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Evaluation of low noise transverse rumble strips in proximity to a stop controlled intersection

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A R T I C L E I N F O

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A B S T R A C T

Transverse rumble strips (TRS) can generate noise and vibration to alert drivers when they approach an intersection. The feasibility of using shallower epoxy filled TRS to substitute for traditional TRS to address noise concerns was evaluated. Twenty-four prove vehicle strikes with TRS were recorded and exterior sound generated by TRS strikes were compared to baseline and epoxy filled sound. Experimental framework was based on the AASHTO SIP Method. Humans can detect differences in noise levels at 3 dB(A), with 5 dB(A) being easily noticed. Compared to traditional TRS, the shallower epoxy filled TRS average sound level measurements dropped from 93 dB(A) to 88 dB(A), a noticeable 5 dB(A) difference. When the peek (max value) of both measurements are compared, the difference in sound was 6 dB(A), or a clearly noticeable change. Additionally, the sound generated from the epoxy TRS is higher than the paved condition, where the TRS was completely paved with asphalt, at 95% CI [-1 dB(A), 9 dB(A)]. This CI range indicates that the epoxy filled TRS strike was indiscernible at least, and clearly noticeable at most compared to a baseline, meaning that the epoxy TRS is noticeable compared to background traffic. Comparing the before condition TRS to the after paved TRS, the average sound level measurement dropped from 94 dB(A) to 83 dB(A), a clearly noticeable 11 dB(A) difference. However, the peak difference in sound measurement is approximately 18 dB(A). This indicates the original TRS is nearly four times louder than the same baseline passing vehicle.

1. Introduction

Transverse rumble strips (TRS) have been used in rural areas to alert drivers that they are approaching a lower speed zone or a stop-controlled intersection. TRS have been shown to reduce crashes by 20 to 30% and general reduce vehicle speeds [1, 2], but are associated with noise concerns [3]. Residents living adjacent to roadways have complained to the Oregon Department of Transportation (ODOT) about the noise generated by TRS. Previous research suggests that modifying the shape of the TRS can reduce the intensity of sound associated with TRS, reducing noise pollution and nearby resident complaints [4].

Transportation noise has been associated with health effects such as sleep disturbance [16–20], annoyance [21], cardiovascular effects [22], and hypertension ischemic heart disease [23]. 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 [24]. 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 [17].

Human perception of sound is dependent on how intense or strong a noise is against other background sounds [5]. All sounds have an intensity or volume, as well as a specific frequency profile [6]. Some sounds are more irritating than others, like short impulsive noises, compared to steady sounds [7]. Generally, people are more sensitive to noise at night, when they are resting [7]. The most noticeable noises have frequencies between 10 and 250 Hz and have been shown to interrupt sleep, add to stress, and potentially cause heart-rhythm disorders [4]. Low frequency noises carry more energy and travel further, potentially affecting more people. The A-weighted decibel dB(A) scale describes the intensity of noise and is based on the range of human hearing [5].

In regard to human hearing, differences of 3 dB(A) between noises are necessary for detecting the distinct sounds and a difference of 6 dB(A) is readily noticeable [8, 9]. Additionally, humans generally hear frequencies between 20 Hz to 20 kHz [10].

One solution to this noise problem is a shallower TRS, which produces a lower noise profile than the traditional TRS. There is a need to quantify scientifically the noise differential between traditional and shallow TRS. Research suggests that shallower RS generate the necessary in-vehicle noise and reduced roadside noise [11, 12]. The objective

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of this study is to evaluate the feasibility of using an epoxy to reduce the depth of traditional milled rumble strips in transverse applications post-installation. A quantitative and empirical comparison of the roadside noises of epoxy filled and traditional transverse rumble strips will give an indication as to whether the epoxy retrofit can potentially be used to resolve roadside noise complaints associated with transverse applications. The research question is "does epoxy retrofit applied to transverse rumble strips effectively reduce roadside noise?"

2. Background

Macroscopic noise evaluations are available based on the characteristics of traffic, such as speed, vehicle type and volume of vehicles, and can be used to determine the expected peak sound pressure [16, 25]. Congestion can reduce the amount of traffic noise, as vehicles travel slower during congestion events [25]. Road surface materials have a large impact on the level of annoyance generated by traffic [18] as well as correlation between road texture and tire/road noise [31]. When the tire rolls along the road surface, and as the tire has grooves, some air is trapped and compressed resulting in a high intensity of sound [32]. Numerous studies have investigated the acoustical pressures that are generated by road-tire interaction and how it can be mitigated. Licitra et al. in 2015 [33], compared two different noise measurement methods to assess the performance of the low-noise pavement surface. They found that the close proximity method (CPX) outperformed the Statistical Pass By (SPB) method. In the same year, Licitra et al. [34] explored the effectiveness of the rubberized surfaces after a one-year installation by using the CPX method. The results of the study have shown that the rubberized surface was very efficient in terms of road noise mitigation. Licitra et al. in 2017 [31] studied the effect of four different tire types and three road surface characteristics on noise levels while using a CPX method. They claimed that it is crucial to use more than one tire in evaluating the road surfaces' performance. Additionally, Licitra et al. in 2019 [35] explored the tire-road noise by modeling the acoustic aging of different pavement types. Authors indicated that pavement with finer aggregate has higher resistant to the acoustic aging factors (i.e. climate). Del Pizzo et al. [36] investigated the correlation between noise and road texture at ten sites on a highway located in Northern Italy while keeping the weather and traffic conditions constant. They found that there is a potential of basic relationship between tire to road texture noise at low and high frequencies. A tentative theoretical and practical framework was developed by Praticò through analyzing the relationship between Hot mix asphalt pavement design and the acoustic [37]. Praticò and Anfosso-Lédée [38] discussed several solutions that could be considered to mitigate the traffic noise with a primarily focus on quitter pavements. The aforementioned studies indicate one common noteworthy finding, which is new pavements and rubberized asphalts have played a major role in mitigating noise emissions.

Noise maps can be developed that consider the configuration and location of buildings to better understand the general spatial distribution of noise impact at specific locations [26]. These maps are highly dependent on temporal conditions, as noise levels are higher during the day due to more activity, and noise sensitivity is higher during the night due to people resting [26]. The type of land use is also important in noise mapping, as people at workplaces, schools or hospitals may be more sensitive to noise disturbance, while most models focus on residential impacts [26]. These models can estimate the background level of noise generated by traffic, which can serve as a baseline for understanding the implications of noise mitigation strategies. Noise levels above 55 dB(A) have been shown to adversely disturb sleep, causing health impacts [17]. Macroscopic models of noise impact often reflect homogenous, steady state conditions, using variables like annual average daily traffic, and average speed values to predict the daily noise impact [16]. More specific dynamic microscopic models have also been developed to better estimate urban traffic noise, which includes a wider variety of speed distribution, vehicle types, as well as acceleration and deceleration events [16]. Other factors, such as how aggressive a driver is and if the engine is gasoline or diesel, have been included microscopic models, with more aggressive driving or diesel engines increasing noise [24]. These microscopic models offer better estimates of peak noise levels, and can be used with real time traffic data to provide monitoring of noise levels based on current conditions [16].

In 2018, the Kansas DOT sponsored a study of how highway noise relates to high-friction surfaces [13]. The research team used a modified version of the AASHTO Statistical Isolated Pass-by (SIP) method. Compared to other noise-evaluation methods, the SIP Method generates large samples of a diverse traffic mix because it is relatively easy to implement with roadside sensors. Data were collected in evenings to minimize the effects of traffic and wind. Weather information was collected during the experiment. A 3-section window was used to evaluate exterior noise measurements. Single-vehicle passes on normal pavement (baseline) were compared to passes on high-friction surfaces. The study found that high-friction surfaces slightly reduce roadside noise, but not by the originally desired 5 dB(A) reduction.

According to AASHTO, 2013, the SIP Method is a standard method for measuring exterior sounds, such as the sound pressure levels (SPLs) of road surfaces. The maximum A-weighted SPL for a given vehicle type is calculated and compared to a baseline ambient sound level to determine the effect of road surface variations (e.g., RS). The method establishes standards for equipment, test sites, traffic conditions, microphone positions, calibration, experimental procedures, and data calculations. Microphones are placed at 8- and 16-m horizontally and 1.5- and 3.65-m vertically from the centerline of the travel lane. The test site should be in an open area along a tangent section of the roadway, away from intersections or areas with frequent acceleration or deceleration. The site should have minimum reflective surfaces, to reduce the incidence of noise obstructions. Fig. 1 summarizes the key criteria of the SIP method [15]

NCHRP Report 882 discusses the effects of weather on highway noise measurement [27]. This report shows how noise propagation is affected by various weather conditions, like wind, inversions, and temperature, and provides tables to adjust observed values based on weather conditions. Distance from the roadway plays a major role in the magnitude of these effects; thus, developing an experiment that locates the microphones close to the roadway minimizes the impact of weather.

An et al. evaluated the interior and exterior noises and vibrations for transverse RS using microphones and one accelerometer [4]. They tested 4 transverse designs and used correlations to compare interior and exterior noise measurements. A linear relationship between interior and exterior noise was strongest for the sedan vehicle and decreased with vehicle size. The truck had the worst fit, likely due to the higher ambient noise generated in heavy vehicles.

3. Data and methods

This section documents the research design, which is based on previous RS sound evaluations [12, 15]. The experiment measures the resultant noise of a probe vehicle striking a traditional and shallow TRS.

3.1. Experimental design

One experimental location was evaluated, the NB ramp terminal of the S. Jefferson Interchange (Exit 238) as shown in Fig. 2a. The before observation focuses on the traditional TRS, and the after observation focuses on the shallower TRS. A passenger car probe vehicle was used to collect at least 3 isolated TRS strikes at 72 km/h, which is lower than posted speed limit 89 km/h. This speed was used as the TRS are close to an intersection. Probe vehicle strikes have been used previously to evaluate rumble strips [13, 12].

The TRS site was located on Jefferson Highway (OR 164) at the NB Interstate 5 exit and entrance ramp, near Millersburg, OR (Fig. 2a). The

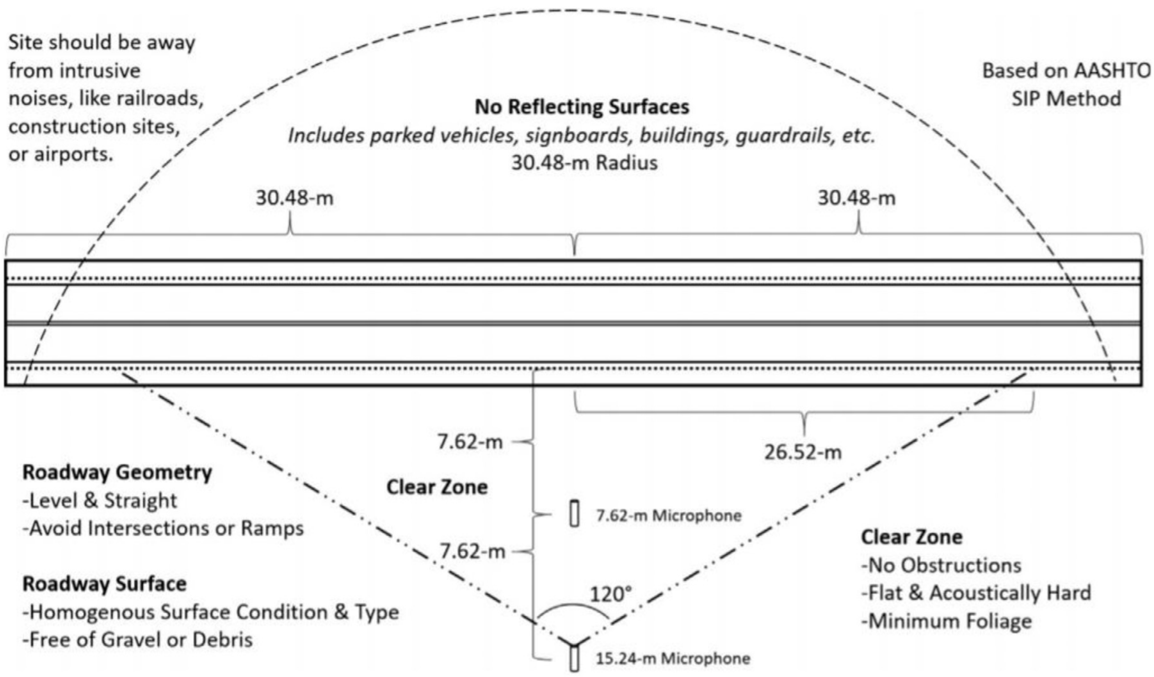

Fig. 1. Site selection guidelines based on AASHTO SIP method [15].

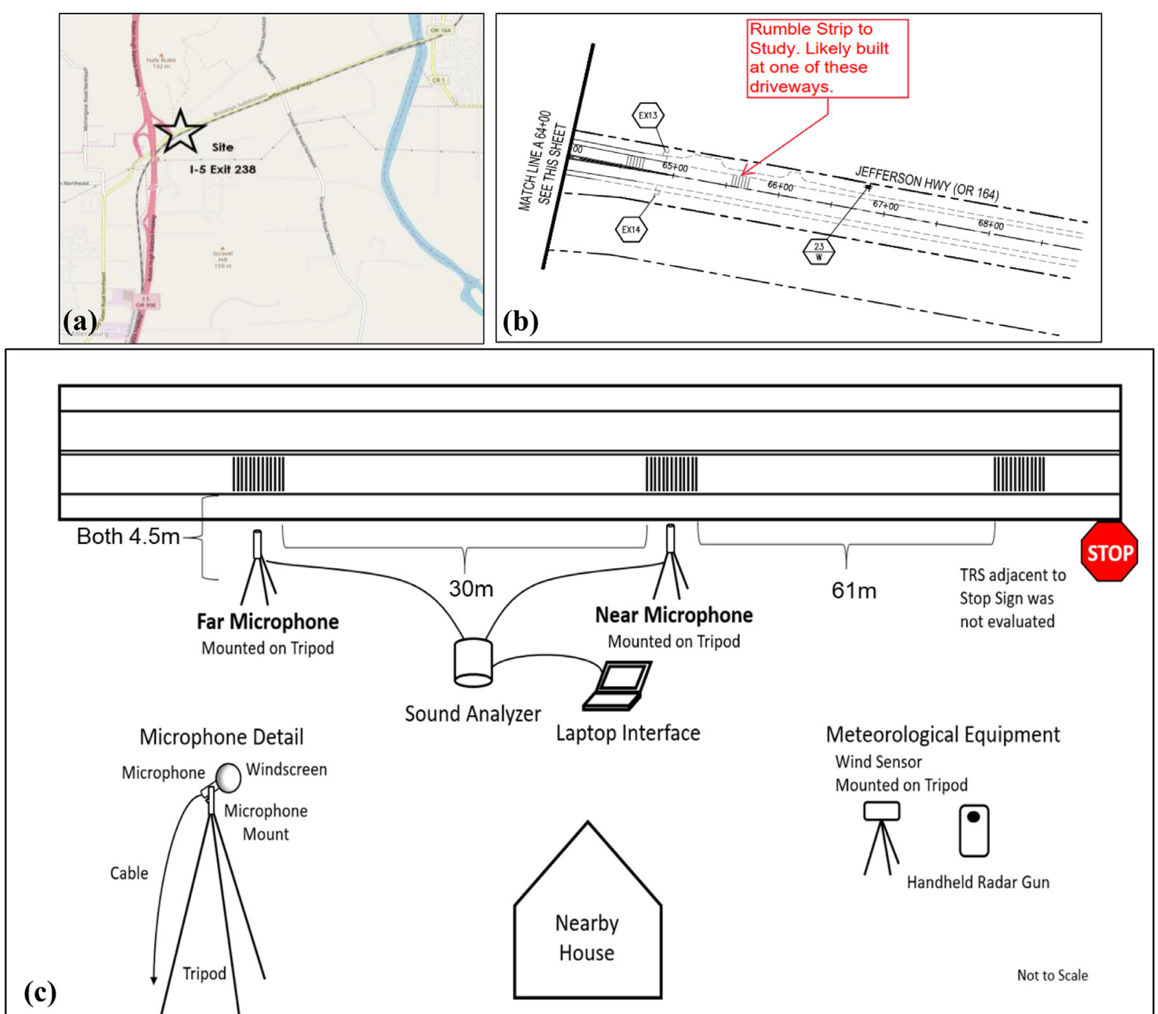

Fig. 2. (a): Site location for testing (© OpenStreetMap contributors); (b): TRS location based on ODOT signage plan SN-01 and (c): TRS sound measurement diagram.

Table 1
Equipment standards (SIP method).

Equipment	SIP standard	Project equipment	Meets standard?
Sound Level Meter	IEC 61672-1	Spider-20E	Meets
Windscreen	Should be used	GRAS Windscreen	Meets
Frequency Analysis Range	50 to 10,000 Hz	Spider-20E	Exceeds
Frequency Analysis Standard	IEC 61260	Spider-20E	Meets
Calibration Instrument	IEC 60942	GRAS 42AG	Meets
Speed Measurement	±2 km/h	Pocket Radar Traffic Advisor	Meets
Temperature Measurement	±2 °C	Windmate 200	Meets
Wind Measurement: Speed	±3 km/h	Windmate 200	Exceeds
Wind Measurement: Direction	±10°	Windmate 200	Meets

weather was clear, sunny, and warm on both days. Wind was calm, and the road surface was dry. All way stop signs were added to the intersection of OR 164 and the I-5 ramp, which was previously stopped controlled on the ramp only. TRS were installed on the approaches to warn drivers of the new stop condition in addition to stop ahead signs (W3–1) equipped with flashing yellow warning lights as shown in Fig. 2c. The specific TRS evaluated in this study are based on the location identified in Fig. 2b. from ODOT.

The SIP Method is a standard method for measuring the sound pressure levels of road surfaces [14]. The maximum A-weighted sound level dB(A) for a given vehicle type is calculated and compared to a baseline ambient sound level to determine the effect of road surface variations. This method establishes standards for equipment, test sites, traffic conditions, microphone positions, calibration, experimental procedures, and data calculations. If excessive background noise, high wind speeds, or partial RS strikes occurred, additional runs were collected. Hurwitz et al. applied this method to evaluating sinusoidal RS, and [12, 39] contains the guidelines of the procedure.

Before equipment purchase or selection, sound recording and analysis equipment were checked against SIP Method Standards to ensure that standards were met or exceeded (Table 1). The sound analyzer exceeded minimum requirements and was higher fidelity than equipment used in previous studies. To measure vehicle speed during testing, the Pocket Radar Traffic Advisor radar unit was used, which met the required tolerance level. Meteorological conditions (wind, temperature, and sky conditions) were measured during sound measurements using the Windmate 200 handheld weather station, which met or exceeded SIP Standards.

Sound measurement was verified by independent calibration device. The GRAS 42AG sound calibrator emits 2 tones (250 and 1000 Hz) at 2 intensities (94 and 114 dB) with 0.02% variability. Tones were measured by the sound equipment to ensure that the sound analyzer correctly identified pitch and intensity. Before field data were collected, the research team verified that the sound analyzer operated to within 0.5 dB of the sound calibrator based on the requirements of the SIP Method. Sound calibration was successfully performed with the project equipment in the lab setting.

3.2. Exterior noise measurement

The setup for exterior measurements is shown in Fig. 2c. Due to site constraints, microphones were located closer than prescribed in AASHTO's SIP Method [14]. The microphones were centered on each TRS group, and the microphone was located above the road surface as shown in Fig. 2c. The microphone closer to the stop sign is referred to as the near microphone throughout this paper, and the other is termed the far microphone. During each TRS strike, the sound level was monitored on the laptop to ensure that the event was 6 dB(A) 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, usually due to traffic in the opposing direction.

Table 2
Tire pressure for probe vehicle.

kPa	Front	Rear
Driver Side	196.5	234
Passenger Side	238	221

3.3. Probe vehicle

A passenger car was rented from Oregon State's motor pool and driven by licensed graduate research assistants. Drivers were instructed to drive at the posted speed at a safe operating distance from other vehicles on the roadway. Two-way radios were used to communicate between the vehicle assistant and the roadside team at the measurement location. The passenger car was a 2017 Hatchback. The tires were Continental ContiProContact 215/55 R 16 93 H. Tire pressures are shown in Table 2.

3.4. Rumble strip characteristics

Geometric characteristics of each TRS type were measured and recorded to document the general properties of the tested TRS in the before and after data collection. Average field geometric characteristics of the before TRS are shown in Fig. 3a. The epoxy filled shallow TRS at the near location is dimensioned in Fig. 3b., and the paved TRS at the far location is shown in Fig. 3c. Large characteristics, such as the total length of the TRS group, were measured to the nearest half centimeter. Smaller characteristics, such as the mill depth, were measured to the nearest 1.60 mm. Mill depth was measured several times at different mills due to slight variances in milling, and the average of these measurements is presented.

The TRS appeared to be installed as specified. Irregularities in pavement aggregates caused some variation in mill depth, as larger aggregate chunks chipped away. Similar variation exists across the epoxy TRS, but the fill appeared consistent. The new pavement at the paved TRS is likely to influence the sound slightly, as the pavement has a generally rougher surface when new.

4. Results and discussion

Exterior sound noise was recorded and evaluated. Data were analyzed and visualized using Minitab software for Windows (version 18.1) and Excel software (version 14.0.1) respectively.

4.1. Exterior sound measurement

A total of 24 sound measurements were collected (10 before, 14 after). Several of the measurements were not used as they had additional ambient traffic noise from other vehicles passing at the time of the strike. Ultimately, 5 measurements were used at the near location for the before and after conditions. Similarly, 3 measurements were used at the far location for the before and after conditions. The measurements were

Fig. 3. (a) Before condition: TRS geometric characteristics. (b) After condition: epoxy filled TRS at near location. (c) After condition: paved TRS at far location.

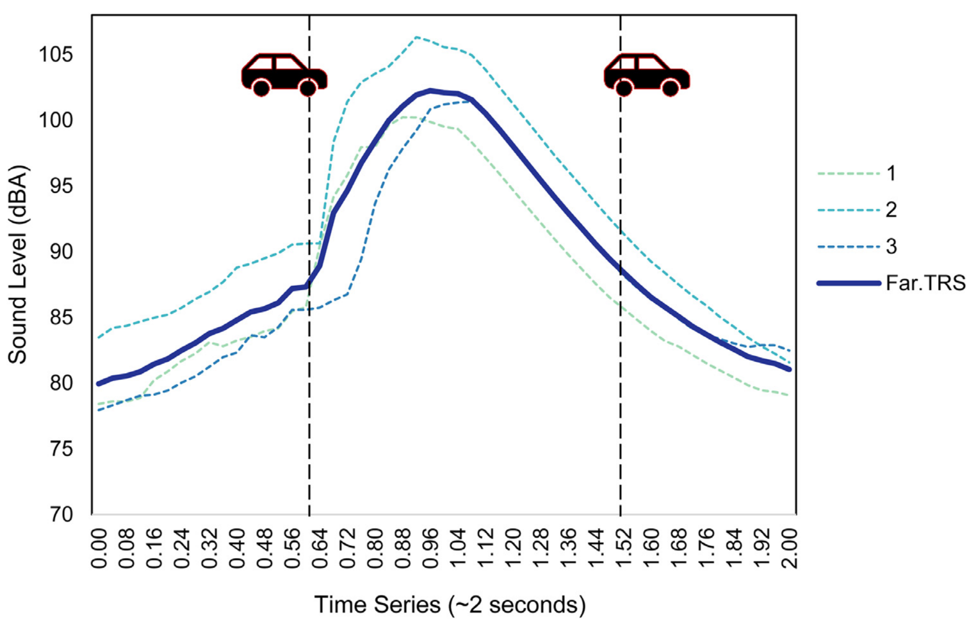

Fig. 4. Exterior sound measurement from passenger car striking the far TRS.

combined using an arithmetic mean. In Fig. 4, the before far TRS individual measurements are shown as dashed lines, and the overall average is shown with the solid line. The first vertical dashed line at ∼ 0.60 s represents the onset when the front axle of the vehicle hits the TRS, while the second one when the rear axle leaves at ∼1.52 s.

Fig. 5 shows the overall time series arithmetic mean. For example, the far TRS value in solid line is the arithmetic mean value of the three measurements that shown in Fig. 4., where the highest intensity sound were observed at ∼1.02 s, which corresponds to the deep TRS, as well as the closest point to the microphone (i.e. when the vehicle is in the middle of the TRS). The near TRS value has similar depth as the far, but with slightly lower sound intensity as its microphone has different surroundings. The next highest signal come from the near epoxy filled TRS. The depth of the TRS has a large influence on the amount of additional noise generated by rumble strip strikes [11,12,15]. The lowest intensity sounds were recorded at the far paved location, where the TRS

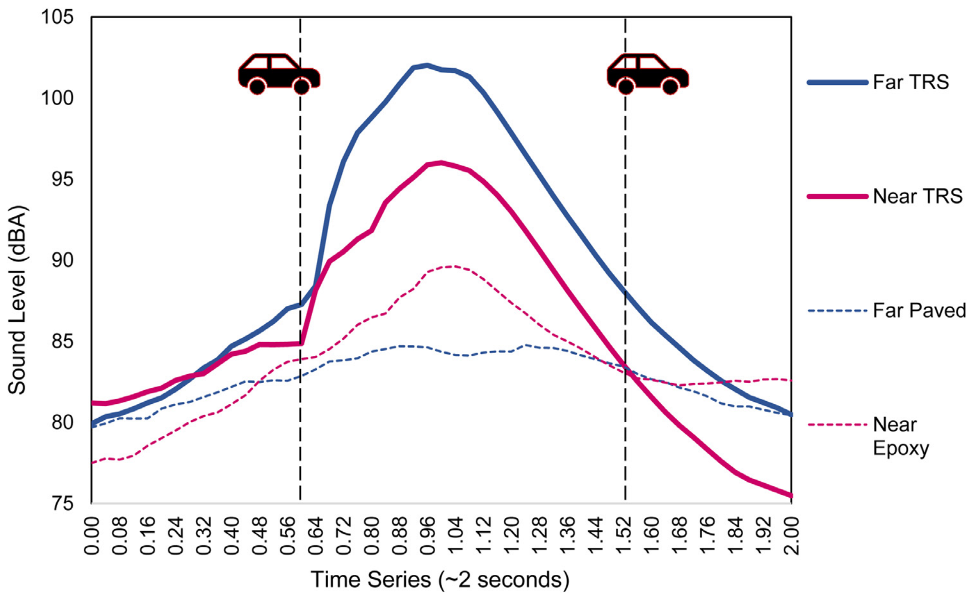

Fig. 5. Exterior sound measurement from passenger car striking the TRS.

Table 3
Descriptive statistics dB(A) magnitudes for the factor groups.

RS type	Scenario	Location/treatment	Mean	SD	Min	Max
Transverse	Before	Far/TRS	96	5	87	102
		Near/TRS	93	4	85	98
	After	Far/Paved	83	1	82	84
		Near/Epoxy	88	3	82	92

was removed with new pavement. This value was used as a baseline for comparison of the other TRS measurements that describes the sound of a vehicle passing the location.

4.2. Descriptive analysis

Table 3 shows the mean (μ), standard deviation (SD), minimum, and maximum sound level in dB(A) for a milled TRS in each factor group. As shown in Table 3, TRS in the before scenario generated the highest average sound level based on the observed field measurements. The sound levels are higher in the presence of milled TRS for both locations. The far location in the before scenario reported the highest mean sound level (μ = 96, SD = 5) with a maximum value of 102 dB(A). This higher sound measurement is likely related to the fact that far microphone was located in more open space when compared to the microphone at near location, which was surrounded by a large tree. Sound-absorbing materials at the site (e.g. trees) plays a role in decreasing the sound levels generated by the by-passing vehicle.

In the after scenario, when the far location was paved, the average sound level measurement dropped from 96 dB(A) to 83 dB(A), a 13 dB(A) difference. For human hearing, this is a clearly noticeable change in the sound level, as discussed in the introduction. When both measurements are compared based on their peak (max value), the difference in sound measurement is approximately 18 dB(A). When the near TRS in the after scenario was treated with epoxy, the average sound level measurements dropped from 93 dB(A) to 88 dB(A), a 5 dB(A) difference. This is a noticeable change in intensity. However, the peak difference in sound measurement was 6 dB(A), or a clearly noticeable change.

Fig. 6 shows a boxplot of sound levels for the two scenarios (before-after) by location (far-near) and treatment type. Roadside noise generated by the TRS strike was higher in the before condition. Alternatively, the alert generated by the TRS strike was reduced when the treatments were applied.

4.3. Statistical analysis

A one-way ANOVA test was utilized on the sound measurements to determine whether the average sound levels differed between the 4-transverse rumble strips (far TRS, near TRS, epoxy filled TRS, and completely paved TRS). These were classified based on the location of the TRS, which represent the before condition, and the type of treatment that was applied, which represent the after condition. Data were analyzed in the Minitab statistical software package (version 19.2020.1). All tests were performed at a 95% confidence level. A statistically significant difference between means was found for at least 1 TRS type, $p < 0.001$ as is shown in Table 4.

To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison was used as is shown in Fig. 7 [28–30]. The main effect results were obtained, where differences can be observed between specific factors while all other factors are held constant. The sound level generated from a far TRS strike (Mean = 96 dB(A)) and near TRS strike (Mean = 93 dB(A)) are higher than the paved condition (Mean = 83 dB(A)), p-value < 0.001, 95% CI [7 dB(A), 18 dB(A)] and p-value = 0.001, 95% CI [4 dB(A), 14 dB(A)] respectively. This CI ranges indicate that the TRS is readily noticeable at least, and nearly doubling the roadside noise at most.

Additionally, the sound level generated from the TRS treated with epoxy (Mean = 88 dB(A)) is higher than the paved condition by about 4 dB(A), p-value = 0.09, 95% CI [1 dB(A), -9 dB(A)], but is statistically significant and lower when compared to both TRS strike (far and near), p-value = 0.001, 95% CI [3 dB(A), 13 dB(A)], and p-value = 0.02, 95% CI [1 dB(A), 9 dB(A)] respectively. This CI range indicates that the epoxy filled TRS was indiscernible at least, and clearly noticeable at most compared to a baseline vehicle pass.

On average, the paved TRS is lower than the far and near TRS strike by 13 dB(A) and 9 dB(A) respectively. These differences between means were also statistically significant, $p < 0.001$, 95% CI [7 dB(A), 18 dB(A)] for the far TRS, and $p = 0.001$, 95% CI [4 dB(A), 14 dB(A)] for the near TRS. This makes sense as the far TRS were modified and paved. This is consistent with previous research that shows TRS add 7–11 dB(A) to roadside noise compared to flat road pavement [4].

The difference of the noise generated from the far TRS and near TRS were not statistically significant, $p = 0.21$, [−8 dB(A), 1 dB(A)]. This finding was expected, during the before scenario both TRS locations had the same depth treatment. The far is slightly higher, as its microphone has different surroundings.

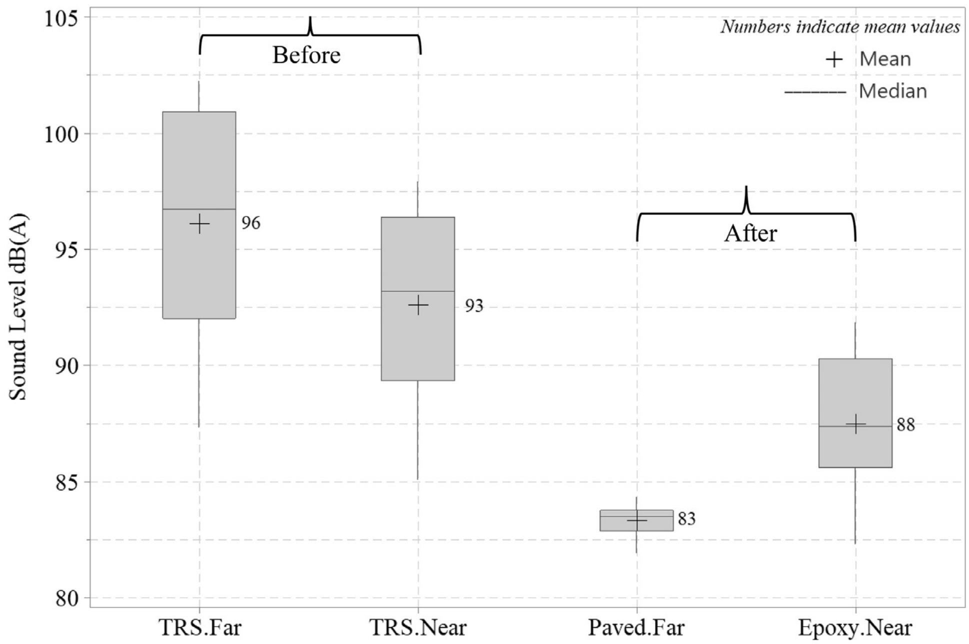

Fig. 6. Boxplots by treatment and location for sound measurements.

Table 4
The ANOVA summary table for exterior sound measurement.

Source of variance	Contribution	DF	SS	MS	*F*	*P*
TRS type	83%	3	306.70	102.23	19.48	<0.001*
Error	17%	12	62.98	5.25		
Total	100%	15	369.68			

* *Significance level of 0.01.*

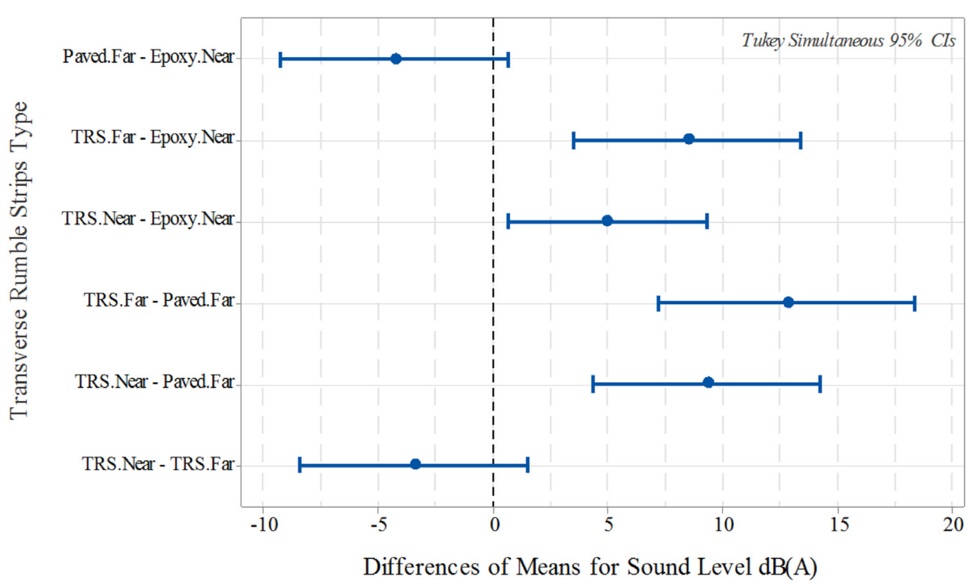

Fig. 7. Post-hoc analysis results between the four TRS.

5. Conclusion

This research study compared exterior sound levels for a probe vehicle striking traditional deep and shallow epoxy filled TRS in a before and after study. The framework for the experiment was based on previous studies of TRS noise and effectiveness, and the AASHTO SIP Method [14].

At least 3 passes were recorded for each factor group, and A-weighted levels were used to calculate differences between TRS conditions. These delta measurements provided an estimate of the increased noise generated by the strike while holding other factors as constant as possible. According to the literature, humans can detect differences in noise levels at 3 dB(A), with 5 dB(A) being easily noticed. A difference of 3 dB(A) between noise sources is the minimum amount needed for a typical human to perceive a difference in sound intensity.

From the results, the research team developed 3 conclusions concerning the use of epoxy to modification of TRS (i.e. decreasing the depth of the TRS from 1.30 cm to ~0.60 cm by filling it with epoxy while keeping the width constant) as an alternative to traditional TRS.

- Compared to the before condition of the deep TRS, the epoxy filled TRS average sound level measurements dropped from 94 dB(A) to 87 dB(A), a 7 dB(A) difference. This is a noticeable change in intensity. However, the peak difference in sound measurement was 11 dB(A), or a clearly noticeable change. Additionally, the sound level generated from the epoxy TRS is higher than the paved condition, a 4 dB(A), but is significantly lower when compared to the TRS strike. This indicates that the epoxy filled TRS was indiscernible at least, and clearly noticeable at most compared to a baseline vehicle pass, meaning that the epoxy TRS is still noticeable compared to background traffic.
- Comparing the original TRS to the after paved TRS, the average sound level measurement dropped from 94 dB(A) to 83 dB(A), a 11 dB(A) difference. This is a clearly noticeable change in sound level. When both measurements are compared based on their peak (max value), the difference in sound measurement is approximately 18 dB(A). This indicates that the original TRS is nearly four times louder than the same passing vehicle on flat pavement.
- In terms of practice, the research results confirmed that an epoxy retrofit applied to transverse rumble strips can effectively reduce roadside noise. Filling TRS with Epoxy provides an intermediary treatment between full depth TRS and repaving the road. The TRS can still be used to improve highway safety (alerting drivers of traffic control device changes), while reducing roadside noise for nearby residences.

In terms of the paper limitations, only one speed was tested for all factor groups, the free flow speed limit of 72 km/h. Increasing the speed has been shown to increase the noise generated in a RS strike, but the consistency of that relationship is unclear [4].

Additionally, only one vehicle was used as the probe vehicle, differences between vehicle types, especially heavy vehicles, were expected, as the suspension, tire characteristics, and vehicle weight influence noise generation.

Only 2 TRS designs were tested (traditional deep, and shallow epoxy). Small changes in RS dimensions, especially mill depth, have a large influence on noise generation. Other mill depths could be used to further reduce noise (shallower) or increase driver alert (deeper).

Many roadway conditions were controlled for between test locations, to minimize differences between measurements during the experiment. The results reflect the pavement type and condition, mill quality, type of sound-absorbing materials at the site (foliage, trees, etc.), and atmospheric conditions at the time of observation. Other locations may generate more or less noise, as these factors will vary across the built environment. However, it is expected that the differences observed between the baseline and strike conditions would be similar, as these variables would have a similar effect on both conditions in other locations.

Further interior alert research is needed to verify the effectiveness of the TRS as a safety countermeasure. Both interior sound levels and haptic feedback should be measured to confirm the interior alert levels. However, the epoxy filled TRS did generate a detectable difference in exterior noise, indicating the potential for a successful alert.

Author contribution statement

The authors Horne (DH) Jashami (HJ), Hurwitz (DSH) confirm contribution to the paper as follows: study conception and design: DH and DSH; data collection: DH and HJ; analysis and interpretation of results: DH, HJ, and DSH; draft manuscript preparation: DH, HJ and DSH. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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