MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

The Influence of Tires on Rumble Strip Noise and Vibration

Donavan, Paul[1]
Illingworth & Rodkin, Inc.
429 E. Cotati Avenue
Cotati, California 94931

ABSTRACT

In 2012, a four-vehicle experimental program was conducted to compare exterior and interior noise and vibration measurements on sinusoidal and conventional ground rumble strips as reported at INTER-NOISE 2013. In 2015, this research was expanded with a fifth vehicle to evaluate the influence of tires on the measured performance of these rumble strips and to examine the sources of pass-by noise. It was found that the variation in levels on and off the rumble strips between different tires on the same vehicle was almost as great as the variation from vehicle to vehicle for both noise and vibration. Using on-board sound intensity methods, it was also shown that noise radiated directly by the tire was not a source of wayside noise for frequencies below about 400 Hz. Body panel vibration levels were measured and found to produce differences in level on and off the rumble strips that are consistent with those of the pass-by measurements. The results and implications of these measurements are presented in this paper.

Keywords: Rumble Strips, Tire Noise, Vehicle Noise
I-INCE Classification of Subject Number: 13

1. INTRODUCTION

In 2012, the California Department of Transportation (Caltrans) installed and tested a unique sinusoidal rumble design or “mumble strip” on the shoulder of a major highway in Northern California. The results of the testing were quite positive in terms of reducing pass-by noise and providing greater driver warning through interior noise and vibration, in comparison to conventional cylindrical design rumble strips.[1] The sinusoidal rumble strip concept was not new and previous European research indicated that lower, A-weighted pass-by noise levels could be produced by these shapes.[2,3,4] The new design was unique with respect to the wavelength and the peak-to-peak depth, which were based on tire geometry and vehicle dynamics.[1] The initial testing in 2012 included four vehicles: three passenger vehicles and one medium-duty truck. Measurements of exterior pass-by noise, exterior on-board noise, interior noise, and vibration levels at a seat track location and on the steering column were made on the mumble strips and conventional rumble strips. The mumble strip design achieved its purposes by reducing pass-by levels by 6.2 dB compared to conventional rumble strips averaged for three different passenger vehicles and by 3.1 dB for a medium-duty truck. Interior noise and vibration level differences on the sinusoidal strips were over 13 dB greater than off strips and were within 1 dB of the on/off difference of the conventional strips. This design has since been patented by Caltrans. In April 2015, a fifth vehicle was tested in the same manner and on-board sound intensity (OBSI) and body panel vibration measurements were added. This second set of measurements had several purposes: 1) expanding the data set to a different size passenger vehicle; 2) examining the effect of different tires, as measured on the same vehicle; and 3) determining where the sound was radiated from, particularly for the lower frequencies.

2. MEASUREMENTS

2.1 Rumble Strip Designs

The 2015 measurements paralleled those of the original 2012 data and included testing of the two rumble strip designs shown in Figure 1. The conventional 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 30.5cm, and flat spots were about 20.3cm in length, with the depression about 10.2 cm. The transition between the depressions and the plateaus were not particularly gradual and tended to generate more higher frequency content compared to the mumble strips. For both 2012 and 2015 measurements, pass-by, interior noise, interior vibration, and exterior noise data were taken for vehicles at a speed of 97 km/h both on and off the rumble strips.

Figure 1: Photographs of mumble strips (left) and cylindrical ground strips (right)

2.2 Sound Pressure Level and Vibration Level Acquisition

For the pass-by measurements, the microphone location was moved such that a 7.5m distance was always maintained from the centerline of the vehicle path and microphone. The measurements were captured using 2-channel Larson-Davis 3000 Real Time Analyzers (RTA). These were set for ⅛-second exponential averaging and sampled every $^1/_{10}$ of a second. The signals were also captured on solid state recorders. From these measurements, the overall maximum pass-by level was determined, as were the one-third octave band levels at the time maximum overall level. Exterior sound pressure level was also measured on the outside of the vehicle while it operated on and off the rumble strips with a microphone location fixed just above the right rear wheel opening.[1]

The interior measurements evaluated 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[5] for each of the passenger vehicles tested. The tactile inputs to the vehicle driver and occupants were quantified with acceleration levels 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 27g model 353B33 accelerometer, and steering column acceleration was measured with a PCB 5.8 g model 352C33 accelerometer.

2.3 Additional Measurements in 2015

For the testing done in 2015, two additional types of measurements were included: OBSI and exterior body panel vibration. The OBSI measurements were intended to isolate the contribution of tire radiated noise to the pass-by noise levels. Due to high vibration levels experienced by conventional OBSI fixturing, a special fixture was developed that provided isolation between the support structure and microphone holder, as shown in Figure 2. OBSI measurements were then successfully obtained on and off the strips. As tires do not radiate sound efficiently below about 300 Hz, it was expected that there would be essentially no additional contribution to exterior noise below this frequency from the tires.[6] To determine if the low frequency sound could be radiated by the exterior body panels, the 5.8g accelerometer was mounted successively on the rear fender, the rear door, and the front fender, as pictured in Figure 3. These data were captured for operation on and off the strips using the RTA.

Figure 2: Modified OBSI fixture mounted on test vehicle (left) and added vibration isolation added to the probe/microphone holder (right)

The 2015 measurements were completed on a 2015 Ford Fusion full-size passenger car. This vehicle filled a size gap that was left from the 2012 measurement program, which included a compact Honda Civic, a mid-size Chevrolet Malibu, a full-size, full-frame Ford Expedition SUV and a medium-duty truck.[1] The Ford Fusion came equipped with Goodyear Eagle LS$_2$ (GDY) tires. To investigate the influence of tire design on the levels produced by the rumble strips, ASTM Standard Reference Test Tires (SRTT) were mounted on the Fusion, and all measurements were repeated. The Goodyear Eagle tire is a low-profile design compared to the more tradition SRTT, as shown in Figure 4.

Figure 3: Body panel acceleration measurement point: front fender (upper left), rear door (upper right), and rear fender (lower center)

Figure 4: SRTT (left) and GDY test tire (right)

3. MEASUREMENT RESULTS

3.1 Comparison to 2012 Results

The overall A-weighted sound pressure levels and acceleration levels measured on the four vehicles from the 2012 testing and the Fusion with both tires from 2015 are shown in Figure 5. These data reinforce the conclusion from the 2012 results that the pass-by levels on the mumble strips are lower than the conventional cylindrical strips, while the interior noise and vibration disturbances are typically equal to or greater than the cylindrical strips. The results for the Fusion are typically within the range of the other vehicles. However, these data indicate some differences in the way the two tires perform on each of the strips. For both pass-by and exterior noise, the GDY tires produce levels about 5 dB lower than the SRTT tires on mumble strips. On the ground strips, the levels for the two tires are about the same. This is more clearly seen in Figure 6, which plots the differences in level on and off the strips. The on/off differences are shown to be consistently less for the GDY tire than for the SRTT, except for interior noise on the conventional strips. The differences caused by the tires are significant enough that the Fusion with the SRTT tires appear to be a different car compared to the GDY tires.

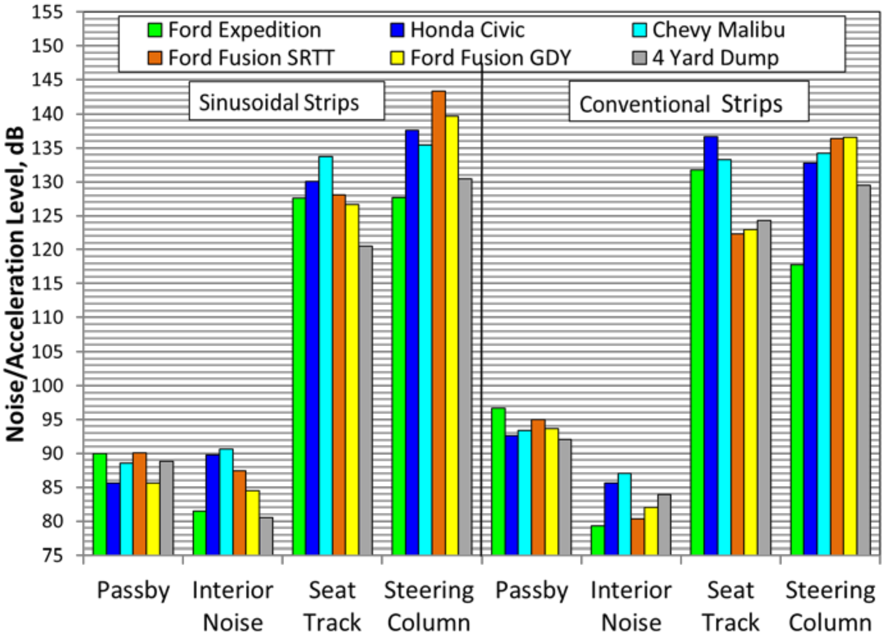

Figure 5: Summary of overall levels measured in 2012 and 2015

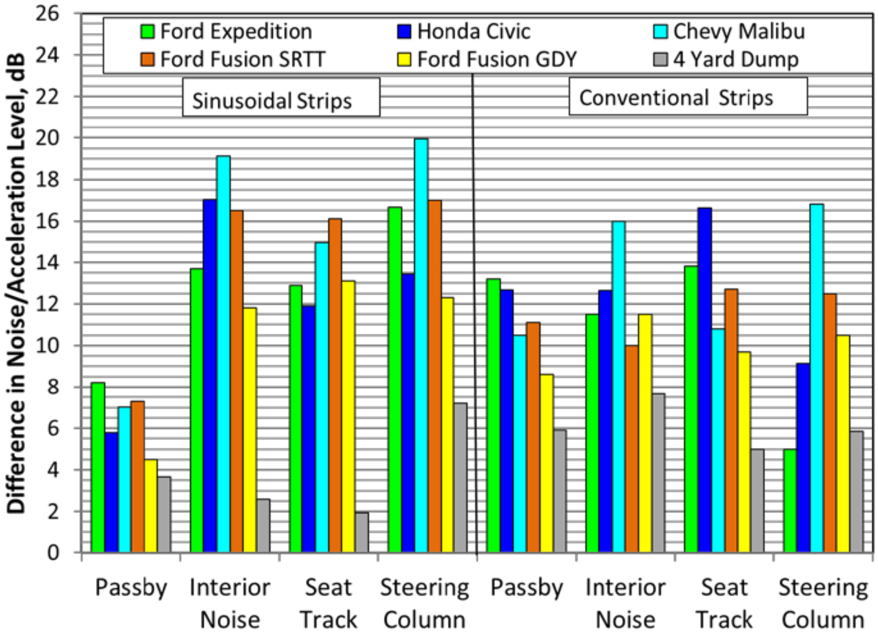

Figure 6: Summary of on/off level differences measured in 2012 and 2015

3.2 SRTT vs. GDY Tires on the Ford Fusion

In Figure 7, the overall exterior noise results comparing the two tires on and off the mumble and rumble strips are isolated for the pass-by data and the on-board exterior data. The differences between on/off the strips is also consistently less for the GDY tire than for the SRTT. From the one-third octave band levels shown in Figure 8, the GDY tire is consistently lower in the bands from 315 Hz up to 10,000 Hz for the mumble strips. For the ground strips, the SRTT only produces higher levels at 80, 630, and 800 Hz. The exterior noise results plotted in Figure 9 show the trends that

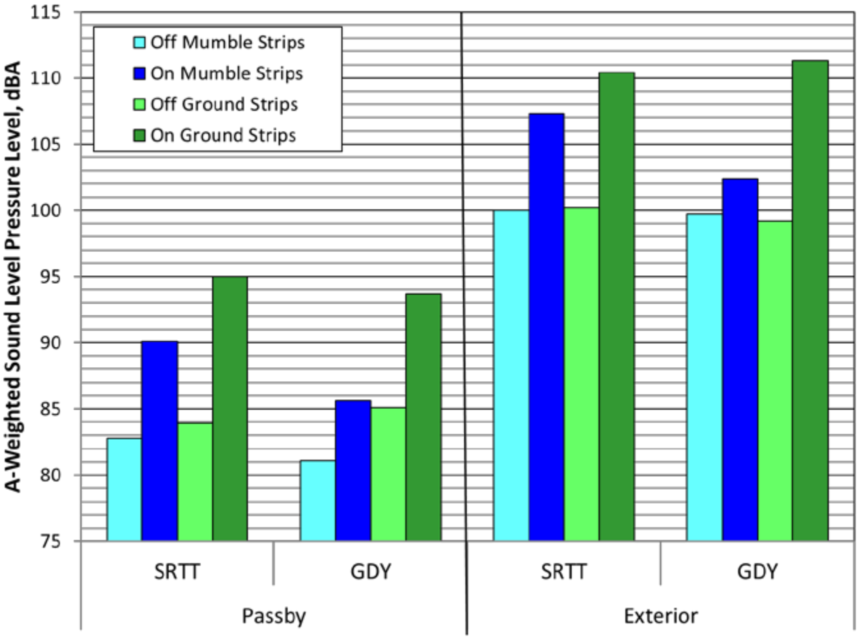

Figure 7: Overall pass-by and exterior noise levels for SRTT and GDY tires on and off mumble and rumble strips

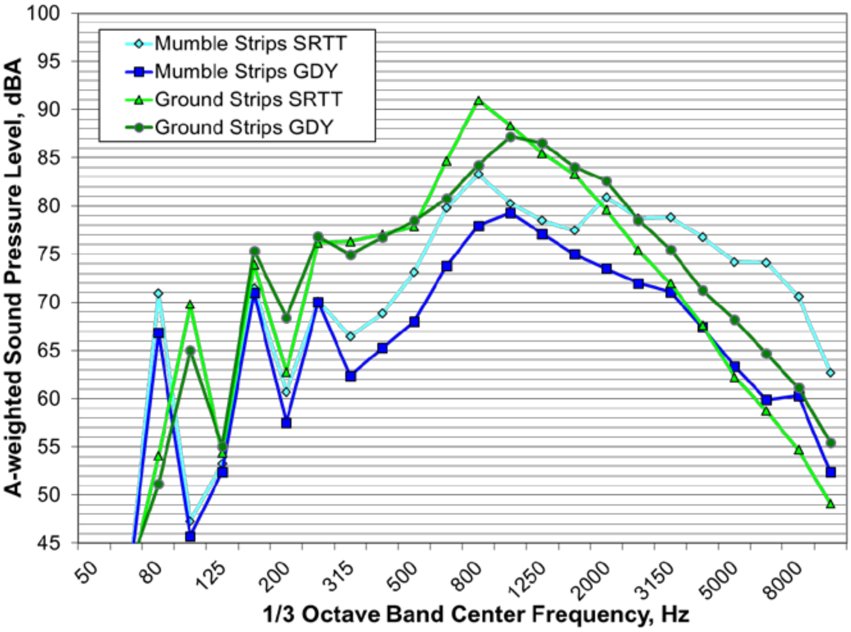

Figure 8: ⅓ Octave band pass-by noise levels measured with GDY and SRTT tires

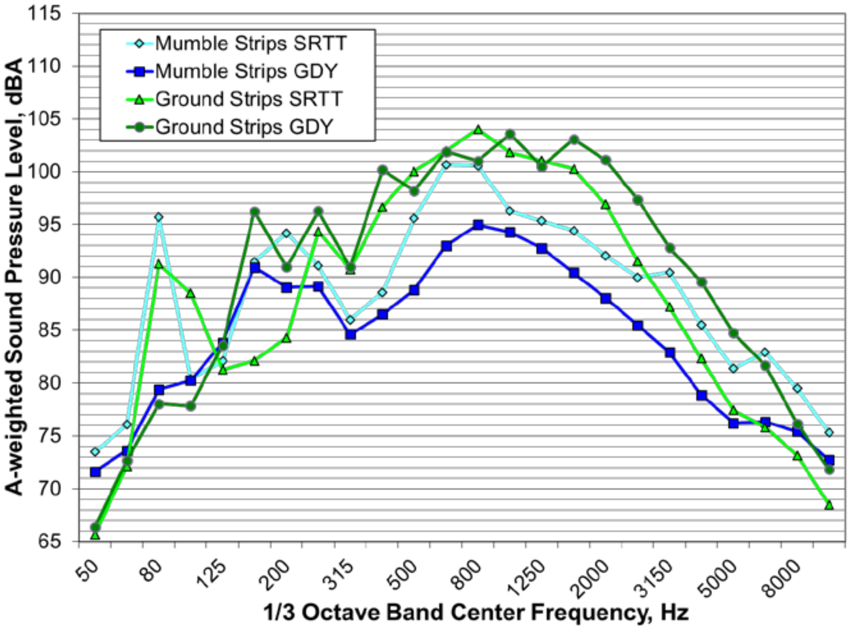

Figure 9: ⅓ Octave band exterior noise levels measured with GDY and SRTT tires

are somewhat different than the pass-by. With the SRTT, the levels at the repetition rates of the two strips (80 and 100 Hz) show higher levels as expected. However, the results for the GDY tire do not indicate elevated levels in these frequencies for either strip. On the mumble strips, the levels for the SRTT are consistently higher than the GDY tires above 315 Hz. Similarly, the higher frequency levels above 1250 Hz are consistently higher for GDY than the SRTT on the ground strips.

The overall response levels for the interior of the Fusion with the two tire sets are shown in Figure 10. For the interior noise and both vibration measurements, the SRTT

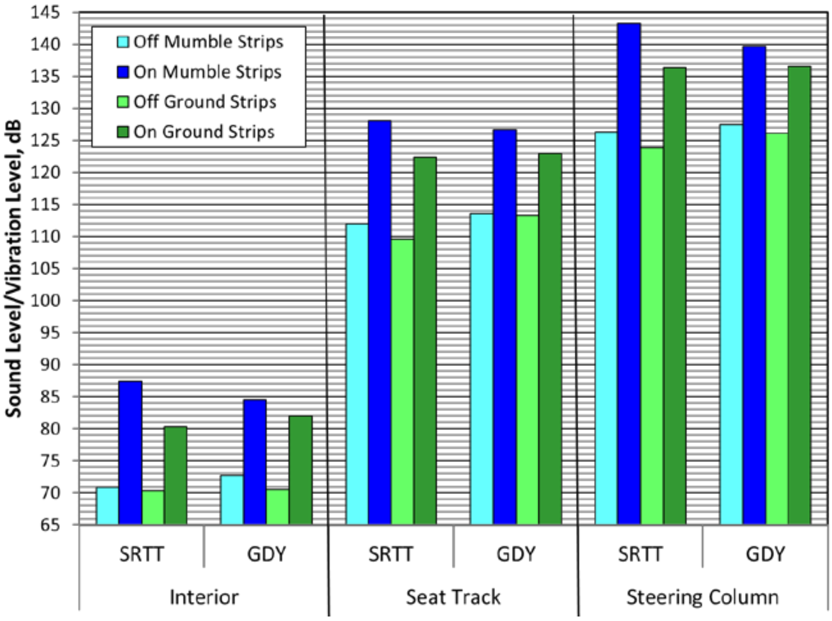

Figure 10: Overall A-weighted interior sound pressure and unweighted vibration levels for GDY and SRTT tires

produces higher levels (2.5 to 7.1 dB) of response on both strips than does the GDY tire. The difference in on/off strips also tends to be slightly higher for the SRTT. In the one-third octave band interior noise levels shown in Figure 11, the 80 Hz band shows up

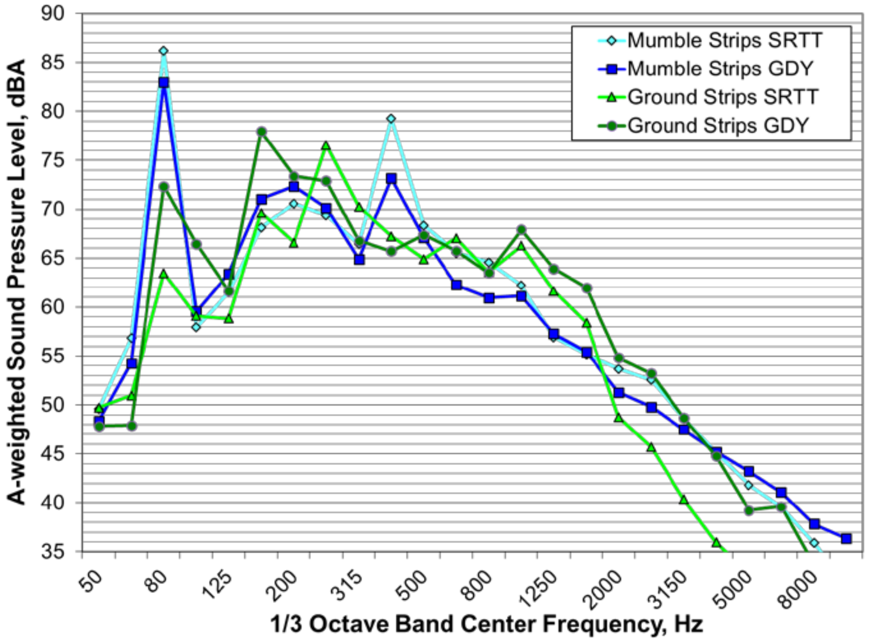

Figure 11: ⅓ Octave band interior sound pressure levels measured with GDY and SRTT tires

prominently for both tires and mumble strips; although, the levels for the SRTT tend to be higher by 3 and 6 dB for the peaks at 80 and 400 Hz, respectively. Although the SRTT on the mumble strips generally provides higher noise levels than the GDY tires, on the ground strips, the spectrum levels for the GDY tires are greater in the 80 to 200 Hz range by about 3 to 9 dB. The peaks in this range contribute to the overall levels of Figure 10 being higher for GDY tire and being slightly higher (1.7 dB) than those of the SRTT on the ground strips.

Comparisons the seat track accelerations for the two strips and two tires are shown in Figure 12. On the mumble strips, although the overall levels for the SRTT and GDY

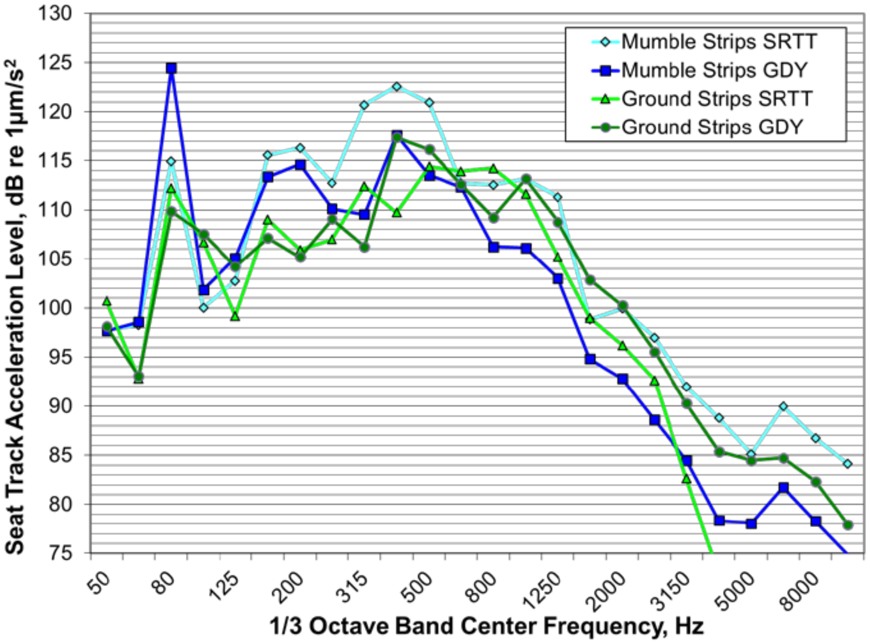

Figure 12: ⅓ Octave band seat track acceleration levels measured with GDY and SRTT tires

tires are within 1.4 dB (Figure 10), the spectral distributions created by the tires are substantially different. For the GDY tire, the highest level occurs at 80 Hz and is about 9 dB greater than the SRTT. Above 125 Hz, the levels for the SRTT are higher by as much as 11 dB at 315 Hz. This indicates that the tire/wheel input is significantly different for the two tires on these strips. On the ground strips, the levels for the two tires are much more similar with little consistent trend as to which produces the higher levels. As indicated in Figure 10, the acceleration levels for the steering column, as shown in Figure 13, are considerably higher than those for the seat track for both tires and on both strips.

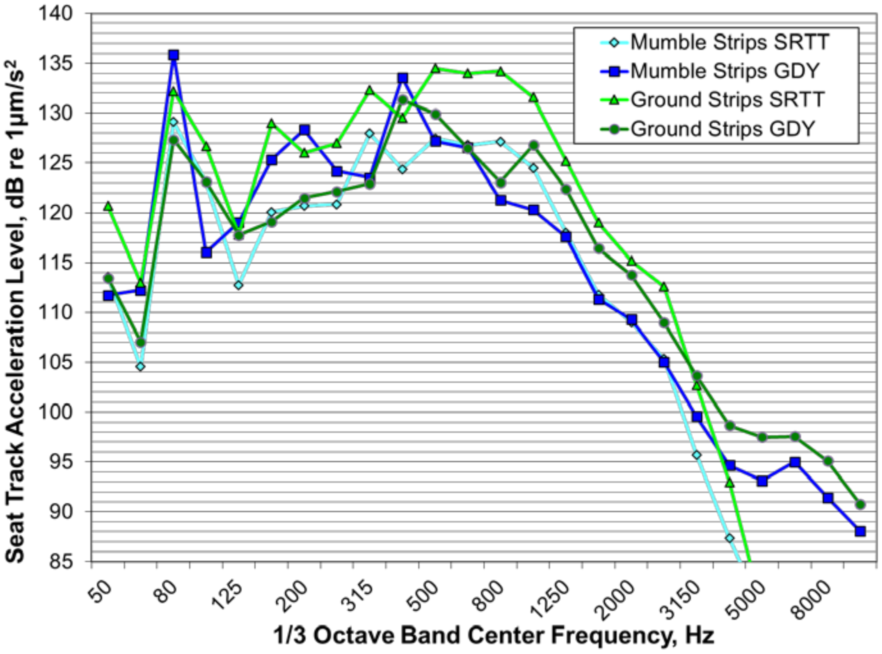

Figure 13: ⅓ Octave band steering column acceleration levels measured with GDY and SRTT tires

On the ground strips, the trends of the SRTT relative to GDY tires are similar to those of the seat track response. For the mumble strips, both tires display the peak at 80 Hz; however, unlike the seat track, the levels are more similar, with the SRTT being only 3 dB less than the GDY. For the seat track, the SRTT had elevated levels at 315 to 500 Hz; however, for the steering column, the SRTT levels were elevated from 500 to 1000 Hz, likely due to the response characteristics of the steering column.

3.3 OBSI Results

In addition to the isolating of the OBSI probes, as shown in Figure 2, the spacing between the microphones was increased to 32mm to more accurately capture the low frequency sound created by the mumble strips. Even with this modification, it was found that the sound intensity was negative up to about 315 Hz in all cases. This indicates the OBSI sound intensity vector is directed toward the tire at least near the tire contact patch. To determine if sound is radiated outward at all from the tire at low frequencies, the sound intensity would have to be averaged over the entire surface of the tire. Such measurements would be better suited using array techniques where many points near the surface of the tire could be measured at once.

Although the sound intensity was negative, the sound pressure measured by the fixture does provide additional information beyond the exterior microphone position at the top of the wheel opening. A comparison of the sound pressure levels from the probes is shown in Figure 14 for the two tires on the two strips. These data capture the behaviors

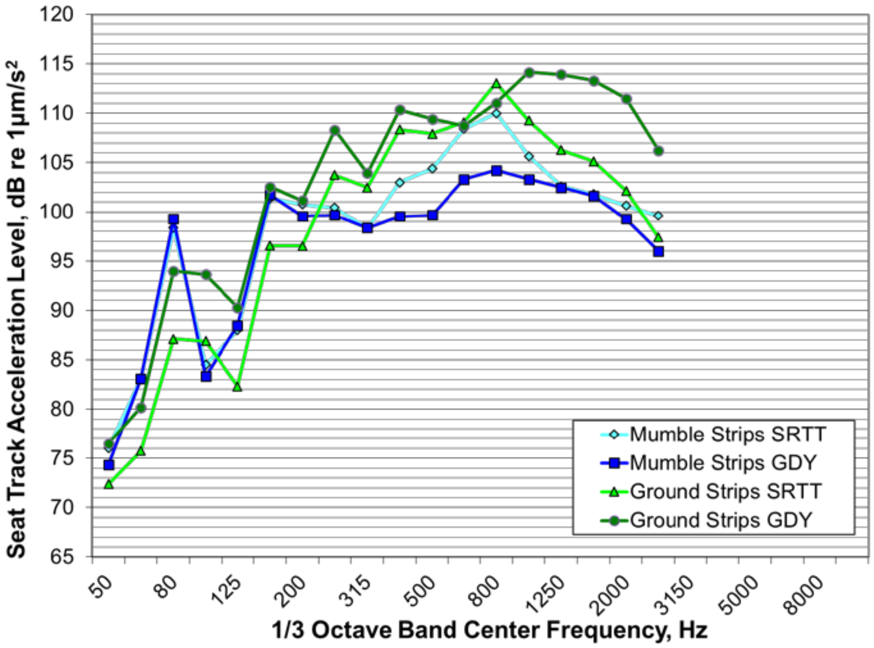

Figure 14: ⅓ Octave band sound pressure levels measured by the OBSI probes for the GDY and SRTT tires

noted previously, that is, the well-defined peak at 80 Hz on the mumble strips and the contribution to the 80 and 100 Hz bands on the ground strips. Generally, the results of Figure 14 show trends at 200 Hz that are similar to those of the exterior microphone data shown in Figure 9. However, the magnitudes of the levels at the OBSI position levels are consistently higher than those of the exterior location. Below 200 Hz, there are also some significant differences. At 80 Hz on the mumble strips, the SRTT and GDY tires both produce nearly equal levels for the OBSI location. For the upper wheel well location, the results for GDY tire do not display a peak at 80 Hz at all. Further, in the 80 and 100 Hz bands, SRTT tires produce noticeably higher levels on the ground strips compared to the GDY in the exterior results (Figure 9). For the OBSI location, these are switched, with the GDY tires producing higher levels (by about 7 dB) for the exterior location (Figure 14). For the 80 Hz peak on the mumble strips, the results for the OBSI location compared much better to the pass-by results than do those of the exterior location. From these results, it appears that measuring exterior sound pressure level at the OBSI location may provide more consistent data for comparison to the other types of data.

3.4 Exterior Body Panel Vibration

Another potential source of exterior noise, as measured in the pass-by tests, is sound radiation from the exterior body panels. From the interior acceleration measurements, it appears that there is enough vibrational energy in the body structure to excite these panels into radiating sound. Given the surface area of the panels, these could contribute substantially to the exterior noise. The overall acceleration levels measured on and off the two strips for the three panels and two tires are shown in Figure 15. As with the interior acceleration and sound pressure level data, the panel acceleration levels display a large difference between on and off the strips with the average being 14.2 dB. Also, the acceleration levels are greater than the seat track and steering column levels. These higher levels are consistent with the panels radiating sound to the exterior. It is also shown that the two fender panels have higher levels, likely because of their rigid attachment to the structure, as opposed to the rear door.

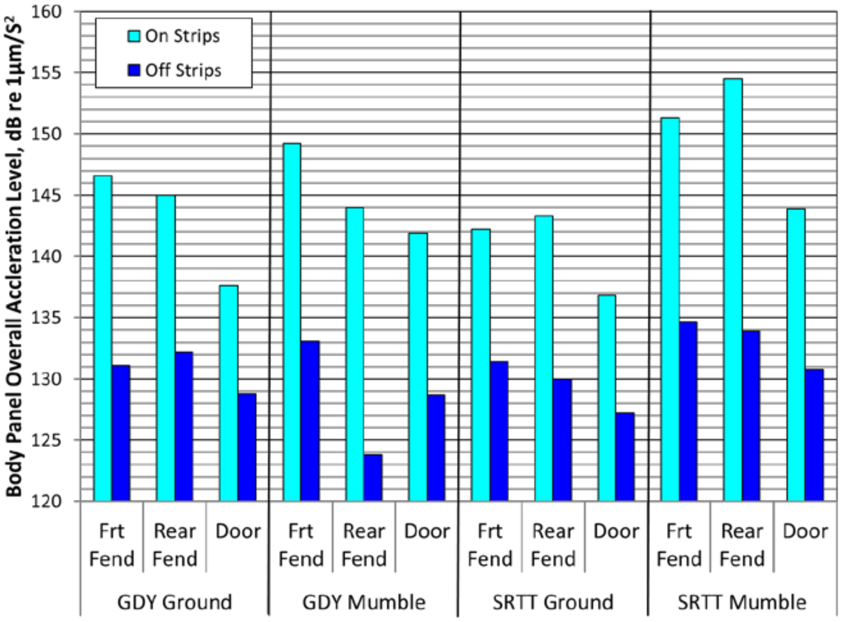

Figure 15: Overall panel acceleration levels on and off strips

Although the results of Figure 15 indicate that the panels could be contributing to exterior noise, the trends for the difference in panel levels on and off the strips are opposite to those of the pass-by results, as seen when comparing the results of Figure 6 to the on/off panel vibration results of Figure 16. For the pass-by measurements, the increase in sound levels on and off the mumble strips was less than for the ground strips.

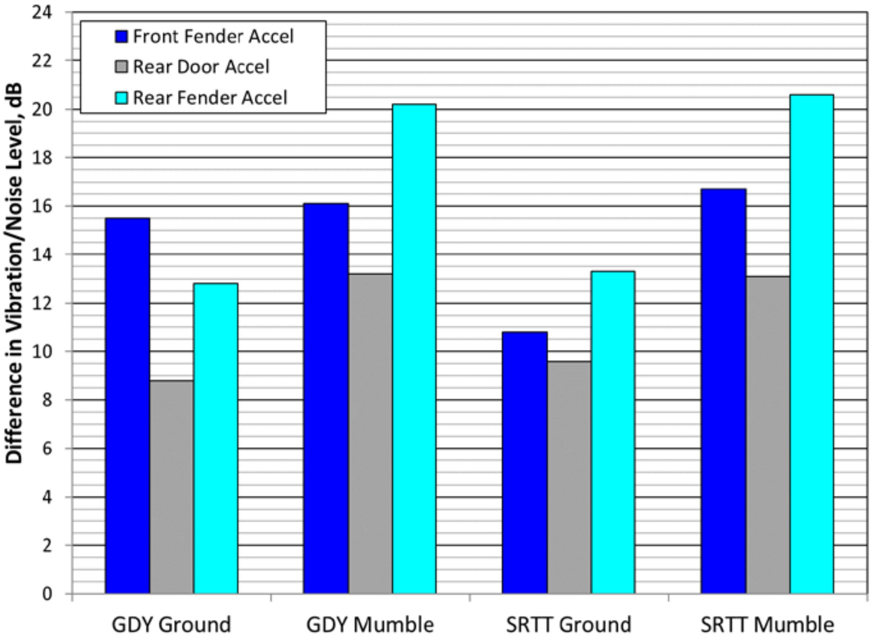

Figure 16: Overall panel acceleration differences for on and off the ground rumble strips and the mumble strips

For the panel vibration, the differences for the mumble are greater than for the ground strips. Since behavior is the opposite of the pass-by results, it is not clear that the differences in pass-by performance are determined by panel vibration. However, the discrepancies for the GDY tire are remedied when the panel acceleration levels are A-weighted to the match the A-weighting of the pass-by levels. A-weighting only partially addresses the discrepancies for the SRTT results. To study the role of panel vibrations further, more measurement points on the panel would be required, as well as examining the phase relationship between the panels and their individual radiation efficiencies.

4. CONCLUSIONS

In general, the noise and vibration results for all test vehicles qualitatively show similar trends and indicate that the sinusoidal design provides benefit in lower exterior noise while maintaining comparable or even greater operator warning input. However, significant differences between individual vehicles are found with variations as great as 10 dB for some measures in overall level and on/off performance. This implies that evaluations of rumble strips should not rely on the results from just one vehicle but rather at least several vehicles spanning a range of characteristics. The addition of a fifth test vehicle added confidence about the performance of the mumble strips compared to the conventional strips, it also increased the scatter in some metrics. Of concern also, is the differences measured by simply changing the tires of the test vehicle. In order to develop a consistent evaluation methodology for rumble strips, more research is needed to understand and account for the variations seen between different vehicles. The measurements also revealed that while tires are not major contributors to sound radiated at frequencies below 400 Hz for pass-by noise, they do influence the interior noise and vibration significantly. Through exterior body panel vibration measurements, it was indicated that these could be the source of the low frequency pass-by noise on rumble strips; however, further research is needed to confirm this.

5. ACKNOWLEDGEMENTS

This research was sponsored by Caltrans in their continuing effort to reduce the impact of highway-related noise on residents near roadways while addressing vehicle occupant safety. The author especially acknowledges the support of Bruce Rymer of Caltrans Headquarters in the conduct of this research.

6. REFERENCES

1. P. Donavan. and Rymer, B., “Design and Evaluation of Quieter Highway Rumble Strips”, Proceedings of Inter-Noise 2013, Innsbruck, Austria, September 2013nternoise 2013
2. G. Watts, R. Stait, N. Godfrey, and R. Layfield, “Optimisation of Traffic Calming Surfaces”, Proceedings of InterNoise 2001, The Hague, The Netherlands, August 2001.
3. J. Kragh, B. Andersen, and S Thomsen, “Low Noise Rumble Strips on Roads – a Pilot Study”, Proceedings of InterNoise 2007, Istanbul, Turkey, August 2007.
4. TRL Traffic Advisory Leaflet, “Rumblewave Surfacing”, Walking and Cycling Unit,Zone 3/17, Great Minster House, 76 Marsham Street, London, SW1P 4DR, 2005.
5. SAE J1477-2000 Measurement of Interior Sound Levels of Light Vehicles, Society of Automotive Engineers Recommended Practice, SAE, 400 Commonwealth Drive, Warrendale, PA.
6. K. Yum, K. Hong, and S. Bolton, “Sound Radiation Control Resulting from Tire Structural Vibration”, Society of Automotive Engineers Noise and Vibration Conference Proceedings, Traverse City, MI, May 2005.