

Comparison of Vehicle Responses to Rumble Strip Inputs of Varying Design

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ABSTRACT

A measurement program was completed to assess driver input versus exterior noise generation for four vehicle designs and two different rumble strip designs. The vehicles included a small compact car, an immediate size car, a full sport utility vehicle, and a medium duty dump truck. The first rumble strip was a conventional design providing shorter wavelength input to the tire. The second was designed to provide longer wavelength, more harmonic input to the tire. The measurements included exterior pass-by noise and on-board exterior noise and interior measurements of sound pressure level and vibration level at the seat track and steering column. In general, the results indicated that the longer wavelength strips produced less overall A-weighted pass-by noise with little or no reduction in interior noise and vibration. Considerable variation in the response of the vehicles was found particularly for steering column vibration and interior noise where the overall differences ranged from about 9 to 17 decibels (dB). The exterior measures produced smaller ranges, from 2 to about 7½ dB; however, the rank ordering of vehicle response was different for the pass-by and exterior on-board results. It was concluded that the interior noise and steering column responses were strongly influenced by vehicle specific characteristics both in terms of isolation and modal response. The results of this study are presented in overall and in ⅓ octave band levels that compare the different test vehicles and test rumble strips.

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INTRODUCTION

Rumble strips are used commonly throughout the United States to alert drivers that they have wandered out of the lane of travel and need to take corrective action. In general, there are two conflicting requirements for rumble strips: producing sufficient warning for vehicle operators and minimizing the exterior noise that can create annoyance in nearby communities. More recently, the exterior noise produced by excursions onto rumble strips has also become a concern for disrupting the habitat of endangered species including the Spotted Owl. Historically, rumble strip design focused on reducing the occurrence of run-off-road incidents due to inattentive or drowsy drivers and attention was on creating a high level of driver/passenger disturbance inside the vehicle. In the 2000's, exterior noise from rumble began to receive more attention particularly in regard to reducing public complaints (1,2). In 2001, concern was also directed at bicyclist issues including fatigue and potential loss of control (3).

In 2012, the California Department of Transportation (Caltrans) installed a newly designed rumble strip on the shoulders of several kilometers of highway in Northern California. Building on research reported from Europe (1,2), a sinusoidal profile specification was developed and implemented for evaluation in comparison to more conventional design rumble strips. The goal of the new design was to maintain or increase audible and tactile warning to the operator and

decrease the exterior noise relative to a conventional design. The sinusoidal design was developed to reduce higher frequency inputs into light vehicle tires which efficiently radiate exterior noise. This was attempted by minimizing abrupt changes in the rumble strip profile and increasing the vibrational input to the vehicle. To document the performance of this design, a program of noise and vibration measurements was completed on the sinusoidal and conventional designs. The results of these measurements are presented and discussed in the remainder of this paper.

RUMBLE STRIPS TESTED

The sinusoidal strips were constructed just at the edge of the outside lane of travel as shown in [Figure 1](#). Due to the presence of existing conventional rumble strip in the shoulder, the new strips were ground in closer to the outer lane of travel than normal. A photograph of the installed sinusoidal strips is shown in [Figure 2](#). These strips are characterized by the wavelength (λ) of the sinusoid and the peak-to-peak amplitude or height of the profile. The wavelength was selected so that the radius of curvature of the sinusoidal depression was greater than 30.5 cm (12 in.) which is typical of the deflected radius of light vehicle tires. If λ approaches 30.5 cm or less, the curvature of the tire will not fit into the depression without creating additional input to the tire and additional exterior noise (1). However, if the λ becomes larger, there is little distortion of the contact patch while the

tire rolls through the depression of the profile. In this case, the vibrational input to the vehicle is reduced. To provide the necessary input to the tire, the wavelength needs to be limited such that there is some distortion of the tire contact patch as it passes over the crest of the sinusoid. By analyzing the geometry of both the tire and sinusoidal depression, a wavelength of 35.6 cm (14 in.) was selected as optimum trade-off between providing too much or too little input to the tire. The peak-to-peak amplitude was selected to be 7.94 mm (5/16 in.) in order to be bicycle-tolerant based on previously reported research (1,4). The frequency of the forcing function produced by the wavelength is also important in the response of the vehicle. Whole vehicle (rigid) modes typically occur below 5 Hz, while first order (whole body) modes of the engine on its mounts occur in the range from about 5 to 12 Hz (5). Body flexure modes begin around 25 Hz and become more localized with increasing frequency. These higher order body modes become more effective at radiating sound at frequencies starting around 40 Hz and continuing higher in frequency (6). Around 50 Hz and above (depending on vehicle interior dimensions), interior cavity acoustic resonance and standing wave modes become important at amplifying the sound further (7). In this same frequency range, the modes of vibration of the tire begin to be encountered (8). However, tires do not radiate sound efficiently below about 300 Hz, and therefore, there is essentially no additional contribution to exterior noise below this frequency from the tires (9). As a result, it is desirable to: 1) minimize the occurrence of lower forcing frequencies below ~40 Hz to avoid larger amplitude vehicle modes and suspension modes; 2) maximize the occurrence of forcing frequencies in the range from 40 Hz to 100 Hz and even up to 200 Hz where there are many vibration modes in the vehicle system to generate interior noise and vibration so as to produce sufficient driver warning; and 3) avoid forcing frequencies starting from about 300 Hz and upwards as this is where exterior sound radiation from tire begins to occur. The design wavelength of $\lambda = 35.6$ cm (14 in.) produces forcing frequencies of 50.3 Hz to 75.4 Hz in the vehicle speed range of 64.4 to 96.5 km/h (40 to 60 mph).



Figure 1. Photograph of the sinusoidal rumble strip profile as built

Conventional rumble strips found on a nearby highway were measured for comparison to the sinusoidal strips. Photographs of these strips are shown in Figure 3. These strips consisted of cylindrical shapes partially ground into the shoulder pavement with relatively large flat, unground spots in between. The spacing of the cylindrical depressions was about 30.5 cm (12 in.) and flat spots were about 20.3 cm (8 in.) in length with the depression about 10.2 cm (4 in.). The transition between the depressions and the plateaus created abrupt changes in the rumble strip profile that can be expected to generate more high frequency content compared to the purely sinusoidal profile of the strips shown in Figure 2.

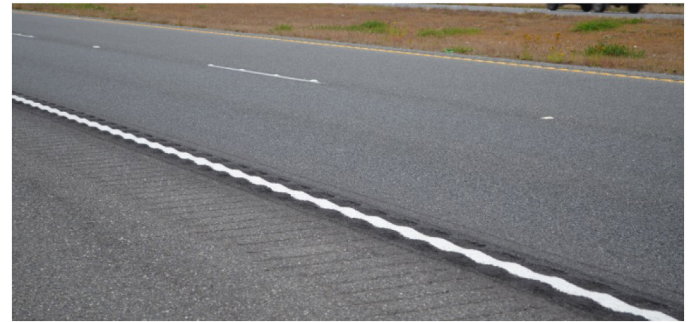


Figure 2. Photograph of the sinusoidal rumble strip profile as installed on the shoulder of U.S. Highway 101



Figure 3. Photograph of the conventional rumble strips found on State Route 299

DESCRIPTION OF THE MEASUREMENTS

Measurement Methods

Four types of noise and vibration data were collected for the evaluation of the rumble strips. Exterior noise measurements included two types: 1) conventional pass-bys; and 2) on-board sound pressure level. These were intended to document the potential of the warning devices to generate noise in the surrounding community and environment. Interior measurements were used to quantify the warning effect for vehicle operators and occupants and included interior noise and vibration data. The data for all measurements were captured in the field using two, 2-channel Larson-Davis 3000 Real Time Analyzers (RTA). These were set for $\frac{1}{8}$ second exponential averaging and sampled every $\frac{1}{10}$ of a second. The signals were also captured on solid state recorders.

Exterior Noise

The most direct comparison of the effects of the warning devices in the community and environment was provided by pass-by noise measurements for each of the test vehicles consistent with the American Association of State Highway and Transportation Officials (AASHTO) test procedure TP 98 for Statistical Isolated Pass-by (SIP) measurements (10). The measurement microphone was located 7.5 m (25 ft) from the centerline of vehicle travel at a height of 1.5 m (5 ft). The events were actually controlled pass-bys with specific operators for the test vehicles. Since measurements were completed with the vehicles operating both on and off the strips, the microphone was then moved accordingly to maintain the 7.5 m (25 ft) distance to vehicle pass-by. The data off of the strips provided a baseline of comparison for the corresponding data on the strips.

It was originally intended to measure the tire/pavement noise source strength on the outside of the vehicle using on-board sound intensity (OBSI) following the AASHTO TP 76 procedure (11). These measurements were attempted at a test speed of 32.2 km/h (20 mph) on the sinusoidal strips; however, the vibration input created unacceptably large vibratory motion of the OBSI fixture. In order to acquire at least some exterior sources, a microphone was secured to the vehicle using a bracket mounted at the top of the right rear tire wheel housing. The 12.7 mm (½ in.) microphone was fitted with a 88.9 mm (3½ in.) diameter windscreen to reduce the effects of air flow. A second windscreen was placed underneath the microphone preamplifier in an attempt to isolate it from vibration as shown in Figure 4. For most of the vehicles and strip designs, this microphone location provided at least a 10 dB difference in level for on and off the warning strips. It was not practical to measure exterior noise on the dump truck in a manner consistent with the light vehicles.

Interior Measurements

The interior measurements were selected to evaluate both the aural and tactile inputs to the vehicle operator and occupants. Interior noise measurements were made at the head position of a right front seat occupant in a manner consistent with the Society of Automotive Engineers (SAE) J1447 procedure (12) for each of the passenger vehicle tested.

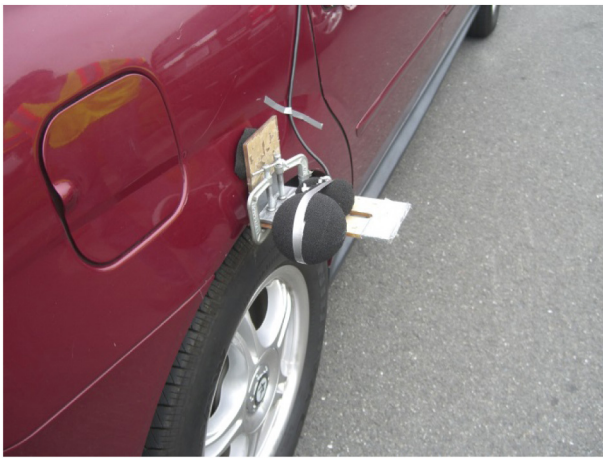


Figure 4. Photograph of the exterior on-board measurement microphone with windscreen as mounted over the right rear wheel well

To quantify the tactile inputs to the vehicle driver and occupants, acceleration levels (re $1\mu\text{m/s}^2$) were measured on the steering column and at the outboard seat track mounting location for the right front seat. These measurement locations were consistent with those used by the US automotive industry for characterizing vibration level relative to human response. The seat track acceleration was measured with a PCB 27 gram model 353B33 accelerometer and steering column acceleration was measured with a PCB 5.8 gram model 352C33 accelerometer.

Test Vehicles and Test Matrix

Four test vehicles were selected to span a range of vehicles rather than to evaluate variations between vehicles of similar design. Specifically, vehicle type, weight, wheelbase, and tire size were

considered. For a shorter wheelbase, smaller tire size, and lighter weight car, a Honda Civic was used. For medium wheelbase, mid-size tire size, and intermediate weight car, a Chevrolet Malibu was used. A Ford Expedition was used to provide a heavier, full-frame vehicle with longer wheelbase and larger tire size. The fourth vehicle was a four-yard, six tire dump truck from the Caltrans fleet. This medium duty truck provided a larger tire size than the passenger vehicles, greater weight and longer wheelbase. Photographs of these four vehicles are shown in Figure 5. The model year of the Malibu was 2005, however, the others are not known.

The measurements were made at 96.5 km/h (60 mph) for all vehicles on all three warning devices. These measurements were readily accomplished without any traffic control as the highway speed limit was either 88.5 or 104.6 km/h (55 or 65 mph). To evaluate the effect of speed on the interior and exterior on-board levels, the Malibu was also tested at 32.2 and 64.4 km/h (20 and 40 mph) on the sinusoidal and ground rumble strips. This testing was limited to one vehicle as it required rolling lane closures to safely accomplish the testing at the slower speeds. The complete test matrix is shown in Table 1. For the interior and exterior on-board noise, measurements were collected in both directions of travel. The matrix then contained 80 combinations of test vehicles, speed, measurement type, and warning device type. For each of these combinations, multiple runs were made to produce consistent results as it was difficult to maintain the wheel path on the center of the warning devices.



Figure 5. Photographs of the four test vehicles

Table 1. Test matrix for sinusoidal strips (SS) & conventional strips (CS)

Vehicle	Speed, km/h	Measure Type for Each Warning Device Type			
		Pass-By	Exterior Noise	Interior Noise	Interior Vibration
Honda Civic	97	SS, CS	SS, CS	SS, CS	SS, CS
Ford Expedition	97	SS, CS	SS, CS	SS, CS	SS, CS
4-Yard Dump	97	SS, CS		SS, CS	SS, CS
Chevy Malibu	97	SS, CS	SS, CS	SS, CS	SS, CS
Chevy Malibu	64		SS, CS	SS, CS	SS, CS
Chevy Malibu	32		SS, CS	SS, CS	SS, CS



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