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Evaluating In-Vehicle Sound and Vibration during Incursions on Sinusoidal Rumble Strips

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Abstract

Rumble strips (RS) are a countermeasure used to reduce roadway-departure crashes by providing audible and haptic alerts to the driver when a vehicle is departing the roadway. This study evaluated the feasibility of using sinusoidal RS as a substitute for more traditional rounded RS. A van, a passenger car, and a heavy vehicle were equipped with sound and vibration sensors to measure the interior noise and haptic feedback of each RS design. A set of typical conditions (with interior climate control fan and radio turned on) were also tested. Data from 75 RS strikes were analyzed. Experimental results demonstrated that the rounded RS doubled interior noise for the passenger car and van (11.3 dBA, 10.0 dBA) but the sinusoidal RS also generated a clearly noticeable interior alert for the passenger car and van (5.8 dBA, 4.6 dBA). The haptic alert provided an increase over the human perception threshold of vibration for all vehicles. The sinusoidal RS interior alert was detectable and within the acceptable range, but not clearly noticeable (5 dBA) when the climate control and radio were active. Alert levels for the rounded RS were >10 dBA, doubling the amount of interior noise for all ambient factor groups (11.2–14.4 dBA).

Roadway-departure crashes accounted for 18,275 fatal crashes in 2017 across the United States (*1*). Many of these crashes are on rural highways. Rumble strips (RS) are a proven safety countermeasure that alerts drivers to a roadway-departure through noise and vibration caused by milled grooves or raised striping on the roadway (*2*). Shoulder rumble strips (SRS) have been shown to reduce fatal rural highway roadway-departure crashes by 33% (*3*). Similarly, centerline rumble strips (CLRS) have been shown to reduce lane-departure crashes by 30% (*3*).

While RS are a proven safety countermeasure, they are also associated with highway noise concerns, especially from people living near roadways where they are installed (*4*). Long-term exposure to road noise has been shown to have negative health impacts, including disturbed sleep (*5*), annoyance (*6*), learning impairment (*7*), and hypertension ischemic heart disease (*8*). A new RS design that uses a shallower sinusoidal pattern has been shown to reduce roadside noise (*9–11*). However, the interior alert, or the noise and vibration generated from an incursion with the RS, must also be sufficient for the RS to remain an effective countermeasure. If the interior alert is adequate, sinusoidal RS could be installed in more locations where noise concerns have prevented their use. RS have a low cost per life saved ($320,000 per life), so extending the application of this countermeasure has the potential to reduce roadway-departure crashes (*1*).

The objective of this study is to evaluate the feasibility of using sinusoidal RS as a substitute for rounded milled RS on roadway segments with roadway-departure crash problems. In-vehicle noises and vibrations are quantitively and empirically compared between sinusoidal and rounded RS to indicate whether the sinusoidal pattern can potentially be used as a substitute for the rounded pattern. Thus, highway safety would be improved by reducing the rates of roadway-departure crashes and associated fatalities and injuries, while nearby residences would not experience as much roadside noise.

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Background

Rumble Strip State of Practice

RS are installed at the edges of the roadway, either on the shoulder (SRS) to reduce roadway-departure crashes, or along the centerline (CLRS) to reduce head-on crashes (*12*). Across the United States, transportation agencies have a variety of standard RS dimensions and application practices, which were compiled in the FHWA's *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities* document (from now on referred to as the FHWA *Standard of Practice* document) (*13*). The report includes an action plan to address deficiencies within the current state of practice and identifies the need for better evaluation of the safety tradeoffs of quieter RS explicitly.

The National Cooperative Highway Research Program (NCHRP) also provides design and application guidance for RS in NCHRP Report 641 (*3*). This report provides information on crash mitigation strategies, typical dimensions, best practices from state agencies, interior alert thresholds, safety countermeasure effectiveness, and application and design criteria (*3*). The report also includes recommendations for future research, including the need for studies to mitigate the noise pollution aspect of RS.

The amount of necessary interior alert from an RS strike differs between these two research summaries. A 6–12 dBA increase in interior noise is recommended by NCHRP 641 for urban facilities. Guidelines are higher for rural freeways, where 10–15 dBA is the target. NCHRP 641 also recommends that alerts not be over 15 dBA, as this may startle the driver. The FHWA *Standard of Practice* report suggests the interior alert be at least 3 dBA and preferably at least 5 dBA. Both documents recognize the lack of standards or minimum thresholds on the amount of haptic or vibration feedback.

According to the FHWA *Standard of Practice* report, the average RS has mills that are 16 in. wide (perpendicular to roadway), 7 in. long (along roadway), between 0.5 and 0.625 in. deep, with a spacing of 12 in. between mills (*13*). Many studies have shown that the depth of RS mill is a key factor correlated with noise generation with deeper mills producing more noise (*3, 14–16*). The speed of the vehicle is also correlated with the amount of noise generated, with faster speeds creating more noise during strikes (*9*, *17*). Some states use narrower RS (<8 in.), in part to accommodate bicycle traffic on narrower shoulders. However, these may be bridged over by the wide dual tires of heavy vehicles, reducing driver feedback, and rendering them ineffective (*3*, *9*).

Sinusoidal Rumble Strips

The motivation behind sinusoidal RS is to mitigate the roadside noise generated during RS strikes. RS strikes have a characteristic frequency of around 80 Hz (*10*, *11*). Exposure to low-frequency vibrations between 10 and 250 Hz have been shown to disturb sleep, contribute to stress, and have negative cardiovascular effects (*18*). These low-frequency vibrations generally travel further than other noises, affecting people further from the road (*19*, *20*). To detect a noise, the intensity of the sound must be higher than the ambient background noise (*21*). Therefore, the time of day plays a critical role in noise disturbance, as there is less background noise at night when people are often resting (*16*). Similarly, impulsive noise, such as RS strikes, are more noticeable than continuous noise (*16*).

Sinusoidal RS are a modification of traditional RS design, using a sinusoidal waveform that is shallower with smoother transitions, reducing the amount of noise generated during a strike (*15*). This design was initially developed and evaluated in Europe, by the Netherlands, Sweden, and the UK, before being studied in California (*16*, *22*). In 2015, the Minnesota Department of Transportation (DOT) evaluated sinusoidal RS designs from California (14 in. spacing; 1/32–5/8 in. depth; 8 in. length) and Pennsylvania (24 in. spacing; 1/8–1/2 in. depth; 8 in. length) in addition to their own, finding the California design to be the most effective (*9*).

In 2018, Caltrans reevaluated the California sinusoidal RS with an updated and expanded sinusoidal RS study (*10*). The newer study documented the development of the California design, and evaluated the interior noise and vibration of sinusoidal, conventional rounded, and raised pavement markers RS (*10*). Initial research suggests that the sinusoidal RS do reduce the exterior roadside noise (*3*, *9*, *10*, *13*). Variations in the shape of the RS, especially the depth, can have a significant influence on the noise and vibration generated during a strike.

Interior Sound Alert

The research methodologies of the U.S. studies for interior sound alert are similar and consistent with the recent FHWA & NCHRP recommendations (*3*, *13*). A microphone placed in the test vehicle records sound levels and frequencies collecting the noise. An accelerometer captures vibration of various vehicles striking sinusoidal RS (*13*, *16*). A comparison between the baseline normal road driving noise and vibration during vehicle RS strikes is used to evaluate the magnitude of the interior alert. SAE International provides guidance for consistently measuring noise on the interior of vehicles in Standard J1477 (*23*).

For the Minnesota DOT study, interior noise was similar for the passenger car and pickup truck for the California and Minnesota (24 in. spacing; 3/8–1/2 in. depth; 16 in. length) designs. The Pennsylvania design produced lower interior sound levels, with a marked reduction in driver feedback (*9*). Noise with the California RS design was generally at a lower frequency, which improved the exterior to interior sound level, while providing sufficient driver feedback.

In the Caltrans study, the sinusoidal RS design decreased exterior sound levels by 3 dBA for heavy vehicles and by 6 dBA for light-duty vehicles confirming that the sinusoidal design reduces roadside noise (*10*). For interior sound measurements of light-duty vehicles, baseline passes produced sound levels of 62.8–72.8 dBA (*10*). Rounded RS passes ranged from 79.3 to 89.8 dBA, and sinusoidal RS passes ranged from 81.5 to 90.6 dBA. Three of the four vehicles produced higher sound levels with the sinusoidal than with the rounded RS.

Haptic Feedback Interior Alert

The haptic feedback generated by RS strikes has been evaluated in several studies, with mixed results. In 2001, Caltrans used four accelerometers attached to the steering wheel to evaluate the haptic feedback generated by traditional RS designs (*15*). The results were inconclusive, as mounting the accelerators on the steering wheel added significant motion to the measured forces.

Future studies would attach the accelerometers to the steering column or seat track. Dulaski and Noyce (*24*) evaluated the haptic feedback of CLRS using two accelerometers mounted to the steering column and the clutch pedal. The average acceleration, variance, and standard deviation were calculated for each axis (X, Y, Z) and values were similar across CLRS and SRS strikes, but noticeably different than background driving (*24*). Analysis of variance (ANOVA) tests only found statistically significant differences between the background and strikes in one direction, which led researchers to conclude that differences in waveforms are detected in haptic feedback, not the magnitude of the vibration.

Minnesota DOT used C-weighted analysis of the sound measurements as a surrogate of the vibration generated on the interior and exterior, but did not offer any conclusions other than that these measurements did not correlate with the sound measurements (*9*). Caltrans evaluated haptic feedback on the steering column and the seat track using accelerometers (*10*). Caltrans measured interior vibration on the seat track and steering column, with baseline steering columns levels of 111.0–127.4 $\mu m/s^2$. Rounded RS passes ranged from 117.8 to 136.6 $\mu m/s^2$, and sinusoidal RS passes ranged from 127.7 to 139.7 $\mu m/s^2$. These values were converted to a dB scale, showing increases in vibration of 10 dB during the strikes compared with the baseline (*10*).

Morioka and Griffin (*25*) discussed different perception thresholds of vibration based on the hand, seat, and foot. Perception thresholds generally follow a logarithmic pattern known as Weber's law, which applies to many psychophysical laws. Very small changes in stimuli are detectable. For sound measurement, 3 dB is typically associated with a detectable change in sound level. A similar detectable change for vibration (in relation to acceleration) is around 0.011 m/s^2 for vibrations ~80 Hz.

Method

The literature review and industry standards were used to develop the experimental design. This study evaluated the interior noise and haptic alert of sinusoidal RS and a traditional rounded RS. Two test locations, one with each design, were selected on the same highway for comparison. Sound and vibration are measured in the interior of three vehicles (A van, a 2015 Dodge Grand Caravan; a passenger car, a 2017 Ford Focus Hatchback; and a heavy vehicle, a 2015 Volvo VHD dump truck) using a microphone, a triaxial accelerometer, and a sound analyzer while striking rounded and sinusoidal RS. Vehicles were driven at the posted speed of 55 mph. Recording of data did not begin until the vehicles' tires were on the rumble strip. At least three passes were recorded for each testing condition and RS design, and weighted averages were used to calculate differences between strike and baseline conditions. Additional runs were collected for the passenger car for the ambient noise evaluation, for a total of 75 measurements. The results are then compared with the guidelines in the FHWA and NCHRP documents and similar studies.

Site Selection

Potential RS locations were examined in Oregon along US-26, where both types of RS are installed. Four potential sinusoidal sites and two rounded sites were evaluated based on-site access, pavement condition, and a field visit. Two sites were selected for a field test. Site A is the sinusoidal RS site on US 26, a four-lane divided highway, with left- and right-shoulder RS. Site B is the rounded RS site on US-26, a four-lane highway with a two-way left-turn lane with CLRS and SRS. The locations are shown in Figure 1.

Interior Alert Vibration Measurement

A TLD356A02 triaxial accelerometer attached to the steering column of the vehicles was used to measure the haptic feedback of the RS strikes as shown in Figure 2. The triaxial accelerometer was factory calibrated by PCB Piezotronics to be within ±1% Hz for the expected range of vibrations and again field calibrated using a Meggitt Ref2500 handheld shaker at three different

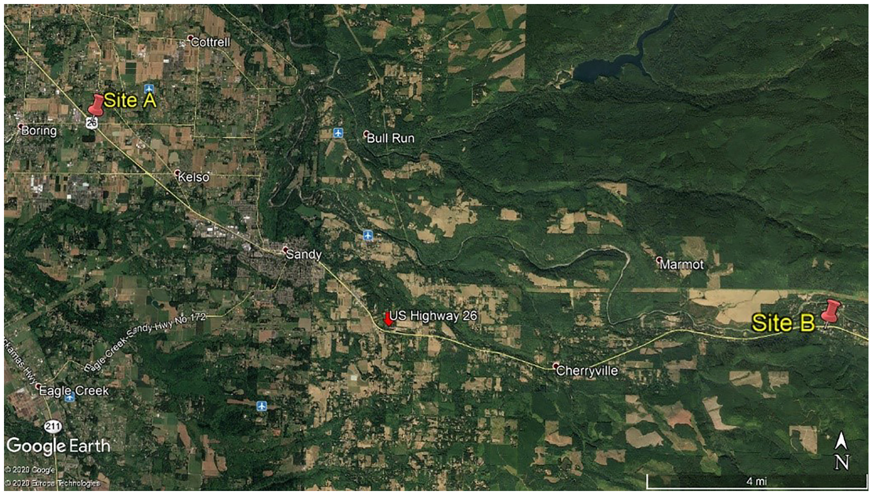

Figure 1. Site locations for testing (© Google Earth Pro).

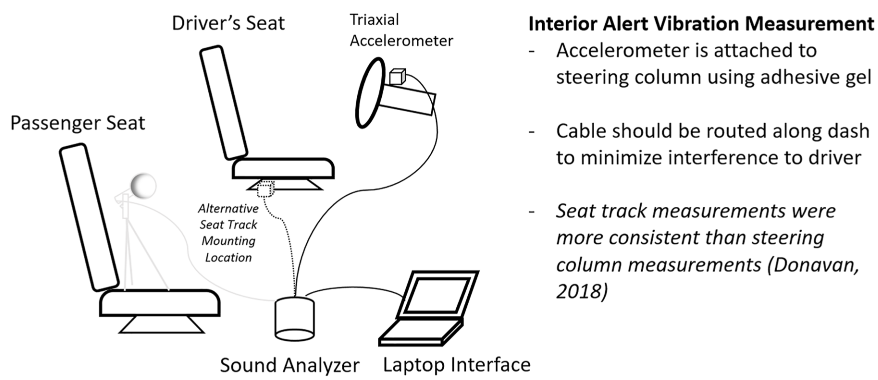

Figure 2. Interior alert vibration measurement diagram

frequencies (61.44, 100.0, and 159.2 Hz). For consistency, the following convention was used for the directions of the three axes. The Y-axis faced the driver, the X-axis was oriented in the horizontal direction, and the Z-axis was oriented in the vertical direction.

Frequency analysis determined that the RS strikes generated noise at the expected specific frequency and increased the highest sound energy levels. Prior studies found specific frequencies of 80 Hz across the vehicle types based on the geometry of the tested RS (*9*, *10*). Similarly, in this study, a specific frequency of 80 Hz was observed for the RS strikes.

Interior Alert Sound Measurement

A microphone was placed on the front seat of the vehicles to record the sound generated during the RS strikes. The microphone was positioned based on SAE Standard J1477 which is an industry standard for measuring interior sound inside light-duty vehicles (*23*). A GRAS 42AG sound calibrator was used to verify that the sound equipment accurately measured two tones (250 and 1000 Hz) at two intensities (94 and 114 dB), with an acceptable margin of error of 0.5 dB. Figure 3 was created to highlight the general specifications of this standard. The microphone was recorded simultaneously with the triaxial accelerometer.

Passenger Car Ambient Interior Alert Measurements

In previous studies, interior sound levels were collected under controlled conditions, with windows closed, the radio off, and climate control off. However, these controlled conditions do not reflect typical driving

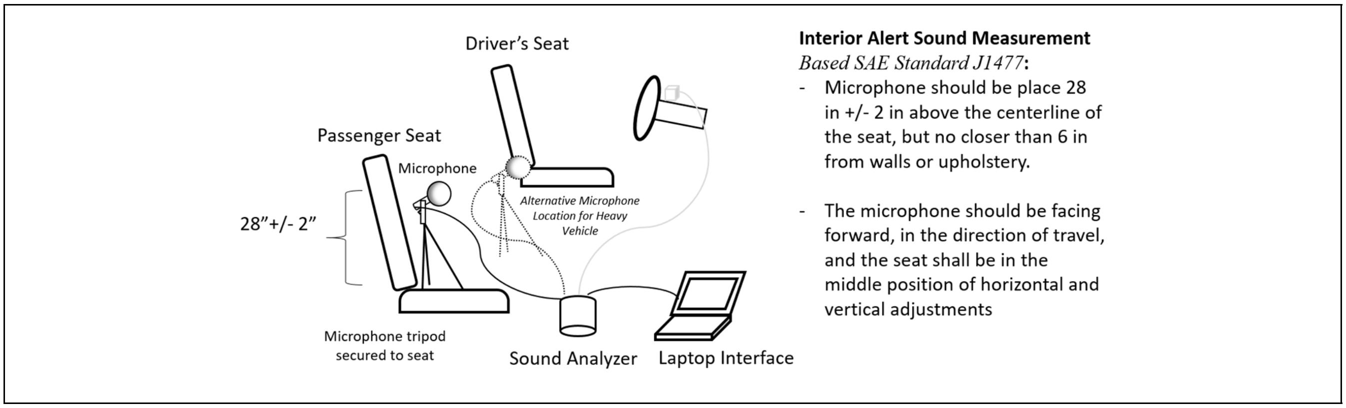

Figure 3. Interior alert sound measurement diagram.

Figure 4. Climate control settings for fan ambient noise.

conditions. Additional ambient noise could reduce the effectiveness of the alert. A sensitivity analysis of interior noise was performed to understand the impact of these other conditions as compared with the control conditions for the interior alert levels. Three conditions were evaluated: the radio on and set to a 3 dB increase in interior noise; the climate control fan on (settings shown in Figure 4); and both radio and fan on simultaneously.

Three conditions—Radio, Fan, and Both—are compared against the baseline condition of no conflicting ambient noise to evaluate the effectiveness of the RS strike during typical driving conditions. These factors have the potential to wash out the audible noise generated by a RS strike. Each ambient noise factor was measured independently. While this approach does not provide a complete counterbalancing of factors, it does significantly reduce the number of required experimental runs.

For the ambient noise factors, the sound analyzer was used to measure the noise generated by the radio and fan. While parked with the engine running, the baseline ambient noise of the car cabin was measured. The radio was then turned on and adjusted until a 3 dB increase in sound was observed (3 dB is the sound level increase that is typically detectable to the human ear). A similar procedure was used to determine the fan speed setting. Various configurations of climate control settings were evaluated to determine the highest sound output using the sound analyzer. The fan speed was set at the highest level and directed through the windshield defrost vents, as shown in Figure 4. These same settings were used in tandem for both cases (radio on and fan on at high speed).

Vehicle Types Evaluated

A van, a 2015 Dodge Grand Caravan, (Figure 5*a*) and passenger car, a 2017 Ford Focus Hatchback, (Figure 5*b*) were evaluated. A 2015 Volvo VHD dump truck (class 8: GVW 52,500 LBS) was used for the heavy vehicle, as shown in Figure 5*c*. The van was equipped with Uniroyal Tiger Paw 225/65 R17 tires. The passenger car was equipped with Continental ContiProContact 215/55 R16 93H tires, and the heavy vehicle was equipped with Bridgestone M854 385 R-22.5 tires in the front and Bridgestone L320 11 R-22.5 tires in the rear. The vehicles were driven at the posted speed of 55 mph while maintaining a safe distance from other vehicles.

Measuring Rumble Strip Characteristics

The physical dimensions of the RS were measured in the field. The sinusoidal RS dimensions are shown in Figure 6*a*, with the depth measured at the crest and trough of the sinusoidal cut. The rounded RS dimensions are shown in Figure 6*b*.

Experimental Data Collected

The sound levels generated by the strikes were compared with baseline sound levels of the three vehicle types driving at speed within the lane to determine the increase in

Figure 5. (*a*) Van striking the sinusoidal rumble strips, (*b*) passenger car, and (*c*) heavy vehicle.

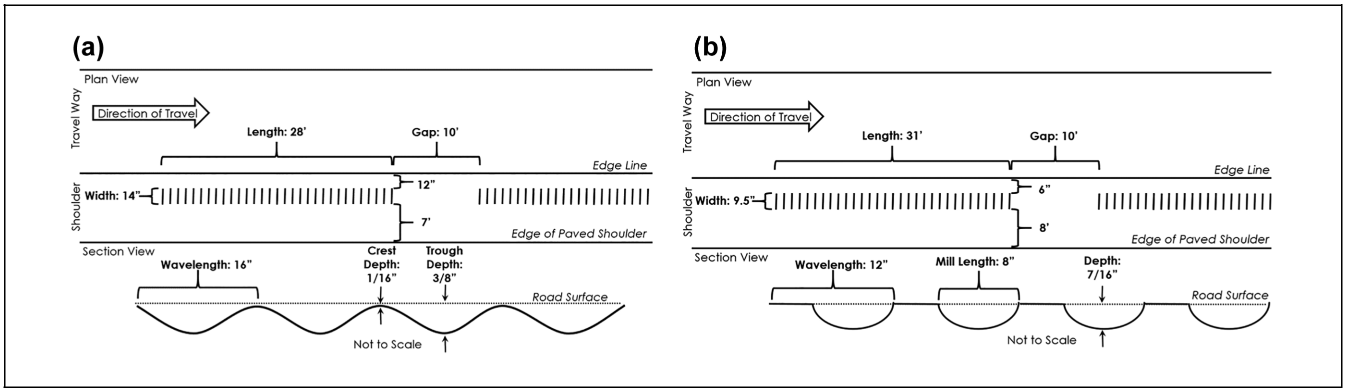

Figure 6. Typical geometric characteristics for (*a*) sinusoidal rumble strips (RS); (*b*) rounded RS

Table 1. Number of Measurements for Each Factor Group

Vehicle type	Rumble strip type	Condition	Interior
Passenger car	Sinusoidal	Baseline	12
		Strike	13
	Rounded	Baseline	13
		Strike	12
Van	Sinusoidal	Baseline	3
		Strike	4
	Rounded	Baseline	3
		Strike	3
Heavy vehicle	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	3
		Strike	3
		Total	75

interior noise during the strike. This comparison was conducted for the sinusoidal and rounded RS locations. A minimum of three recordings were captured for each experimental case. Additional runs were captured if the vehicle did not maintain good contact with the RS, or for excessive background noise as shown in Table 1. The roadway-departure angle was controlled by keeping the tire in the RS well placed before and after the actual recorded period. Therefore, the departure angle was 0°. Additional runs were collected for the passenger car to support the ambient noise evaluation (*4*), for a total of 75 measurements.

Performance Measures

The selected performance measures for comparison are based on previous research and standards. For the sinusoidal RS and rounded RS, the baseline condition was subtracted from the strike condition to generate a delta (Equations 1 and 2). This represents the increase of noise that was generated from the strike when all other variables were held constant. The final performance measure is the weighted average of the difference. NCHRP 641 recommends a 6-dBA increase in the interior noise to alert drivers that they are leaving the roadway (*3*). The delta, representing the interior alert that is generated by the RS strike, was compared with the recommended alert levels established in NCHRP 641 and by FHWA (*3*, *13*).

$$\Delta \text{ Rounded } dB = RS \text{ Strike } dB - \text{Baseline } dB \qquad (1)$$

$$\Delta \text{ Sinusoidal } dB = RS \text{ Strike } dB - \text{Baseline } dB \qquad (2)$$

Calculating the interior haptic feedback was based on the Dulaski and Noyce study (*24*). Acceleration for the three axes (X, Y, and Z) was resolved into a single resultant vector using Equation 3 for each time step. Each component vector was orthogonal to the others, simplifying calculation of the resultant. Acceleration was calculated in relation to acceleration because of gravity (g). Resultant vectors for the baseline condition were subtracted from the strike condition, to estimate the change in haptic alert because of the strike as shown in Equation 4. These values were compared with the haptic perception threshold (0.00112 g) identified in the literature as the threshold where the haptic alert was detectable (*25*). ANOVA was used to understand the statistical difference between the strike and background conditions. All statistical analyses were performed at a 95% confidence level using the statistical software Minitab for Windows (version 19.2) (*26*).

$$\left|\overrightarrow{\text{Resultant}}\right| = \sqrt{x^2 + y^2 + z^2} \qquad (3)$$

$$\text{Strike Vibration Level} - \text{Baseline Vibration Level} = \Delta \text{ Haptic Alert} \qquad (4)$$

Results

Interior Sound Measurement

The interior alert delta was measured by comparing the interior sound levels during normal flat road conditions (baseline) and striking the various RS (strike). Drivers maintained steady conditions for a 10-s period while the data were gathered. The interior alert was calculated for each of the vehicle types and the two RS types. An example of this data (dashed lines) is shown in Figure 7, the interior sound measurements for the passenger car striking the rounded RS compared with the baseline. The average value for the three runs was then calculated to estimate the average amount of interior noise for the strike (111.8 dBA) and baseline (100.4 dBA) conditions as solid lines in Figure 7. The interior alert delta for the rounded RS (11.4 dBA) more than doubled the noise (>10 dBA) in the interior of the passenger car.

The procedure was repeated for the sinusoidal RS with the passenger car data shown in Figure 8 with the baseline average (99.0 dBA) and strike average (104.8 dBA) identified by the thick lines. The amount of interior alert is 5.8 dBA for the sinusoidal RS, indicating a clearly noticeable increase in interior noise (>5 dBA).

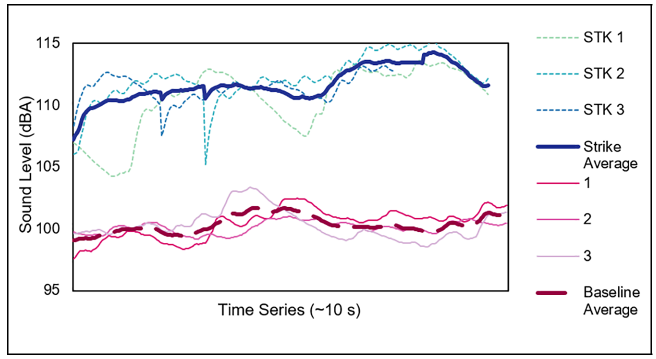

Figure 7. Interior sound comparison for the passenger car on the rounded RS.
Note: RS = rumble strip.

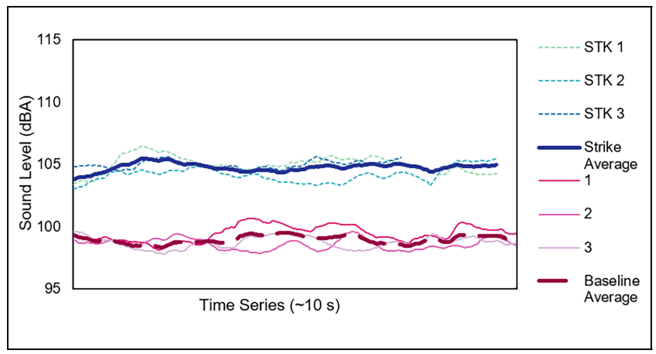

Figure 8. Interior sound comparison for the passenger car on the sinusoidal RS.
Note: RS = rumble strip.

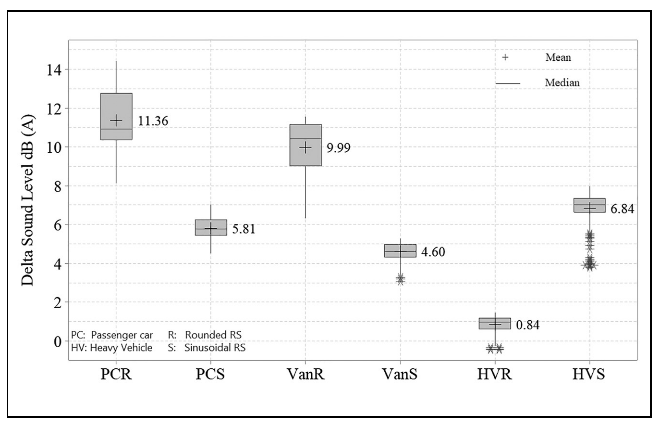

Figure 9. Boxplots by vehicle and RS type for interior delta sound measurements.
Note: RS = rumble strip.

Statistical Analysis. The procedure was repeated for the three vehicles (passenger car [PC], Van, and Heavy Vehicle [HV]) and the two RS types (Rounded [R] and Sinusoidal [S]) with the average values shown as boxplots in Figure 9. The values are in the clearly noticeable

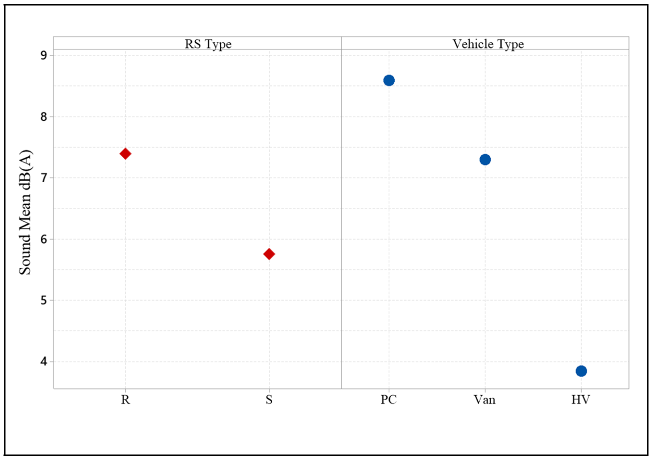

Figure 10. Main effect factors of interior sound measurement.
Note: PC = passenger car; HV = heavy vehicle; RS = rumble strip.

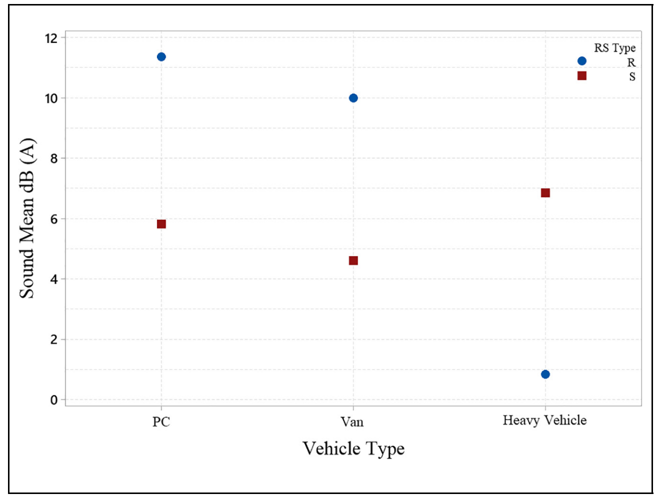

Figure 11. Interaction comparison of interior sound measurement.

range (>5 dBA), except for the HV striking the rounded RS. Tire bridging of the dual tires of the HV over the narrower rounded RS is suspected, as notified in the literature, nullifying the interior alert.

A two-way ANOVA test was used to statistically measure the difference between the interior alert means based on the three vehicle types and two RS types. Each test condition was replicated three times resulting in a total of 3 × 2 × 3 (18) passes which were used to conduct the analysis. RS type tested as statistically significant ($F(1, 12) = 96.62$, $p < 0.001$), as well as one of the vehicles being statistically different ($F(2, 12) = 161.65$, $p < 0.001$). A Tukey HSD post hoc pairwise comparison was used to calculate the group means for each of the main effects as shown in Figure 10. This comparison shows the influence of each factor with all other factors held constant (*27*, *28*). Across the vehicle types, the rounded RS was about 2 dB louder than the sinusoidal RS. Across the RS types, the PC and van had noticeably more interior noise than the HV with the PC the loudest (M = 4.50 dB(A), and M = 3.39 dB(A) respectively).

The combined effects of RS type and vehicle type on the mean sound level had a statistically significant interaction ($F(2, 12) = 111.53$, $p < 0.001$) as shown in Figure 11. Pairwise comparisons indicate that the interior sound levels were significantly less for the PC and van for the sinusoidal RS (M = 5.81 dB[A], and M = 4.59 dB[A] respectively). The heavy vehicle had the opposite pairwise comparison (M = 0.84 dB[A]), with the rounded RS generating less interior sound.

Interior Noise Measurements: Ambient Noise Levels

To better understand the influence of ambient noise conditions on the interior alert level, additional interior sound levels were measured in the passenger car. In

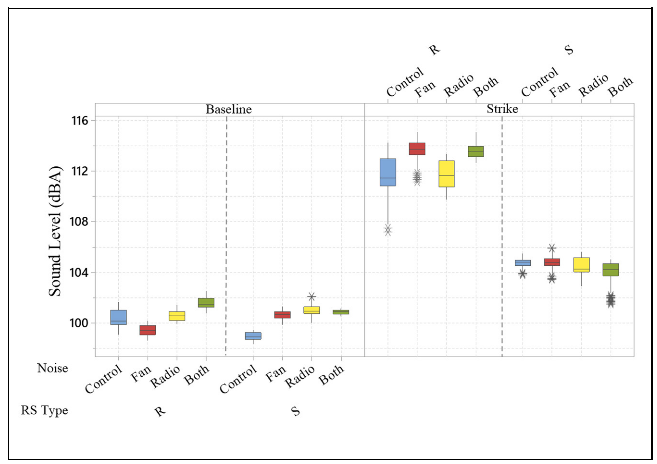

Figure 12. Boxplot comparison of ambient interior sound measurements.

typical driving conditions, climate control and the radio are often used, increasing the sound levels inside the vehicle. The average sound levels are shown in a boxplot in Figure 12, with the baseline conditions for both RS types being very similar (<3 dBA difference). The strike conditions have similar clusters, with the rounded interior sound higher than the sinusoidal.

Statistical Analysis of Ambient Conditions. A three-way ANOVA test was used to evaluate the difference between the factors (strike type, RS type, and noise type). Each scenario was replicated three times resulting in a total of 2 × 2 × 4 × 3 factorial design (48) passes which were

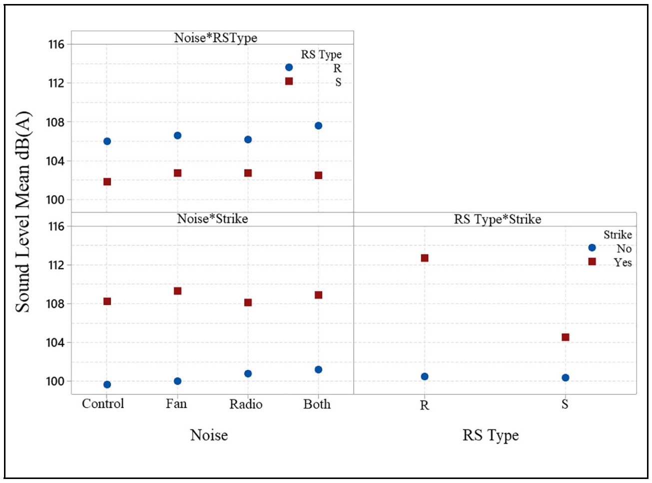

Figure 13. Two-way interaction plots for interior vehicle measurements.
Note: RS = rumble strip.

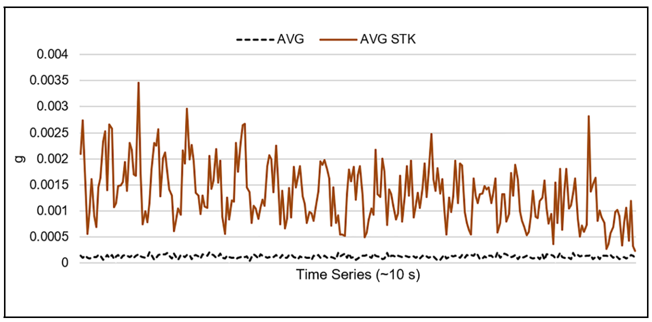

Figure 14. Vibration measurements for the heavy vehicle striking the sinusoidal rumble strip.

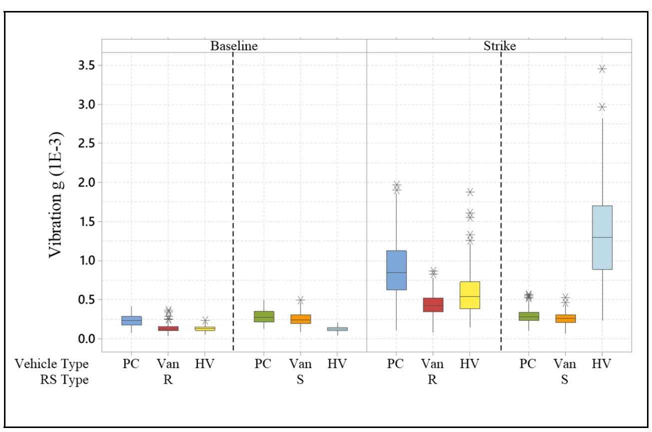

Figure 15. Boxplot comparison of vibration measurements.
Note: PC = passenger car; HV = heavy vehicle; RS = rumble strip.

used to conduct the analysis. RS type had statistically significant differences ($F[1, 32] = 9.12$, $p < 0.001$), as well as strike condition ($F[1, 32] = 195.12$, $p < 0.001$). At least one of the four ambient noise conditions was different ($F[3, 32] = 10.45$, $p < 0.001$). The main effects were estimated using a Tukey HSD post hoc pairwise comparison to find the differences for each factor with the other factors held constant. Figure 13 shows that the combined effect of the RS type (Noise * RS type) had a consistently higher sound level for the rounded RS. The combined effects of the ambient condition (Noise * Strike) showed a slight increase in interior sound for the Fan, Radio, and Both for the baseline and strike condition. The baseline conditions were similar for each RS, while the rounded RS strike had a higher sound level than the sinusoidal ($M = 8.31$ dB[A] difference), as shown in the combined effects for the RS type (RS type * Strike).

Interior Vibration Measurement

Three accelerometers recorded the interior vibration. A resultant vector was calculated using Equation 4 to estimate the total steering column acceleration, or the haptic feedback. The resultant haptic feedback was calculated for the baseline and strike conditions. The resultant vector for the three runs was averaged together to estimate the average haptic feedback. Figure 14 shows an example of this average haptic feedback for the HV sinusoidal RS strike and baseline conditions. The strike value often exceeded the perception threshold of 0.00112 g, indicating a detectable amount of vibration, compared with the baseline condition that is under the perception threshold.

Figure 15 shows a boxplot of the various vehicle types interacting with two RS types in the baseline and strike conditions. These values indicate the increased in-vehicle vibration because of the RS strike for each factor group. Acceleration values were converted to milli- (10^{-3}) g to simplify interpretation of the results. A change of 1 milli-g represents the necessary vibration to exceed the perception threshold.

The interior vibration generated by the rounded RS strike was higher than the baseline for all vehicle types. The interior vibration generated by the sinusoidal RS strike for the passenger car or van was similar to that of the baseline. These values represent the average of three out-of-phase strikes. The means are, therefore, expected to be lower than the observed measurements.

Statistical Analysis. A three-way ANOVA test was performed on vibration measurements to determine whether average vibration differed between the baseline and strike conditions, the two RS types (rounded and sinusoidal), or the three vehicle types (passenger car, van, and heavy vehicle). Each scenario was replicated three times resulting in a total of $2 \times 2 \times 3 \times 3$ (36) passes which were used to conduct the analysis. There was a statistically significant difference for the strike condition ($F[1, 24] = 112.03$, $p < 0.001$). Similarly, there was a statistically

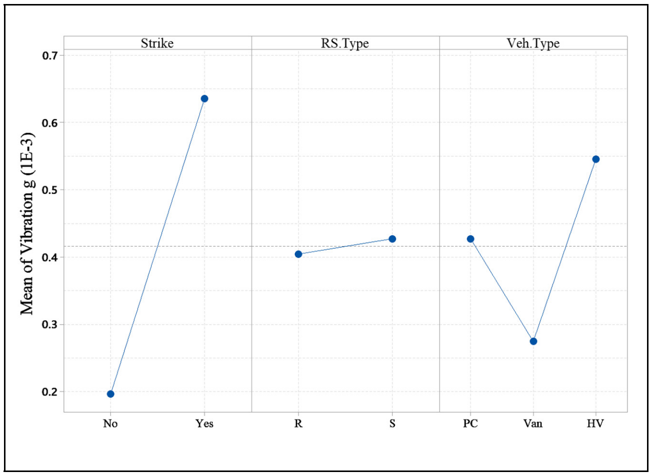

Figure 16. Main effect factors of interior vibration measurements.
Note: PC = passenger car; HV = heavy vehicle; RS = rumble strip.

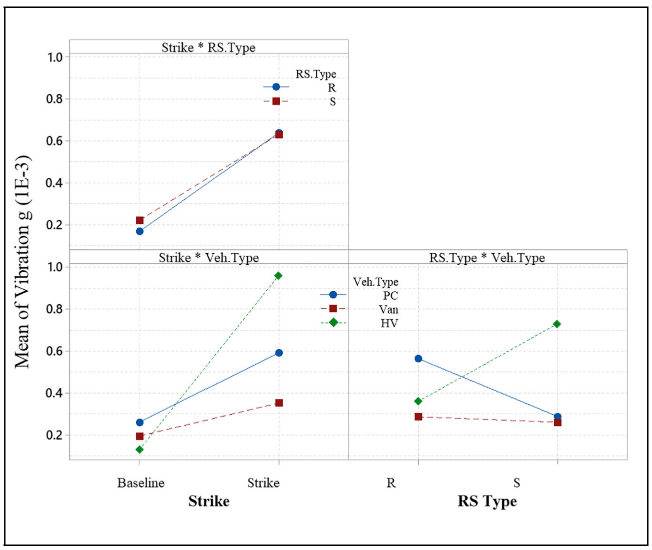

Figure 17. Two-way interaction plot of mean vibration by rumble strip (RS) type and vehicle.
Note: PC = passenger car; HV = heavy vehicle.

significant difference between the means for at least one vehicle type ($F[2, 24] = 11.35$, $p < 0.001$). For the interaction effects, there was a statistically significant interaction between the combined effects of strike condition with RS type ($F[1, 24] = 54.86$, $p < 0.001$) and with vehicle type ($F[2, 24] = 8.21$, $p < 0.01$) on the vibration measurements, and between RS type, strike and vehicle type ($F[2, 24] = 69.50$, $p < 0.001$).

To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison test was performed. Main effect plots are shown in Figure 16, in which differences are observed between specific factors with all other factors held constant. The strike condition showed an increase of ~0.44 milli-g between baseline and strike conditions for all strikes (sinusoidal and rounded). For RS type, the vibration for the sinusoidal RS was ~0.02 milli-g higher than the rounded RS, because of the large increase in vibration for the heavy vehicle for the sinusoidal RS. For vehicle type, the passenger car and heavy vehicle generated higher vibration magnitudes than the van. The low differences for the van observations were likely because of individual vehicle suspension characteristics.

Figure 17 plots the mean vibration at each level of each factor. Results of pairwise comparisons show that, regardless of vehicle type, striking the sinusoidal or rounded RS generated significantly higher vibrations than the baseline condition ($M = 0.43$ milli-g difference, $p < 0.001$). Regardless of the strike condition, the heavy vehicle generated significantly greater vibration ($M = 0.37$ milli-g difference) while striking the sinusoidal RS than striking the rounded RS ($p < 0.001$), whereas the passenger car had a lower vibration level for the sinusoidal RS ($M = 0.28$ milli-g, $p < 0.001$). There was no statistically significant difference in vibration for the van between RS types ($M = 0.02$ milli-g difference, $p > 0.05$).

Discussion

Noise generated by the rounded RS strike doubled the interior noise levels for the passenger car and van (10 dBA). The sinusoidal RS strike created a noticeable alert in these vehicles, although the levels were less than the 6-dBA guidance provided in NCHRP 641. FHWA suggests that 5 dBA is sufficient to alert the driver, which the van and passenger car met. The interior alert generated by the vehicle striking the sinusoidal RS design was sufficient to warn drivers under test conditions (*13*). The rounded RS doubled interior noise for the passenger car and van (11.3 dBA, 10.0 dBA). The sinusoidal RS generated a clearly noticeable interior alert for the passenger car and van (5.8 dBA, 4.6 dBA). The Tukey HSD post hoc pairwise comparison revealed the rounded RS was about 2 dB louder than the sinusoidal RS across all vehicle types.

In the Caltrans study, five test vehicles, including a dump truck, were evaluated for interior and exterior noise and vibration at a 60 mph pass-by speed (*10*). Additional measurements were made with one vehicle, a Chevy Malibu, to better understand the relationship of speed to RS noise and vibration generation (*10*). The Minnesota DOT study evaluated three vehicles: a passenger car, a pickup truck, and an empty semi-trailer truck (*9*).

Individual vehicle characteristics, including suspension features, tire dimensions and air pressure as well as type, age, and weight of the vehicle, all influence the noise that is generated when the vehicle strikes a RS. Interior characteristics also influence how much of the sound propagates into the cab of the vehicle for the driver alert. Across the three studies, eight passenger vehicles and three heavy vehicles have been evaluated while striking RS for interior and exterior performance (*9*, *10*). In general, the passenger vehicle results are similar, confirming the effectiveness of the sinusoidal RS, whereas the heavy vehicle results differ across the studies, suggesting a need for more research for heavy vehicle RS design.

Ambient interior noise conditions generated when the radio and climate control system are on influenced detectability of the RS alert in the passenger car. Statistical analysis showed that the addition of each factor resulted in a barely detectable (1 dBA) increase in background noise, which decreased the relative size of the alert. A Tukey HSD post hoc pairwise comparison found that the ambient conditions, strike levels, and RS type were all significantly different ($p < 0.001$). The sinusoidal alert decreased from 5.8 to 3.2 dBA with both radio and fan on. The interior alert was detectable and within the FWHA acceptable range but was not clearly noticeable (5 dBA). Alert levels for the rounded RS were >10 dBA, doubling the amount of interior noise for all ambient factor groups (11.2–14.4 dBA) which exceeds the NCHRP and FHWA thresholds. This shows that the sinusoidal RS design generates a detectable alert under normal driving ambient noise conditions. However, this alert is lower than the NCHRP standard for a clearly noticeable alert.

The sinusoidal RS evaluated in the Minnesota DOT study had interior sound level increases of $\geqslant 10$ dBA, with peaks at ~80 and 160 Hz (*9*). In the Caltrans study, interior sound and vibration measurements were comparable, with both RS types generating alerts ~13 dB higher than baseline (*10*). Interior alert levels were $\geqslant 10$ dB across the vehicle types and RS types, with larger alerts at the 80 Hz frequency (up to 32.6 dBA). The interior sound alerts from this study are somewhat lower than the reported values from Minnesota DOT and Caltrans. However, the values are at or above the suggested thresholds. These studies, however, provided the maximum sound levels generated during the strikes, whereas this study averaged the values over a 10-s window, a more conservative measurement. In general, the three studies agree that sinusoidal RS generate a sufficient interior sound alert. In addition, the departure angle of vehicles was not considered in this study, though research (*29*) has shown that it can affect the exterior noise generation.

For the heavy vehicle, the sinusoidal RS generated a clearly noticeable interior alert (6.8 dBA). The rounded RS interior alert for the dual-tire heavy vehicle was imperceptible (0.8 dBA). Literature suggests that this result was because of the bridging of the dual tires over the narrow rounded RS (*9*). Figure 18 demonstrates the tire bridging phenomena. The sinusoidal RS generated a significant increase in haptic feedback of the heavy vehicle as well. These results indicate that the wider RS design allowed the tires of the heavy vehicle to interact with the RS, inducing more vibration than the rounded design.

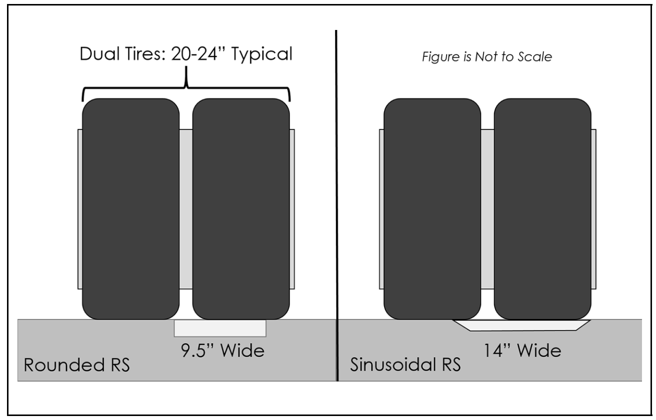

Figure 18. Bridging effect for dual-tire heavy vehicles.
Note: RS = rumble strip.

This indicates that wider RS trigger an effective response for heavy vehicles. Thus, installing a wider (sinusoidal or rounded) RS would extend the effectiveness of this countermeasure to heavy vehicles.

Analysis of data from steering column accelerometers shows that the rounded RS generated sufficient haptic alert for all vehicle types (>0.002 g). The passenger car and van had similar vibration levels for both RS. However, two-way interaction analysis for the vibration data shows an increase in vibration values for all vehicle types for both RS strikes. The heavy vehicle sinusoidal RS strike recorded the highest values for any of the factor groups. In the Caltrans RS study, they noted that different vehicles had noticeably different vibration signatures, especially for the steering column (*10*). The interior vibration generated by the sinusoidal RS strike for the passenger car or van was similar to that of the baseline. Minnesota DOT used a C-weighted analysis of the sound measurements as a surrogate for vibration measurements but offered no conclusions in relation to the haptic feedback for the RS (*9*). Caltrans measured interior vibration on the seat track and steering column (*10*). They reported the absolute value results of the vibration, as well as converting the results into a dB scale showing increases in vibration of 10 dB for all vehicle types during the strikes compared with the baseline (*10*). Comparing the haptic feedback results across these studies is difficult, as each study provided different units and techniques for measurement. However, the general conclusions are similar, namely that the sinusoidal RS generated sufficient haptic feedback. The lack of federal guidance about haptic feedback for RS, as well as the sparse literature concerning haptic feedback for RS, indicate that more research is needed to better standardize the evaluation vibration during RS strikes.

Conclusions

RS provide audible and haptic feedback to a driver when a vehicle is departing a lane and are a proven safety countermeasure. However, the noise generated by RS can be an issue for nearby residential land uses. The shallower and scalloped sinusoidal RS provide a quieter alternative to traditional rounded designs. To be an effective safety countermeasure, an RS must generate sufficient interior alerts, both audible and haptic.

The research presented in this paper adds to the evidence that sinusoidal RS design generates an effective interior alert, confirming the sinusoidal RS as an effective safety countermeasure for passenger vehicles. This conclusion is supported by two similar research studies by the Minnesota Department of Transportation (DOT), and the California Department of Transportation (Caltrans). Across the studies, the sinusoidal RS generated a clearly noticeable increase in interior sound levels. The traditional rounded RS also generated sufficient interior alert.

This paper further explored the interior alert considering the increased ambient noise produced by climate fans and radio in a passenger car. An additional evaluation of ambient noise conditions was conducted to better represent typical driving conditions. The radio and climate control were tested to understand how this additional interior noise affected the interior alert. While the ambient conditions did increase the interior noise, they did not reduce the interior alert below the acceptable levels for the passenger car.

The analysis found that the alerts for the heavy vehicle were different from the passenger vehicles. The rounded RS did not generate a detectable alert, while the sinusoidal RS generated a sufficient interior alert because the wide dual tires bridged the narrower rounded RS.

The haptic feedback was evaluated, showing an increase over the human perception threshold for vibration for all vehicle types. This result is similar to the Caltrans study, which found that the sinusoidal RS provided sufficient haptic feedback (*10*). However, there is a lack of federal guidance in relation to haptic feedback thresholds and significant variation across the studies in how haptic feedback is evaluated.

Future research should consider additional vehicle types and configurations. In addition, evaluating a wider variety of RS widths would provide a more comprehensive understanding of the relationship of this characteristic to the performance of RS alerting heavy vehicles of roadway departures. Other RS configurations, like rumble strips, thermoplastic pavement markings, or raised pavement markers, could be evaluated using this methodology to understand the effectiveness of these countermeasures as well.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: D. Horne, H. Jashami, C. M. Monsere, S. Kothuri, D. S. Hurwitz; data collection: D. Horne, H. Jashami, S. Kothuri; analysis and interpretation of results: D. Horne, H. Jashami, C. M. Monsere, S. Kothuri, D. S. Hurwitz. draft manuscript preparation: D. Horne, H. Jashami, C. M. Monsere, S. Kothuri, D. S. Hurwitz. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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Data Accessibility Statement

Supplementary data to this article will be made available on request from the corresponding author at david.hurwitz@oregonstate.edu.

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