A survey on road noise prediction for milled shoulder rumble strip designs

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Abstract: Cell phones, navigation systems and extended work hours are only some of the causes of distracted or fatigued driving, which increases the likelihood of crashes in road networks. To address this problem, Departments of Transportation (DOTs) nationwide have implemented warning devices called rumble strips, which can be installed on road pavements to alert the drivers of lane departures. While rumble strips are successful in preventing drivers from running off road, they create additional roadside noise, which sometimes becomes annoying for the residents in the vicinity. Ongoing research aims to mitigate rumble strip noise. This survey synthesises the current state of knowledge for noise assessment of rumble strips and identifies current gaps in existing techniques and associated models to guide future research efforts to best address rumble strip effectiveness.

Keywords: shoulder rumble strip; rumble strip design; milled rumble strip; road noise; alerting device; alarming device.

Reference to this paper should be made as follows: Kalathas, P., Hurwitz, D., Parrish, C., Glover-Cutter, K.M. and Zhang, Y. (2018) 'A survey on road noise prediction for milled shoulder rumble strip designs', *Int. J. Vehicle Noise and Vibration*, Vol. 14, No. 3, pp.251–269.

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1 Introduction

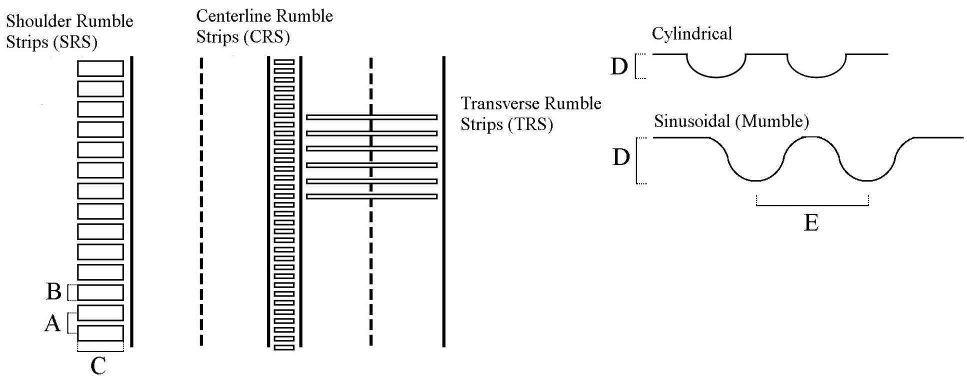
Rumble strip devices have been shown to be a highly effective measure for preventing distracted and/or drowsy drivers and may assist in preventing autonomous cars from lane departures in the future. In contrast with visual information or flashing lights, rumble strips alert the drivers by providing tactile and audible signals (Liu, 2015). They have also been used with great success as a speed mitigation measure when approaching areas where speed reduction or the driver's attention is required, such as near schools or work-zones. Figure 1 demonstrates the main rumble strip applications along with the two main designs and their design parameters. Since being introduced in 1955, rumble strips have been adopted globally with well-documented effectiveness worldwide (Hardwood, 1993). Spring (2003) presented results from several states in the US demonstrating that after the installation of shoulder rumble strips (SRS), a 72% crash reduction was achieved. Torbic et al. (2009) stated that a 40% reduction in total target crashes (TOT) and 64% in fatal injury crashes (FI) were reported. Hegewald (2009) presents the statistics from Germany, where 43% of run-off-road (ROR) and 34% of crashes due to 'other mistakes' (usually attributed to inattentive or fatigued drivers), were eliminated after the installation of SRS. The latest rumble strip NCHRP synthesis reports that some agencies have experienced crash reductions up to 76.9% (Smadi and Hawkins, 2016).

Despite the positive results of milled SRS on road safety, DOTs frequently receive negative feedback from residents who complain about the noise from rumble strips. These complaints are focused on the noise interfering with their daily routine and the environment. Specific complaints include claims that noise disturbs residents' work and sleep, as well as that it increases the average noise level of the area affecting the wildlife in the vicinity, including how these animals communicate (CTC and Associates LLC, 2012; Babisch et al., 2001; Stansfeld et al., 2005; Warren et al., 2006; Swaddle and Page, 2007; Hammer et al., 2014). Additionally, studies on transverse rumble strips show increase in hourly noise level up to 6 dBA and an overall mean increase of 9-10 dBA after the installation of centreline rumble strips, an increment that humans perceive as sound level doubling (Sabato et al., 2013; Sabato and Niezrecki, 2016; Gates et al., 2013; HDR, 2014).

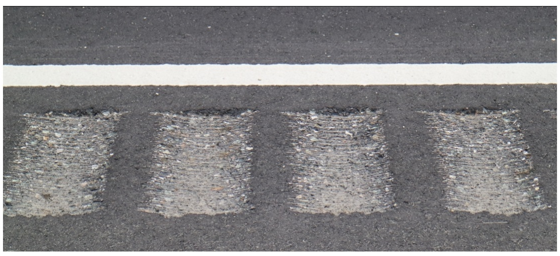
Given the effectiveness of rumble strips for increased driver safety, DOTs may have an interest in installing these devices where needed. However, perceived impact on the acoustic environment reduces installation near residential areas (CTC and Associates LLC, 2012). Alternative rumble strip designs exist, but to objectively and systematically evaluate available designs a comprehensive review that analyses quantitative methods of evaluating different rumble strip designs is needed. To this end, the objective of this review is to synthesise key findings and techniques from peer reviewed journal and conference papers, masters/PhD theses, technical papers, and technical reports from state DOTs/USDOT related to milled SRS, and to present the techniques and related noise prediction models in a consistent, organised framework to assist state DOTs and researchers in making use of the current body of knowledge to address the pressing issues outlined above.

In the following section, we present the conventional rumble strip design and the emerging sinusoidal 'mumble' strip design, as well as related experiments, measurements and results that point out the differences between the two designs. In Section 3, we discuss the impact of rumble strips on average noise level and the limitations that current noise mitigation measures have. Furthermore, we analyse the latest road noise prediction models, standardisation methods, and noise prediction formulas. Section 4 presents new trends in designing and analysing noise and other properties of vehicles and rumble strips. These trends involve acoustic modelling of physical components supplementing field measurements, rather than empirical and statistical studies. A discussion follows in Section 5 on rumble strip designs from the literature and their efficiency, with sound level difference (SLD) from the ambient noise summarised graphically. Lastly, this survey presents the limitations of current milled SRS that can be addressed in future optimisation research, balancing the safety of the road users with nearby residents' quality of life.

Figure 1 (a) Left, top view of the rumble strips by application: shoulder, centreline and transverse, right, side view of cylindrical and sinusoidal (mumble) rumble strip designs (b) Photo of a cylindrical shoulder rumble strip



(a)



(b)

Note: Rumble strip desing parameters are spacing = A, length = B, width = C, depth = D, wavelength = E.

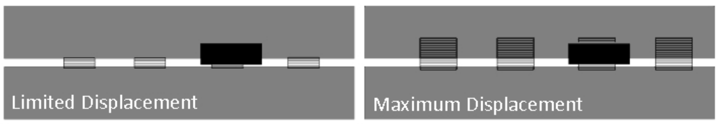
2 Milled shoulder rumble strip designs

2.1 Conventional milled shoulder rumble strip designs

There are four classes of milled SRS corresponding to different construction methods: milled, rolled, formed and raised. Milled SRS have generally become the favoured design among DOTs, due to the flexibility of installation at any time on asphalt or concrete shoulders (Bahar et al., 2001; Russell and Rys, 2005; Torbic et al., 2009). Shoulder rumble strip dimensions and shapes vary across DOTs with respect to specific applications. Usually, narrower and shorter rumble strips that are closer to the shape of the rolled rumble strips produce more audible than tactile feedback, and use shoulder space thriftily (Torbic et al., 2009; Daniel, 2007). Studies show that football shaped designs and increasing-intensity rumble strips produce no change to the feedback signal to the drivers (Gardner et al., 2007; Sandberg, 2015).

Figure 2 Geometric characteristics of rumble strip design: (a) side view, (b) top view and (c) interior SLD for different rumble strip geometries for car, truck and CV (see online version for colours)

(a)



(b)

			Sound Level Difference (dBA)		
			Car	Truck	CV
Rumble strip geometry	Width (m)	0.107	1	2	0
		0.152	3	6	1
		0.203	11	13	0
		0.267	13	13	NP
		0.305	20	17	7
	Spacing (m)	0.305	19	16	8
		0.61	14	15	5
		0.914	12	11	0
	Length (m)	0.051	15	6	2
		0.178	24	18	8

	Torbic et al. (2009) standards for sound level difference
Not enough feedback	< 6 dBA
Acceptable feedback	[6 dBA - 12 dBA] [10 dBA - 15 dBA]
Potentially dangerous feedback	> 15 dBA

(c)

Note: Blue: dBA $<$ 6, green: 6 $\leq$ dBA $\leq$ 15, red: dBA $>$ 15.

Source: Original data is from the work of Miles and Finley (2007) and Torbic et al. (2009)

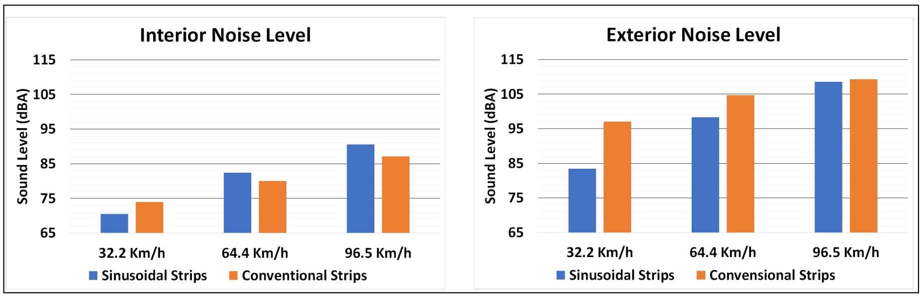
Torbic et al. (2009) performed an extensive research analysing rumble strips and how construction parameters along with pavement specifications and conditions affect rumble strip efficiency. This effort resulted in the development of a detailed guide for rumble strip construction, known as *'NCHRP Report 641'*. This report sets standards regarding recommended audible feedback signal ranges for drivers. Creating two groups of road networks, urban roads and freeways, the authors suggest that for urban roads the feedback signal should have SLD in the range of 6–12 dBA. Alternatively, for freeways the SLD should be in the range of 10–15 dBA. Below these limits drivers will not be able to identify feedback signals, while SLD above 15 dBA might be shocking for drivers, or the signal might reach the threshold of pain.

Miles and Finley (2007) performed a detailed study to identify how rumble strip design parameters affect efficiency. More precisely, the study examined the influence of vehicle speed, vehicle type, pavement type, rumble strip type, spacing, length and width on the sound that is produced. Figures 2(a) and 2(b) show graphically the effect of SRS length and width on tyre displacement whereby the tyre reaches maximum displacement when the length and width increase. Figure 2(c) presents the SLD value for each design parameter in the context of the recommended ranges. The results reveal that width values between 0.203 m and 0.267 m provide feedback above 11 dBA for the car and the truck, which falls in the recommended range. For spacing between 0.61 m and 0.914 m and length up to 0.051 m, the rumble strips provided sufficient feedback for car and truck vehicles. However, Figure 2(c) reveals that caution must be exercised, considering that some of the values for width, spacing, and length may produce feedback that exceeds the recommended range. In contrast, none of the designs gave enough feedback for commercial vehicles (CVs) on freeways. Furthermore, those designs that gave feedback above 6 dBA for CVs on rural roads are the same designs that produce excess feedback for the car and truck.

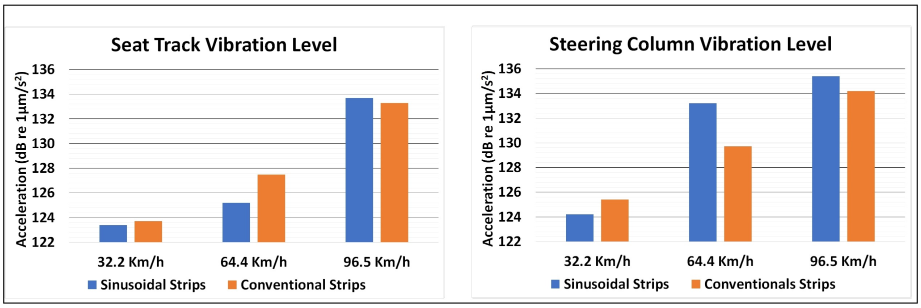
2.2 Emerging designs for milled SRS

Sinusoidal milled SRS, colloquially referred to as mumble strips have been noted to reduce noise in residential neighborhoods and efficiently alert drivers (Kragh et al., 2007). The difference between conventional and sinusoidal designs hinges on the reduction of tyre deformation while falling into the cavity of the strips, potentiating a reduction in noise without compromising efficiency for the sinusoidal design (Transportation Research Board, 2017). Donavan and Rymer (2015) measured the noise and vibration levels from two different shoulder rumble strip designs inside, outside next to the wheel, and at a distance of 7.62 m for four different vehicles. Figure 3(a) shows the results for the noise and vibration signals measurements on three different speeds using a Chevrolet Malibu. It can be seen that exterior noise levels at 7.62 m are reduced by 13 dBA for the speed of 32.2 km/h and 6 dBA for 64.4 km/h, which are typical speeds near residential zones. For the speed of 96.5 km/h, the exterior noise was 1 dBA lower than the conventional rumble strip noise. This study showed that for 64.4 km/h and 96.5 km/h, sinusoidal rumble strips exhibit 2.5–3.5 dBA greater interior noise than conventional rumble strips. Figure 3(b) shows that the tactile feedback from both designs was found to be similar for speeds of 32.2 km/h and 96.5 km/h. However, for the speed of 64.4 km/h, the seat track vibration level from the sinusoidal design was 2.3 dB lower, and the steering column signal was 3.5 dB higher than the signals from the conventional design. The authors conclude that sinusoidal rumble strips have improved interior to exterior noise ratio, keeping both the interior noise level and the tactile signals in the recommended range.

Figure 3 Noise and vibration signal measurements on sinusoidal and conventional rumble strips (see online version for colours)



(a)



(b)

Source: Original data is from the work of Donavan and Rymer (2015).

Terhaar and Braslau (2015) took measurements for three different shoulder rumble strip designs including two sinusoidal and one conventional. The results were collected from a distance of 15.24 m, with the specific sinusoidal designs having an at least 6.5 dBA lower exterior sound level than the conventional design. The authors introduce the terms ‘sound detectability’ and ‘detectability factor’, arguing that a sound can be detectable from the ambient noise if, at any frequency, there is a SLD above the detectability factor. The detectability factor was reported to be 7 dBA, and measurement results revealed that noise from sinusoidal designs can be detectable up to 609.6 m, while for conventional designs, the distance is up to 762 m for the speed of 48.3 km/h and extends to more than 914.4 m for both designs at the higher speed of 96.5 km/h.

Table 1 Sinusoidal rumble strip dimensions from the work of Terhaar and Braslau (2015) and Donavan and Rymer (2015)

Dimensions (m)	*Terhaar and Braslau (2015)*		*Donavan and Rymer (2015)*
	Strip 1	*Strip 2*	*Strip 1*
Wavelength	0.356	0.61	0.356
Width	0.203	0.203	NP
Depth	0.016	0.013	0.008

Note: NP: Not presented.

Table 2 Interior SLD (see online version for colours)

Interior sound level difference (dBA)				
Terhaar and Braslau (2015)			*Donavan and Rymer (2015)*	
Vehicle	*Strip 1*	*Strip 2*	*Vehicle*	*Strip 1*
Chevrolet Malibu	17	5	Ford Expedition	13.7
Chevrolet Silverado	8	5.5	Honda Civic	12.8
Volvo Semi-Trailer	1.5	1	Chevrolet Malibu	19.1
			International Four-Yard	2.6

Note: Blue: dBA < 6, green: $6 \leq$ dBA ≤ 15, red: dBA > 15.

Source: Original data is from the work of Terhaar and Braslau (2015) and Donavan and Rymer (2015)

Donavan and Rymer (2015) and Terhaar and Braslau (2015) concluded that sinusoidal SRS exhibit lower noise levels. Table 1 shows the dimensions of the sinusoidal rumble strips used in these studies, while Table 2 and Table 3 present the results for the interior and exterior SLD. Table 2 shows that the interior SLD between on and off rumble strip levels increases above 6 dBA and 10 dBA only for some of the designs and only for specific vehicles. In one case for the pickup (Chevrolet Silverado) and for all the cases for the CVs (Volvo Semi-Trailer and International Four-Yard), the SLD is below 6 dBA, and therefore below the recommended feedback range. Additionally, attention is required since some designs resulted to SLDs that exceed the recommended feedback range. Table 3 reveals that even though the sinusoidal designs reduce the exterior noise level, they still produce SLD above the detectability factor for some designs and vehicles.

State DOTs are experimenting with road noise mitigation techniques and formulating the parameters that affect noise emissions. The next section presents methods and modelling tools used for road noise prediction and examines how rumble strip noise has been calculated where installed on road sections.

Table 3 Exterior SLD (see online version for colours)

Exterior sound level difference (dBA)				
Terhaar and Braslau (2015)			*Donavan and Rymer (2015)*	
Vehicle	*Strip 1*	*Strip 2*	*Vehicle*	*Strip 1*
Chevrolet Malibu	12	4.5	Ford Expedition	8.2
Chevrolet Silverado	7.5	3.5	Honda Civic	5.8
Volvo Semi-Trailer	1.5	0	Chevrolet Malibu	7
			International Four-Yard	3.7

Note: Green: dBA < 7, red: dBA ≥ 7.

Source: Original data is from the work of Terhaar and Braslau (2015) and Donavan and Rymer (2015)

3 Road noise and noise prediction

Road noise can present a problem near residential developments owing to disturbance and potential health hazards. In addition, studies that link road traffic noise with high blood pressure and cardiovascular diseases are briefly reviewed by Qatu et al. (2009). The United States Environmental Protection Agency (US EPA) and Environmental Health Perspective (EPH) recommend daily average noise level exposure of 70 dBA and 55 dBA respectively (Hammer et al., 2014). To address road noise in their vehicles, companies investigate ways to reduce road noise and vibrations, such as passive, active and hydro-pneumatic suspension systems (Qatu, 2012). On the other hand, to ensure road noise levels below the recommended threshold, DOTs are equipped with prediction frameworks such as the 'traffic noise model (TNM)' software (Hankard et al., 2006; FDOT, 2015). Noise prediction is important due to the fact that noise mitigation measures are costly and may have limited effectiveness. In fact, Rochat and Reiter (2016) stated that to reduce a noise by 10 dBA requires high and expensive barriers, while it is very difficult or close to impossible to reduce a noise that is more than 15 dBA louder than the acceptable limit. The findings from their study are summarised in Table 4.

Table 4 Difficulty of noise reduction using noise barriers

Insertion loss, dB	*Degree difficulty*	*Reduction in sound energy, %*	*Relative reduction in loudness*
5	Simple	68	Readily perceptible
10	Attainable	90	Half as loud
15	Very difficult	97	One-third as loud
20	Nerly impossible	99	One-fourth as loud

Note: In general, increasing insertion loss requires increasing barrier height.
From Highway Traffic Noise, NHI course 142051.

Source: Original data is from the work of Rochat and Reiter (2016)

3.1 Existing road noise prediction models

Tansatcha et al. (2005) suggested a noise prediction model that differentiates vehicle types. The dBA level for each vehicle type is measured at 15 m perpendicular to the passing road starting 5 s before the vehicle passes the measurement point and extending up to 5 s after. These measurements are denoted as $Leq(10s)$. Eventually, the hourly noise levels $Leq(1h)$ are predicted using equation (1).

$$L_{eq}(1h), i = L_{eq}(10s), i + 10log\left[\frac{D_0}{D}\right]^{1+\beta} + 10logN_i - 25.563 \tag{1}$$

where

i Vehicle types (1–8) (automobile, light truck, medium truck, heavy truck, full trailer, semi-trailer, bus and motorcycle).

D_0 Reference distance of the measurement (15 m).

D Perpendicular distance from the observer to the centre line of the traffic lane.

β Ground effect adjustment.

N_i Number of vehicle per hour in class i.

In Europe, the road noise level is predicted by the CNOSSOS-EU framework, which is common throughout transportation agencies. This framework has the ability to predict the sound power level L_W for each different vehicle type as well as for desirable individual frequency bands (Kephalopoulos et al., 2012). CNOSSOS-EU's main equation for vehicles' rolling sound power level $L_{WR,i,m}$ for a specific frequency band and vehicle type prediction is described in equation (2).

$$L_{WR,i,m} = A_{R,i,m} + B_{R,i,m} \text{ x } log\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i,m}(v_m) \quad (2)$$

where

R	Rolling noise
i	Frequency band
m	Vehicle category
$A_{R,i,m}, B_{R,i,m}$	Coefficients for each vehicle category at v_{ref} = 70 km/h
v_{ref}	Reference speed, 70 km/h
v_m	Speed of the vehicle
$\Delta L_{WR,i,m}(v_m)$	Rolling correction coefficients for vehicle category (v_m).

Lastly, in the USA, the Federal Highway Administration (FHWA) provides 'TNM' software for designing road networks and predicting noise emissions. The TNM software uses various parameters to estimate the road noise level such as humidity, temperature, pavement type, and vehicle percentages, and incorporates noise reduction from sound barriers (Hankard et al., 2006; FDOT, 2015). These parameters are updated frequently after evaluation of on-site measurements from the FHWA.

Using the noise prediction models described above, agencies aim to manage noise emissions from road networks; however, rumble strips are an additional noise source not currently included in these noise prediction models. The following section presents studies focusing on estimating rumble strip noise in road networks and interior cabin vehicle noise.

3.2 Noise prediction involving rumble strips

Since the tyre/road interaction is one of the main road noise sources having acceptable levels controlled by the law, the agencies are working intensively to find ways to predict the noise amplitude based on the tyre and pavement characteristics (Mohamed et al., 2013). Although numerous studies and noise prediction models have been developed for traditional road networks, studies that address the contribution of rumble strip noise are limited. The investigation by Caltrans (CTC and Associates LLC, 2012) mentions that the primary solution to resident complaints about rumble strip noise is to remove rumble strip devices from urban areas and stop installation on highways before the approach of urban neighborhoods. Other states suggest that public education is another potential approach since residents become more receptive as their understanding of the safety benefits increases.

Torbic et al. (2009) used statistical modelling to derive equations for SLD prediction, which agree with the findings from previous studies including those of Miles and Finley

(2007) and Donnell et al. (2009). The equations incorporate additional parameters that affect the performance of rumble strips, such as the location of the rumble strips, the angle of departure, the type of the rumble strips, and the road pavement type and condition.

$$\begin{aligned} SLD = {} & 8.650 + 0.027S - 1.689L - 0.271A + 0.267Le + 0.771W \\ & + 4.494D - 0.394Sp + 2.652RST - 1.391PVS - 2.596PVC \end{aligned} \tag{3}$$

where

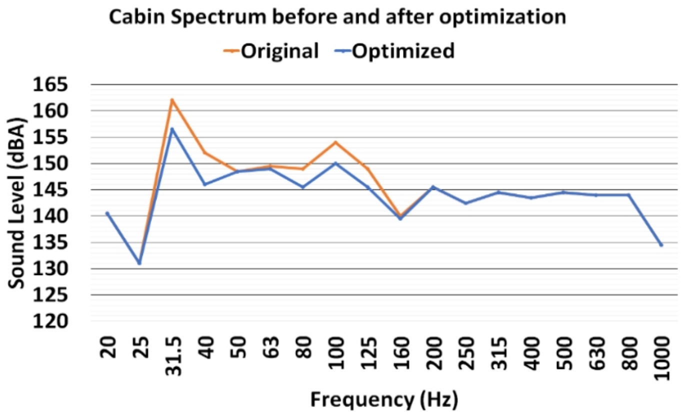
S	Vehicle speed (mph)
L	Location indicator (1: shoulder; 0: centreline)
A	Angle of departure (degrees)
Le	Length of rumble strip (inches)
W	Width of rumble strip (inches)
D	Depth of rumble strip (inches)
Sp	Spacing between rumble strips (inches)
RST	Rumble strip type indicator (1: milled; 0: rolled)
PVS	Pavement surface type indicator (1: concrete; 0: asphalt)
PVC	Pavement surface condition indicator (1: wet; 0: dry).

Even though the formula found by Torbic et al. (2009) may provide reasonable interior SLD estimates for conventional SRS, this equation does not take into account the vehicle type. Furthermore, it is not suitable for exterior SLD calculation or for SLD calculation from sinusoidal rumble strip designs. The terms 'spacing' and 'width' do not apply to sinusoidal designs, since these are by nature continuous designs, meaning that the tyre rolls on the rumble strip without breaking contact. In the section that follows, we present physics-based methods that could be applied to rumble strip design and estimation of respective noise emissions. These methods are adopted from other engineering fields, where they have been used for an extended time with reliable results.

4 Physics-based methods of rumble strip noise prediction and experimentation

In contrast to design selection based on statistical analysis from measurement data, an emerging approach in noise and pavement research is to leverage physical modelling methods from other mature research areas, including the aircraft, automotive, and construction industries. The finite element method/analysis (FEM/FEA) that involves coupled acoustic-mechanical computer simulation helps to estimate various components and effects from the vehicle-road and the tyre-rumble strip interaction. This method makes use of knowledge from continuum mechanics, and incorporates numerical solutions from mathematics and computer science to simulate each scenario, approximate the behaviour of physical components and calculate phenomena such as noise, vibration and fracture (Abbas-Bayoumi and Becker, 2011; Qiang et al., 2010). Additionally, for vibro-acoustics analysis where the wavelengths vary, the boundary element method (BEM) and statistical energy analysis (SEA) are used along with FEA. BEM and FEA analyse structures that support low frequency vibrations and SEA is suitable for high frequency analysis (Wang et al., 2010). At the present time, some industries are successfully using these methods to design, analyse, and optimise their products before proceeding to manufacturing. This approach allows designers to create a variety of product designs and fine-tune their performance by experimenting with their parameters and geometry (Brinkmeier et al., 2006; Prakash et al., 2012; Ejsmont, 2000).

Figure 4 Vehicle cabin noise optimisation (see online version for colours)



Source: Original data is from the work of Wang et al. (2010)

Wang et al. (2010) performed estimation of the vehicle cabin interior noise using FEA and SEA models, which were validated with field tests. The cabin was excited at its four mount points, and the sound level was calculated using FEA and BEM for structures that support long wavelengths, such us the frame and the door pillars, and the rest of the cabin's interior was analysed using SEA. After the calculation of the overall sound level of the cab, using panel acoustic contribution analysis and energy transfer path contribution analysis, the interior parts that contributed the most were identified. Those parts then were optimised, and the new measurements showed a 3–5 dBA reduction in frequencies of interest as shown in Figure 4.

Dai and Cao (2007) examined different methods of low frequency noise reduction in tractor cabin interiors utilising harmonic analysis and FEA modelling. The methods under investigation were

a applying sound absorbing material

b addition of mass on vehicle's panels

c applying damping material on the vehicle's panels

d changing the stiffness of the panels by modifying the vehicle's frame.

The results reveal that the sound absorbing materials and the added mass performed poorly in mitigation of low frequency noise. The application of damping material efficiently smoothed out the low frequency resonances, while the added stiffness made the interior more responsive in creating more resonances at even lower frequencies.

These examples demonstrate the potential for computer simulation to efficiently solve complex problems using physics and mathematical-based approaches, providing engineers with tools to perform extensive and repeatable scenarios in a cost efficient manner.

5 Discussion

Table 5 summarises data from the milled shoulder rumble strip designs found in the literature (Miles and Finley, 2007; Torbic et al., 2009; Donavan and Rymer, 2015; Terhaar and Braslau, 2015). There are a total of 34 designs reviewed and compared. We included factors such as geometry, interior SLD, exterior SLD and the theoretical interior SLD calculated using equation (3). We also note that designs 1, 2, 26, 27, and 28 are sinusoidal designs. The table focuses on presenting a variety of rumble strip designs and their SLD data showing their deviation from the values calculated using the current theoretical formulations. To keep the table consistent, the interior SLD for the designs given by Torbic et‘al. (2009) were recalculated assuming dry pavement conditions using the formula given by the authors. To represent these findings graphically in the context of recommended SLD ranges for freeways and urban roads, the data from Table 5 are graphed in Figure 5 and Figure 6. Figure 7 presents the exterior SLD, highlighting the range below 7 dBA based on the detectability factor.

Table 5 shows that the conventional designs 3 and 8 have similar geometry and therefore, are expected to have similar interior SLD, as confirmed by the theoretical calculations presented in the last column. However, the field measurements reveal that while the car’s interior SLD value agree for design 8, the value for design 3 differs by 7 dBA. In addition, the formula in Torbic et al. (2009) suggests that the designs 3 and 20 should have similar interior SLD 17 dBA. Once again, the field measurements posed discrepancy to the theoretical prediction showing car’s interior SLD to be 10 dBA and 24 dBA respectively. Designs 26 to 28 are the same sinusoidal design while 29 to 31 are the same conventional design. The field measurements revealed that the same design on different vehicles can potentially have different interior and exterior SLDs. While field measurements accurately capture the amplitude of the interior and exterior signals created by rumble strips, they may be affected by confounding variables, including atmospheric and environmental variables, such as wind speed and direction, atmospheric pressure, topography and vegetation cover, in addition to equipment type and quality. These issues make every field measurement unique in terms of place, time, condition, vehicle type, and testing equipment, which can produce measurements that are not repeatable.

The results show that current designs for milled SRS perform efficiently for passenger cars and light trucks in some cases, but they perform poorly for CVs on freeways, leaving a portion of drivers without the safety benefits afforded by rumble strips. Figure 5 highlights the designs 15, 16 and 20 that create a feedback for CVs slightly above 6 dBA, conforming with suggestions from Torbic et al. (2009) for rural roads. However, these designs provide feedback for passenger and pick-up vehicles higher than the recommended range, which might be potentially harmful for the driver. The results in Figure 6 reveal that for freeways, only designs 13, 14, 17 and 18 produce enough feedback for both passenger and pick-up vehicles based on the recommended range, but designs 13, 17 and 18 do not produce enough feedback for CVs. For design 14, the authors did not provide any measurement regarding CVs. It is important to say that sinusoidal designs are not producing noise levels that fall within the green bands (i.e., the recommended feedback ranges) for all vehicles. More research and experimentation are needed to increase the longevity of this type of design.

Table 5 Summary of tested designs from literature (see online version for colours)

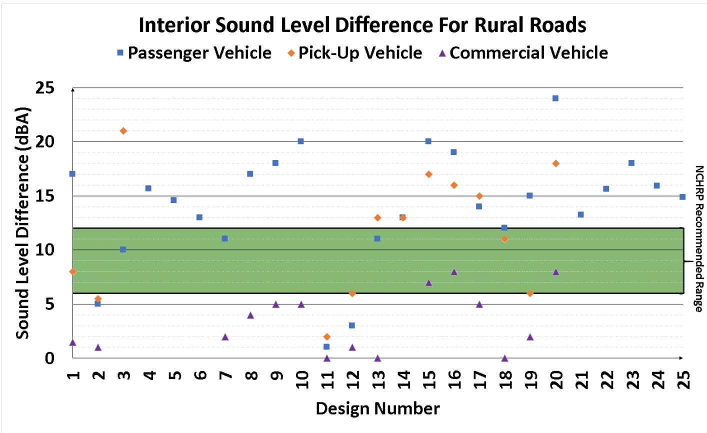
	Rumble Strip Geometry Parameters					Interior SLD			Exterior SLD			Estimated SLD based on the NCHRP formula
Design #	Length (m)	Width (m)	Depth (m)	Spacing (m)	Type	Car	Pick-up	Commercial Vehicle	Car	Pick-up	Commercial Vehicle	
Terhaar and Braslau (2015) 72.4 Km/h												
1		0.203	0.016	0.356	Sinusoidal	17	8	1.5	12	7.5	1.5	
2		0.203	0.013	0.61	Sinusoidal	5	5.5	1	4.5	3.5	0	
3	~ 0.152	0.406	0.013	0.305	Conventional	10	21	NP	19.5	14	NP	17 (+7)
Torbic et al. (2009) 72.4 Km/h												
4	0.127	0.406	0.009	0.305	Conventional	15.6	NP	NP	NP	NP	NP	15.6
5	0.127	0.305	0.009	0.305	Conventional	14.6	NP	NP	NP	NP	NP	14.6
6	0.127	0.152	0.009	0.305	Conventional	13	NP	NP	NP	NP	NP	13
Miles and Finley (2007) 88.5 Km/h												
7	0.127	0.406	0.006	0.305	Conventional	11	NP	2	NP	NP	NP	15.3 (+4.3)
8	0.152	0.406	0.01	0.305	Conventional	17	NP	4	NP	NP	NP	16.7 (-0.3)
9	0.178	0.406	0.013	0.305	Conventional	18	NP	5	NP	NP	NP	18
10	0.191	0.406	0.016	0.305	Conventional	20	NP	5	NP	NP	NP	19(-1)
11	NP	0.102	NP	NP	Conventional	1	2	0	NP	NP	NP	
12	NP	0.152	NP	NP	Conventional	3	6	1	NP	NP	NP	
13	NP	0.203	NP	NP	Conventional	11	13	0	NP	NP	NP	
14	NP	0.267	NP	NP	Conventional	13	13	NP	NP	NP	NP	
15	NP	0.305	NP	NP	Conventional	20	17	7	NP	NP	NP	
16	NP	0.203	NP	0.305	Conventional	19	16	8	NP	NP	NP	
17	NP	0.203	NP	0.61	Conventional	14	15	5	NP	NP	NP	
18	NP	0.203	NP	0.914	Conventional	12	11	0	NP	NP	NP	
19	0.051	0.305	0.013	0.305	Conventional	15	6	2	NP	NP	NP	13 (-2)
20	0.178	0.305	0.013	0.305	Conventional	24	18	8	NP	NP	NP	17 (-7)
Torbic et al. (2009) 88.5 Km/h												
21	0.127	0.152	0.009	0.305	Conventional	13.2	NP	NP	NP	NP	NP	13.2
22	0.152	0.305	0.009	0.305	Conventional	15.6	NP	NP	NP	NP	NP	15.6
23	0.178	0.406	0.013	0.305	Conventional	18	NP	NP	NP	NP	NP	18
24	0.127	0.406	0.009	0.305	Conventional	15.9	NP	NP	NP	NP	NP	15.9
25	0.127	0.305	0.009	0.305	Conventional	14.8	NP	NP	NP	NP	NP	14.8
Donovan and Rymer (2015) 96.5 Km/h												
26		NP	0.008	0.356	Sinusoidal	13.7	NP	2.6	8.2	NP	3.7	
27		NP	0.008	0.356	Sinusoidal	12.8	NP	2.6	5.8	NP	3.7	
28		NP	0.008	0.356	Sinusoidal	19.1	NP	2.6	7	NP	3.7	
29	0.102	NP	NP	0.305	Conventional	11.5	NP	7.6	13.2	NP	5.9	
30	0.102	NP	NP	0.305	Conventional	16.8	NP	7.6	12.7	NP	5.9	
31	0.102	NP	NP	0.305	Conventional	16	NP	7.6	10.5	NP	5.9	
Torbic et al. (2009) 104.6Km/h												
32	0.127	0.152	0.009	0.305	Conventional	13.5	NP	NP	NP	NP	NP	13.5
33	0.152	0.305	0.009	0.305	Conventional	15.9	NP	NP	NP	NP	NP	15.9
34	0.178	0.406	0.013	0.305	Conventional	18.3	NP	NP	NP	NP	NP	18.3

Notes: Interior SLD, Blue: dBA $<$ 6 dBA, green: 6 $\leq$ dBA $\leq$ 15, red: dBA $>$ 15.
Yellow denotes feedback for speed that can be used either in rural roads or freeways but the feedback value is acceptable only for one of the recommended ranges.
Exterior SLD, Green: dBA $<$ 7 dBA, red: $\geq$ 7 dBA. Data not presented = NP.

Source: Original data is from the work of Miles and Finley (2007), Torbic et al. (2009), Donavan and Rymer (2015) and Terhaar and Braslau (2015)

Note on Table 5 that exterior SLD were only measured for five designs and not for every vehicle type. Figure 7 shows that only design 2 produces external SLD below the detectability factor. In general, while additional exterior noise data sets do exist in the literature, standardised field test methods do not exist, and due to field conditions that are naturally sensitive to external factors (road type, road surface condition, environmental parameters, etc.) experimental repeatability is also limited. For instance, Donavan and Rymer (2015) took exterior noise measurements from a distance of 7.62 m while Terhaar and Braslau (2015) measured the exterior noise at 15.24 m. This makes the comparison of the three rumble strip designs (1, 2, 26–28) difficult, since it is known that only the distance doubling can reduce a sound signal by 6 dBSPL. However, to address this limitation, highly replicable computer modelling approaches similar to Wang et al. (2010) could be leveraged for testing multiple designs and parameters in a controlled, economical way to narrow down key designs for field validation. Integrating computer modelling may also increase the opportunity for collaboration and expansion of these models to include other data inputs like acceleration for estimating tactile signals. Collectively, this combination of numerical simulation and field tests may lead to optimised solutions.

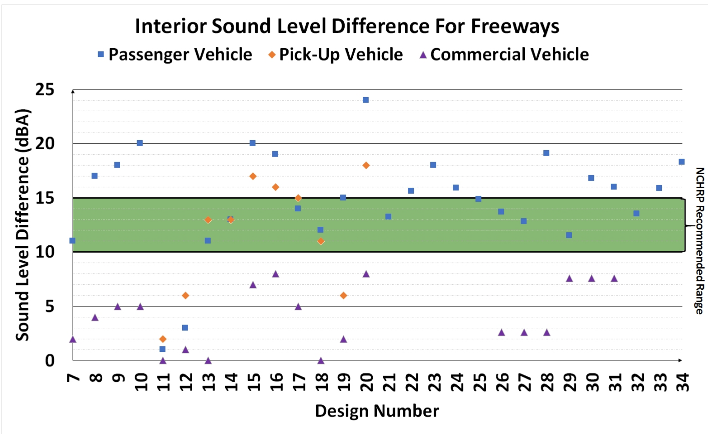
Figure 5 Interior SLD for rural roads (see online version for colours)



Note: The green band spans the recommended dBA range for rural roads (speeds 72.4–88.5 km/h).

Source: Original data is from the work of Miles and Finley (2007), Torbic et al. (2009), Donavan and Rymer (2015) and Terhaar and Braslau (2015)

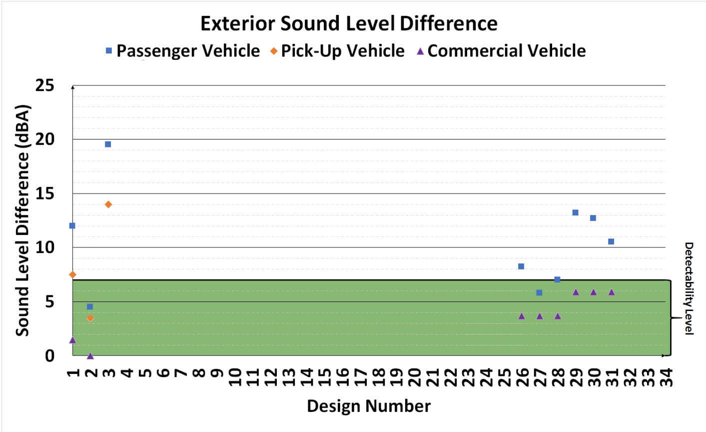
Figure 6 Interior SLD for freeways (see online version for colours)



Note: The green band spans the recommended dBA range for freeway roads (speeds 88.5– 104.6 km/h).

Source: Original data is from the work of Miles and Finley (2007), Torbic et al. (2009), Donavan and Rymer (2015) and Terhaar and Braslau (2015)

Figure 7 Exterior SLD (see online version for colours)



Note: The 7 dBA margin highlighted in green band represents the threshold based on the detectability factor.

Source: Original data is from the work of Miles and Finley (2007), Torbic et al. (2009), Donavan and Rymer (2015) and Terhaar and Braslau (2015)

6 Limitations of existing tools and models

The final portion of this review focuses on assessing limitations of existing models and tools that can be used by state DOTs to evaluate rumble strip designs, with the goal of guiding future research to best address DOT needs. Section 2 presented the different kinds of rumble strips that are used and discussed the trend towards sinusoidal designs for potential exterior noise reduction, though a standardised testing method is not currently available.

In Section 3.2, we briefly reviewed the formula for calculating interior SLD using designated parameters for conventional rumble strips. This empirically derived formula works only for predicting interior SLD and only audible feedback. Currently, there is no formula for predicting exterior SLD or one that incorporates the tactile feedback that rumble strips produce. Furthermore, this formula does not take into account vehicle types, which affect SLD substantially as demonstrated in Table 5. Table 5 reveals significant differences between the measured SLD value and the calculated one, highlighting the limitations of a derived formula from non-standardised methods where micro-differences in road type, geometry and weather are not considered. Current rumble strip designs have limited effect on CVs, which may be problematic for freeway installation and noise mitigation. Only three out of the thirty designs manage to create sufficient audible feedback, and only for rural road assessment.

Finally, the FHWA's current Transportation Noise Model does not include rumble strip noise as input. Considering that rumble strips are becoming a standard roadway feature, incorporating their noise into analytic noise prediction models could be useful to predict potential needs for future noise mitigation. This means that to calculate the average daily noise level of an area, statistical data for rumble strip hits would also need to be included into noise prediction models, along with the noise level generated from each rumble strip design.

7 Conclusions and future works

Rumble strips are useful for warning drivers about lane departures to prevent crashes, but these safety devices add to roadway noise for nearby residences. This review summarises key findings from current rumble strip studies with varying designs, compares standardised versions of equations that can be used by state DOTs to evaluate certain designs, and presents new options for evaluating rumble strip designs through simulation and numerical modelling to potentially reduce costs associated with extensive field data acquisition. The outcome of this work reveals potential options for future work to address residential noise from rumble strips while also maintaining the safety benefit from these devices. First, numerical simulation and field analysis methods could be integrated to optimise rumble strip designs to be effective for CVs. Since emerging designs currently measure performance based on tactile feedback signal, development of a recommendation for a sufficient tactile threshold would help guide rumble strip construction. Given the limitation of current rumble strip noise prediction formulas for sinusoidal rumble strip noise prediction, research is also needed to analyse sinusoidal rumble strip designs and provide an initial formulation. Numerical simulation will also help provide a better understanding of the underlying phenomena from the tyre-rumble strip interaction, leading to targeted solutions and potentially innovative new designs. Finally, an updated road noise prediction model that incorporates shoulder rumble strip noise, together with traffic data and vehicle types, is needed to fully assess roadway noise.

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