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Mitigating roadside noise pollution: A comparison between rounded and sinusoidal milled rumble strips

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ABSTRACT

Shoulder or centerline rumble strips (RS) generate noise and vibration to alert drivers when they are departing the travel lane. Although inexpensive to install, easy to maintain, and have documented safety benefits, RS are not installed on many roadway segments primarily due to noise concerns of nearby property owners. This study evaluated the feasibility of using sinusoidal RS as a substitute for rounded milled RS on roadway segments in Oregon (U.S.A.) with lane-departure crash problems. Exterior sound levels generated by rounded and sinusoidal RS strikes were compared to baseline sound levels for three vehicle types (passenger car, van, and heavy vehicle) to establish sound generation and alerts of the two designs. A total of 39 vehicle strikes of RS were recorded in a controlled field experiment. Rumble strip strikes by the passenger car and van generated less exterior noise with the sinusoidal (3.1 dBA) than with the rounded (passenger car: 5.4 dBA, van: 4.6 dBA) design. Results for the heavy vehicle were complicated due to bridging of the narrower rounded rumble strip by the tires. The wider cut of the sinusoidal RS generated a clearly detectable increase in exterior roadside noise for the heavy vehicle.

1. Introduction

Environmental noise exposure has been linked to health effects such as sleep disturbance (Can and Aumond, 2018; Kaddoura et al., 2017; Murphy and Douglas, 2018; Soares et al., 2017; Muzet, 2007; de Kluizenaar et al., 2009), annoyance (Miedema and Oudshoorn, 2001; Fredianelli et al., 2019), cardiovascular effects (Babisch et al., 2005), learning impairment (Lercher et al., 2003; Chetoni et al., 2016), and hypertension ischemic heart disease (Van Kempen and Babisch, 2012). Thus, it is important to avoid unwanted sound and particularly to reduce the noise exposure from road traffic. About half of urban noise is generated by transportation (Calvo et al., 2012). Mitigating environmental noise can happen at the source by reducing the amount of noise generated, or at the receiver by reducing the amount of noise experienced (Murphy and Douglas, 2018). Environmental noise impact is difficult to predict however, as the physical environment is complex, and individual buildings have different sound insulating conditions (Murphy and Douglas, 2018). Therefore it is necessary to mitigate noise at the source as well as the receiver to achieve holistic reductions in environmental noise impact (Murphy and Douglas, 2018; Hurwitz et al., 2019b).

One mitigation strategy is to reduce the amount of noise generated by roadway features, such as rumble strips (RS), to reduce infrequent impulsive noise. RS generate noises and vibrations that alert drivers when they are departing the roadway reducing the

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incidences of run-off-road fatal injury crashes by 33% and all run-off-road crashes by 15% (Torbic et al., 2009). Although inexpensive to install, easy to maintain, and long-lasting, RS generate noise. In many areas with run-off road crashes that could be mitigated by RS, concerns about noise impacts limit their widespread application.

The sinusoidal RS is an alternative design that decreases the amount of exterior noise generated with a vehicle strike while providing sufficient interior noise and haptic feedback to alert the driver that they are leaving the travel lane (Himes et al., 2017). Sinusoidal RS are milled into the pavement like traditional, rounded RS but use a continuous cut that changes depth following a sinusoidal wave.

Sinusoidal RS were first developed in Europe and evaluated in the Netherlands, Sweden and Britain before being investigated in the United States in California by the California Department of Transportation (Caltrans) (Caltrans, 2012). The Minnesota Department of Transportation (MnDOT) then evaluated the proposed California sinusoidal design versus a Pennsylvania and Minnesota design (Terhaar and Braslau, 2015). The Oregon Department of Transportation (ODOT) and Caltrans then simultaneously evaluated sinusoidal RS in 2018 (Donavan and Buehler, 2018).

This paper summarizes the results of field research in Oregon that evaluated the feasibility of using sinusoidal RS as a substitute for rounded milled RS on roadway segments with lane-departure crash problems. Exterior sound levels generated by rounded and sinusoidal RS strikes were compared to baseline sound levels for three vehicle types (passenger car, van, and heavy vehicle) to establish sound generation of the two designs. The study benchmarks the existing noise generation of the rounded RS, and tests if the sinusoidal RS generates less noise. A total of 39 vehicle strikes of RS were recorded in a controlled field experiment for comparison. The results are compared to other evaluations of sinusoidal RS in the United States.

2. Background

The FHWA *State of the Practice* document has an extensive literature review regarding exterior noise evaluation of RS (Himes et al., 2017). Six studies have been identified from this document, that evaluate the exterior noise associated with RS through a variety of road materials, RS sizes, RS spacing and vehicle types (Finley & Miles, 2007; Rys et al., 2010; Kragh, 2007; Datta et al., 2012; Sexton, 2014). Key findings indicate that exterior noise is related to the speed of the vehicle, as well as the depth of the RS (Rys et al., 2010; Datta et al., 2012).

MnDOT performed exterior vehicle noise testing on 3 sinusoidal RS designs – California, Pennsylvania, and Minnesota designs – using 3 vehicle types at 3 speed thresholds (Terhaar and Braslau, 2015). The dBA levels increased proportionally with vehicle speed and vehicle weight. The California and Minnesota designs produced similar exterior sound levels, with the Minnesota design being slightly louder at the highest speed. Noise with the California RS design was generally at a lower frequency, which improved the exterior sound level, while providing sufficient driver feedback.

In April 2018, CalTrans published a study comparing sinusoidal, conventional rounded, and raised pavement marker RS (Donavan and Buehler, 2018). The study described the development of the sinusoidal design based on tire dimensions to create a quieter RS that still generates a sufficient alert for the driver. Noise was evaluated using a modification of the AASHTO SIP Method. Five test vehicles were evaluated at a 96.6 kph pass-by speed. As the study methodology in this research is very similar, the results of this study are compared to the CalTrans report.

3. Methods

3.1. Site selection

The experimental design was based on the AASHTO SIP Method (AASHTO, 2013). SIP criteria require a clear area free of trees and other reflecting surfaces. Fig. 1, created by the authors, summarizes the key criteria of the SIP method. To explore sinusoidal and rounded RS, sites were selected on the same route, US-26, for comparability. Based on the criteria and using online maps, test sites were selected on US-26, southwest of Gresham OR, to measure sound levels.

Site A is the location of the sinusoidal RS test site, located in Boring, OR. At this location, US 26 is a 4-lane divided highway, with left- and right-shoulder RS. Site B is the location of the rounded RS test site, located east of Sandy, OR. At this location, US 26 is a 4-lane highway with a 2-way left-turn lane with both centerline and shoulder RS. Only the shoulder RS were tested.

3.2. Exterior noise measurement

The setup for exterior measurements is shown in Figs. 2 and 3. The near microphone was mounted 1.52 m above the ground, and the far microphone was mounted at 3.66 m. Equipment was selected based on SIP Method guidelines (AASHTO, 2013). The literature recommends a strike time of 10 s (Terhaar and Braslau, 2015). To alert the driver of the test vehicle to the required length to start and end the RS strike, two cones were placed 243.84 m apart on the shoulder. This distance is based on an 88.5-kph vehicle speed, which was verified for each strike using a radar gun. During each RS strike, the recording was monitored on a laptop to ensure that the event was 6 dB louder than the background noise. This decibel difference ensures that the strike event is detectable and independent from the influence of other noise. Additional runs were recorded if there was excess background noise.

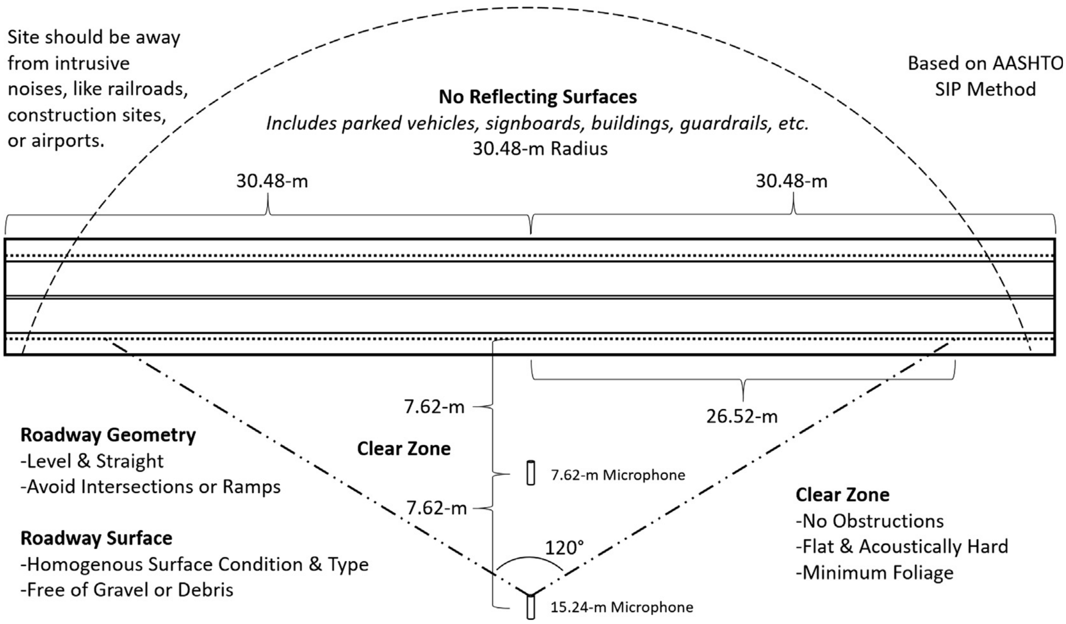

Fig. 1. Site selection guidelines based on AASHTO SIP method.

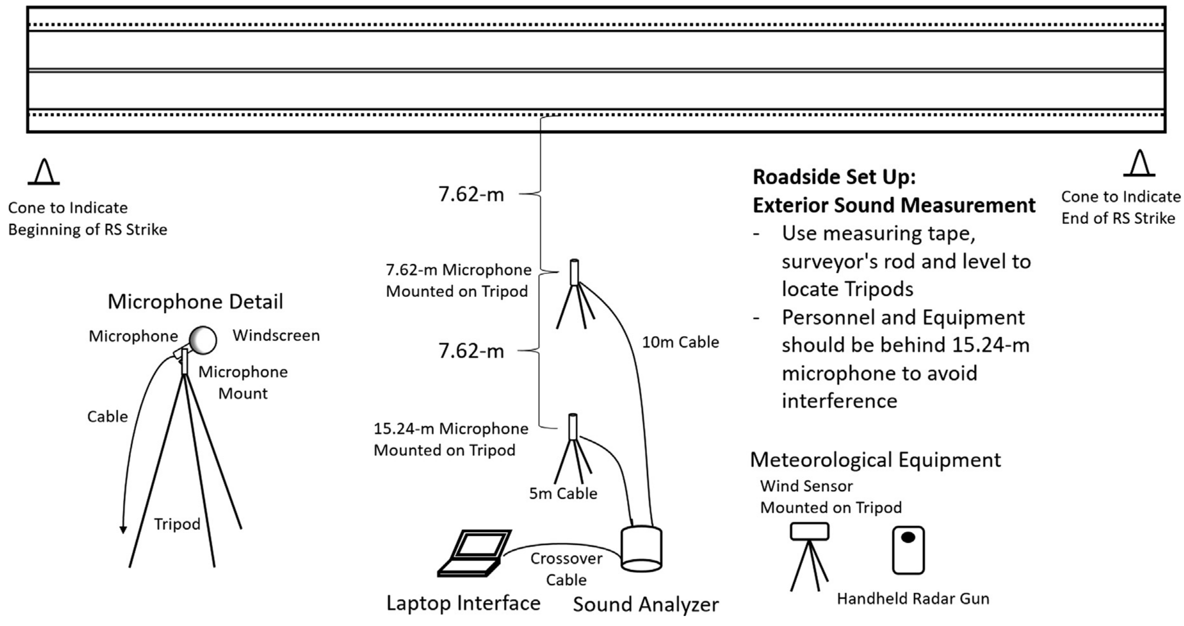

Fig. 2. Exterior sound measurement diagram.

3.3. Meteorological conditions

Meteorological conditions were recorded before the experiment and at one hour intervals during testing. If wind speed exceeded 17.7 kph at the time of measurement, the maximum threshold to avoid interference, additional vehicle passes were performed. Wind direction was noted, to explain potential data discrepancies. Temperatures should be within ± 13.9 °C between measurements to minimize the influence of temperature on data. Sky conditions were recorded as clear, scattered clouds, partly cloudy, mostly cloudy, or overcast. Pavement was visibly dry; tests were not performed during wet conditions to avoid damaging the sound equipment.

3.4. Vehicle types evaluated

A 2015 Dodge Grand Caravan (Fig. 4-Left) and 2017 Ford Focus Hatchback passenger car (Fig. 4-Center) were rented from Oregon

Fig. 3. Exterior sound measurement setup.

Fig. 4. Left: Van striking the sinusoidal RS; Center: Passenger car; Right: Heavy vehicle.

State University's motor pool and driven by licensed graduate students. A heavy vehicle was also tested, a Volvo VHD dump truck (Fig. 4-Right), which was supplied by the Oregon Department of Transportation (ODOT) and driven by an ODOT equipment operator with a Commercial Driver's License (CDL) from the Sandy Maintenance Division. Drivers were instructed to drive at the posted speed at a safe operating distance from other vehicles on the roadway.

In the Caltrans sinusoidal RS study, two types of tires (SRTT and GDY) were tested on a Ford Fusion to determine the sensitivity of tires on RS noise (Donavan and Buehler, 2018). Tire characteristics do influence the amount of sound generated in RS strikes, as much as 5 dB for certain frequencies (Donavan and Buehler, 2018). However, the interior sound and vibration alert was sufficient to warn the driver for both tires (Donavan and Buehler, 2018). For this study, the tires on the vehicles were held constant across the experiment. Therefore, a sensitivity analysis of the impact of the tire characteristics is not included. The van was equipped with Uniroyal Tiger Paw 225/65 R17. The passenger car was equipped with Continental ContiProContact 215/55 R16 93 H tires. The heavy vehicle was equipped with Bridgestone M854 385 R-22.5 in the front and Bridgestone L320 11 R-22.5 in the rear.

3.5. Rumble strip characteristics

Geometric characteristics of each RS type were measured and recorded to document the general properties of the tested RS. Average field geometric characteristics of the sinusoidal RS are shown in Fig. 5, and the rounded RS is shown in Fig. 6. Mill depth was measured several times at different mills due to slight variances in milling, and the average of these measurements is presented.

Fig. 7 shows a photograph from each site. Irregularities in pavement aggregates caused some variation in mill depth, as larger aggregate chunks chipped away. The sinusoidal RS (on the left) had a slightly wider and more scalloped shape to the edge of the mill. The mills were continuous, with the maximum mill depth at the trough of the wave and the minimum at the crest. The maximum depth of the sinusoidal mill was less noticeable than that of the rounded design. The rounded RS (on the right) had a distinctive separation between each of the mills. The shape was generally rectangular (in plan view), with more defined edges. The maximum depth of the rounded mill was deeper than that of the sinusoidal design. The sinusoidal RS design is wider and shallower than the rounded RS design as shown in Fig. 7.

3.6. Experimental data collected

Sound levels generated by rounded and sinusoidal RS strikes were compared against baseline conditions across 3 vehicle classes (passenger car, van, and heavy vehicle). Starting at the sinusoidal RS location, exterior noise was measured for the baseline and strike conditions. After exterior measurements at the sinusoidal RS location, the research team moved to the rounded RS location. Equipment was then set up on the roadside for measurements for the rounded RS. Based on the literature, at least 3 recordings were made for each experimental case. If excessive background noise, high wind speeds, or partial RS strikes occurred, additional runs were collected. A total of 39 exterior measurements were collected (breakdown by factor groups of vehicle type, rumble strip type, and condition in Table 1).

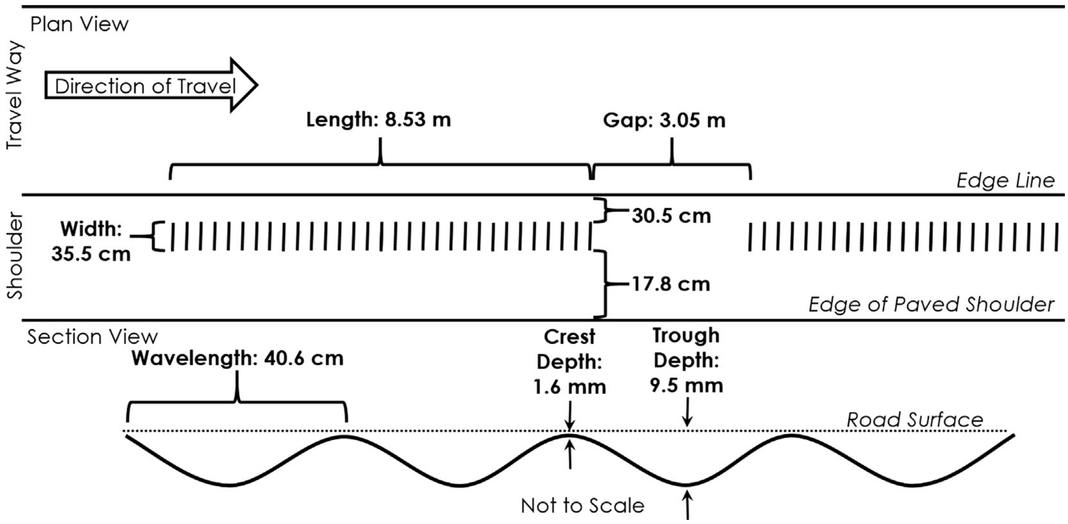

Fig. 5. Sinusoidal RS geometric characteristics.

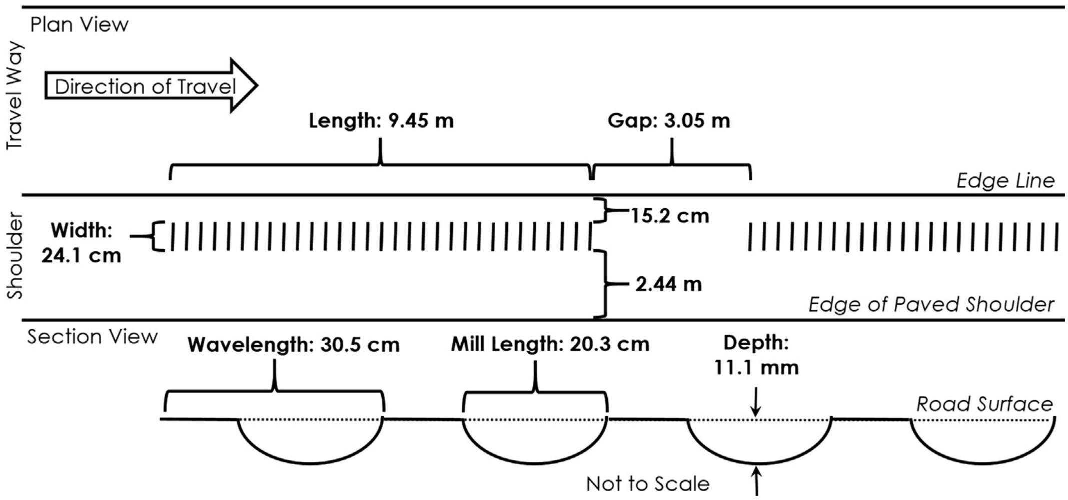

Fig. 6. Rounded RS geometric characteristics.

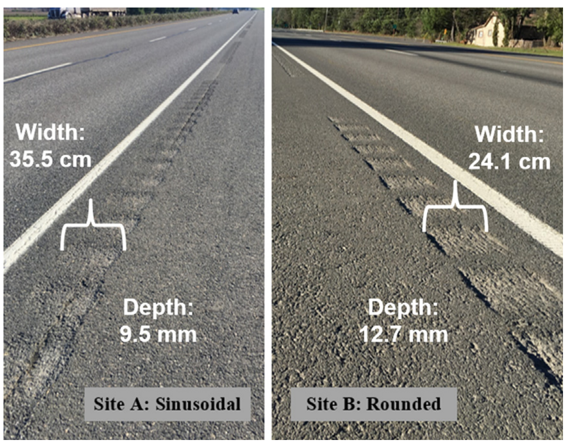

Fig. 7. Visual comparison of RS designs.

Table 1
Number of measurements for each factor group.

Vehicle type	Rumble strip type	Condition	Exterior noise samples
Passenger Car	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	3
		Strike	3
Van	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	4
		Strike	5
Heavy Vehicle	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	3
		Strike	3
	Total	**39**	

3.7. Performance measures

Performance measures for this study were chosen based on previous research and standards. Terhaar's framework plots the sound pressure level (SPL) against the 1/3-octave band for the ambient and RS strike noise levels (Terhaar et al., 2016). This method shows the frequencies at which the RS strike exceeds the background noise, indicating the distinguishable noise generated by the RS strike. The weighted average of the factor group values were used as the performance measure. Fig. 8 shows how the RS strike frequencies were compared to the baseline conditions. For both RS types, the noise observed for the baseline condition was subtracted from the strike condition (Eqs. (1) and (2)), to obtain the amount of additional noise that was generated from the strike when all other variables were held constant for each factor group.

$$\Delta \ Rounded \ \ dB = RS \ \ Average \ \ Strike \ \ dB - Average \ \ Background \ \ dB \tag{1}$$

$$\Delta \ Sinusoidal \ \ dB = RS \ \ Average \ \ Strike \ \ dB - Average \ \ Background \ \ dB \tag{2}$$

4. Results

4.1. Meteorological conditions

Average values for meteorological conditions at each site during data collection are shown in Table 2. Despite some variability between conditions, baseline and strike conditions for each factor group were recorded near each other to minimize variability and to obtain consistent deltas between measurements. Observed dBA differences between factor groups could vary slightly due to weather conditions, particularly wind speed. Based on the experimental set up, NCHRP 882 suggests that the measurement would be 1 dBA louder than the ideal condition based on the 12/7/17 Site B conditions (Kaliski et al., 2018). However, this increase would affect both the baseline and strike conditions, resulting in a very similar magnitude difference between the measurements.

4.2. Noise measurement

A *t*-test was used to identify differences in central tendencies between the 7.6- and 15.2-m microphones for the sinusoidal RS with

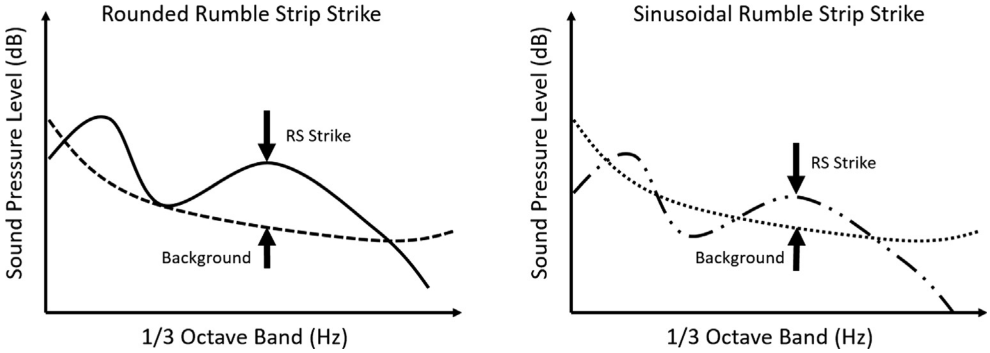

Fig. 8. Framework for sinusoidal noise reduction during exterior sound measurement.

Table 2
Measurements of meteorological conditions.

Date	Site	Average wind speed (KPH)	Average wind Direction	Average temperature (°C)	Sky condition
12/7/17	A	15.3	114°	10	Clear
12/7/17	B	17.2*	156°	7.2	Clear
12/12/17	A	4.8	74°	3.3	Scattered Clouds
12/12/17	B	9.0	89°	5.6	Scattered Clouds
12/13/17	A	3.9	90°	5	Clear
12/13/17	B	7.9	88°	2.8	Clear

* Windspeeds sometimes exceeded 17.7 kph threshold, necessitating 3 additional runs.

the passenger car. A statistically significant difference between these microphones was observed ($p < 0.05$). Higher noise was captured at 7.6 than at 15.2 m; this result was expected because the sound intensity decreases with distance from the source. Measurements from both microphones were averaged before further analysis was conducted.

To verify that RS measurements actually contained the additional noise profiles of the RS strikes, the frequency of sound pressure was evaluated. Based on the relationship between the speed of the vehicle and the size of the rumble strip, a specific frequency is expected. Previous research has predicted 80 Hz based on the conditions of the studied RS (Kalathas et al., 2019, Donavan and Buehler, 2018). For this study, the expected frequency is explained by vehicles traveling at 88.5 kph (24.60 m/s) striking a 40.6-cm (0.41-m) wavelength RS. Dividing the speed by the RS wavelength provided 60.5 strikes/s (Hz), which were transferred through the body of the vehicle producing the characteristic noise.

Fig. 9 compares exterior measurements for the passenger car during the rounded RS strike condition (in blue) and the baseline condition (in red). This comparison shows the intensity of each frequency for the total measurement and does not relate to time. The expected peak demonstrating additional sound intensity ~80 Hz is present, confirming the presence of the RS noise recorded in the strike condition.

A dB histogram was analyzed to compare conditions for the same exterior passenger car measurement, without the influence of time. Fig. 10 shows the sum of the observed dB measurements across the total measurement and does not relate to a time series. The strike condition for the rounded RS is shown in blue, and the baseline condition for the passenger car is in red. Two features are apparent. The first feature is a large increase in a specific dB related to the RS strike, around 73 dB. This dB corresponds to the amount of noise present at that sound level, and is not an indication of the frequency of the sound intensity. The second feature is an increase in the highest dB levels on the right tail of the distribution. The highest dB levels are the basis of the analysis, indicating how much the sound intensity is increased by the addition of the RS strike. The highest dB level for the baseline (red) is ~86 dB, whereas the highest dB level for the strike is 91 dB, with a peak of ~89 dB. The strike condition has a noticeable increase in the highest dB levels (increase in sounds with the most energy).

After confirming measurement of the RS strikes, specific strike and baseline events were isolated in the datasets. During field measurements, recordings began as the vehicle approached and continued as the vehicle passed the RS (~15 s). The probe vehicles (PC, van, and HV) were noticeable above the background noise for a shorter period (~3 s). Individual recordings were reviewed to identify when the peak noise intensity occurred.

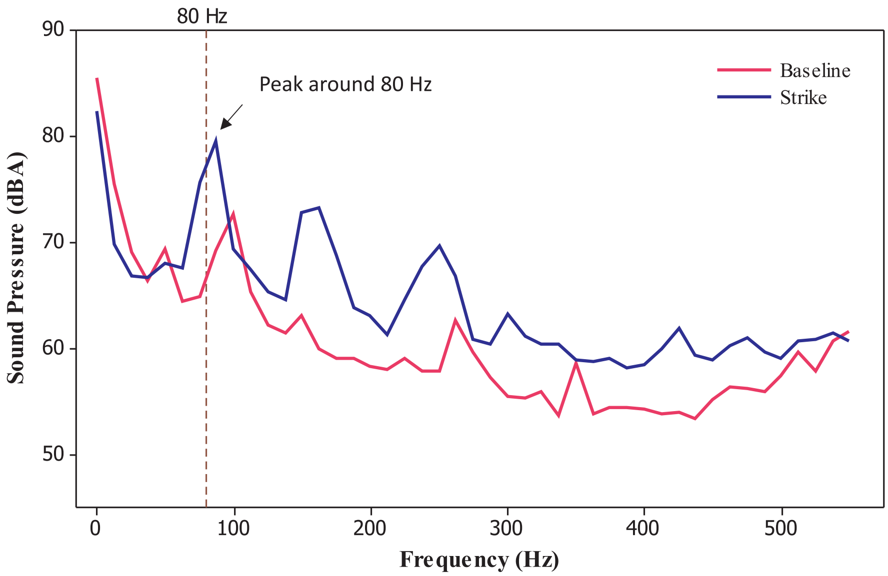

Fig. 9. Exterior sound measurement frequency comparison.

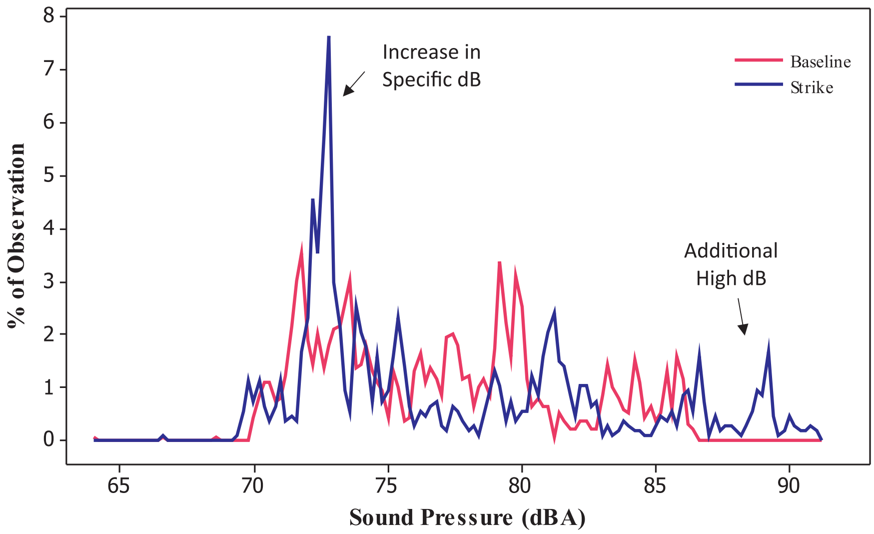

Fig. 10. Exterior dB histogram for baseline and strike conditions.

As dBA is a logarithmic scale, a weighted average was used to average the 3 strike and 3 baseline conditions for each factor group (see Table 1) across the time series. Fig. 11 shows the strike and baseline exterior sound measurements of the passenger car at the rounded RS site, and the weighted average values for the strike and baseline conditions. A total weighted average was calculated to determine the difference between the strike and baseline conditions for the total measurement. For this rounded strike, the strike average was 90.3 dBA (vs. 83.9 dBA for baseline). The difference (6.4 dBA) is sufficiently large to be noticeable to human hearing (> 5 dBA), confirming that the RS strikes produce a clearly noticeable increase in road noise.

The procedure was repeated for each factor group. Fig. 12 shows exterior measurements for the passenger car at the sinusoidal location. The baseline average was 85.3 dBA compared to the strike average of 87.1 dBA. The difference (1.8 dBA) was barely noticeable (< 3 dBA), indicating that the perception of road noise would be nearly the same for the baseline and strike conditions. As this measurement was taken immediately adjacent to the road, noise propagation should follow the same relationship, with the RS strike being perceived as normal road noise.

Table 3 shows average measurements for the baseline and strike conditions for each factor group. Baseline measurements were generally within the barely noticeable range (< 3 dBA) for each vehicle type, indicating similar pavement, weather, and ambient noise conditions between the two locations.

Fig. 13 shows boxplots for differences between the observed time series of strike and baseline conditions, indicating the increase in road noise, for each factor group. The figure labels denote the vehicle type and the type of strike (e.g. passenger car, rounded strike (PCR). Differences in the rounded RS strike over baseline for the passenger car and van were in the clearly noticeable range (5 dBA). The sinusoidal RS strike for the passenger car was noticeable (3 dBA) over baseline, whereas the sinusoidal RS strike for the van was imperceptible from baseline road noise (0 dBA). The heavy vehicle had a barely noticeable noise for the rounded RS strike compared

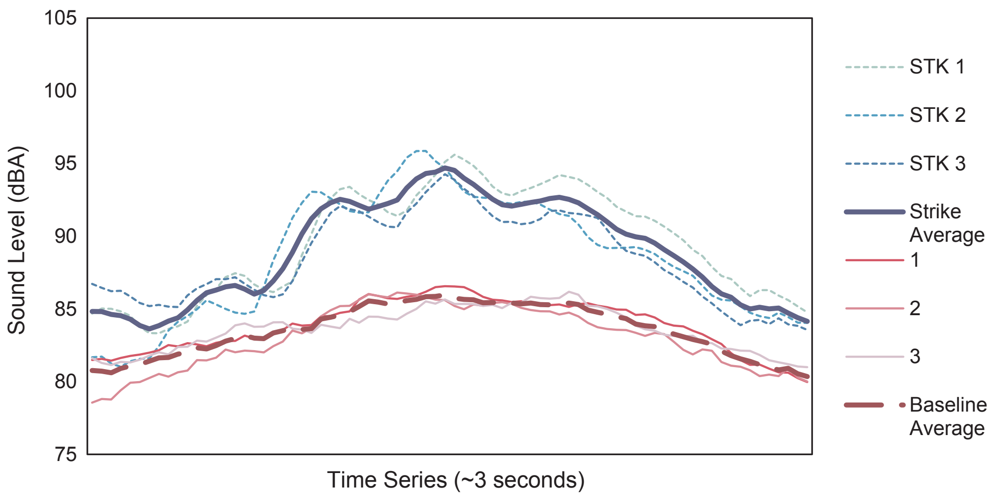

Fig. 11. Exterior sound measurement from passenger car striking the rounded RS.

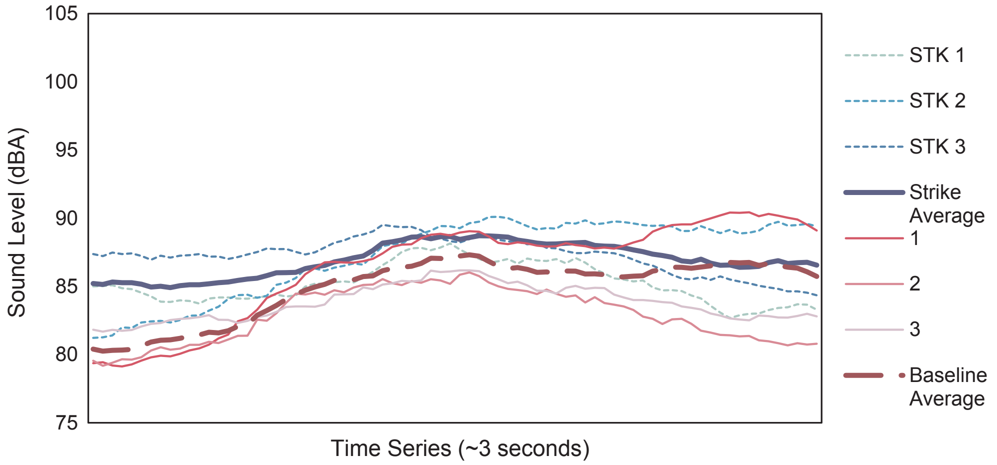

Fig. 12. Exterior sound measurements for the passenger car striking the sinusoidal RS.

Table 3
Average dBA magnitudes for the factor groups.

Vehicle type	RS Type	Condition	Exterior Avg dBA
Passenger Car	Sinusoidal	Baseline	84.6
		Strike	87.1
	Rounded	Baseline	83.9
		Strike	90.3
Van	Sinusoidal	Baseline	85.9
		Strike	86.0
	Rounded	Baseline	89.4
		Strike	94.2
Heavy Vehicle	Sinusoidal	Baseline	88.5
		Strike	94.5
	Rounded	Baseline	91.6
		Strike	95.0

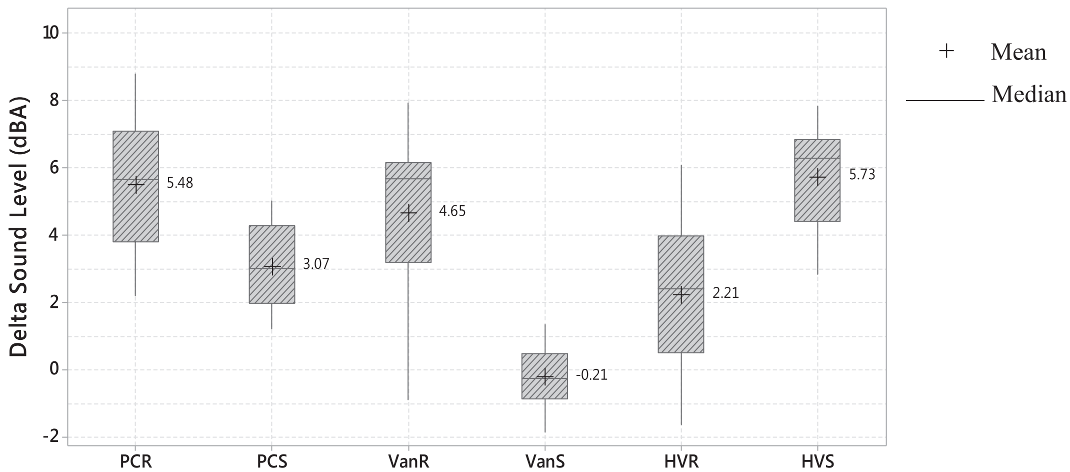

Fig. 13. Boxplots by vehicle and RS type for exterior delta sound measurements. PC, passenger car; HV, heavy vehicle; R, rounded RS; S, sinusoidal RS.

to baseline, which increased to a noticeable noise for the sinusoidal RS strike. This increase was likely due to the wider RS of the sinusoidal RS, which allowed the dual tires of the heavy vehicle to interact with the RS instead of bridging over it. This conclusion is supported by previous studies of RS width.

Table 4
The ANOVA summary table for exterior sound measurement.

Source of variance	df	MS	*F*	*P*
RS Type (R, S)	1	12.36	19.02	< 0.001*
Vehicle Type (PC, Van, HV)	2	9.80	15.07	< 0.001*
RS Type * Vehicle Type	2	27.56	42.40	< 0.001*
Error	12	0.65		

* Significance level of 0.01.

4.3. Statistical analysis

Data were analyzed in the Minitab statistical software package (version 18). All tests were performed at a 95% confidence level. Two-way ANOVA was performed on the strike and baseline exterior sound measurement deltas to determine whether average sound differed between the 2 RS types (rounded and sinusoidal) and between the 3 vehicle types (passenger car, van, and heavy vehicle). Table 4 shows that there was a statistically significant difference for RS type ($p < 0.001$) and between the means for at least 1 vehicle type ($p < 0.001$).

To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison test was performed, and main effect plots were used (Fig. 14). In this graph, the differences are observed between specific factors with all other factors held constant. For RS type, the noise of the rounded RS was ~1.25 dBA higher than that of the sinusoidal RS. For vehicle type, both the passenger car and heavy vehicle generated more noise than the van, with the passenger car producing the highest delta ($p < 0.0001$).

There was a statistically significant interaction between the combined effects of RS type and vehicle type on sound measurement ($p < 0.001$) (Table 4). Fig. 15 plots the delta mean sound at each level of RS and vehicle type, as well as pairwise comparisons. The heavy vehicle generated more noise when striking the sinusoidal RS than when striking the rounded RS ($p < 0.001$). The passenger car and van generated less noise while striking the sinusoidal RS compared to the rounded RS ($p < 0.001$ for both).

5. Discussion

For the passenger car or van, the exterior noise measured at 7.62 and 15.24 m from the roadside was less when striking the sinusoidal design compared to the rounded design. Rounded RS strikes generated a **clearly noticeable** increase in roadside noise of ~5 dBA over baseline (passenger car: 5.4 dBA, van: 4.6 dBA). The sinusoidal RS strike produced a **noticeable** increase in roadside noise for the passenger car (3.1 dBA) but an **imperceptible** change from baseline for the van (−0.2 dBA). Differences between vehicle types were expected, as the suspension, tire characteristics, and vehicle weight influence noise generation. Both vehicles showed similar decreases in exterior sound, indicating that the sinusoidal design did in fact reduce roadside noise. This provides further evidence of the sound reduction potential of the sinusoidal design, confirming the results of other state agencies.

The dual-tire heavy vehicle did not generate high exterior (2.2 dBA) noise with the rounded RS strike. The MnDOT study suggested that RS be wider than 20.32 cm to address heavy vehicle tire bridging (Terhaar and Braslau, 2015). This was confirmed by the observational data that indicated bridging of the dual tires over the narrow RS reduced the rounded RS noise. As the dual tires are much wider than the width of the RS, noise and vibration are significantly reduced. The sinusoidal RS generated a detectable increase

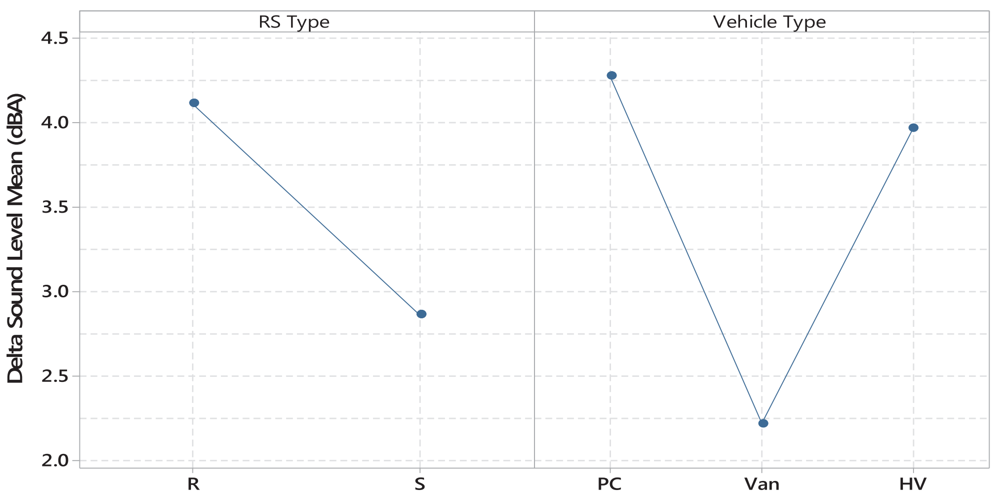

Fig. 14. Main effect factors of exterior sound measurement.

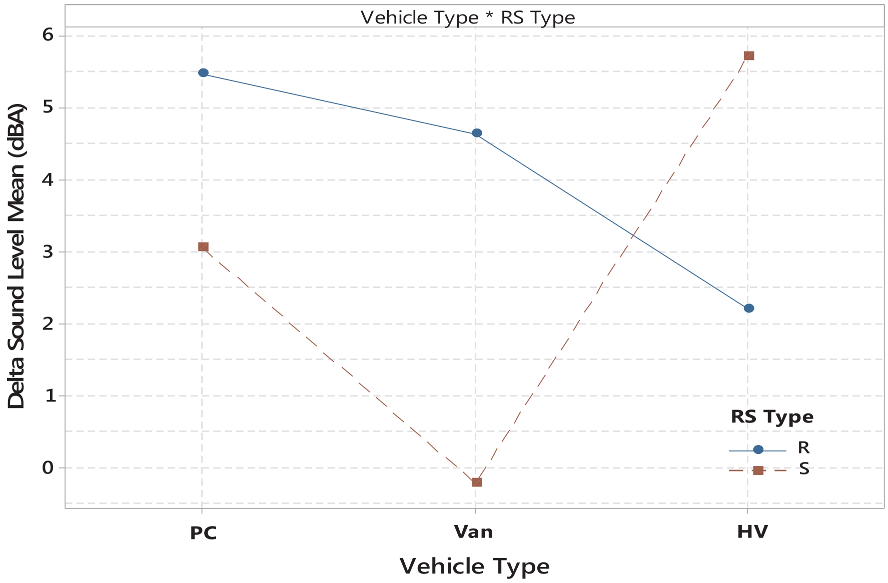

Fig. 15. Factor interactions for exterior sound measurement.

in exterior noise of 5.7 dBA. This increase in exterior noise associated with the sinusoidal RS being wider allowing the dual tires to interact, generating the additional noise. The heavy vehicle sinusoidal RS strike is similar to the exterior noise of the passenger car striking the rounded RS. Thus, installing a wider (sinusoidal or rounded) RS would likely extend the effectiveness of this countermeasure to heavy vehicles.

The results from this research compare well to two recent evaluations of sinusoidal rumble strips. Minnesota Department of Transportation (MnDOT) evaluated exterior vehicle noise from three sinusoidal RS designs (Terhaar and Braslau, 2015). The study compared three vehicle types and three different speeds groups (Terhaar and Braslau, 2015). It found that the exterior sound levels for the Minnesota and California designs similar, and both generated a sufficient interior alert (Terhaar and Braslau, 2015). The Pennsylvania design generated the lowest exterior noise, but did not generate a sufficient interior alert (Terhaar and Braslau, 2015).

The California Department of Transportation (Caltrans) preformed a similar sinusoidal RS study simultaneously with the Oregon study (Donavan and Buehler, 2018). The Caltrans sinusoidal RS design decreased exterior sound levels by 3 dBA (for heavy vehicles) to 6 dBA (for light-duty vehicles) (Donavan and Buehler, 2018). For exterior sound measurements of light-duty vehicles, baseline passes produced sound levels of 79.9–81.8 dBA (Donavan and Buehler, 2018). Rounded RS passes ranged 92.6–96.7 dBA, and sinusoidal RS passes ranged 85.6–90.0 dBA. Peak frequencies were observed at 80 and 160 Hz for the sinusoidal RS. The 80 Hz frequency is explained by vehicles traveling at 96.6 kph (26.8 m/s) striking a 35.6-cm (0.36-m) wavelength RS. Dividing the speed by the RS wavelength provided 75.4 strikes/s (Hz), which were transferred through the body of the vehicle producing the characteristic noise. Interior sound and vibration measurements were comparable, with the both RS types generating alerts ~13 dB higher than baseline insure a sufficient alert to the driver (Donavan and Buehler, 2018).

Table 5 compares some of the results from the MnDOT and Caltrans study to the present study. The passenger car data reported for both the external studies was a Chevy Malibu, but the heavy vehicles were different, with Caltrans using a 4 yard dump truck and MnDOT a tractor and trailer. The physical geometry of the sinusoidal RS designs varies across the studies. The MnDOT design was the widest and deepest, though had the shortest wavelength. The Caltrans design was most narrow, and shallow. The ODOT design has

Table 5
Comparison of results to similar studies (Terhaar and Braslau, 2015; Donavan, 2018).

		Sinusoidal designs			Rounded designs		Units
		MnDOT	Caltrans	Present Study	Caltrans	Present Study	
Geometry	Wavelength	30.5	35.6	40.6	30.5	30.5	cm
	Depth	9.5 to 12.7	7.9	1.6 to 9.5	7.9	11.1	mm
	Width	40.6	20.3	35.5	n/a	24.1	cm
	Speed	96.6	96.6	88.5	96.6	88.5	kph
Exterior Delta	Passenger Car	18.5	7.1	3.1	10.5	5.5	dBA
	Heavy Vehicle	n/a	3.7	5.7	5.9	2.2	dBA
Interior Delta	Passenger Car	15.5	19.1	5.8	16	11.4	dBA
	Heavy Vehicle	n/a	2.6	6.8	7.6	0.8	dBA

the longest wavelength. The rounded designs were also compared between Caltrans and ODOT, with similar wavelengths, but slighter deeper for ODOT. The speeds were the same between the MnDOT and Caltrans study, but ODOT was slightly slower, which is expected to reduce the intensity of the noise.

In Table 5, the delta between the baseline measurement and the strike value is reported to show the relative increase of the sound during a RS strike. This comparison to the baseline helps to control the differences in pavement materials, vehicle types, speeds and other characteristics. The delta for the Caltrans sinusoidal RS was 3 dB less than the rounded design for the passenger vehicle. A decrease (2.4 dB) was also found for the ODOT passenger vehicle between the RS types. The Caltrans study found lower noise from the sinusoidal RS and traditional RS for the heavy vehicle. Whereas the ODOT sinusoidal RS increased the exterior noise compared to the rounded RS. The lower noise for the rounded RS is related to the tire bridging over the narrower rounded RS for the dual tire truck. The Caltrans study did suggest that tire bridging may have reduced the response for the heavy vehicle. The MnDOT study did not compare against a rounded design, but the MnDOT sinusoidal RS produced the highest delta (18.5 dB) of the three RS studies (Terhaar and Braslau, 2015).

A RS is only effective if the interior alerts to the driver are noticeable. The interior alerts, or the difference between the background and strike sound levels measured inside the vehicle (Hurwitz et al., 2019a), are also presented in Table 5. The two other studies found the sinusoidal RS produce a readily noticeable increase in interior noise. Caltrans reported a larger alert for the sinusoidal design compared to their rounded design, though both are large enough to alert the driver. The MnDOT design produced a large alert of 15.5 dB for the passenger car (Terhaar and Braslau, 2015). For the heavy vehicle, Caltrans reported an insufficient interior alert (< 5 dB) for the sinusoidal RS compared to the sufficient alert for the rounded. Heavy vehicle data was not presented for the MnDOT sinusoidal design (Terhaar and Braslau, 2015). The present study also included an experimental analysis of interior noise but the methods, sampling approach, and data analysis are significantly different than the exterior evaluation and are not reported in this paper for brevity. However, the results were generally consistent with those from MnDOT and Caltrans.

Constructability, cost and maintenance are also important considerations in selection or RS type. A survey of RS contractor experience and equipment was developed to better understand the state of practice of RS installation. Contractors provided information about best practices from their experiences, installation cost, equipment type, and performance. Contractors suggested that sinusoidal rumble strips take three times longer to cut than traditional due to the continuous nature of the cuts. This increase in cutting time would increase the marginal cost of sinusoidal RS compared to rounded RS. Asphalt pavement is generally preferred, as concrete cuts are even slower, though concrete can be cut if it has been recently poured. Specific cutting heads may be required for sinusoidal cuts depending on the milling machine, increasing initial capital cost.

6. Conclusions

This research study compared exterior sound levels of three typical vehicle classes striking traditional rounded and sinusoidal rumble strips (RS) to baseline conditions. The values are based on the average difference between the baseline and strike conditions over a 3 s period for at least 3 strikes. This study compared the results of the exterior noise evaluation to similar studies. The results of this study are similar to other studies, showing a decrease in exterior noise with the sinusoidal RS design

The sinusoidal RS strike generated less exterior noise than the rounded RS for the passenger car and van. This statistically significant reduction varied for the vehicles, with the passenger car having a noticeable reduction (2.3 dBA), while the van had clearly noticeable reduction in roadside noise (4.8 dBA). This reduction in roadside noise is an indication that switching to a sinusoidal RS design could be used as a mitigation method for reducing source environmental noise.

The exterior noise increased 3.5 dBA for the heavy vehicle for the sinusoidal RS compared to the rounded RS. This increase is related to the dual-tires of the heavy vehicle bridging over the narrower rounded RS, but interacting with the wider sinusoidal RS. This conclusion is also supported by the Minnesota Department of Transportation study, which indicated that RS should be wider than 20.32 cm to address tire bridging (Terhaar and Braslau, 2015). Installing wider RS of all types could help to extend the effectiveness of this safety countermeasure to heavy vehicles.

RS are designed to alert the driver that they are leaving the travel lane with an intense sort duration noise which can wake nearby sleeping residents. Reducing the intensity of this noise could allow for wider adoption of this effective safety countermeasure. Changing the RS design is a relatively low cost alternative, compared to cost of crashes due to avoiding the countermeasure, or installing sound walls. The results of this study are generally consistent with two other independent state agency studies, confirming that sinusoidal RS are an effective safety countermeasure while reducing roadside noise.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2019.10.006.

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