Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety

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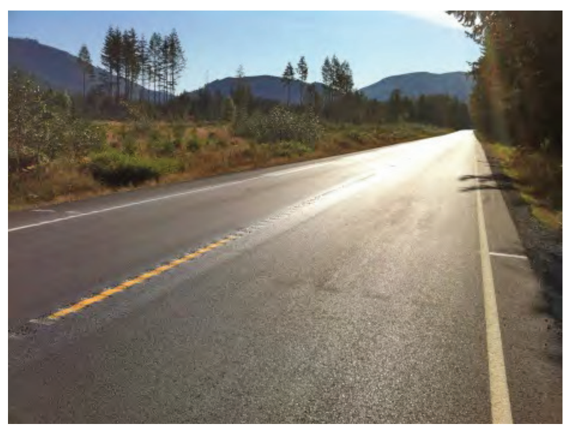
May 2018



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WSDOT Research Report

WA-RD 881.1

Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety

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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 new centerline and shoulder rumble strip designs to determine overall sound levels and 1/3-octave band frequencies. Results suggest that some designs can have lower exterior sound levels and sufficient interior sound levels. This report does not recommend a specific design; WSDOT will determine how to use the results of this research in future decisions about rumble strip design.

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Introduction

Rumble strips are an effective countermeasure to keep vehicles on the roadway and reduce the frequency of crashes. Drivers are alerted by the noise and vibration within the vehicle cabin caused by the uneven rumble strip surface. While the in-cabin noise and vibration from rumble strips are intentional and needed for safety, the noise due to incidental contact of vehicle tires with rumble strips can also be heard outside the cabin where there may be no direct safety benefit. The report refers to rumble strip noise heard outside of the vehicle cabin as “exterior rumble strip noise.” Exterior rumble strip noise is a source of disturbance and the cause of complaints from roadside residents.

The work described in this report builds on an internal report of a previous investigation about the external noise characteristics of rumble strip designs that utilize the traditional milling method, varying physical characteristics such as depth, width, and length. Among the findings was an indication of the potential for lower noise with shallower milling designs with less width. The current work also references recent work by Minnesota DOT and others about the “sinusoidal” designs that are promising in reducing external noise.

The primary objective in this research was an evaluation of one sinusoidal and three traditional rumble strip designs that are promising based on previous findings in their potential for reducing external noise due to incidental contact, while maintaining their ability to alert the driver.

The following steps were taken to develop the report conclusions.

- Measure both interior and exterior sound levels from new WSDOT rumble strips designs.
- Compare measured values to measurements collected for WSDOT standard rumble strip designs and to the predicted noise levels of the new designs.
- Identify the rumble strip design pattern that exhibits the lowest 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, 2009)

Background

What are rumble strips?

Rumble strips are texture added to a road centerline or shoulder that are meant to alert an unfocused, inattentive, or fatigued driver that their vehicle is about to leave the traveled lane (Figure 1). Rumble strips have proven to be cost-effective for reducing the frequency of collisions and state departments of transportation and local agencies are expanding their use of centerline and shoulder rumble strips, particularly on undivided rural highways.

Figure 1: Image of milled centerline rumble strip (CLRS)

Rumble strips are typically ground into the roadway along the centerline alignment or either just outside or directly beneath the outside lane fog line (Figure 2). Various construction methods and materials can be used and include button, rolled, formed and profiled rumbles strips, but ground or milled rumble strips are the most commonly used (Federal Highway Administration, 2011). Their popularity is partly due to ground and milled rumble strips being the only design proven to generate sufficient noise and vibration for commercial vehicles (Finlay and Miles, 2007).

Figure 2: Grinding CLRS on SR 97

WSDOT only allows a tight range of depth in the current standard centerline and shoulder 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 measured noise levels from the various designs is sparse.

How do rumble strips work?

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

While there is some uncertainty about the stimuli levels needed 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. To be effective, it has been generally recommended that rumble strips produce a 10 – 15 A-weighted decibel (dBA) sound level increase above in-cabin levels while driving in the travel lane. However, NCHRP Report 641 suggests that in-cabin sound level increases can be about 6-12 dBA when roadways are adjacent to residential land uses (Torbic, 2009).

Where and when are rumble strips used?

Centerline 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 greater than 35mph, lane width of 12 feet or greater and total paved roadway width of at least 24 feet (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) 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. Section 1600.07(1)(c) of the WSDOT Design Manual further clarifies that centerline rumble strips are placed on the centerline of undivided highways to alert drivers (Washington State Department of Transportation, 2012).

For run off the roadway to the right (ROTRR) collisions, shoulder rumble strips may be used to reduce the collision frequency. However, there are important policy constraints guiding the use of shoulder rumble strips (SRS) on undivided roadways compared to CLRS and, therefore, SRS use is more limited.

The WSDOT Design Manual provides additional information and design considerations for both types 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 greater hazard than the barrier, rumble strips only alert drivers that they are leaving the traveled lane. Rumble strips are not used in place of a physical barrier device but the two may be used in combination.

Why is rumble strip noise information 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 their urban counterparts, which can make rumble strip noise more disruptive because there is a greater relative change in sound levels.

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

> *Sporadic* - Standard traffic noise is dominated by the noise from tires on pavement and 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 further than higher frequency sounds, so they can affect more people, and can be more annoying to the average person than standard traffic noise sound frequencies between 500 Hz – 5 kHz. For residences very close to the roadway, the sound energy may be frequencies low enough to be perceived as vibration.
>
> *Tonal* - Standard traffic noise contains a number of audible sound frequencies that have similar levels. Noise from rumble strips has less energy spread 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. Both the overall sound levels and frequency data were needed to understand the characteristics of external rumble strip sound from the various rumble strip designs so that a preferred design can be identified.

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 does WSDOT hope to achieve with this research?

The primary research objective is to evaluate new rumble strip designs that were predicted, based on previous work, to reduce external rumble strip noise disturbance at adjacent properties and maintain the same safety benefits of WSDOT's standard rumble strip design. The agency combined field measurements and results from the previous WSDOT rumble strip report (WSDOT, 2014) to determine if the new rumble strip designs promote safety and reduce the noise heard by roadside residents. The research effort will determine the effectiveness of the new rumble strip designs and modify the predictive model if applicable. If a preferred rumble strip design is identified, WSDOT Standard Plans and Design Manual will be updated to incorporate the new information.

What was not measured?

The report does not include information on background sound levels with no traffic or pass-by sound levels with traffic operating in the traveled lane only. Instead, this project maintained a narrow focus on comparing relative external and vehicle interior sound levels between designs in recognition that final design decisions are made based on individual project circumstance.

The applied measurement methodology included the vehicle passing over the rumble strip and at the SR 155 location included measurements of the vehicle not on the rumble strip. The rumble strip measurements were based on maximum sound levels, which were inevitably from the tire-rumble strip interaction. Pavement type would play a greater role for average sound levels or for measurements that mixed rumble strip driving with driving in the traveled lane.

Rather than referring to safety performance, this report is specific to performance of rumble strip designs with respect to the acceptable sound level range for warning a driver, per the Federal Highway Administration (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 or SRS design. The sample size for each unique design is sufficient to be informative for no/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 does not provide recommendations for where rumble strips should be used because the placement decision process is beyond the scope of this effort.

Study Overview

Previous research and current WSDOT rumble strip designs and practices were reviewed and evaluated (WSDOT, 2014) to determine the current state of the practice and understanding on external rumble strip noise. The review summarizes rumble strip designs used in other US states and internationally and was compared to current WSDOT designs. It was also used to help determine the boundaries of rumble strip designs for WSDOT to consider based on external noise and acoustic performance.

Sound level measurements were collected from four different rumble strips designs at two locations in Washington State. These measurements were used to help WSDOT understand the effectiveness of new designs to produce the lowest external noise while maintaining the ability to alert the driver. Options are described for updated rumble strip designs by WSDOT.

NCHRP Report 641 developed guidance for the design and application of shoulder and centerline rumble strips as an effective motor vehicle crash reduction measure, while minimizing adverse effects for motorcyclists, bicyclists, and nearby residents. The most relevant outcomes of the work to this effort were the recommendations for in-cabin sound and vibration levels needed for safety, a discussion on external rumble strip noise effects 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, with equations provided for determining rumble strip dimensions for a range of operating conditions. It 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 survey results from residents living near where CLRS had been installed. The majority found the external noise “acceptable” or “tolerable” and believed the safety benefits to drivers outweighed the additional external noise. However, studies have shown noise impacts from rumble strip 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 provide examples of efforts taken by states to address complaints about rumble strip noise from nearby residents, including:

- 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.

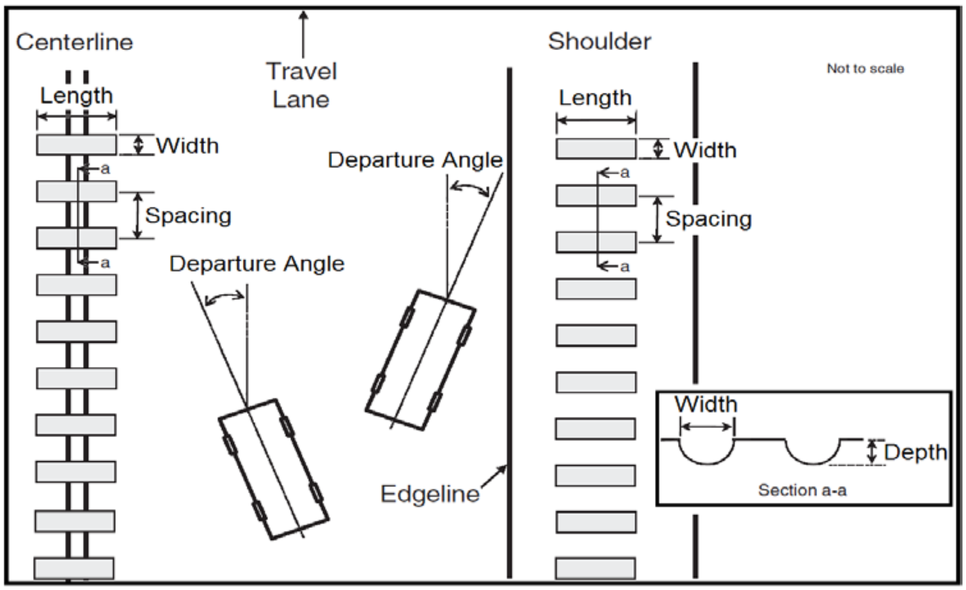
The research concludes that increasing groove depth, length, and/or width can increase interior noise and vibration.

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 based on rumble strip dimensions.

Rumble Strip Designs

States use various rumble strip designs depending on project circumstances and pavement types. While variables like rumble strip groove pattern, depth, width, shape, and spacing also change by state, the majority of rumble strips in US are rectangular, approximately 9-12 inches long, 5-8 inches wide, and ¼ - ¾ inches deep (Figure 3). Cylinder and sinusoidal, or "football," shaped rumble strips have been tested in Europe (Kragh, 2007), along with new trademarked designs Rippleprint and Rumblewave (Caltrans, 2012) [1]. No information on experience with these patented designs in the US was available.

Figure 3: Rumble Strip Design "Descriptors" (WSDOT Design Office)



The Federal Highway Administration (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 how they are installed, their size and shape, and the amount of noise they produce (Federal Highway Administration).

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

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

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 capabilities; however, tire drop depends on tire properties, vehicle speed, and spacing of the cuts/grooves.

What rumble strip designs are currently used in Washington State?

WSDOT first installed centerline rumble strips on SR 522 near Maltby in 1995 (Olson, 2011). As of 2010, WSDOT had constructed approximately 1,800 miles of centerline rumble strips and 275 miles of shoulder rumble strip 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.

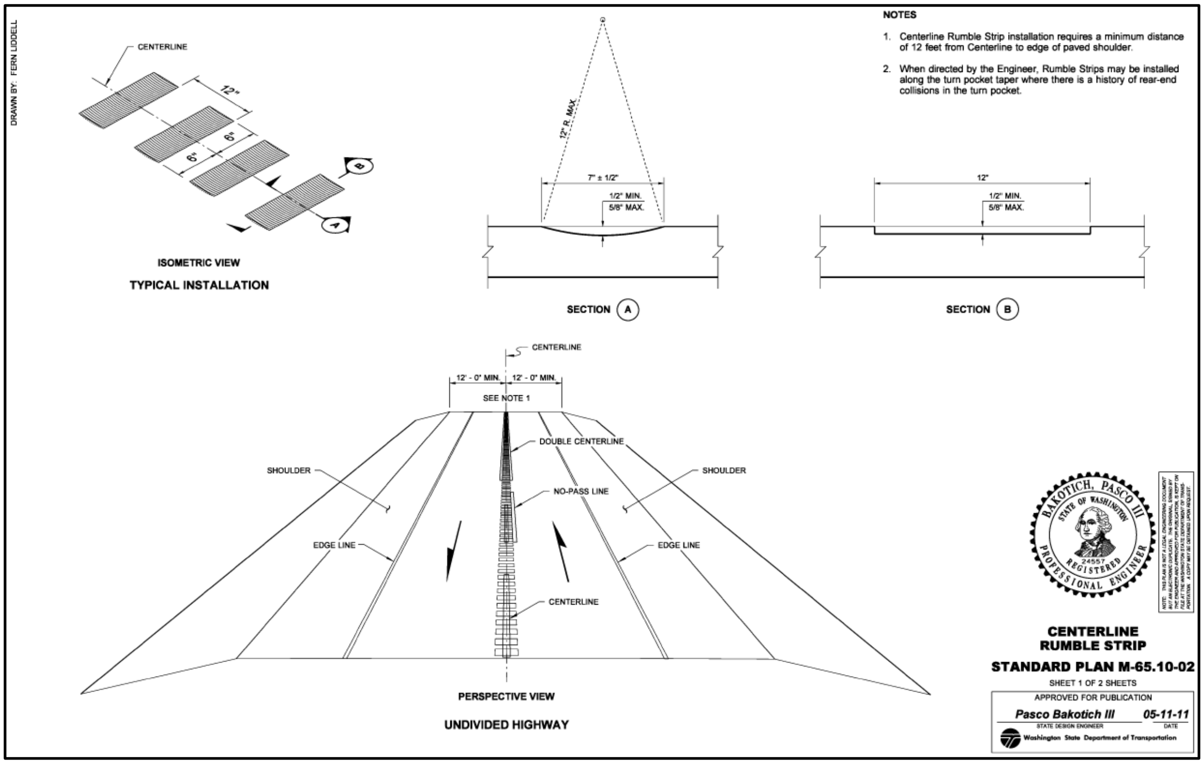
The majority of WSDOT rumble strips have used an aggressive pattern to ensure sufficient noise inside the cabin to re-focus the driver's attention. Table 1 describes the full range of centerline rumble strip designs currently installed on WSDOT maintained roadways compared to the designs outlined in 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 4.

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 4: WSDOT Standard Plan for Centerline Rumble Strips (*August 6, 2012, page 557*)*



What locations were used to evaluate external rumble strip noise?

Two measurement locations were selected in Washington State to evaluate new CLRS and SRS designs (Figure 5). Each of the selected locations had a unique set of design characteristics that 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 (ruler).

Figure 5: Map Showing the Location of Rumble Strips Test Locations

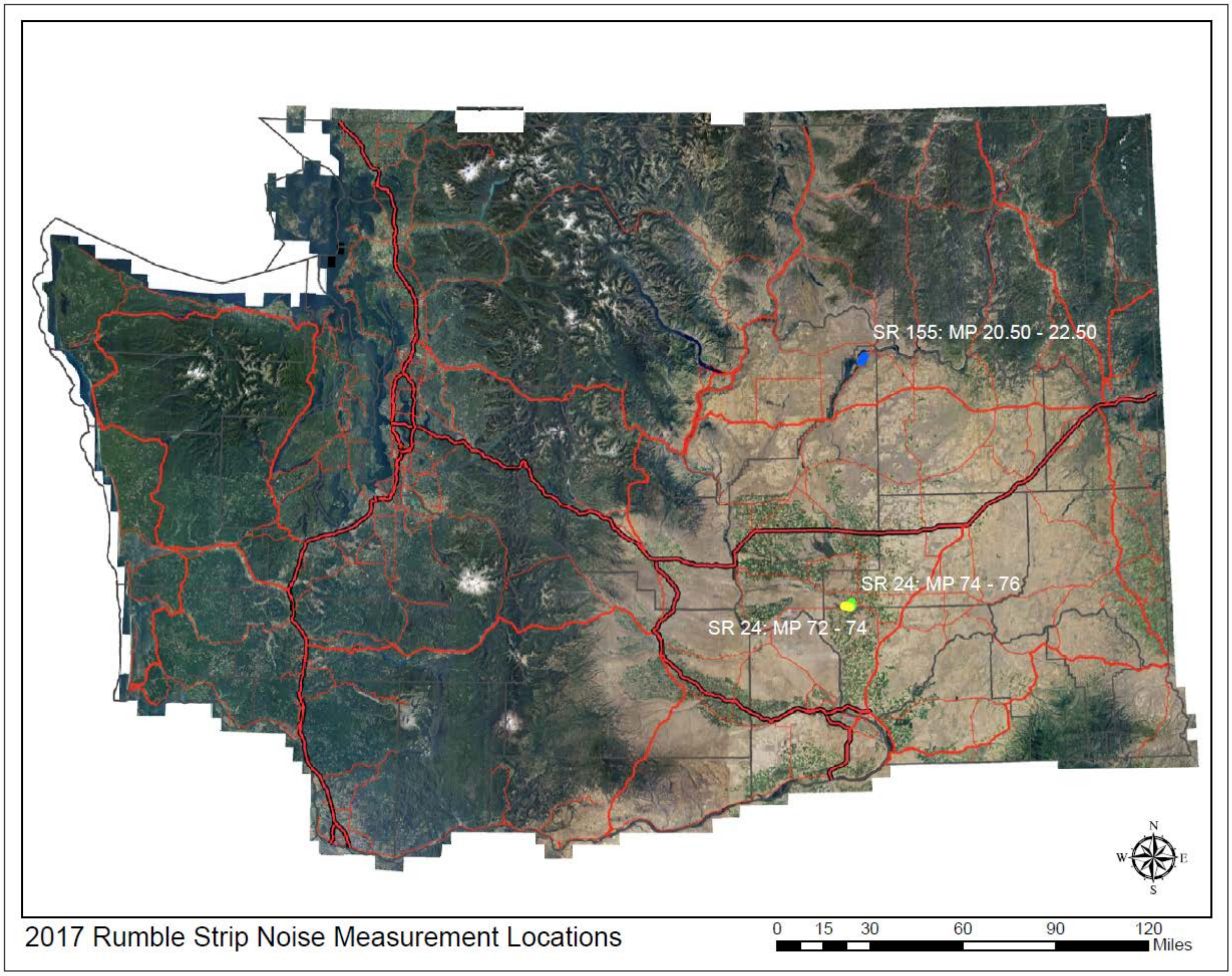


Table 2: Centerline and Shoulder Rumble Strip Measurement Locations

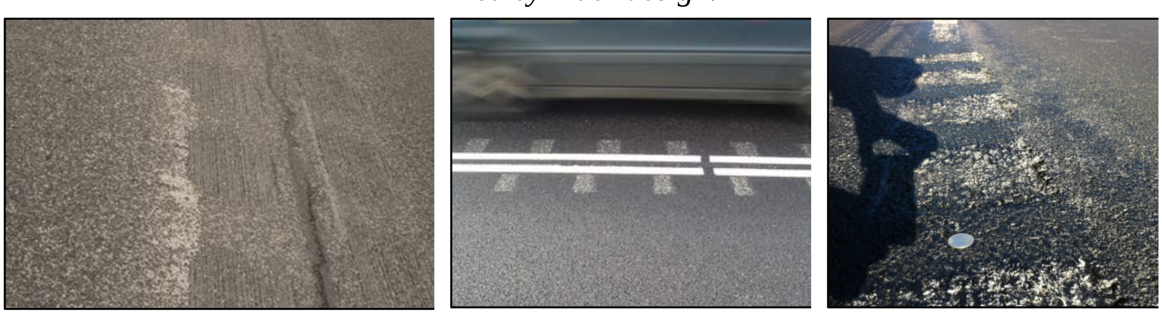
SR	Begin MP	End MP	Design Type	Depth (in.)	Width (in.)	Length (in.)	Spacing (in.)	Rumble Strip Type	Sound Level Measured?
155	20.50	22.50	Sinusoidal	0.50	12.00	16.00	-	Center	Yes
24	74	76	1	0.25	6.9	8.00	18.00	Shoulder	Yes
24	74	76	2	0.25	6.9	12.00	18.00	Shoulder	Yes
24	72	74	3	0.25	6.9	12.00	12.00	Shoulder	Yes

WSDOT uses a milled cylinder segment design. The sinusoidal rumble strip measurement location on SR 155 is similar to the new design being used in Minnesota and California (CLRS 12-inch wide at full depth, 16-inch period, ½-inch depth, tapered groove) (Figure 6).

Figure 6: Sinusoidal Centerline Rumble Strip Profile

The three SRS designs for the measurement locations on SR 24 were based on predicted values for quieter designs (WSDOT 2014). The designs are of the milled cylinder type described above and shown in Figure 7.

Figure 7: From left to right - European "Sinus", rectangular (Kragh, 2007), and WSDOT milled cylinder design.



Rumble Strip Noise Measurements

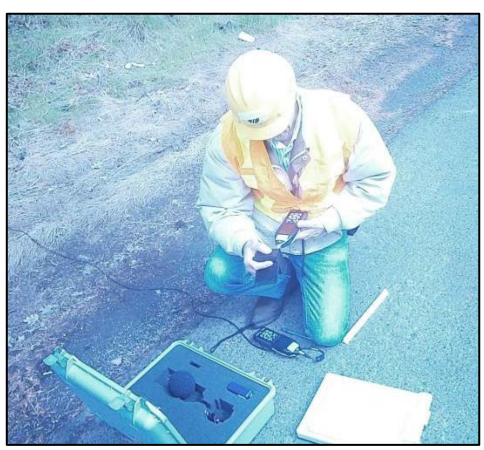
Measurement equipment

Sound levels were measured for a 2010 Ford Escape hybrid with all season light SUV/crossover tires (Michelin Latitude Tour) and a new tire tread depth of 12.5/32 of an inch (Figure 8). The tires had been driven approximately 35,000 miles at the time of measurements. Similar to 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, 2009).

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

Three Larson Davis Sound Track LxT Type 1 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 measurements at each location 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 prior to measurements.



Measurement Methodology

Measurements were collected using a sound level collection methodology consistent with the American Association of State Highway and Transportation Officials (AASHTO) provisional specification TP 98: *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."

Measurements were consistent with the measurement equipment, selection of test sites, traffic conditions, meteorological conditions, and microphone positions described in the TP 98 test procedure. 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 in either rural areas with no development or areas with low density residential development.

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

Figure 10: Example of noise meter placement at roadside

The microphone further from the road (at 50 feet) is at 12 feet above the lane surface height to reduce the effect of ground surface types on sound propagation (i.e., “ground effects”). A third microphone was placed inside the vehicle cabin on the passenger side (Figure 11).

Figure 11: Example of noise meter placement at roadside

Measurement Duration - 10 second measurements were collected with the test vehicle passing the microphone approximately 5-seconds into the measurement period. 20-second measurements were collected inside the test vehicle.

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 miles per hour (mph) to ensure consistency between measurements.

Traffic - Measurements were considered valid if the test vehicle was isolated from other vehicles and clearly the dominant noise source.

Near Lane and Far Lane – For the CLRS, measurements were collected from the test vehicle passing in the near lane and far lane relative to the sound level meter location. SR 155 is an undivided highway with one lane in either direction. For the SRS measurements the test vehicle only passed in the near lane relative to the sound levels meter. SR 24 is an undivided highway with one lane in either direction.

Numbers of Measurements – Ten simultaneous measurements at each location were collected in each direction for the CLRS and a single direction for the SRS.

Measurements were evaluated for overall maximum sound level (L_{max}) over a 10 second period and by 1/3 octave band frequency to determine if there were tonal components to the rumble strip designs. Frequency was measured using a 1/3 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.

Measurement Results

Sinusoidal Rumble Strip

Results for the sinusoidal rumble strip are described in Table 3. A two-sample t-test was performed comparing the near lane and far lane data collected for the sinusoidal CLRS site. There was no significant difference between the near and far measurements ($p < 0.05$) so the near and far data was combined in subsequent analyses.

The combined measurement results were logarithmically averaged for each microphone position. The microphone at 50 feet is, of course, quieter than the microphone at 25 feet because sound energy attenuates over distance.

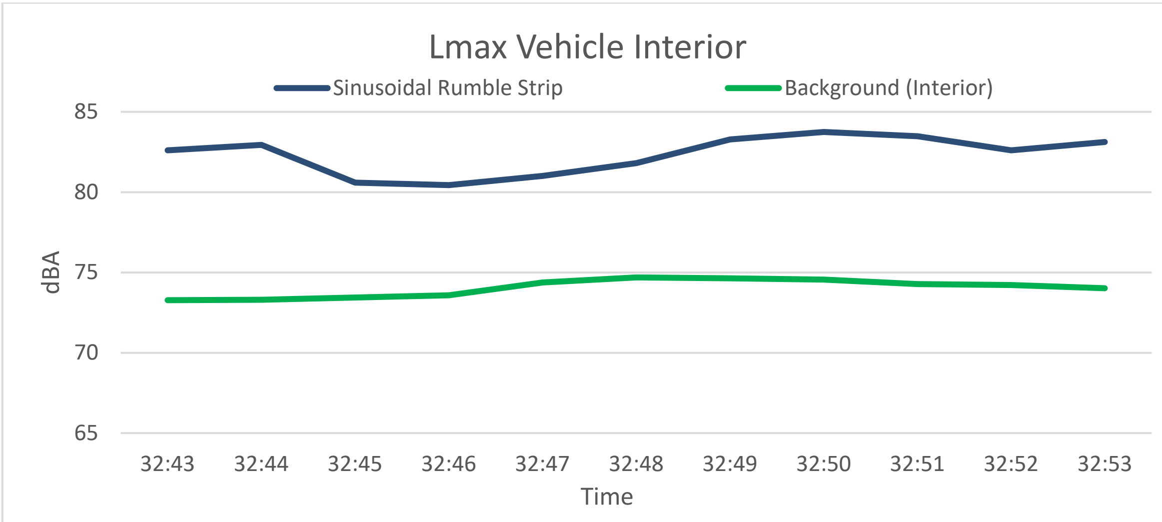
Table 3 shows that for the sinusoidal rumble strip for both the Lmax and LAeq the average sound level inside the vehicle was 7 dB to 8 dB higher than interior background sound levels (not running on the rumble strip). This is within the acceptable range of 6 to 12 dB required to alert the driver according to NCHRP 641. The wayside measurements of the sinusoidal rumble strip were approximately 3 dB to 6 dB higher than a single vehicle passing without the rumble strip. Compared to the 2014 noise measurements (WSDOT, 2014) in which the Lmax values ranged between 80 and 96 dBA at 25 feet and 76 to 93 dBA at 50 feet. A t-test was conducted to evaluate the differences between the sinusoidal rumble strip and the 2014 L_{max} measurements. The values for the sinusoidal rumble strip are statistically significantly lower at 50 feet compared to all 2014 sites and the majority of the 25 feet sites ($p < 0.05$).

Table 3: Sinusoidal Rumble Strip Design Average Equivalent (L_{Aeq}) and Average Maximum (L_{max}) Sound Levels

SR	Vehicle Interior Sinusoid (dBA)		Vehicle Interior Background (dBA)		Wayside 25 feet (dBA)		Wayside 50 feet (dBA)		Wayside No Rumble Strip 25 feet (dBA)		Wayside No Rumble Strip 50 feet (dBA)	
	L_{Aeq}	L_{max}	L_{Aeq}	L_{max}	L_{Aeq}	L_{Amax}	L_{Aeq}	L_{max}	L_{Aeq}	L_{max}	L_{Aeq}	L_{max}
SR 155	80	82	73	74	72	82	68	76	68	76	65	71

The L_{max} values plotted for background and sinusoidal rumble strip measurements in the interior of the vehicle cabin during the 10-second measurement show a 6 to 9 dB increase over background during the period when the vehicle was running over the rumble strip (Figure 12).

Figure 12: Interior Vehicle Cabin L_{max} Sound Levels vs. Interior Background Sound Levels for Sinusoidal CLRS



Average 1/3rd Octave band frequencies were also measured for the interior of the test vehicle (Figure 13). The large spike at 80 Hz for the sinusoidal rumble strip measurement corresponds to the frequency of the tires hitting the peaks of the sinusoid wave pattern on the rumble strip. There is a second smaller peak, or harmonic, at 160 Hz as well. Between approximately 200 Hz and 500 Hz the noise levels for these frequencies are relatively consistent.

Figure 13: Interior Cabin 1/3rd Octave Noise Levels vs. Interior Background Sound Levels for Sinusoidal CLRS

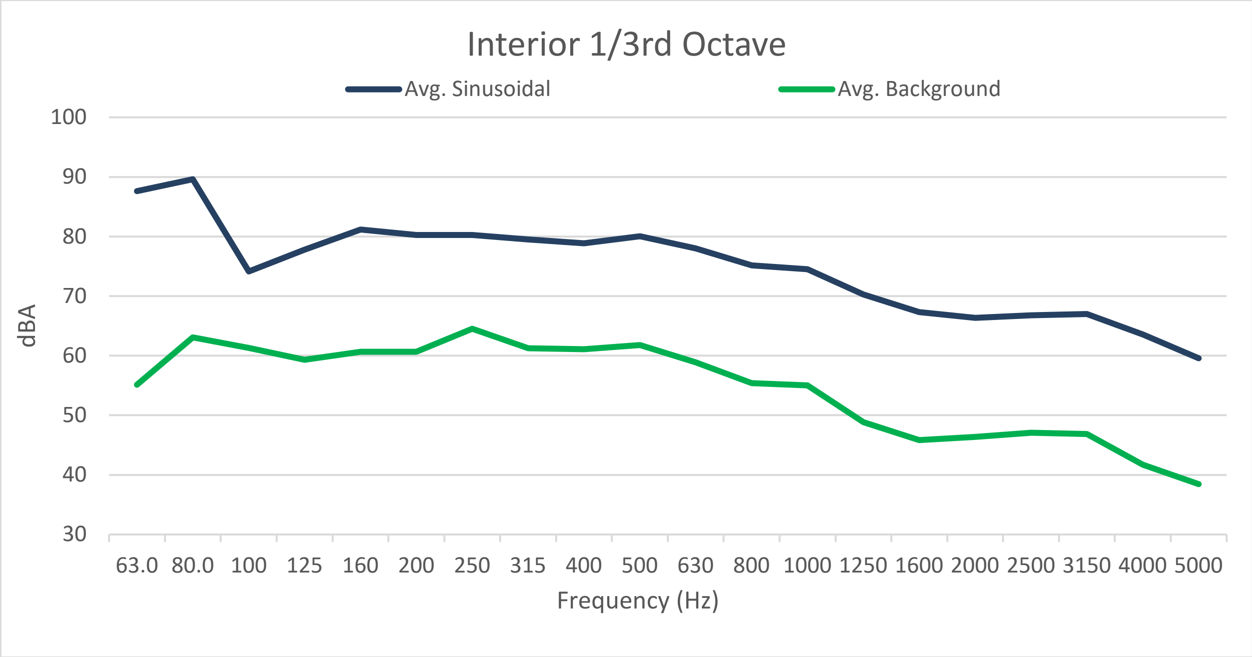
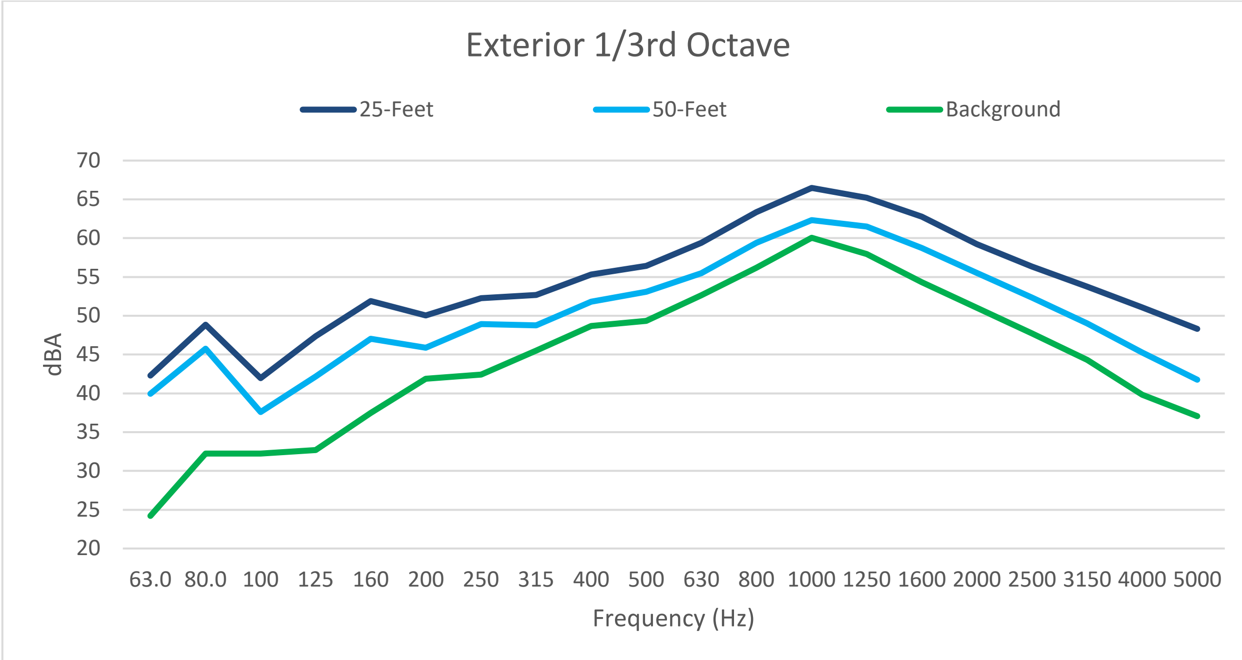


Figure 14 indicates that for the 1/3rd Octave band wayside measurements there is a peak at 80 Hz at both the 25 foot and 50 foot measurement location which is due to the vehicle tires hitting the sinusoid peaks at 60 mph and the resulting harmonic at 160 Hz. The dominant peak is at 1000 Hz, which is typical for highway traffic sounds as can be seen in the matching peak for the background measurement and likely due to the other two tires not on the rumble strip.

Figure 14: 1/3rd Octave Frequencies at 25 Feet and 50 Feet for the Sinusoidal CLRS



New Rumble Strip Designs

Results for the new SRS rumble strip patterns are described in Table 4. The measurement results were logarithmically averaged for each microphone position.

Table 4 shows that for the new rumble strip designs for both the Lmax and LAeq the average sound level inside the vehicle was 7 dB to 13 dB higher than interior background sound levels (not running on the rumble strip). This is within the acceptable range of 6 to 12 dB required to alert the driver according to NCHRP 641. The wayside measurements without the rumble strip were 76 dBA Lmax at 25 feet and 71 dBA Lmax at 50 feet. The wayside measurements of the new rumble strip design were approximately 9 dB to 17 dB higher than a single vehicle passing without the rumble strip. Compared to the 2014 noise measurements (WSDOT, 2014) in which the Lmax values ranged between 80 and 96 dBA at 25 feet and 76 to 93 dBA at 50 feet the values for the new designs are within the same range as the 2014 measurements.

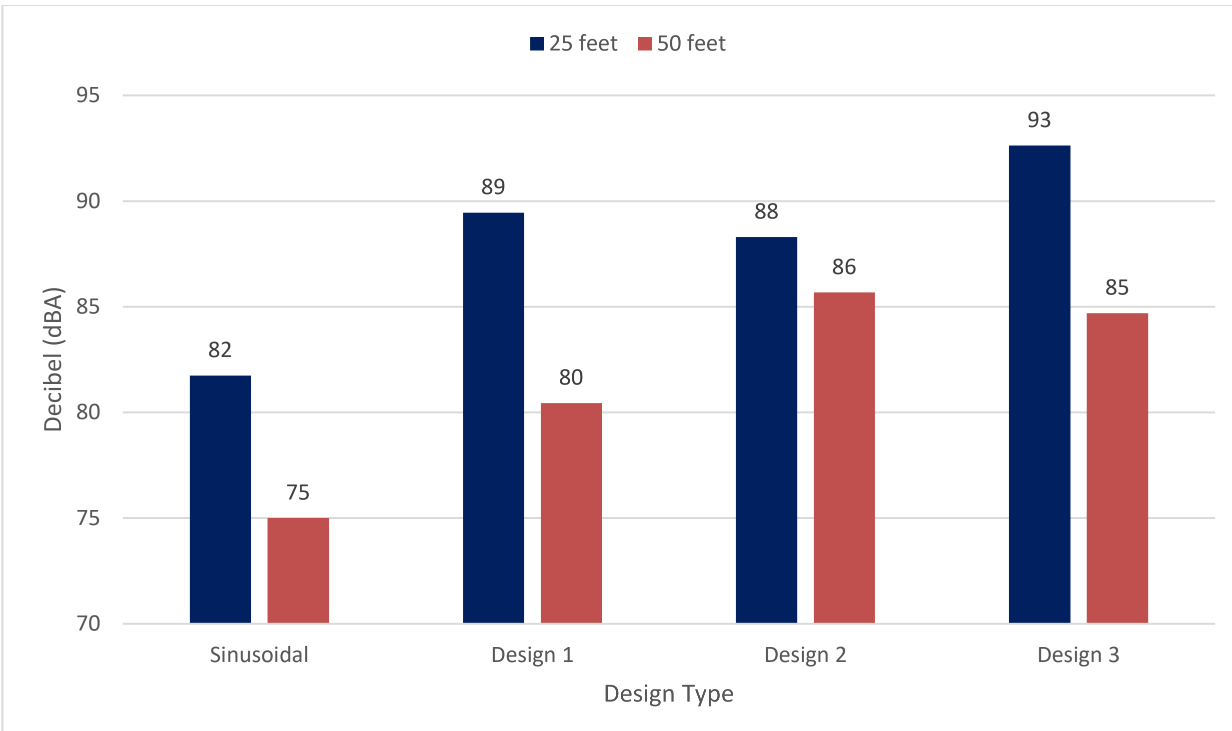
Table 4: Dimensions of Measured Rumble Strip Designs and Average L_{Aeq} and Maximum (L_{max}) Sound Levels

SR	Design Dimensions (in.)				Vehicle Passing (L_{Aeq} dBA)		Vehicle Passing (L_{max} dBA)		Vehicle Interior (L_{max} dBA)	Vehicle Interior No Rumble (L_{max} dBA)
	Depth	Width	Length	Spacing	25'	50'	25'	50'		
	0.25	6.9	8	18	77	71	89	80	81	74
SR 24	0.25	6.9	12	12	76	76	88	86	87	74
	0.25	6.9	12	18	81	77	93	85	82	74

*-Sinusoidal rumble strip 12-inches wide at full depth, 16-inch period (peak to peak), ½-inch depth, tapered grove.

The average L_{max} value is plotted for each rumble strip type at the 25 foot and 50 foot measurement locations (Figure 15). The measurement for the sinusoidal design is 6 dB to 10 dB lower at 25 feet than the other design types, which is roughly a halving of the wayside sound levels. Among the other three designs, Design Types 1 and 2 are 4 to 5 dB quieter at 25 feet than Design Type 3, which is a noticeable reduction. The differences in the sound level measurements at the 50 foot location can possibly be explained below by the relative frequency content of each signal.

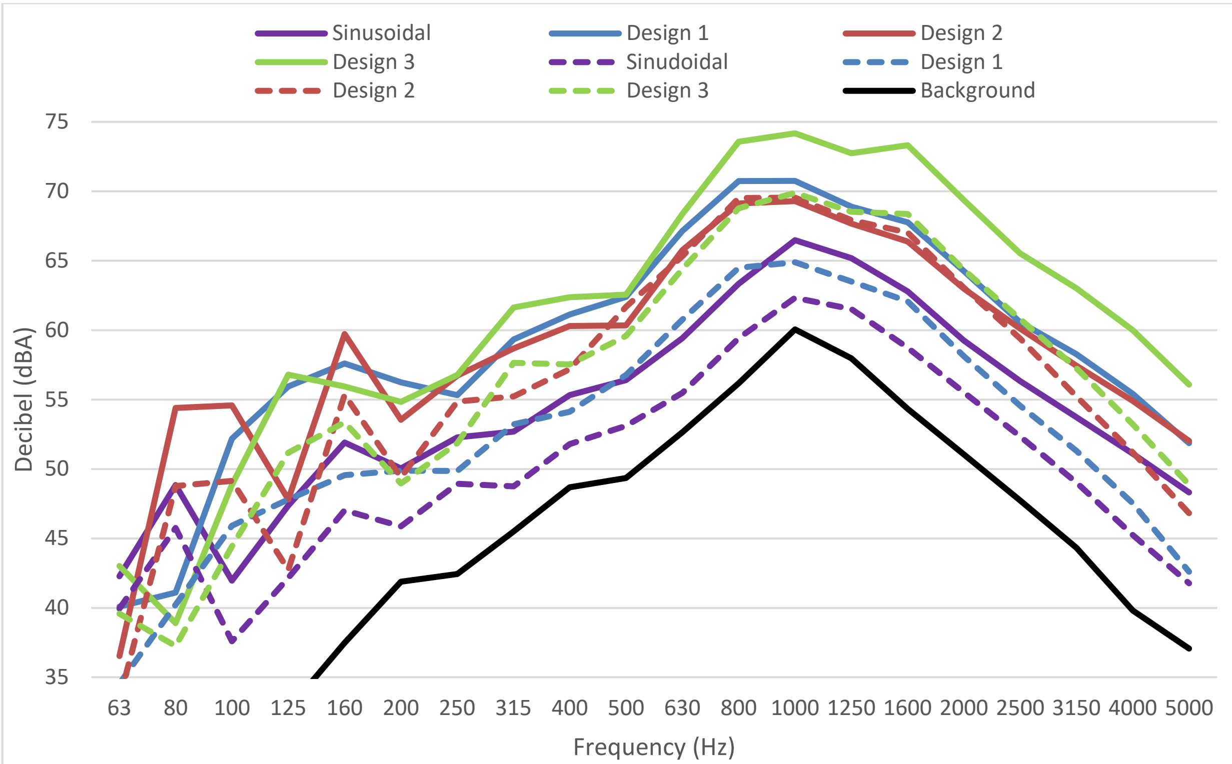
Figure 15: Average Maximum Sound Levels for a Single Vehicle at 25 feet and 50 feet (Lmax)



Frequency Spectrum

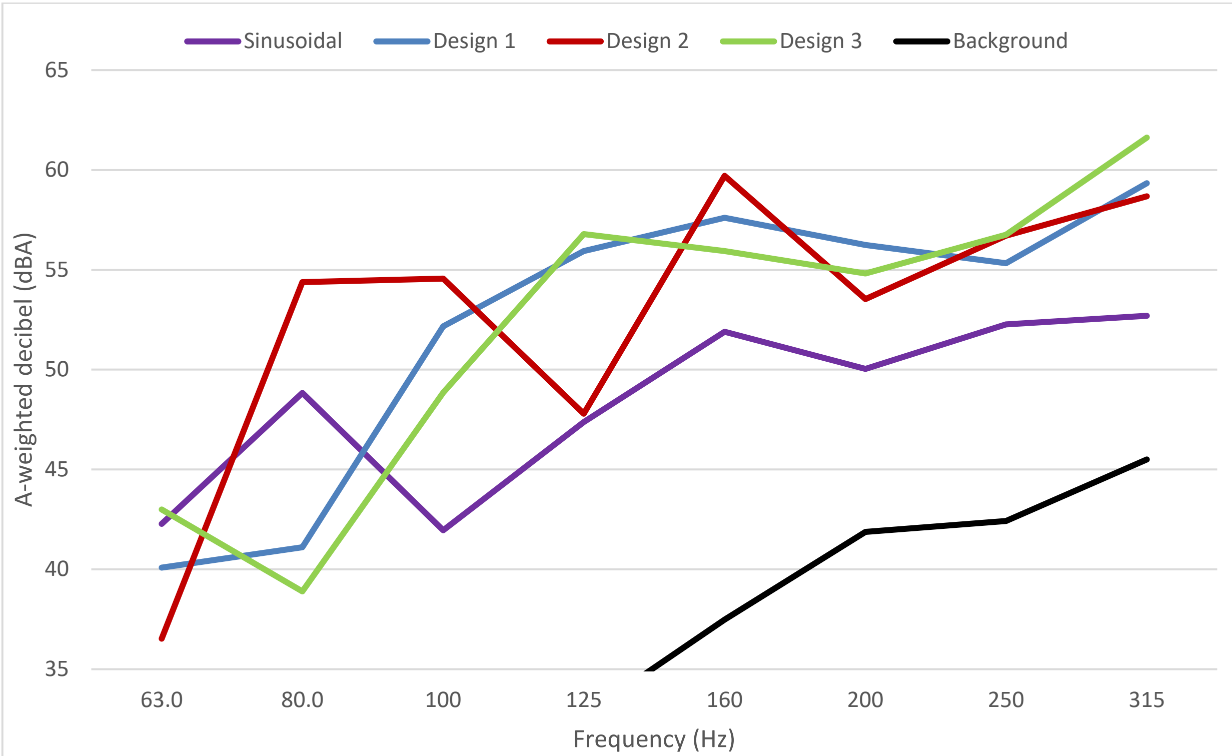
Frequency characteristics using a 1/3 octave band A-weighted filter were collected. Figure 16 shows the measured results from the test vehicle passing on SR 155 (sinusoidal) and SR 24 (Design Type 1 to 3) to highlight the relative difference in sound levels at the different octave bands. The sinusoidal curve was lower than the other three design types and a somewhat flatter curve, which can result in less annoying sound levels. For the three different design types below 315 Hz, the peaks resulting from the tire hitting the rumble strip at 60 mph are seen and they vary somewhat depending on the design. However, above about 800 Hz in the most sensitive range the three curves diverge showing that Design 3 is louder overall than Designs 1 and 2, which are more similar. Specific results for each measurement location are included in Appendix A.

Figure 16: Average 1/3rd Octave Band Sound Levels for a Single Vehicle at 25 Feet (solid line) and 50 Feet (dashed line)



At the lower frequency bands between 63 Hz and 315 Hz there are generally two distinct peaks at 80 Hz and 160 Hz, which match the frequency of the tire hitting the rumble strips at 60 mph (Figure 17). At these frequency bands, Design Type 2 is actually louder than Design type 1 or 3 and Design Type 1 and 3 are a little flatter at these frequency bands implying that the sound levels would be less annoying.

Figure 17: 1/3 Octave Band Measurement Results between 63 Hz and 315 Hz at 25 feet



Comparison of 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 the interior sound levels. Interior sound levels are reported as the difference between background levels inside the vehicle cabin while driving in the travel lane compared to noise levels in the vehicle cabin while traveling over the rumble strip. All the measured designs achieved at least the "target noise level." Qualitative descriptors include the following that all meet the minimum 6 dBA interior noise level increase described in NCHRP 641.

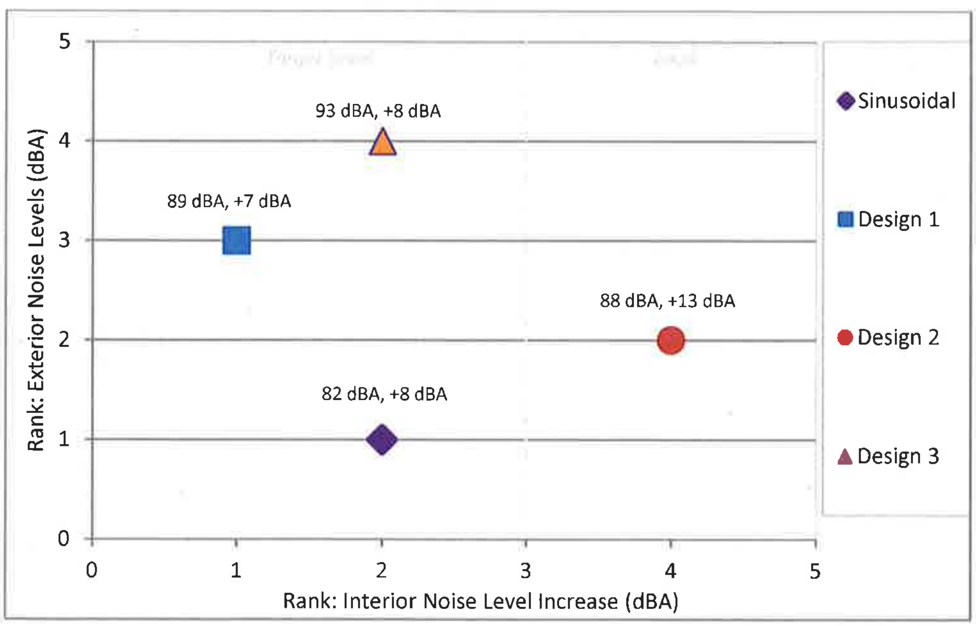
- Target Noise Level (+ 6 - 11 dBA)
- Loud (+ 11-14 dBA)
- Potential to Startle (+ >15 dBA)

Table 5: Comparison of Interior Noise Levels with Exterior Noise Levels (L_{max})

Design Type	Design Dimensions (in.)				Average Interior Sound Level Increase Above Background			Avg. Exterior Measured Values	
	Depth	Width	Length	Spacing	Lmax (dBA)	Descriptor	Rank Order	Lmax (dBA)	Rank Order
Sinusoidal	0.5	12	16	-	8	Target Level	2	82	1
Design 1	0.25	6.9	8	18	7	Target Level	1	89	3
Design 2	0.25	6.9	12	12	13	Loud	4	88	2
Design 3	0.25	6.9	12	18	8	Target Level	2	93	4

Figure 18 graphically compares the interior sound level increases to the measured exterior sound levels. This graph provides another view of how the sinusoidal design ranks well for external noise, while maintaining the target interior noise. All of the measured rumble strip designs meet the safety thresholds identified in NCHRP Report 641 (Torbic, 2009) of at least 6 dBA increase over background inside the vehicle cabin and other generally accepted increases of 10 dBA or more.

Figure 18: Graphic Comparison of Rank Order for Interior and Exterior Noise Levels



Linear Regression Modeling

A single factor ANOVA was performed on the raw data to consider whether there is a significant difference among the sound levels measured for the three cylinder milled designs, and the physical characteristics of the rumble strips associated with those results. The results indicate that the measurements among these three designs are significantly different from one another ($p < 0.05$).

New Designs

A multiple regression was conducted using the Lmax measurements at 25 feet and regressing them against length and spacing since depth and width were held constant amongst the three new designs. The results were normally distributed and had homogeneous variances.

Both the length and spacing were significant. The regression had an adjusted R square of 0.41 indicating that 41% of the effects on rumble strip noise can be explained with these variables (Table 6). The regression model for predicting sound levels at 25 feet from the shoulder rumble strip using the two variables is as follows:

Rumble Strip dB(A) at 25 feet = 66.28 + 0.93Length + 0.84Spacing;

$$\text{Adjusted } R^2 = 0.41$$

Table 6: Regression Model of Sound Level Measurements (Lmax)at 25 Feet

Variable	Parameter Estimate	Standard Error	t - Statistic	P > |t|	95% Confidence Interval Lower	95% Confidence Interval Upper
Intercept	66.282745	5.412242755	12.24681671	1.47061E-11	55.08666783	77.47882216
Length (inches)	0.933432813	0.285063984	3.274467721	0.003328454	0.343733034	1.523132593
Spacing (inches)	0.838748763	0.194341418	4.315851825	0.000256243	0.43672291	1.240774616

$R^2 = 0.46$
Adjusted $R^2 = 0.41$

- The rumble strip length dimension indicator is significant and positive. A 1 inch increase in rumble strip length is associated with an almost 1 dBA increase in the external sound level.
- The rumble strip spacing dimension indicator is significant and positive. A one inch increase in rumble strip spacing is associated with a 0.8 dBA increase in external sound levels.

Conclusions

The primary research objective was to determine the internal and external acoustic performance of new rumble strip designs intended to reduce external noise associated with incidental contact.

Sound Level Results

To determine the acoustic performance of the tested CLRS (sinusoidal) and three new designs (SRS), sound level measurements were collected at four locations Exterior noise levels, including their 1/3 octave band frequencies, and interior noise levels were evaluated.

Exterior Sound Levels

- Overall, exterior sound levels (i.e., sound energy) are the major contributor to annoyance at the wayside from vehicles hitting rumble strips.
- The sinusoidal rumble strip on SR 155 had the lowest measured overall sound level at the wayside, followed by Design Types 1 and 2 on SR 24 (see Appendix B).

1/3 Octave Band Frequencies

- Isolated frequencies can also contribute to annoyance associated with noise, especially at lower frequencies that travel further than “spikes” at the high end of the audible frequency range.
- The sinusoidal and shoulder rumble strip designs all shared an 800 Hz dominant frequency and peaks at 80 and 160 Hz with some variation in where the peaks occurred and the relative sound levels of the peaks dependent upon the design.

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 2 to 8 dBA and standard deviation ranged from 0.6 to 3 dBA.

Interior Sound Levels

- Interior levels identify which design increases 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 – 15 dBA, with a preference towards levels nearer the maximum.
- The designs evaluated in this report are predicted to increase in-cabin sound levels between 7 dBA and 13 dBA. These increases are qualitatively described as within the “target level” for the sinusoidal, Design Type 1 and Design Type 3 with Design Type 2 being classified as “loud” per NCHRP report 641.

Overall

- The sinusoidal and Design Type 1 are considered the highest performing of the measured sections because they shared the following characteristics:
    - Lowest overall sound levels
    - Flatter or less ‘spikey’ 1/3octave bands in the lower frequencies
    - Within the acceptable range for interior sound levels

Sound Levels and CLRS Designs

Results suggest that some rumble strip designs can have lower exterior sound levels and sufficient interior sound levels. This report does not recommend a specific design and WSDOT HQ Design will determine how to use the results of this research in future decisions about rumble strip design.

Design range for the lowest exterior noise

Results from a model based on sound level measurements were compiled for different combinations of rumble strip design parameters (see Table 7). The 2014 WSDOT report indicated that a spacing of 12 inches had the potential to reduce wayside noise levels. The regression modeled results for this report indicates that holding the length constant at 12-inches and decreasing the spacing can produce lower wayside noise levels. However, there is a break point where minimizing the spacing will also not produce sufficient interior noise levels to alert the driver. Therefore, based on the measured results the non-sinusoidal design using 12-inch length and 12-inch spacing (Design 2) combination produced the lowest noise levels at 25 feet (red outline in Table 7).

Table 7: Regression Modeled Levels of Sound Level Measurements (Lmax) at 25 Feet

Length (inches)	Spacing (inches)	Lmax (dBA)
8	18	89
9	18	90
10	18	91
11	18	92
12	18	93
12	12	88
12	11	87
12	10	86
12	9	85
12	8	84
12	7	83

Other CLRS designs to consider

- If additional design combinations are considered, a shorter spacing may further reduce exterior sound levels while still meeting the requirements for interior noise levels. The variables would need to be tested individually to provide data on the interaction between variables. These designs are outside the current range in WSDOT Standard Plans, but within the range considered in NCHRP 641.

Additional observations on the results

- The exterior sound levels reported here can inform project-specific decisions about rumble strip design, along with other considerations including the amount of truck traffic, bicycle usage, weather, roadway geometry, and crash history.

Acknowledgements

Mike Walker, Laura Escude and Hillary Pope supported the field measurements. John Donahue and Brad Manchas from the WSDOT Design Office also supported this work by providing their expertise and time in review of this report. Jon Peterson, WSDOT Research and Library Services, oversaw the research and supported the effort in numerous ways. Big thanks to everyone.

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Appendix A

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

SR 155

Depth	Width	Length	Spacing
0.5	12	16	-

	Measurement Date and Start Time	Avg. Lmax	63Hz	80.0Hz	100Hz	125Hz	160Hz	200Hz	250Hz	315Hz	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz	
25' Near Lane - Lmax	8/21/2017 13:25	83	38	52	40	50	52	48	49	53	55	55	59	64	66	65	63	60	56	54	52	50	
	8/21/2017 13:28	85	31	54	47	44	54	51	55	55	57	59	62	65	68	67	66	62	60	58	55	53	
	8/21/2017 13:31	81	44	46	41	50	49	51	49	51	54	54	58	63	66	65	62	59	55	52	49	46	
	8/21/2017 13:35	81	43	42	38	48	46	47	47	50	53	54	58	62	66	64	61	58	54	51	48	45	
	8/21/2017 13:39	83	35	51	38	48	55	50	50	54	56	57	61	64	67	67	64	62	59	57	54	51	
	8/21/2017 13:44	81	44	47	40	49	48	51	48	52	54	55	58	63	66	65	62	59	56	53	50	47	
	Averages	82	**42**	**50**	**42**	**48**	**52**	**50**	**51**	**53**	**55**	**56**	**60**	**64**	**67**	**66**	**63**	**60**	**57**	**55**	**52**	**49**	
25' Far Lane - Lmax	8/21/2017 13:20	81	43	41	37	47	46	49	48	49	54	54	58	63	65	64	61	57	53	50	47	45	
	8/21/2017 13:23	78	46	33	36	46	46	48	48	50	54	54	57	61	64	62	59	55	52	49	46	43	
	8/21/2017 13:26	80	39	43	37	48	48	50	48	51	55	55	59	62	65	63	60	56	53	50	47	45	
	8/21/2017 13:30	84	37	52	40	46	57	51	59	55	57	58	61	65	68	67	65	61	57	54	52	49	
	8/21/2017 13:33	79	46	39	38	47	46	48	46	50	54	54	58	62	65	62	60	56	52	49	46	43	
	8/21/2017 13:36	81	41	41	39	47	51	50	50	52	56	56	59	63	67	65	62	59	55	53	50	47	
	Averages	81	**42**	**49**	**42**	**47**	**52**	**50**	**52**	**53**	**55**	**56**	**59**	**63**	**66**	**65**	**63**	**59**	**56**	**54**	**51**	**48**	
50' Near Lane - Lmax	8/21/2017 13:24	75	35	50	36	45	47	45	45	48	51	52	55	60	62	62	59	56	52	49	45	43	
	8/21/2017 13:27	78	29	50	41	38	50	47	50	51	54	56	58	61	64	64	61	59	56	53	49	45	
	8/21/2017 13:30	74	41	42	37	45	44	46	45	45	50	51	54	59	62	61	58	55	51	47	43	40	
	8/21/2017 13:34	73	42	38	35	43	41	43	43	46	50	50	54	58	61	60	56	54	50	46	42	39	
	8/21/2017 13:38	77	32	48	35	43	49	46	46	49	52	55	57	60	63	62	59	57	54	51	48	44	
	8/21/2017 13:43	75	42	42	35	44	42	46	44	47	50	52	54	59	62	61	58	55	52	48	44	41	
	Averages	80	39	47	37	43	47	46	46	48	52	53	56	59	62	62	59	56	53	50	46	43	
50' Far Lane - Lmax	8/21/2017 13:24	74	41	38	34	43	42	44	44	46	50	51	54	58	61	60	57	53	49	46	42	39	
	8/21/2017 13:27	73	44	31	34	41	41	45	44	48	51	52	54	58	61	59	56	53	49	45	41	38	
	8/21/2017 13:30	74	38	40	34	43	43	46	46	47	52	53	55	59	62	60	58	54	50	47	43	40	
	8/21/2017 13:34	77	33	49	36	39	53	47	56	51	53	54	57	60	64	63	61	57	53	50	46	43	
	8/21/2017 13:38	72	44	35	34	42	41	44	45	48	50	51	54	58	61	60	57	53	49	45	41	38	
	8/21/2017 13:43	74	40	40	35	43	44	46	46	49	52	53	55	59	62	61	59	55	51	48	44	41	
	Averages	74	41	43	35	42	47	46	50	48	52	52	55	59	62	61	58	54	51	47	43	40	54

SR24

Depth	Width	Length	Spacing
0.25	6.9	8	18

	Measurement Date and Start Time	Avg Lmax	**63Hz**	**80.0Hz**	**100Hz**	**125Hz**	**160Hz**	**200Hz**	**250Hz**	**315Hz**	**400Hz**	**500Hz**	**630Hz**	**800Hz**	**1kHz**	**1.25kHz**	**1.6kHz**	**2kHz**	**2.5kHz**	**3.15kHz**	**4kHz**	**5kHz**
25' Near Lane - Lmax	9/18/2017 13:31	89	39	39	46	53	59	56	53	59	62	63	66	71	70	68	67	63	60	57	54	51
	9/18/2017 13:38	84	35	42	56	55	55	54	53	56	59	60	64	66	67	65	64	60	57	53	50	47
	9/18/2017 13:40	90	36	42	56	52	55	56	55	57	61	62	67	70	71	68	67	63	59	58	55	51
	9/18/2017 13:46	87	34	40	53	51	55	55	53	56	61	62	65	70	69	67	66	63	60	57	53	50
	9/18/2017 13:49	85	37	38	48	53	51	52	56	57	55	58	61	66	68	65	65	62	57	54	52	48
	9/18/2017 13:53	92	41	42	53	58	59	58	57	60	63	64	69	73	72	70	69	66	63	60	58	53
	9/18/2017 13:56	90	41	40	47	56	57	56	52	58	60	60	67	70	71	69	68	64	60	57	54	51
	9/18/2017 13:58	90	42	44	52	58	58	57	60	62	63	63	68	71	72	70	68	66	62	60	57	54
	9/18/2017 14:02	91	43	39	49	57	59	58	54	61	61	64	69	72	71	70	70	65	62	59	56	53
	9/18/2017 14:04	92	43	42	50	59	60	57	54	62	63	63	69	73	73	71	69	66	63	61	58	54
	Averages	89	41	52	56	58	56	55	59	61	62	67	71	71	69	68	64	61	58	55	52	40
50' Near Lane - Lmax	9/18/2017 10:55	81	34	33	44	46	49	49	50	54	55	57	61	65	65	64	62	58	54	51	47	43
	9/18/2017 10:59	77	30	38	50	45	47	49	50	49	53	55	58	62	62	61	58	55	51	47	44	39
	9/18/2017 11:01	81	30	35	47	45	48	50	48	50	53	56	60	64	65	61	60	57	52	50	46	41
	9/18/2017 11:04	79	31	34	49	46	48	50	49	52	55	57	61	65	65	64	63	59	56	52	48	43
	9/18/2017 11:08	77	35	33	43	47	46	48	48	50	51	53	58	62	64	62	61	58	54	50	46	42
	9/18/2017 11:13	83	35	36	48	51	51	52	51	55	56	59	63	67	67	65	64	60	57	54	51	45
	9/18/2017 11:16	81	35	34	43	48	51	51	50	53	54	57	61	65	65	64	62	59	54	51	47	43
	9/18/2017 11:22	74	22	39	26	34	31	36	44	48	46	42	43	51	59	61	56	41	37	38	36	33
	9/18/2017 11:29	81	37	33	44	50	50	51	50	55	55	58	63	66	65	64	63	59	56	53	48	44
	9/18/2017 11:33	82	37	36	47	51	51	52	51	57	56	58	63	67	67	65	64	60	57	54	50	45
	Averages	80	35	40	46	48	50	50	50	53	54	57	61	64	65	64	62	58	55	51	48	43

SR 24

Depth	Width	Length	Spacing
0.25	6.9	12	12

	Measurement Date and Start Time	Avg. Lmax	63Hz	80.0Hz	100Hz	125Hz	160Hz	200Hz	250Hz	315Hz	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz	4kHz	5kHz
25' Near Lane - Lmax	9/18/2017 11:54	84	44	53	42	55	58	55	56	57	56	59	61	65	66	64	62	60	56	53	51	48
	9/18/2017 11:58	86	32	57	43	45	57	50	57	58	58	57	63	66	66	65	64	61	57	54	53	50
	9/18/2017 12:00	89	30	58	50	46	59	54	57	61	62	62	68	70	70	69	67	64	62	59	57	54
	9/18/2017 12:03	91	32	51	59	44	62	53	58	60	62	62	67	72	72	70	68	66	63	59	57	54
	9/18/2017 12:06	88	31	58	47	44	58	52	58	60	61	60	66	68	67	67	67	63	60	57	55	53
	9/18/2017 12:11	91	40	51	59	48	62	56	59	62	62	62	67	72	72	71	69	65	63	61	58	55
	9/18/2017 12:13	90	30	53	57	45	62	53	57	58	62	62	67	71	72	70	68	65	61	60	57	54
	9/18/2017 12:19	86	34	47	56	45	57	56	55	56	59	58	65	68	68	67	65	62	59	56	53	49
	9/18/2017 12:24	86	30	53	47	44	59	51	55	55	59	60	66	69	68	65	64	61	57	55	51	48
	9/18/2017 12:26	83	28	43	47	41	58	46	51	51	55	55	61	65	65	62	61	57	54	51	48	45
	Averages	88	37	54	55	48	60	54	57	59	60	60	66	69	69	68	66	63	60	57	55	52
50' Near Lane - Lmax	9/18/2017 11:57	83	29	50	37	39	54	48	55	55	56	60	64	67	67	67	66	62	58	53	49	45
	9/18/2017 12:00	87	27	53	44	42	55	49	55	56	58	63	66	71	71	68	67	63	60	56	53	48
	9/18/2017 12:02	87	28	47	54	40	58	49	56	56	58	63	67	71	71	70	69	65	61	57	53	48
	9/18/2017 12:05	85	30	53	40	38	55	49	56	55	57	61	65	69	68	68	67	62	59	54	51	46
	9/18/2017 12:10	89	38	46	54	41	57	51	57	58	59	64	67	72	72	70	69	65	61	57	53	48
	9/18/2017 12:12	87	28	48	51	38	57	49	54	55	58	63	66	70	70	69	68	64	60	56	52	48
	9/18/2017 12:19	85	32	43	51	39	52	53	53	56	56	61	65	69	68	67	66	62	58	54	50	45
	9/18/2017 12:23	84	27	49	41	37	54	46	55	52	56	61	64	68	68	65	64	61	57	53	48	43
	9/18/2017 12:25	84	27	42	45	36	54	44	49	51	55	58	62	66	67	66	64	60	56	52	47	42
	9/18/2017 13:30	84	39	37	43	50	53	50	52	55	57	59	64	68	69	68	68	64	61	57	53	49
	Averages	86	33	49	49	43	55	49	55	55	57	62	65	70	70	68	67	63	59	55	51	47

SR 24

Depth	Width	Length	Spacing
0.25	6.9	12	18

	Measurement Date and Start Time	Avg. Lmax	**63Hz**	**80Hz**	**100Hz**	**125Hz**	**160Hz**	**200Hz**	**250Hz**	**315Hz**	**400Hz**	**500Hz**	**630Hz**	**800Hz**	**1kHz**	**1.25kHz**	**1.6kHz**	**2kHz**	**2.5kHz**	**3.15kHz**	**4kHz**	**5kHz**
25' Near Lane - Lmax	9/18/2017 13:31	91	43	40	47	56	56	55	59	61	60	62	68	73	74	72	73	69	65	62	58	55
	9/18/2017 13:38	93	43	38	49	57	57	55	55	61	63	63	68	74	75	74	74	70	66	64	61	57
	9/18/2017 13:40	92	44	36	46	57	56	56	57	59	62	62	68	73	74	73	73	69	66	63	60	55
	9/18/2017 13:46	85	38	39	47	50	47	48	49	55	58	58	62	66	68	67	67	64	59	57	53	48
	9/18/2017 13:49	93	44	38	48	57	57	55	55	61	63	63	69	74	75	74	74	70	66	64	61	57
	9/18/2017 13:53	92	42	40	51	56	57	53	58	64	62	63	69	73	75	72	74	69	65	63	59	56
	9/18/2017 13:56	93	43	37	50	57	57	54	56	63	64	63	69	74	75	74	74	71	67	64	61	57
	9/18/2017 13:58	94	42	38	53	58	56	53	55	64	63	64	70	76	75	74	74	70	66	64	61	57
	9/18/2017 14:02	92	44	43	47	57	56	56	57	60	62	62	68	74	74	73	73	69	66	63	61	57
	9/18/2017 14:04	92	44	37	45	57	55	57	58	62	63	62	70	74	74	72	73	69	65	63	60	56
	9/18/2017 14:07	92	44	38	47	57	56	56	58	60	62	64	68	73	74	73	73	69	66	63	60	56
	Averages	93	43	39	49	57	56	55	57	62	62	63	68	74	74	73	73	69	66	63	60	57
50' Near Lane - Lmax	9/18/2017 13:37	84	38	36	44	51	55	48	50	57	57	59	64	69	70	69	68	64	61	57	53	48
	9/18/2017 13:39	84	40	34	42	51	54	50	51	56	57	59	64	69	70	68	68	65	61	58	53	48
	9/18/2017 13:46	78	40	40	43	44	44	45	50	53	53	54	57	61	64	62	61	58	54	50	46	42
	9/18/2017 13:48	84	41	36	44	52	54	49	49	57	58	59	64	69	70	69	69	65	61	57	54	49
	9/18/2017 13:53	84	40	37	46	52	55	47	57	63	59	61	65	69	70	69	69	65	62	58	54	49
	9/18/2017 13:55	85	39	34	45	51	55	48	50	58	59	60	65	70	71	70	70	66	62	58	54	50
	9/18/2017 13:57	85	39	34	48	51	53	47	50	58	58	61	66	70	71	70	70	65	62	58	54	50
	9/18/2017 14:02	85	40	42	44	52	53	50	51	56	58	60	64	69	70	69	68	65	61	58	54	49
	9/18/2017 14:04	85	39	35	41	51	50	51	52	56	57	60	65	70	70	68	68	64	61	57	53	48
	9/18/2017 14:06	84	39	35	43	52	53	50	51	56	58	60	64	68	70	68	68	65	61	58	54	50
	Averages	85	40	37	44	51	53	49	52	58	58	60	64	69	70	69	68	64	61	57	53	49

Appendix B

The measurement offsets of 25 feet and 50 feet were measured from the center of the near lane for both the centerline and shoulder rumble strip measurements. To standardize the measurements for both the centerline and shoulder rumble strip measurements to account for the difference in the distance from the source to the measurement location the measured values must be re-calculated.

The distance from the centerline rumble strip to the measurement location is 31 feet (25 feet + 6 feet = 31 feet; assuming a 12 foot lane width and only one lane in each direction). The distance from the shoulder rumble strip to the measurement location is 19 feet (25 feet – 6 feet = 19 feet; assuming a 12 foot lane width and only one lane in each direction).

The difference in decibels or transmission loss between 31 feet and 19 feet can be calculated using:

$$10*LOG_{10}(31/19) = 2 \text{ dB}$$

Therefore, for example, if we add this 2 dB difference to the sinusoidal rumble strip measured value to compare to the Design 1, we would get 84 dBA at 25 feet for the sinusoidal rumble strip versus 89 dBA for Design 1 resulting in a 5 dBA difference between the two designs which is a noticeable difference.

Alternatively, if we subtract the 2 dB difference from Design 1 we would get 87 dBA compared to 82 dBA for the sinusoidal rumble strip or a 5 dBA difference. The differences at the 50 foot measurement location is less than 5 dBA.