribute to exterior sound levels. Therefore, this report does not recommend a specific CLRS design, and WSDOT HQ Design will have to determine how to use the results of this research in future decisions about CLRS design.

Results for Same CLRS Design at Different Locations

SR 202 and SR 203 were built to a WSDOT standard specification that allows a tight range of acceptable rumble strip dimensions. Despite the fact they utilized the same specification, the sound levels between these sections varied by more than 7 dBA.

Potential Connection between Groove Length and Spacing

SR 410 and SR 6 were the quietest sections and shared the same groove length (8-in.) and spacing (12-in.) but had different groove depths and widths. In this case, the length and spacing produced consistent exterior noise, which suggests that these dimension components may be important contributors to the variations in exterior noise levels produced by different designs.

CLRS Design Range for the Lowest Exterior Noise

The following CLRS design had the lowest exterior noise levels:

- Depth: 0.375 in. to 0.5 in.
- Width: 6 in. to 6.9 in.
- Length: 8 in.
- Spacing: 12 in.

Other CLRS Designs to Consider

If additional CLRS design combinations are considered, a shallower depth or shorter length may further reduce exterior sound levels. The variables should be tested individually to provide data on the interaction among variables. Both designs described in Table 7 are outside the current range allowed by WSDOT Standard Plans but within the range considered acceptable by NCHRP.

Table 7: Suggested future design combinations for testing

Tested Variable	Design Dimensions (in.)			
	Depth	Width	Length	Spacing
Shallower Depth	0.25	6.0	8	12
Shorter Length	0.375	6.0	6	12

Additional Observations on the Results

- The exterior sound levels reported here can inform project-specific decisions about CLRS design, along with other considerations, including the amount of truck traffic, bicycle usage, weather, roadway geometry, and crash history.
- The actual exterior sound levels from shoulder rumble strips (SRS) could be higher than the CLRS values gathered for this project, but the general results should also apply to SRS.

References

AASHTO Provisional Standards. 2014 Edition. TP98-13 *Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-By Method (SIP)*

Caltrans. (2012). *Traffic Noise Generated by Rumble Strips.* California.

Federal Highway Administration. (2011, November 7). *Technical Advisory: Shoulder and Edge Line Rumble Strips.* Retrieved June 24, 2013, from FHWA Safety Program: http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/t504039/

Federal Highway Administration. (n.d.). *Rumble Strip Types*. Retrieved June 24, 2013, from FHWA Safety Program: http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/rumble_types/

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

Karkle, D. E., M.J Rys, E.R. Russell (May 2011). "Centerline Rumble Strips: Study of External Noise." *Journal of Transportation Engineering*, American Society of Civil Engineers.

Kragh, J., B. Andersen, and S. Thomsen (2007). "Low Noise Rumble Strips on Roads - A Pilot Study." *Proceedings of the Internoise 2007 Conference.* Istanbul, Turkey.

Olson, D. B. (2011). *Performance Analysis of Centerline Rumble Strips in Washington State, WA-RD 768.1.* Washington State Department of Transportation: Olympia, WA.

Torbic, D. J. et al. (2009). *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.* Washington, D.C.: Transportation Research Board.

Washington State Department of Transportation. (2012, July). Section 1600.07 (1)(c). *WSDOT Design Manual*. Olympia, WA.

Washington State Department of Transportation. (2012, August 6). Standard Plan for Centerline Rumble Strips. *2012 WSDOT Standard Plans*. Olympia, WA.

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Appendix A—CLRS Measurement Results

The following tables provide detailed measurement results for the CLRS measurement test sections.

SR 06

Depth	Width	Length	Spacing
0.5	6.9	8	12

	Measurement Date and Start Time	Direction	Avg. Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2013/04/17 14:09:13	WB	77.3	60.9	60.9	64.1	62.6	67.7	72.7	71.0	70.0	62.3	57.9	57.1	54.0
	2013/04/17 14:28:43		82.9	71.3	71.3	69.5	73.6	79.0	75.4	72.9	70.5	68.3	64.3	60.1	57.7
	2013/04/17 14:31:09		82.1	68.3	68.3	69.1	73.7	78.8	75.2	72.5	70.1	67.2	64.8	60.6	57.1
	2013/04/17 14:55:21		82.0	69.1	69.1	69.2	74.4	77.1	74.5	71.8	69.0	68.5	64.2	63.6	61.4
	2013/04/17 14:56:08		82.3	66.7	66.7	67.5	72.9	77.8	77.5	72.8	70.5	68.5	64.9	61.3	58.2
		Averages	80.1	67	67	68	71	76	75	72	70	67	63	61	58
25' Far Lane - Lmax	2013/04/17 14:05:48	EB	83.1	68.2	68.2	66.4	71.8	79.5	77.0	73.3	72.6	69.9	65.9	62.3	59.2
	2013/04/17 14:10:20		84.7	72.6	72.6	71.3	74.6	81.1	76.5	75.2	71.7	68.9	65.3	61.1	58.4
	2013/04/17 14:16:21		81.5	64.2	64.2	66.6	69.8	75.5	77.4	72.1	70.3	66.9	63.9	60.9	58.2
	2013/04/17 14:20:10		83.8	68.6	68.6	68.4	74.9	79.8	78.4	76.4	72.9	71.3	67.2	67.7	63.5
	2013/04/17 14:23:49		84.5	68.5	68.5	69.6	74.1	80.8	77.4	74.5	73.6	71.7	68.0	64.1	60.5
		Averages	83.5	68	68	68	73	79	77	74	72	70	66	63	60
50' Near Lane - Lmax	2013/04/17 14:02:04	WB	75.4	61.8	61.8	61.5	67.8	70.7	69.9	66.1	63.0	59.9	57.5	55.4	52.5
	2013/04/17 14:30:26		76.7	64.3	64.3	64.5	68.3	72.9	68.3	67.1	65.6	61.8	58.6	55.5	52.5
	2013/04/17 14:36:29		77.8	64.3	64.3	66.8	70.9	73.3	70.4	71.4	66.4	63.4	60.2	56.7	53.4
	2013/04/17 14:57:04		75.7	63.4	63.4	63.2	67.1	71.5	68.2	65.3	63.0	61.7	58.0	57.9	55.1
	2013/04/17 14:57:51		75.9	59.4	59.4	62.5	68.3	71.8	70.5	65.6	64.3	60.9	58.1	56.1	52.0
		Averages	76.3	63	62.6	63.7	68.5	72.0	69.5	67.1	64.4	61.5	58.5	56.3	53.1
50' Far Lane - Lmax	2013/04/17 14:09:28	EB	82.0	65.0	65.0	69.3	75.6	77.6	74.1	72.2	69.7	68.4	64.6	60.6	55.6
	2013/04/17 14:12:04		82.0	65.7	65.7	66.0	72.0	74.7	70.4	68.1	65.0	62.3	59.3	56.9	53.3
	2013/04/17 14:18:05		76.2	59.5	59.5	61.2	67.1	69.6	70.0	70.5	68.7	63.8	60.6	56.4	53.0
	2013/04/17 14:21:53		78.8	62.1	62.1	62.8	68.4	73.6	73.3	70.9	69.2	65.4	63.3	63.2	58.4
	2013/04/17 14:25:33		79.5	61.1	61.1	62.8	69.2	76.2	72.4	71.1	68.8	65.3	65.1	63.4	58.5
		Averages	79.7	63	63	66	72	74	72	70	68	65	61	58	54

SR12

Depth	Width	Length	Spacing
0.5	6.9	12	24

	Measurement Date and Start Time	Direction	Avg. Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	'11/02/04 16:22:43	WB	83	69.1	72.8	77.2	77.6	76.2	72.2	69.4	65.6	64.0	62.3	59.3	54.3
	'11/02/04 16:38:52		90	74.3	79.7	83.0	85.8	83.2	82.4	77.9	72.6	71.0	66.6	63.3	60.6
	'11/02/04 16:51:19		86	72.6	75.3	79.3	82.4	78.7	76.1	72.7	69.8	68.2	64.5	62.5	59.5
	'11/02/04 16:55:13		88	74.5	74.3	79.4	82.5	82.3	78.9	74.6	71.4	69.6	68.2	65.2	60.8
	'11/02/04 17:01:24		82	65.4	71.7	75.8	76.2	77.6	72.4	69.3	67.3	64.1	61.1	58.8	56.0
		Averages	86	71	75	79	81	80	76	73	69	67	65	62	58
25' Far Lane - Lmax	'11/02/04 16:47:54	EB	86	73.1	74.0	78.2	80.0	79.0	77.0	73.6	70.2	67.5	65.1	63.2	60.0
	'11/02/04 16:53:55		87	75.0	76.1	79.7	81.0	79.9	77.8	75.4	71.7	69.0	66.4	62.9	60.9
	'11/02/04 16:58:18		90	76.8	77.0	82.4	82.6	85.0	84.5	80.8	77.8	75.0	71.9	68.5	64.3
		Averages	88	75	76	80	81	81	80	77	73	70	68	65	62
50' Near Lane - Lmax	'11/02/04 16:22:43	WB	83	69.1	72.8	77.2	77.6	76.2	72.2	69.4	65.6	64.0	62.3	59.3	54.3
	'11/08/04 16:38:19		80	65.6	69.1	66.0	68.6	68.9	66.8	67.2	69.8	67.4	65.5	65.7	59.7
	'11/08/04 16:52:22		79	67.3	69.9	73.6	74.0	70.9	68.5	66.1	63.6	62.3	57.9	54.1	49.4
	'11/08/04 16:56:12		81	67.1	68.8	73.5	76.0	74.7	70.9	67.7	65.3	63.4	61.5	59.6	54.2
	'11/08/04 17:02:21		76	65.9	65.9	72.1	71.0	70.0	66.6	64.1	63.4	60.3	58.7	56.8	51.7
		Averages	80	67	69	72	73	72	69	67	66	63	61	59	54
50' Far Lane - Lmax	'11/08/04 16:48:56	EB	80	66.5	71.0	73.6	73.3	71.7	71.5	68.8	65.9	62.3	58.2	56.3	53.7
	'11/08/04 16:54:57		81	70.4	72.3	73.5	75.8	73.1	72.5	70.6	66.9	62.7	59.9	56.6	53.3
	'11/08/04 16:59:21		82	70.5	72.8	74.7	76.9	76.9	76.0	73.1	70.8	66.9	65.5	60.4	55.7
		Averages	81	69	72	74	75	74	73	71	68	64	61	58	54

SR14

Depth	Width	Length	Spacing
0.5	6.9	10	12

	Measurement Date and Start Time	Direction	Avg Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2013/04/17 10:42:54	WB	93.6	79.3	81.6	85.5	87.7	87.4	85.3	82.3	82.6	81.9	79.0	74.8	70.8
	2013/04/17 10:45:11		87.5	71.6	73.1	79.0	82.2	80.6	79.7	76.3	76.2	73.2	70.2	67.0	62.7
	2013/04/17 11:01:57		92.8	75.9	80.7	84.7	88.2	87.5	83.7	81.0	81.4	81.8	77.5	73.7	69.8
	2013/04/17 10:57:17		85.6	73.4	73.8	78.1	79.7	80.0	78.1	74.9	72.8	70.2	68.3	64.7	60.4
	2013/04/17 11:12:21		83.7	71.0	70.8	76.1	78.5	78.9	74.8	71.7	71.3	67.2	65.7	62.3	60.0
		Averages	89	74.2	76.0	80.7	83.3	82.9	80.3	77.2	76.9	74.9	72.1	68.5	64.7
25' Far Lane - Lmax	2013/04/17 10:37:26	EB	87.4	76.1	74.7	80.3	82.2	79.7	81.3	79.4	76.0	73.1	69.1	65.9	62.8
	2013/04/17 10:40:13		90.1	78.7	76.8	83.6	83.2	83.5	83.7	79.5	76.8	72.9	68.7	65.0	63.6
	2013/04/17 10:43:41		98.2	87.0	85.9	89.2	94.5	91.8	89.8	88.2	85.6	83.1	81.2	78.6	74.7
	2013/04/17 10:50:34		98.3	85.4	85.9	90.2	93.8	91.4	88.6	86.1	84.7	81.8	79.4	76.3	73.9
	2013/04/17 10:53:12		88.8	71.6	75.3	81.7	83.8	81.7	80.5	78.4	74.8	71.4	68.1	63.8	59.4
	2013/04/17 10:55:45		98.1	86.3	86.5	90.5	92.6	92.8	89.4	85.3	84.6	81.1	77.9	76.2	73.0
		Averages	93	81	81	86	88	87	86	83	80	77	74	71	68
50' Near Lane - Lmax	2013/04/17 10:41:53	WB	84.2	73.0	74.3	77.5	79.6	76.8	77.2	74.4	71.6	69.2	66.5	63.1	59.1
	2013/04/17 10:53:50		80.2	69.0	71.1	73.1	74.8	75.3	72.9	68.7	65.4	63.4	60.7	55.3	52.9
	2013/04/17 10:46:51		81.6	67.4	68.8	74.0	75.4	73.8	73.1	70.2	69.7	67.0	61.4	58.2	55.7
	2013/04/17 10:59:00		79.9	66.7	69.2	71.2	74.8	73.7	72.5	68.4	67.1	63.1	59.1	55.2	52.7
	2013/04/17 11:14:03		78.4	65.5	67.3	71.6	72.7	72.3	70.0	67.9	66.1	64.0	61.1	56.2	52.9
		Averages	81	68.3	70.1	73.5	75.5	74.4	73.1	69.9	68.0	65.3	61.7	57.6	54.7
50' Far Lane - Lmax	2013/04/17 10:42:47	EB	88.6	80.6	77.6	81.6	82.2	80.8	79.8	76.8	75.5	75.9	71.2	66.2	62.9
	2013/04/17 10:45:24		92.8	81.2	82.7	85.2	88.4	87.1	84.4	79.7	79.4	78.1	75.2	71.5	67.7
	2013/04/17 10:52:17		93.0	79.9	83.2	85.4	89.1	86.7	82.4	80.3	78.4	76.7	73.7	69.9	65.6
	2013/04/17 10:57:28		92.4	82.1	83.0	85.3	87.6	86.6	82.1	78.8	77.4	75.7	73.2	68.4	65.1
	2013/04/17 11:03:40		86.5	69.9	77.1	79.5	81.5	79.3	78.2	75.2	73.6	72.5	69.7	64.4	61.9
	2013/04/17 11:07:05		94.8	82.4	83.8	86.8	90.7	88.2	83.6	81.7	79.8	79.2	76.9	71.8	68.7
		Averages	91	81	81	84	87	85	82	79	78	77	73	69	65

SR28

Depth	Width	Length	Spacing
0.375	6.9	12	24

	Measurement Date and Start Time	Direction	Avg. Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2013/04/18 11:57:02	WB	89.9	76.9	76.9	81.4	86.1	82.4	81.2	79.3	78.2	74.3	71.1	67.4	64.7
	2013/04/18 12:01:50		89.7	77.6	78.0	82.9	84.3	82.0	81.4	80.9	78.6	75.9	71.7	68.6	64.5
	2013/04/18 12:07:27		82.2	69.0	69.4	73.3	77.5	74.7	73.1	72.0	69.2	65.7	61.8	58.5	56.5
	2013/04/18 12:33:32		87.0	74.3	72.7	79.8	81.1	80.4	78.0	77.4	74.9	71.9	68.4	65.0	62.2
	2013/04/18 13:02:54		91.5	82.5	78.7	83.0	84.0	83.6	84.1	83.7	82.8	76.6	74.5	70.8	67.0
	2013/04/18 13:38:12		86.9	74.9	73.3	78.8	81.7	80.4	78.1	76.5	73.8	71.1	66.6	63.9	60.4
		Averages	88	76	75	80	82	81	79	78	76	73	69	66	63
25' Far Lane - Lmax	2013/04/18 12:05:43	EB	91.5	78.3	78.0	82.3	88.1	84.0	82.6	81.4	80.1	77.7	74.3	72.0	66.7
	2013/04/18 12:50:02		90.4	78.0	76.3	81.9	86.6	82.9	81.7	80.2	78.5	75.1	73.6	68.0	65.2
	2013/04/18 12:54:34		85.2	72.2	71.7	77.5	81.2	78.3	77.1	74.0	71.9	69.8	66.6	62.8	60.5
	2013/04/18 12:58:18		90.3	78.7	76.4	81.3	87.1	83.4	81.2	80.3	79.0	77.6	72.0	68.8	65.4
	2013/04/18 13:01:04		89.9	77.0	74.6	82.2	85.0	83.0	81.5	79.8	78.5	76.2	72.7	70.0	65.9
	2013/04/18 13:08:04		88.7	74.1	73.2	82.1	83.3	83.4	80.1	77.2	75.1	71.7	66.4	64.0	60.4
	2013/04/18 13:16:00		91.2	75.2	77.0	83.6	87.8	84.7	80.6	80.8	77.5	72.5	68.0	65.7	62.4
	2013/04/18 13:18:37		93.6	79.0	80.9	87.5	89.3	86.9	84.4	82.8	80.2	79.3	75.3	73.2	71.6
		Averages	88	77	76	82	86	83	81	80	78	75	71	68	65
50' Near Lane - Lmax	2013/04/18 11:57:06	WB	84.8	72.6	72.9	78.1	79.5	76.5	77.3	76.0	74.6	72.1	69.5	65.8	61.5
	2013/04/18 12:01:51		88.2	72.2	73.4	82.0	80.1	78.8	78.9	79.7	78.4	74.9	71.0	67.8	64.3
	2013/04/18 12:07:29		77.8	63.8	64.1	68.5	71.4	69.3	71.0	68.5	65.9	64.5	59.9	56.4	51.5
	2013/04/18 12:33:33		82.7	67.5	69.7	75.2	76.5	74.4	75.3	74.0	71.7	69.3	68.3	62.4	57.2
	2013/04/18 13:02:55		87.3	75.5	74.5	78.5	79.3	78.9	80.3	78.9	79.6	74.0	71.9	67.5	64.6
	2013/04/18 13:38:13		83.1	69.3	69.3	74.5	77.0	74.8	76.7	74.4	72.3	69.7	66.6	63.8	58.1
		Averages	84	70	71	76	77	75	77	75	74	71	68	64	60
50' Far Lane - Lmax	2013/04/18 12:05:44	EB	84.9	76.6	74.9	77.3	79.9	77.0	74.8	73.8	72.5	70.5	69.3	66.0	62.8
	2013/04/18 12:50:12		83.9	73.2	74.1	76.2	79.3	76.1	75.0	73.4	72.0	70.3	66.5	62.8	58.9
	2013/04/18 12:54:35		78.9	63.0	65.3	69.9	74.2	71.6	71.1	67.7	66.2	63.5	62.6	59.7	54.1
	2013/04/18 12:58:20		84.3	74.3	69.6	79.0	79.3	76.8	74.4	73.4	71.8	68.0	66.5	63.6	60.3
	2013/04/18 13:01:05		82.9	71.1	72.0	76.0	78.9	77.1	75.4	73.8	70.1	69.7	67.0	65.0	61.4

	2013/04/18 13:08:05		81.5	69.3	67.1	73.8	77.3	75.9	73.2	69.8	68.0	67.8	67.8	65.4	60.2
	2013/04/18 13:16:00		83.5	68.3	70.9	77.6	79.7	77.7	74.4	71.8	69.9	66.1	64.0	61.1	56.8
	2013/04/18 13:18:38		86.8	77.6	76.0	81.2	82.9	79.9	77.8	76.3	75.2	73.8	71.6	68.5	62.5
		Averages	83	72	71	76	79	76	75	72	71	69	67	64	60

SR97

Depth	Width	Length	Spacing
0.375	6	8	18

	Measurement Date and Start Time	Direction	Avg. Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2012/07/26 14:38:26	WB	86.9	63.0	64.9	69.1	69.8	67.8	65.9	63.9	60.4	56.8	53.8	50.2	48.0
	2012/07/26 14:44:18		85.9	72.9	74.0	79.7	80.9	78.4	75.8	74.0	69.0	67.6	61.1	57.6	55.2
	2012/07/26 14:49:27		83.9	71.6	72.7	77.4	77.5	75.9	75.7	74.4	68.5	65.4	61.6	58.2	56.1
	2012/07/26 14:56:14		87.5	73.5	76.7	81.8	83.6	78.7	76.1	75.2	71.9	67.9	65.5	62.1	59.6
	2012/07/26 15:01:02		83.7	69.7	71.5	76.9	77.7	77.7	75.8	75.2	70.1	67.8	63.4	60.8	58.8
	2012/07/26 15:08:31		87.1	74.1	77.2	81.3	81.5	79.7	80.2	79.5	73.2	68.9	68.9	65.8	62.6
		Averages	86	71	73	78	78	76	75	74	69	66	62	59	57
25' Far Lane - Lmax	2012/07/26 14:35:45	EB	87.2	72.5	75.3	78.5	80.7	81.8	78.9	75.3	72.5	70.1	65.5	63.7	59.7
	2012/07/26 14:46:52		86.0	70.1	75.2	79.2	78.7	79.9	78.7	74.9	71.4	68.4	64.6	59.8	57.0
	2012/07/26 14:58:15		82.3	68.5	67.7	72.4	76.5	77.9	73.9	71.0	68.0	64.2	60.4	58.0	55.6
	2012/07/26 15:05:08		87.2	73.0	75.4	80.3	81.5	81.9	78.9	76.0	73.6	69.3	64.8	62.6	59.0
	2012/07/26 15:11:21		88.0	73.2	76.4	80.7	82.8	81.8	80.7	79.4	74.2	70.4	68.2	64.5	60.1
		Averages	86	71	74	78	80	81	78	75	72	68	65	62	58
50' Near Lane - Lmax	2012/07/26 14:38:32	WB	81.7	70.9	71.7	75.5	77.0	75.5	72.4	69.8	64.9	61.1	59.1	55.8	51.9
	2012/07/26 14:44:24		80.4	68.8	68.3	75.2	75.4	73.2	70.5	68.5	63.0	61.5	57.7	54.7	51.7
	2012/07/26 14:49:34		81.5	67.8	70.2	74.9	75.5	73.6	72.0	70.5	63.7	61.0	58.3	54.7	50.9
	2012/07/26 14:56:22		83.4	69.2	73.1	76.4	77.8	76.0	75.5	71.8	67.1	65.6	64.9	61.6	55.8
	2012/07/26 15:01:09		61.6	62.4	60.5	65.0	70.3	72.3	68.7	64.7	62.0	57.9	54.7	51.6	47.7
	2012/07/26 15:08:38		83.2	71.7	73.1	77.4	78.1	77.0	72.9	70.7	66.8	64.5	63.8	59.9	55.2
		Averages	82	68	69	74	76	75	72	69	65	62	60	56	52
50' Far Lane - Lmax	2012/07/26 14:35:53	EB	81.1	66.9	69.2	74.1	77.1	75.6	72.5	69.4	65.6	63.3	61.4	56.8	51.0
	2012/07/26 14:41:27		80.4	65.3	68.6	74.4	75.4	74.1	71.0	69.2	65.9	61.3	58.3	54.9	50.7
	2012/07/26 14:47:00		81.0	73.2	76.4	80.7	82.8	81.8	80.7	79.4	74.2	70.4	68.2	64.5	60.1
	2012/07/26 14:58:22		76.2	71.1	72.4	77.2	79.7	77.4	72.3	70.2	66.4	62.5	60.0	57.2	52.3
	2012/07/26 15:11:28		81.6	67.2	72.0	74.4	76.9	76.4	73.9	70.1	68.1	64.0	62.1	58.3	53.3
		Averages	80	69	72	76	78	77	74	72	68	64	62	58	53

SR 202

Depth	Width	Length	Spacing
0.5	6	12	12

	Measurement Date and Start Time	Direction	Avg. Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2013/09/26 22:08:33	NB	85	69.5	69.9	78.1	80.4	76.6	73.7	73.4	70.9	67.0	64.6	63.8	61.2
	2013/09/26 22:13:05		83	68.0	70.4	74.1	78.9	76.0	72.2	72.5	69.4	65.7	62.9	62.2	60.7
	2013/09/26 22:15:40		81	66.7	65.2	70.6	74.8	75.4	73.5	72.7	70.5	66.6	62.7	59.7	57.5
	2013/09/26 22:18:06		82	68.0	68.3	74.6	76.4	75.2	73.7	73.2	68.8	64.6	63.1	61.6	60.2
	2013/09/26 22:19:44		82	68.4	69.7	72.2	77.0	74.6	73.9	73.3	70.0	66.4	63.2	60.4	59.2
		Averages	83	68	69	74	78	76	73	73	70	66	63	62	60
25' Far Lane - Lmax	2013/09/26 22:09:43	SB	85	67.3	69.6	74.9	79.0	77.9	73.9	77.0	74.2	73.6	72.5	68.7	65.2
	2013/09/26 22:14:01		85	67.5	69.7	73.1	77.0	77.2	78.3	77.6	74.9	72.7	69.2	65.2	62.0
	2013/09/26 22:16:36		86	70.8	69.3	75.4	79.0	78.3	79.1	79.0	75.9	75.6	72.5	70.0	66.9
	2013/09/26 22:19:03		86	70.8	71.6	78.3	81.8	78.4	75.6	77.0	73.2	69.9	65.9	63.6	61.0
	2013/09/26 22:20:51		83	64.9	67.8	72.3	76.8	77.0	75.3	74.7	72.5	68.5	64.9	63.0	60.6
		Averages	85	68	70	75	79	78	76	77	74	72	69	66	63
50' Near Lane - Lmax	2013/09/26 22:17:26	NB	80.0	65.2	68.8	71.7	74.1	73.5	71.3	69.1	70.8	66.5	64.1	61.4	61.3
	2013/09/26 22:22:23		82.1	66.2	69.6	74.2	78.9	75.8	75.1	70.5	67.9	64.2	61.8	59.0	57.6
	2013/09/26 22:24:12		81.6	66.2	69.4	72.0	78.3	74.2	74.5	70.7	67.6	64.0	61.5	58.5	56.5
	2013/09/26 22:26:13		84.3	66.9	70.2	75.7	81.3	77.0	78.2	73.7	71.2	67.5	63.8	58.9	57.0
	2013/09/26 22:27:45		80.0	65.4	67.8	72.6	76.3	71.4	70.2	68.7	65.8	63.5	60.5	57.1	55.8
		Averages	82	66	69	73	78	74	74	71	69	65	62	59	58
50' Far Lane - Lmax	2013/09/26 22:19:01	SB	82.1	66.4	68.3	73.0	73.8	74.1	75.4	74.6	71.5	68.6	64.6	61.8	59.0
	2013/09/26 22:23:05		82.8	64.5	67.4	73.8	78.0	76.4	74.9	75.1	73.2	70.2	67.4	66.5	58.4
	2013/09/26 22:25:06		84.8	70.0	71.2	73.3	78.4	76.4	76.6	77.5	73.6	73.5	70.6	64.5	60.3
	2013/09/26 22:26:50		83.1	67.6	68.9	74.7	77.6	76.4	75.1	75.4	73.1	71.4	67.3	63.2	60.6
	2013/09/26 22:29:30		82.7	66.3	66.8	70.3	75.3	74.6	76.7	75.1	73.0	70.1	64.5	61.0	57.6
		Averages	83	67	69	73	77	76	76	76	73	71	67	63	59

SR 203

Depth	Width	Length	Spacing
0.5	6	12	12

	Measurement Date and Start Time	Direction	Avg. Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2013/09/26 20:08:54	SB	86.9	72.5	76.0	80.2	82.3	79.5	78.2	77.8	73.5	71.2	68.3	63.3	56.5
	2013/09/26 20:11:44		87.7	74.1	77.4	79.6	84.6	80.8	77.3	74.2	72.2	69.9	64.8	61.4	59.3
	2013/09/26 20:16:52		88.4	73.9	76.7	82.3	82.3	80.4	79.6	79.2	76.8	73.4	68.0	64.7	58.7
	2013/09/26 20:20:11		87.9	74.2	75.6	80.5	83.8	80.5	80.0	77.2	75.1	72.6	70.1	65.0	59.6
	2013/09/26 20:28:40		86.8	73.6	76.1	79.2	83.1	79.6	78.2	78.0	75.6	72.1	70.6	64.3	58.3
		Averages	88	74	76	80	83	80	79	77	75	72	68	64	58
25' Far Lane - Lmax	2013/09/26 20:09:50	NB	90.3	75.8	80.1	83.3	86.9	81.5	79.2	76.5	73.3	71.4	67.7	64.6	61.3
	2013/09/26 20:12:42		90.3	77.1	81.6	85.4	86.9	82.5	81.9	80.7	77.1	75.6	71.8	68.6	64.9
	2013/09/26 20:14:25		91.7	79.6	80.7	85.5	88.4	84.1	85.5	82.1	79.7	76.6	73.5	69.8	65.0
	2013/09/26 20:15:58		94.1	82.7	84.4	87.4	90.0	85.9	83.6	82.8	78.7	77.3	74.2	70.6	68.2
		Averages	92	79	82	85	88	83	83	81	77	75	72	68	65
50' Near Lane - Lmax	2013/09/26 20:12:16	SB	88.8	73.5	77.6	81.1	85.0	83.2	78.1	76.0	75.8	71.4	69.0	66.8	62.7
	2013/09/26 20:15:06		89.6	73.4	78.1	83.3	85.2	82.8	80.6	80.0	76.7	72.5	70.4	66.3	63.0
	2013/09/26 20:21:52		89.6	75.9	79.2	82.6	84.9	83.0	79.2	77.9	76.8	73.5	70.5	68.3	65.3
	2013/09/26 20:26:29		89.3	74.0	79.9	81.4	83.6	83.1	78.9	77.8	76.4	72.9	71.3	65.9	63.3
	2013/09/26 20:33:23		91.4	78.8	80.8	83.2	85.8	86.0	80.0	80.1	77.7	76.6	72.1	68.4	65.7
		Averages	90	75	79	82	85	84	79	78	77	73	71	67	64
50' Far Lane - Lmax	2013/09/26 20:13:12	NB	91.5	78.4	82.9	85.9	86.9	83.2	82.5	79.8	77.7	72.8	70.9	68.6	64.1
	2013/09/26 20:16:05		92.4	80.2	83.7	86.8	86.9	84.4	83.6	81.9	79.5	78.1	74.7	70.8	66.9
	2013/09/26 20:19:21		94.1	83.1	84.5	84.9	89.2	86.0	82.6	82.4	79.7	75.9	74.4	71.2	67.6
	2013/09/26 20:21:14		90.1	74.1	80.3	83.4	85.1	82.6	79.2	78.3	76.8	73.6	69.9	66.3	62.8
		Averages	92	79	83	85	87	84	82	81	78	75	72	69	65

SR 410

Depth	Width	Length	Spacing
0.375	6	8	12

	Measurement Date and Start Time	Direction	Avg Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	'11/09/20 10:54:31	WB	80.1	66.3	68.4	71.1	74.0	73.7	72.5	71.5	70.1	65.8	62.4	59.0	55.1
	'11/09/20 10:56:29		82.8	65.3	68.5	73.2	78.5	76.7	74.7	71.5	69.9	66.8	63.8	59.8	56.0
	'11/09/20 10:59:27		80.3	62.9	66.8	68.9	76.0	73.3	72.0	71.9	67.4	64.4	60.3	57.1	53.5
		Averages	81	65	68	71	76	75	73	72	69	66	62	59	55
25' Far Lane - Lmax	'11/09/20 10:55:48	EB	81.2	69.9	69.8	70.4	76.0	76.7	72.9	73.5	68.7	65.5	62.4	59.2	55.6
	'11/09/20 10:58:46		82.5	71.2	69.3	73.6	77.4	75.0	76.1	74.5	70.7	67.9	65.4	60.9	59.2
		Averages	82	71	70	72	77	76	75	74	70	67	64	60	57
50' Near Lane - Lmax	'11/09/20 10:54:31	WB	75.7	63.4	61.3	67.8	70.3	69.1	66.3	65.5	63.3	59.6	55.2	53.5	49.9
	'11/09/20 10:56:29		77.4	65.3	62.4	69.9	73.4	70.3	69.1	66.5	64.3	60.9	57.3	52.9	50.1
	'11/09/20 10:59:27		74.8	58.4	61.7	65.9	70.0	67.9	66.2	66.5	62.2	58.0	53.9	50.0	46.9
		Averages	76	62	62	68	71	69	67	66	63	59	55	52	49
50' Far Lane - Lmax	'11/09/20 10:57:01	EB	76.1	64.8	63.7	65.1	70.6	70.8	68.6	68.0	66.0	62.1	59.4	54.1	49.5
	'11/09/20 10:59:59		77.8	66.3	65.1	70.9	72.3	69.6	70.5	68.4	64.4	61.7	59.0	55.9	52.9
	'11/09/20 11:01:48		76.1	63.8	65.0	67.3	69.2	68.9	70.3	69.4	65.8	62.4	58.6	54.7	50.9
		Averages	77	65	65	68	71	70	70	69	65	62	59	55	51

SR 507

Depth	Width	Length	Spacing
0.375	6	6	12

	Measurement Date and Start Time	Direction	Lmax	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	2013/04/17 18:35:27	SB	86.4	72.1	72.6	79.2	81.4	79.7	78.7	75.4	75.2	69.8	68.0	63.4	60.8
	2013/04/17 18:38:05		84.3	69.2	70.6	75.3	80.8	77.4	75.6	72.0	71.2	67.9	65.5	60.8	57.8
	2013/04/17 18:45:45		94.6	78.6	83.0	87.6	91.2	87.7	82.9	81.5	80.6	78.3	76.7	70.8	68.0
	2013/04/17 18:48:00		93.0	75.9	82.0	86.8	89.0	86.3	81.8	80.1	79.6	76.9	76.0	71.5	67.5
	2013/04/17 18:50:13		96.2	85.0	80.8	91.9	91.3	88.6	85.4	83.3	81.7	81.3	78.6	76.1	70.6
	2013/04/17 18:54:22		93.3	76.6	82.4	86.7	89.5	86.6	82.7	80.2	79.5	75.5	75.6	72.1	66.6
	2013/04/17 18:56:36		95.0	80.1	84.6	87.7	91.1	87.3	85.1	82.5	82.6	79.2	77.4	74.9	70.0
		Averages	*92*	*76.8*	*79.4*	*85.0*	*87.8*	*84.8*	*81.7*	*79.3*	*78.6*	*75.6*	*74.0*	*69.9*	*65.9*
25' Far Lane - Lmax	2013/04/17 18:42:19	NB	93.3	80.2	81.7	86.7	90.4	84.5	82.8	79.7	78.0	76.7	72.2	69.7	64.9
	2013/04/17 18:44:50		96.3	83.7	84.8	89.6	92.4	86.8	83.6	81.5	80.1	77.2	74.2	71.3	67.2
	2013/04/17 18:49:13		97.1	84.6	87.5	91.2	93.0	89.3	86.4	84.1	82.1	78.3	75.1	72.0	68.7
	2013/04/17 18:51:22		97.5	82.9	85.8	92.0	94.5	89.7	87.5	83.6	82.9	79.8	77.0	74.5	71.1
	2013/04/17 18:57:50		94.8	81.7	83.8	88.4	91.4	84.0	82.3	80.9	79.6	76.4	73.6	71.5	66.1
	2013/04/17 19:00:29		94.1	79.7	82.2	88.4	90.7	85.3	84.1	80.3	78.4	74.8	72.0	68.8	64.9
		Averages	*96*	*82.1*	*84.3*	*89.4*	*92.1*	*86.6*	*84.5*	*81.7*	*80.2*	*77.2*	*74.0*	*71.3*	*67.1*
50' Near Lane - Lmax	2013/04/17 18:37:12	SB	81.4	67.2	69.2	74.6	77.8	75.3	72.3	69.3	68.1	64.5	60.3	57.8	52.5
	2013/04/17 18:39:47		78.0	62.9	65.8	70.1	74.8	70.9	69.5	67.7	66.4	64.5	59.4	55.1	51.3
	2013/04/17 18:47:29		88.2	73.8	76.5	82.7	84.7	82.3	77.3	75.9	75.0	73.6	68.6	63.9	59.5
	2013/04/17 18:49:42		87.4	73.4	74.4	81.5	84.6	80.9	76.1	75.3	74.2	73.3	69.2	63.4	59.4
	2013/04/17 18:51:55		90.4	82.5	75.8	84.1	86.8	83.3	80.0	79.9	79.0	78.0	73.2	68.2	62.2
	2013/04/17 18:56:05		86.6	72.0	75.1	80.9	83.8	79.3	76.3	74.6	72.0	70.5	67.4	63.6	59.4
	2013/04/17 18:58:18		88.6	75.0	78.5	81.4	85.2	81.2	78.7	77.0	76.1	75.4	70.8	64.6	59.7
		Averages	*86*	*72.4*	*73.6*	*79.3*	*82.5*	*79.0*	*75.8*	*74.2*	*73.0*	*71.4*	*67.0*	*62.4*	*57.7*
50' Far Lane - Lmax	2013/04/17 18:44:02	NB	87.0	74.2	77.9	79.5	83.5	77.4	76.8	73.7	72.6	69.5	67.2	62.5	57.5
	2013/04/17 18:46:33		90.2	76.0	80.4	83.0	86.9	81.0	79.5	77.0	74.0	71.1	69.7	64.8	61.9
	2013/04/17 18:50:57		91.4	78.7	81.4	83.5	87.5	82.7	80.6	78.7	76.1	72.8	71.1	67.4	63.3

	2013/04/17 18:53:05		91.5	77.1	82.2	85.8	88.7	83.0	81.3	77.1	75.8	73.6	71.6	67.9	62.8
	2013/04/17 18:59:33		89.0	77.1	79.0	80.9	85.4	79.4	78.4	76.5	73.3	70.6	68.3	65.3	60.9
	2013/04/17 19:02:12		88.0	75.5	79.3	80.5	84.4	79.2	77.1	74.8	71.4	68.6	64.7	61.9	57.5
		Averages	*90*	*76.4*	*80.0*	*82.2*	*86.1*	*80.4*	*78.9*	*76.3*	*73.9*	*71.0*	*68.8*	*65.0*	*60.7*

Appendix B—WSDOT Design Manual

1600.07 Other Roadside Safety Features, (1) Rumble Strips, (c) Centerline Rumble Strips: *Centerline rumble strips are placed on the centerline of undivided highways to alert drivers that they are entering the opposing lane. They are applied as a countermeasure for crossover collisions. Centerline rumble strips are installed with no differentiation between passing permitted and no passing areas. Refresh pavement markings when removed by centerline rumble strips.*

A March 2011 WSDOT study found that centerline rumble strips were highly effective across the state highway network, and most effective on roadways where: the AADT is less than 8,000, the combined paved lane and shoulder width is 12 to 17 feet, and the posted speed is 45 to 55 mph. Apply the following criteria when evaluating the appropriateness of centerline rumble strips:

- An engineering analysis indicates a crossover collision history with collisions considered correctable by centerline rumble strips. Review the collision history to determine the frequency of collisions with contributing circumstances such as inattention, apparently fatigued, apparently asleep, over the centerline, or on the wrong side of the road.
- Centerline rumble strips are most appropriate on rural roads, but with special consideration may also be appropriate for urban roads. Some concerns specific to urban areas are noise in densely populated areas, the frequent need to interrupt the rumble strip pattern to accommodate left-turning vehicles, and a reduced effectiveness at lower speeds (35 mph and below).

- Ensure the roadway pavement is structurally adequate to support milled rumble strips. Consult the Region Materials Engineer to verify pavement adequacies.
- Drivers tend to move to the right to avoid driving on centerline rumble strips. Centerline rumble strips are inappropriate when the combined lane and shoulder widths in either direction are less than 12 feet. (See Chapters 1130 and 1140 for guidance on lane and shoulder widths.) Narrow lane and shoulder widths may lead to dropping a tire off the pavement when drivers have shifted their travel path. Consider including centerline rumble strips on short sections of roadway that are below this width for route continuity.
- Centerline rumble strips are not appropriate where two-way left-turn lanes exist.

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[i] http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/t504040/