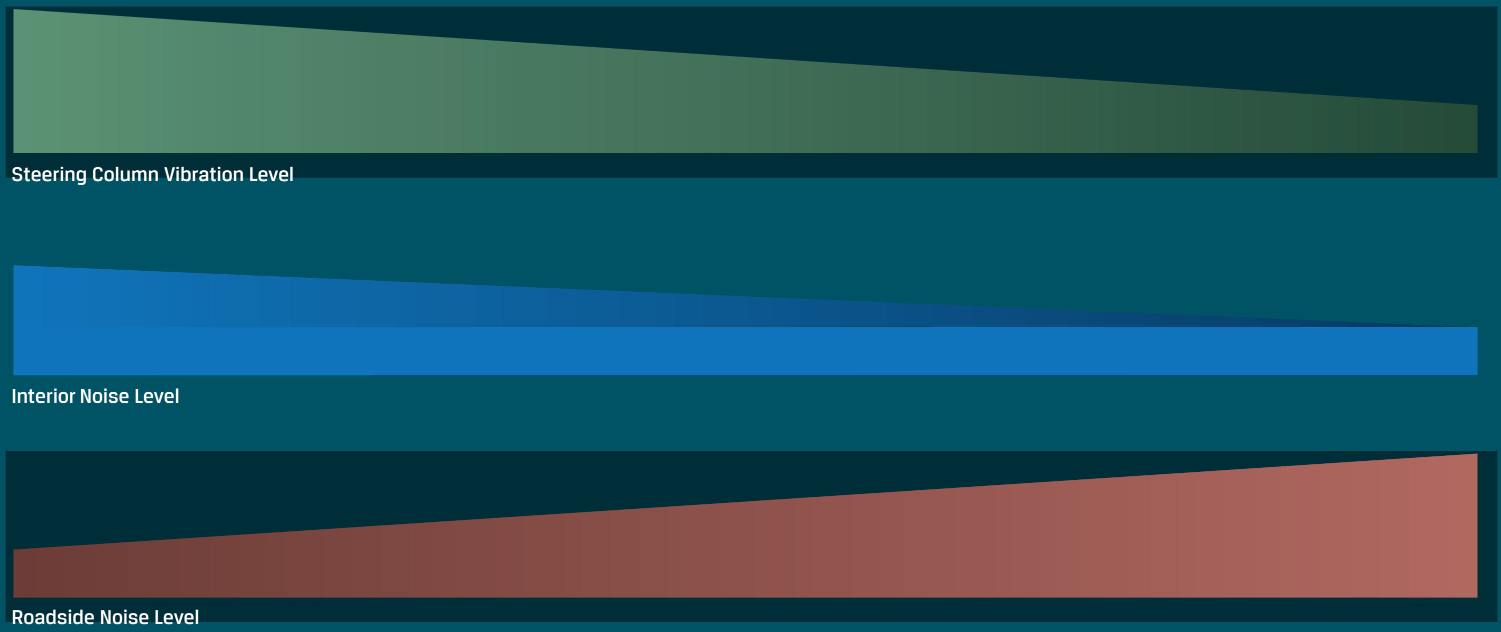
April 2018

# Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips *versus* Conventional Ground-In Rumble Strips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15. Abstract

This work began as a result of concerns and complaints related to elevated roadside noise levels generated by rumble strip strikes. This study is unique because it is the first to merge automotive noise and vibration engineering principles with highway engineering, and combines concepts initiated in European studies, General Motors sound and vibration work, and Caltrans' quieter pavement studies. The optimal shape for the sinusoidal rumble strip ("mumble" strip) profile is based upon tire geometry, tire dynamics, and typical light vehicle response functions. The goal, which was achieved by the sinusoidal rumble strip, was to maintain or elevate interior noise and vibration levels while reducing exterior pass-by noise levels.

| 16. Key Words<br><br>Rumble strip, sinusoidal rumble strip, mumble strip, pass-by noise, tire/pavement noise, vibration, exterior noise, one-third octave band, interior noise, seat track acceleration, steering column acceleration, Standard Reference Test Tire (SRTT), panel vibration, OBSI. | 17. Distribution Statement<br><br>Available to the general public | 18. No. of pages<br><br>119 |
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# Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Rumble Strips


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## Preface

Excessive traffic noise is a perennial issue for transportation departments and in many situations excessive noise levels can be attenuated with more thoughtful consideration of the highway design elements that are primarily responsible for generating noise. These highway design elements include the type of pavement and pavement marking/warning devices. Noise generated by different transportation elements can possibly be reduced with more focus on their design and acoustic characteristics.

This Caltrans rumble strip study is unique because it is the first to merge automotive noise and vibration engineering principles with highway engineering. The idea for this sinusoidal rumble strip combines concepts initiated in European studies, General Motors sound and vibration work, and Caltrans' quieter pavement studies. Dr. Paul Donavan, a former General Motors automotive engineer, selected the optimal shape for the sinusoidal rumble strip profile based upon tire geometry, tire dynamics, and typical light vehicle response functions. The goal achieved by the sinusoidal rumble strip was to maintain or elevate interior noise and vibration levels and reduce exterior pass-by noise levels. Haptic feedback through the steering column was also increased with the rumble strip. The recommended sinusoidal profile is designed for a light passenger vehicle operating at 40-60 mph and was evaluated for a single outboard (shoulder) wheel path. The primary exterior measurement was pass-by noise level at 25 feet from the vehicle, both on and off the rumble strip.

The width of the sinusoidal rumble strip should be wide enough to accommodate a light vehicle tire. A typical passenger car contact patch width is less than 8 inches and a sport utility vehicle (SUV) or light truck tire may be as wide as $10^{+}$ inches. This research demonstrates that when the sinusoidal or "mumble" strip is struck by a typical light vehicle, sound levels generated outside of the vehicle will be lower than the Caltrans standard ground-in rumble strips. Rumble strips are usually placed beyond the normal wheel path. The noise generated by a wheel strike depends on the number of times a rumble strip is struck and its placement relative to the normal wheel path. For this research, the maximum pass-by noise was evaluated instead of sound exposure because rumble strip strikes are normally infrequent and short in duration. Typically, rumble strip strikes can be characterized as intermittent and brief impulses and this impulse noise doesn't measurably elevate longer-term ambient noise levels. The effectiveness of the sinusoidal design on centerline rumble strips was also not evaluated in this research and is reserved for future investigation based on these principles. Implementation and design details such as lateral spacing from the edge-of-traveled-way and pavement stripes and skips or breaks to accommodate bicyclists will need to be addressed by traffic safety engineers. This rounded sinusoidal profile should be friendlier to bicycle wheels; however, this aspect was not examined in this study. Thermoplastic application and thickness may also need to be considered and evaluated.

Focusing more attention on reducing transportation infrastructure noise levels with careful acoustic design will promote health and livability in roadside communities.

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# Executive Summary


A proposed design to reduce the exterior noise produced by the passage of tires over off-the-road warning devices (rumble strips) was developed based on research in Europe and on an analysis of a tire rolling over a sinusoidal profile ground into the pavement. The concept of the sinusoidal profile, or "mumble" strip, is to move some the higher frequency excitation produced on a conventional rumble strip with abrupt changes in profile to lower frequencies that can be associated with the repetition rate, or frequency, of the sine wave shape. The concept was to decrease the overall A-weighted exterior sound level while still maintaining adequate disturbance inside the vehicle to alert the operator and occupants of off-the-road excursions.

In 2012, mumble strips following the recommended design were installed by Caltrans District 1 in Humboldt County along US Highway 101. In September 2012, these mumble strips were evaluated for exterior noise and interior disturbance. Conventional warning devices, specifically, ground rumble strips and Type A pavement markers, also were evaluated. Exterior pass-by noise, exterior on-board noise, interior noise, and vibration levels on the seat track and on the steering column were measured in four test vehicles. In April 2015, a fifth vehicle was tested in the same manner with the addition of on-board sound intensity and body panel vibration measurements. The results of all of these measurements indicated that, compared with conventional warning devices, mumble strips reduced the overall A-weighted exterior noise levels by more than 6 decibels (dB) for four different types of passenger vehicles. For the fifth vehicle, a medium duty, 4-yard dump truck, the reduction with the mumble strips was slightly more than 3 dB compared with the ground rumble strips.

In general, the interior disturbance levels created by the mumble strips were comparable to those generated by the ground rumble strips. For the passenger vehicles, the differences in interior noise, and seat track and steering column vibration were about 13 dB during travel on either the mumble strips or ground rumble strips compared with travel off the warning strips. For the truck, these differences were lower, although the steering column vibration was 7.2 dB greater during travel on the mumble strips compared with travel off the mumble strips, which was greater than the difference measured for the ground rumble strips. Subjectively, it was observed that the noise and vibration generated by both types of warning devices were adequate to alert vehicle operators and occupants.

Although the mumble strips did reduce the overall A-weighted exterior noise levels produced by the warning devices, they also generate pronounced tonal sounds at lower frequencies related to the repetition rate of the strips. It is not known at this time whether these sounds will be as objectionable to residents and wildlife as the higher overall A-weighted levels produced by conventional rumble strips. As a result, recommendations to further optimize the performance of the mumble strips include reducing the amplitude (depth) of the mumble strip design and/or decreasing the repetition rate (frequency) of the mumble strips.

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# Table of Contents

# List of Tables and Figures

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# Chapter 1 Introduction

Rumble strips are a proven measure to reduce the frequency and severity of lane and roadway departure collisions due to inattentive or drowsy drivers. Historical data indicates collisions can be reduced 20 to 50 percent, depending on the roadway environment and facility type where rumble strips are installed. Much of the early research on rumble strips was focused on creating a high level of driver and passenger disturbance inside the vehicle. However, the noise generated outside of a vehicle when it contacts rumble strips can concern residents and resource agencies. The development of quieter rumble strips that are effective in alerting motorists of the need for a steering correction will improve safety on those roadway segments with noise-sensitive roadside receptors.

In 2001, concern was raised that conventional rumble strips could cause bicyclists to lose control or become fatigued (Bucko and Khorashadi 2001). At the same time, residents who lived nearby roadways where run-off-road excursions were common complained about exterior noise resulting from rumble strips. Exterior noise produced by excursions onto rumble strips has also become a concern because the noise could disrupt the habitat of endangered bird species. In the 2000s, attention was given to reducing public complaints about exterior noise from rumble strips (Watts et al. 2001; Kragh et al. 2007).

Warning devices need to produce sufficient signal inside the vehicle to alert the vehicle operator while producing the lowest possible noise level outside of the vehicle to minimize the impact on nearby residents and wildlife. To address these two competing objectives, a proposed “mumble” strip was designed based on experiences from Europe and new analysis specific to this Caltrans project. This proposed design was constructed in Caltrans District 1 and tested for exterior and interior noise and vibration performance in September 2012. The purpose of this report is to describe the basis of the mumble strip design recommendation and to document the results of the testing performed in District 1.

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# Chapter 2 Development of Recommended Design

The recommended sinusoidal design for the mumble strip is shown in Figure 1. As indicated, the primary features of the design are the peak-to-peak amplitude (or depth into the pavement) and the separation between successive peaks (or the wavelength). The choices of the values for these parameters are discussed in this chapter.

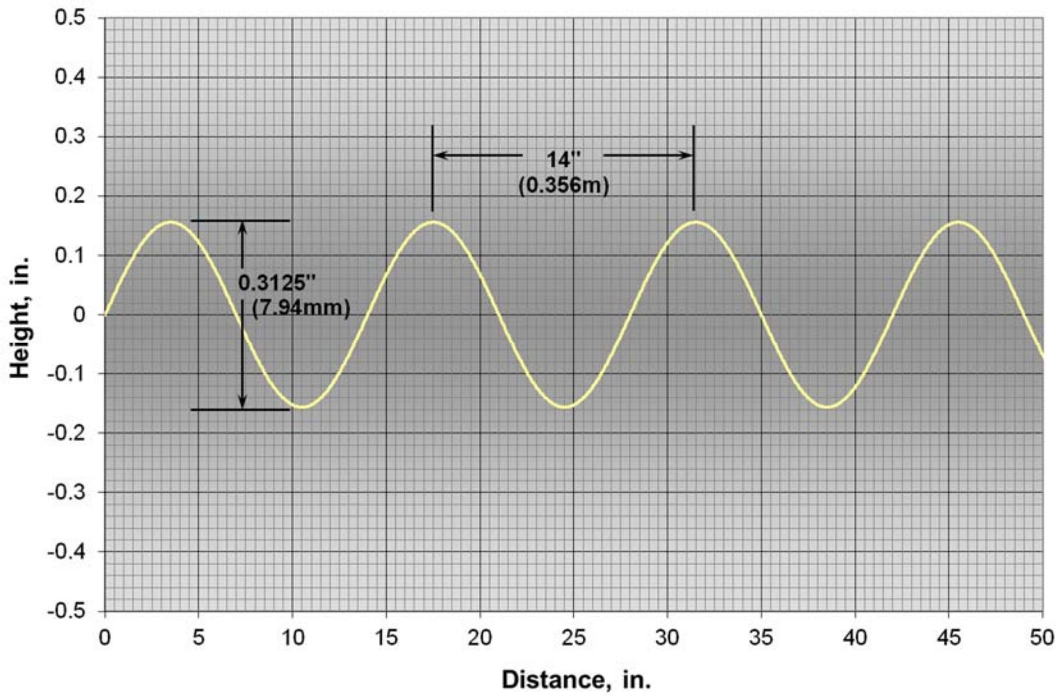


**Figure 1: Recommended sinusoidal profile for mumble strips**

## 2.1 Peak-to-Peak Amplitude

As shown in Figure 1, the mumble strip design features a full depth, peak-to-peak sinusoidal amplitude of $^5/_{16}$ inches. In District 1, bicycle operation is allowed on highway shoulders and, as a result, this dimension was specified by the District based on the information generated and reported by the Pennsylvania Department of Transportation (PennDOT) (Elefteriadou et al. 2000) and Caltrans (Bucko and Khorashadi 2001). The PennDOT study found that a range from ¼ to ⅜ inches was "bike-tolerant," with ¼ inch being preferred. The Caltrans study found that rolled-in or ground-in indentations with a depth of $^5/_{16}$ inches were optimal for bicycle compatibility. The depth required to produce noticeable interior vehicle noise and vibration to alert drivers was not well documented in the literature (Kragh et al. 2007). However, a depth of about $^5/_{16}$ inches (8.42 millimeters) had been found to produce interior noise level increases over tire/pavement noise of at least 6 dB, with corresponding increase in vibration levels (Watts et al. 2001).

## 2.2 Sinusoidal Wavelength

The issue of sinusoidal wavelength, λ, for the mumble strip in the pavement is somewhat more problematic than the amplitude. Research performed in the United Kingdom found that a wavelength of 14.2 inches (0.36 meters) was optimal for producing a noticeable interior noise level and virtually no increase in exterior noise level for vehicle speeds of 30 miles per hour (mph) (Watts et al. 2001). In other research in Demark, a wavelength of 23.6 inches (0.6 meters) was used; however, no interior data was taken (Kragh et al. 2007). The British study concluded that the exterior noise begins to increase as the wavelength decreases to about 13¾ inches, while longer wavelengths generated insufficient interior noise and vibration. The longer wavelength in the Danish study was based on maintaining the same forcing function frequency at 50 mph (80 kilometers per hour) that the British obtained at 30 mph. However, the correlation between forcing frequency and interior noise and vibration was not examined and remains uncertain.

### 2.2.1 Tire Contact Patch Considerations

To develop a recommended wavelength for a speed range from 40 to 60+ mph, the tire geometry and deformation can be considered in relation to the pavement geometry. The footprints of three different tires are shown in Figure 2. The ASTM Standard Reference Test Tire (SRTT) is P225/60R16 in size, while the Goodyear Aquatred and Uniroyal Tiger Paw tires are both P205/70R15 in size.

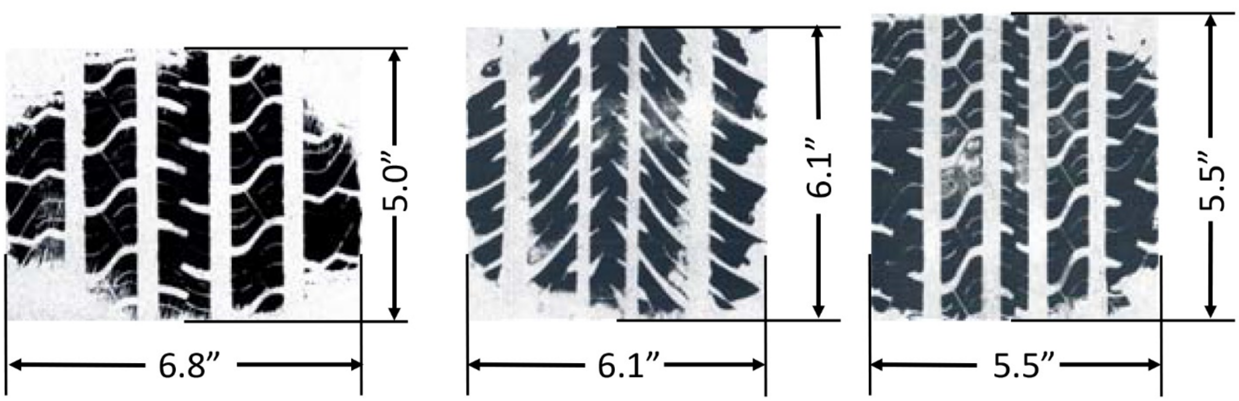


**Figure 2: Tire contact patch geometries for three typical size passenger car tires: SRTT reference tire, Goodyear Aquatred III, and Uniroyal Tiger Paw (left to right)**

For these tires, which are typical for medium to full size cars, the range in the tire contact patch length is 5 to 5½ inches with the length being inversely related to the tire width for the same loading. The nominal deflected radius of these tires and most other passenger car tires is about 12 inches. The scaled geometry for sinusoidal pavement profiles with λ = 23.6 inches and λ = 14 inches is shown in Figure 3 for total depth of $^5/_{16}$ inches along with the dimension of the tire and tire contact patch length. Compared with the dimension of the profile, the tire is quite large initially, suggesting minimal input to the tire and vehicle. To better visualize the relationship of the profile to the tire, the vertical scale of the profile for the λ = 23.6 inch case is doubled and shown in Figure 4. This figure indicates that, as the tire rolls over the pavement, there would be little distortion of the tire contact patch by the contour of pavement because the longer wavelength results in little distortion of the tire contact patch. In this case, very little difference in interior noise and vibration is expected between having the profile present or not. Thus, a wavelength of 23.6 inches would minimize the increase in exterior noise due to the profile, but may not generate sufficient energy that could transmitted into the vehicle as noise or vibration.

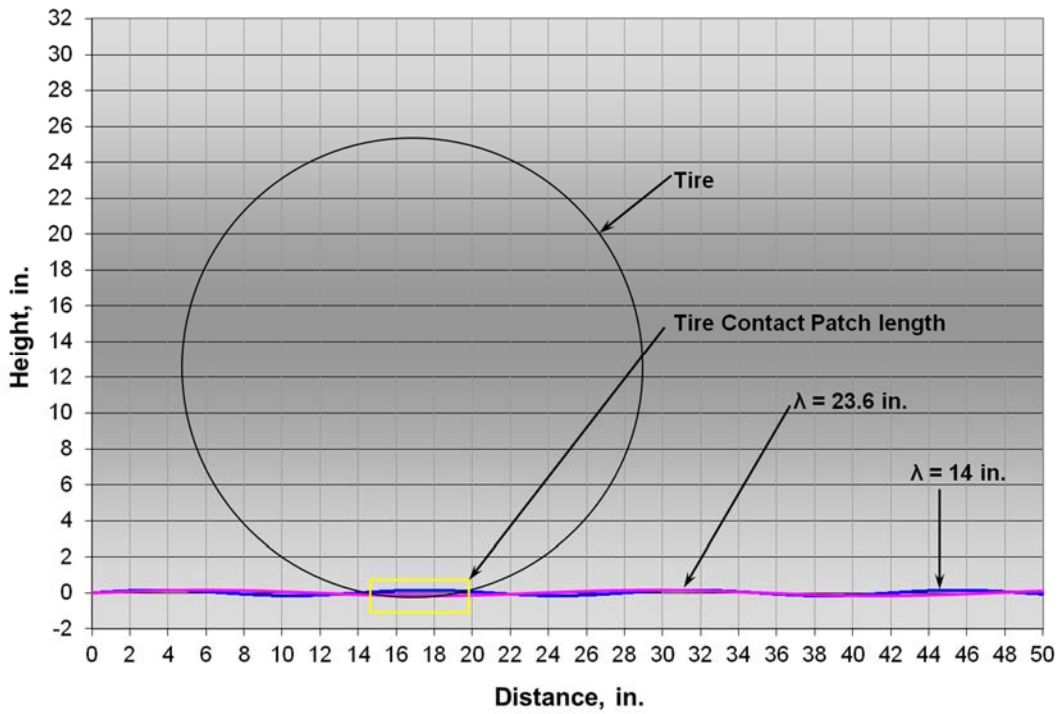


**Figure 3: Relative geometries of rumble strip profiles, typical passenger car tire, and tire contact patch length**

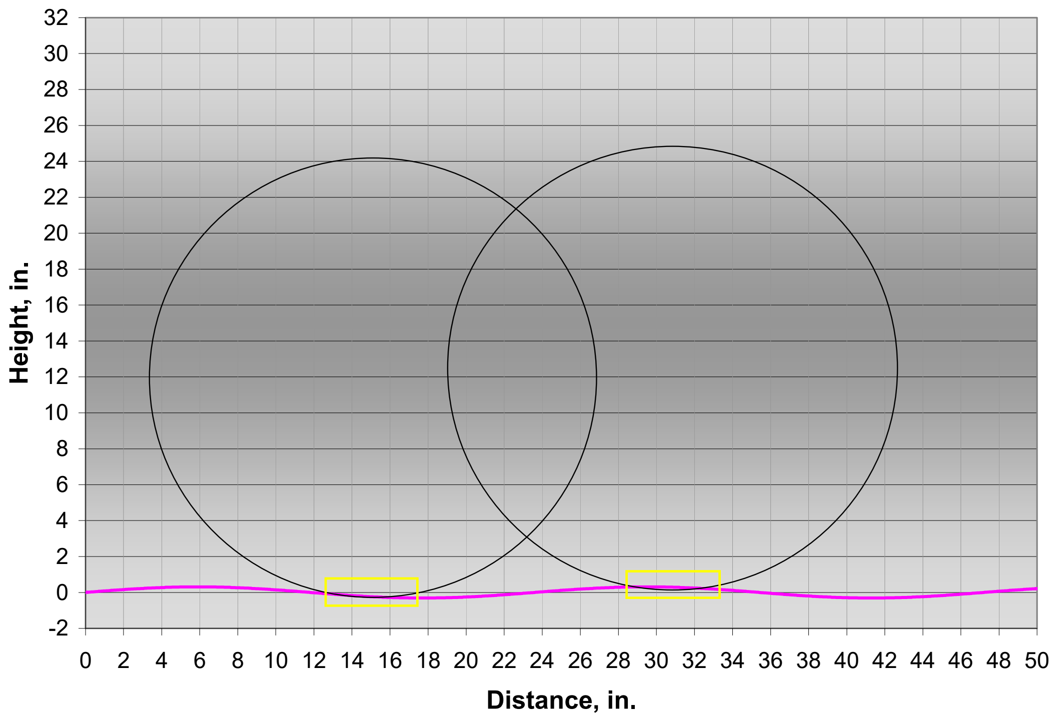


**Figure 4: Relative geometries of typical passenger car tire, tire contact patch length, and exaggerated rumble strip profiles of λ=23.6 inches**

The case for λ = 14.2 inches is illustrated in Figure 5. For this profile, when the tire is in a depression, the curvature of the profile almost matches that of the tire, effectively lengthening the contact patch as the loading is supported over a longer distance. When the tire passes over the raised portion of the profile, the curvature of the pavement is such that the load is applied over a distance shorter than the contact patch as the profile penetrates more into the tire. This fluctuating distortion of the contact patch then applies vibrational input to the tire at the forcing frequency defined by vehicle speed and the wavelength of the profile. If the radius of curvature of road profile becomes smaller than the 12-inch radius of the tire (i.e. when λ is less 12 inches), the tire no longer fits into the depression created in the pavement. This can produce a response in which the tire slaps against the pavement as it attempts to envelope the depression and result in the higher noise levels noted in the British study (Watts et al. 2001). Further, as the tire rolls over the sharper crest of the profile, it may no longer completely conform to the road profile and create some additional exterior slapping noise. As a result, a value of about λ = 14 inches maybe best suited for generating interior response without excessive exterior noise regardless of vehicle speed.

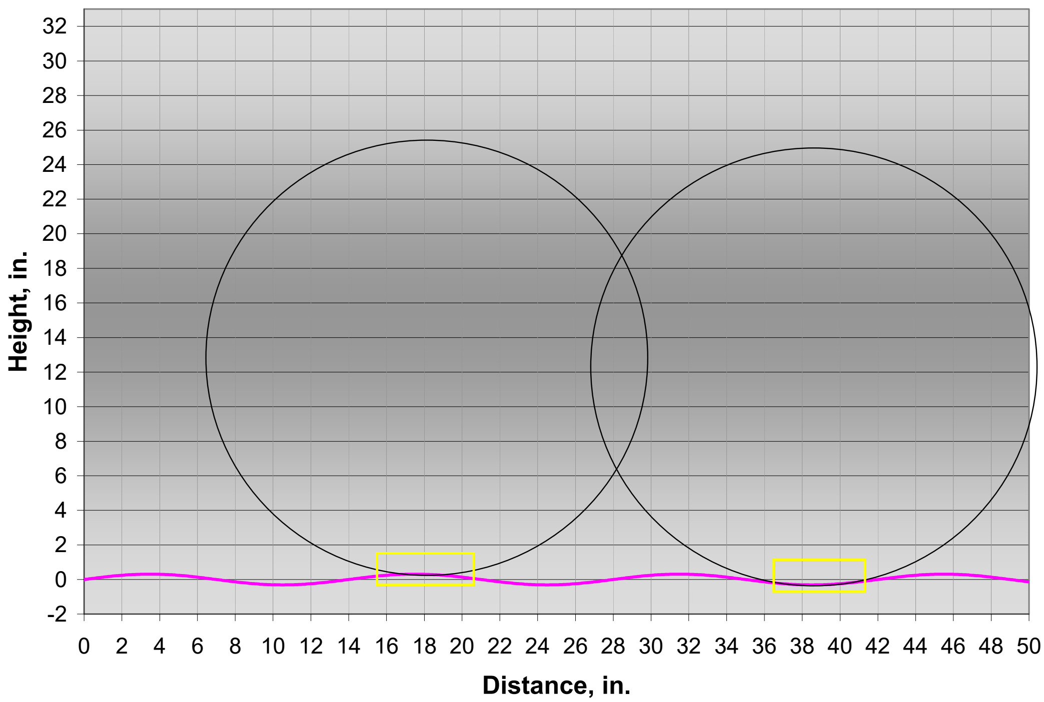


**Figure 5: Relative geometries of typical passenger car tire, tire contact patch length, and exaggerated rumble strip profiles λ=14 in.**

### 2.2.2 Forcing Frequency Considerations

The relationship between vehicle speed and the frequency of excitation to the vehicle is shown in Figure 6 for λ = 23.6, 14, and 12 inches. In selecting a wavelength, the forcing frequency of the rumble strip and the typical response of the vehicles should also be considered. Whole vehicle (rigid) modes typically occur below 5 Hertz (Hz), while first order (whole body) modes of the engine on its mounts occur in the range from about 5 to 12 Hz (Banner et al. 2001). 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 (Constant et al. 2001). 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 (Jen and Lu 2007). In this same frequency range, the modes of tire vibration begin to be encountered (Wheeler et al. 2005). However, tires do not radiate sound efficiently below about 300 Hz; therefore, there is essentially no additional contribution to exterior noise below this frequency (Yum et al. 2005).

From this analysis, it is concluded that it is desirable to: 1) minimize the occurrence of forcing frequencies, below about 40 Hz to avoid larger vehicle modes and suspension modes; 2) maximize the occurrence of forcing frequencies in the range of 40 Hz to 200 Hz where there are many vibration modes in the vehicle system to generate interior noise and vibration; and 3) avoid forcing frequencies of more than about 200 Hz because this is where exterior sound radiation from the tire begins to result. Based on these considerations, λ = 14 inches appeared to be good candidate to produce the desired interior noise and vibration while minimizing the exterior noise.

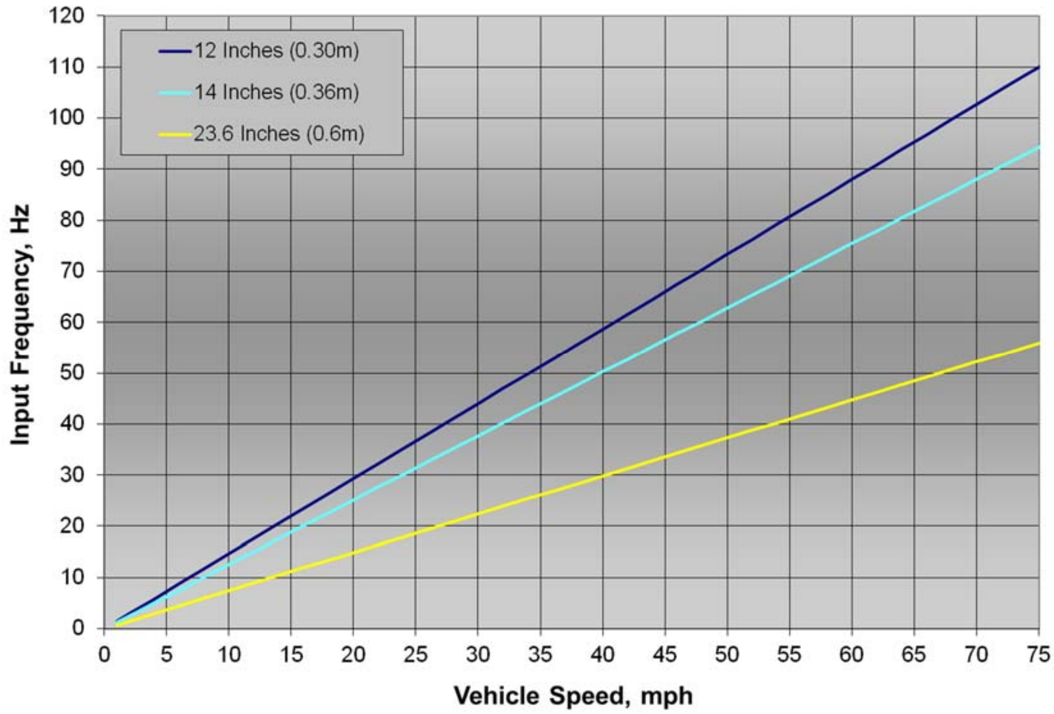


**Figure 6: Forcing function frequency as a function of vehicle speed for different λ values**

## 2.3 Summary

Based on the considerations of being bike friendly, producing minimal exterior noise, and producing maximum interior noise and vibration, the profile shown in Figure 1 appeared to be a good choice for constructing mumble strips for further evaluation. Based on the PennDOT study, the design should be tolerable to bicyclists. In regard to width, it was recommended that width be sufficient that a typical tire, such as the P225/60R16, could ride completely in the profile, implying a width of about 8 inches or greater.

# Chapter 3 Description of the Measurements

This chapter describes the actual warning devices tested, measurement methods, and test vehicles.

## 3.1 Off-the-Road Warning Devices Tested

Three designs of off-the-road warning devices were evaluated: the recommended mumble strip design, a more conventional ground rumble strip, and applied raised pavement markers.

### 3.1.1 Mumble Strip Design

The main purpose of the testing was to document the performance of the mumble strip design proposed in Figure 1. Strips of this design were ground into the shoulder of a section US Highway 101 just north of Arcata, California. The mumble strips were constructed at the edge of the outside lane of travel because there were existing rumble strips cut into the shoulder farther away from the lane of travel. Figure 7 contains photographs of the mumble strips as installed in the northbound direction. Figure 8 contains a close-up photograph of the installed mumble strip. The principles described in Chapter 2 regarding varying tire contact patch geometry, as illustrated in Figure 5, can be seen in the Figure 9 photographs. These two photographs show the tire for the Chevrolet Malibu test vehicle when it is at the peak of the sinusoidal mumble strip and at the trough. The photographs show that the length of the contact patch is shorter when the tire is on the peak of the sinusoid (Figure 9a) then when the tire is in the trough (Figure 9b). This change in the contact patch geometry is intended to drive input to the tire that would be transmitted into the vehicle primarily as vibration at the rates defined by Figure 6 for the 14-inch wavelength. Further, as the tire rolls over the mumble strip, there are no abrupt changes in the profile that would tend to generate higher frequency exterior noise.

**Figure 7: Photographs of mumble strips installed on US Highway 101**

**Figure 8: Close-up photograph of mumble strips installed on US Highway 101**

**Figure 9: Photographs of the test tire on crest of the mumble strip (left) and in the valley of the mumble strip (right)**

On the opposite side of the highway (southbound direction), the mumble strip appeared to have a somewhat different profile, as shown in Figure 10. On this side, the sinusoidal shape is not full depth and the top has a flat plateau. However, the transition between the sinusoid and the flat top is somewhat gradual and may not necessarily generate higher frequency input. Also, because of the plateau, the distortion of the contact patch may be reduced somewhat from the full depth mumble strip, which would potentially reduce the input to the vehicle. The distance between the troughs was 14 inches, as it was in the northbound direction. The performance of the warning devices on either side of the highway was measured and is documented in the appendix.

**Figure 10: Photographs of mumbles installed on the southbound side of US Highway 101**

### 3.1.2 Conventional Ground Rumble Strips

For comparison to the mumble strips, conventional ground rumble strips located on nearby State Route (SR) 229 east of Arcata were also measured. Figure 11 contains photographs of these rumble strips. 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 12 inches, with flat spots about 8 inches in length and depressions about 4 inches long. The strips had been placed in both the eastbound and westbound directions of travel and appeared to be similar from one side of the highway to the other. The transition between the depressions and the plateaus was not particularly gradual and could be expected to generate higher frequency content compared with the mumble strips in Figures 7 and 10.

**Figure 11: Photographs of ground rumble strips on State Route 299**

### 3.1.3 Type A Pavement Markers (Dots)

A small section of Type A pavement markers, or dots, was also installed among the mumble strips on US Highway 101. Figure 12 contains photographs of these warning devices. One hundred dots were installed at 12 inches on center, producing a total length of about 100 feet with mumble strips on either end. The raised pavement markers were 4 inches in diameter with a maximum height of about 1 inch. The short length of the dots and their proximity to the mumble strips made it difficult to get clean, consistent data on them and, as a result, only limited data are reported.

**Figure 12: Photographs of Type A raised pavement markers (dots) installed on US Highway 101**

## 3.2 Measurement Methods

Four types of noise and vibration data were collected for the evaluation of the different warning devices. Two types of exterior noise measurements were taken: 1) conventional pass-bys; and 2) on-board sound pressure level. These measurements were intended to document the potential of the warning devices to generate noise in the surrounding environment. Interior noise and vibration measurements were intended to quantify the warning effect on vehicle operators and occupants and included interior noise and vibration data. The data for all measurements were captured in the field using 2-channel Larson Davis 3000 Real Time Analyzers (RTAs). The RTAs were set for $\frac{1}{8}$ second exponential averaging, or “fast” sound level meter response, and sampled every $^{1}/_{10}$ of a second. The signals were also captured on solid state recorders.

### 3.2.1 Exterior Noise

The most direct comparison of the noise effects of the warning devices in the environment was provided by pass-by noise measurements on each of the test vehicles. These measurements were consistent with the American Association of State Highway Officials (AASHTO) test procedure TP 98 for Statistical Isolated Pass-by (SIP) measurements (American Association of State Highway and Transportation Officials 2012a). The set-up for these measurements at a mumble strip installation is shown in Figure 13. The measurement microphone was located 25 feet from the centerline of vehicle travel at a height of 5 feet. The events were controlled pass-bys with either Caltrans or Illingworth & Rodkin, Inc. (IR) operators for the test vehicles. The pass-bys were done at a speed of 60 mph only. The vehicles passed by in platoon fashion. First, measurements with the vehicle operating on the strips were completed for all vehicles. Then the microphone was moved closer to the road so that is was 25 feet from the center of the outside lane of travel, which was then used by the test vehicles. The data from pass-bys off the strips provided a baseline of comparison for the corresponding data from pass-bys on the strips. Because the pavement on US Highway 101 at the dots was similar to that at the mumble strips, no baseline pass-bys off the dots were measured at that location. Sound pressures were measured using ½ inch Larson Davis model 2560 random incidence microphone fitted to a ½ inch Larson Davis model PRM 900C microphone preamplifier.

**Figure 13: Photograph of Malibu pass-by measurement on the mumble strips on US Highway 101**

The 2012 tests were intended to measure the tire/pavement noise source strength on the outside of the vehicle using on-board sound intensity (OBSI) measurements consistent with the AASHTO TP 76 procedure (American Association of State Highway and Transportation Officials 2012b). These measurements were attempted at a test speed of 20 mph on the mumble strips; however, the vibration input created a very large transverse oscillatory motion of the OBSI fixture, ruling out OBSI measurements with the conventional set-up. To acquire at least some exterior sources, a microphone was secured to a vehicle using the L-bracket of the OBSI fixture mounted at the top of the right rear tire wheel housing, as shown in Figure 14. The ½ inch Larson Davis 2560 microphone was fitted with a 3½ inch diameter windscreen to reduce the effects of air flow, and a second windscreen was placed underneath the microphone preamplifier in an attempt to isolate it from vibration. For most of the vehicles and strip designs, the microphone in this location identified a difference of at least 10 dB for vehicles traveling on the warning strips compared with vehicles traveling off the warning strips. OBSI measurements were conducted in 2015 with the use of a modified fixture, as discussed in Chapter 7.

**Figure 14: Photograph of on-board microphone mounted above the wheel opening at the right rear tire of the Civic test vehicle**

### 3.2.2 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 J1447 procedure for each of the passenger vehicle tested (Society of Automotive Engineers 2000). For the medium truck included in the testing, the interior microphone was positioned opposite the head location in the center of the cab. Photographs of the interior microphone mounted in one of the passenger vehicles and in the medium truck are shown in Figure 15. The microphone system was the same as used for the exterior noise measurements.

To quantify the tactile inputs to the vehicle driver and occupants, acceleration levels were measured on the steering column and at the outboard seat track mounting location for the right front seat. Photographs in Figure 16 show accelerometers mounted in these positions in one of the passenger vehicles. These measurements were consistent with those widely used by the U.S. automotive industry for characterizing vibration level relative to human response (Meinhardt et al. 2011). The seat track acceleration was measured with a PCB 27 gram model 353B33 accelerometer and steering column a PCB 5.8 gram model 352C33 accelerometer.

**Figure 15: Photographs of the interior noise microphone mounted in the Malibu test vehicle and in the 4-yard dump truck**

**Figure 16: Photographs of accelerometers mounted on the seat track (left) and the steering column (right) on the Malibu test vehicle**

## 3.3 Test Vehicles and Test Matrix

Altogether, the five test vehicles tested spanned a range of vehicle type, weight, wheelbase, and tire size. For a shorter wheelbase, smaller tire size, and lighter weight car, a Caltrans fleet Honda Civic was used. For medium wheelbase, mid-size tire size, and intermediate weight car, an IR Chevrolet Malibu was used. A Ford Expedition from the Caltrans fleet was used to represent a heavier, longer wheelbase and larger tire size vehicle. The forth 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. In 2015, a Ford Fusion passenger car was used to provide a wheelbase between that of the Malibu and Expedition and a low-profile tire design. Figure 17 contains photographs of these five vehicles. The three passenger cars were all unibody construction with the suspension components attached directly into the body structure through isolators. The Expedition was a body-over-frame construction in which the suspension components attached to a full frame through isolators and the body attached to the frame through isolators, providing double isolation. The 4-yard dump truck was also full frame design with the cab isolated from the frame.

The measurements were made at 60 mph for all vehicles. These measurements were readily accomplished without any traffic control because the highway speed limit was either 55 or 65 mph and traffic volume allowed for clean, isolated pass-by measurements. To evaluate the effect of speed on the interior and exterior on-board levels, the Malibu was also tested at 20 and 40 mph on the mumble strips and rumble strips. This lower speed testing was limited to one vehicle because it required rolling lane closures to safely accomplish. The complete test matrix is shown in Table 1. Interior and exterior on-board noise measurements were collected in both directions of travel. The matrix then contained 88 combinations of test vehicles, speed, measurement type, and warning device type. For each of these combinations, multiple runs were made to produce consistent results because it was difficult to maintain the wheel path on the center of the narrow warning devices.

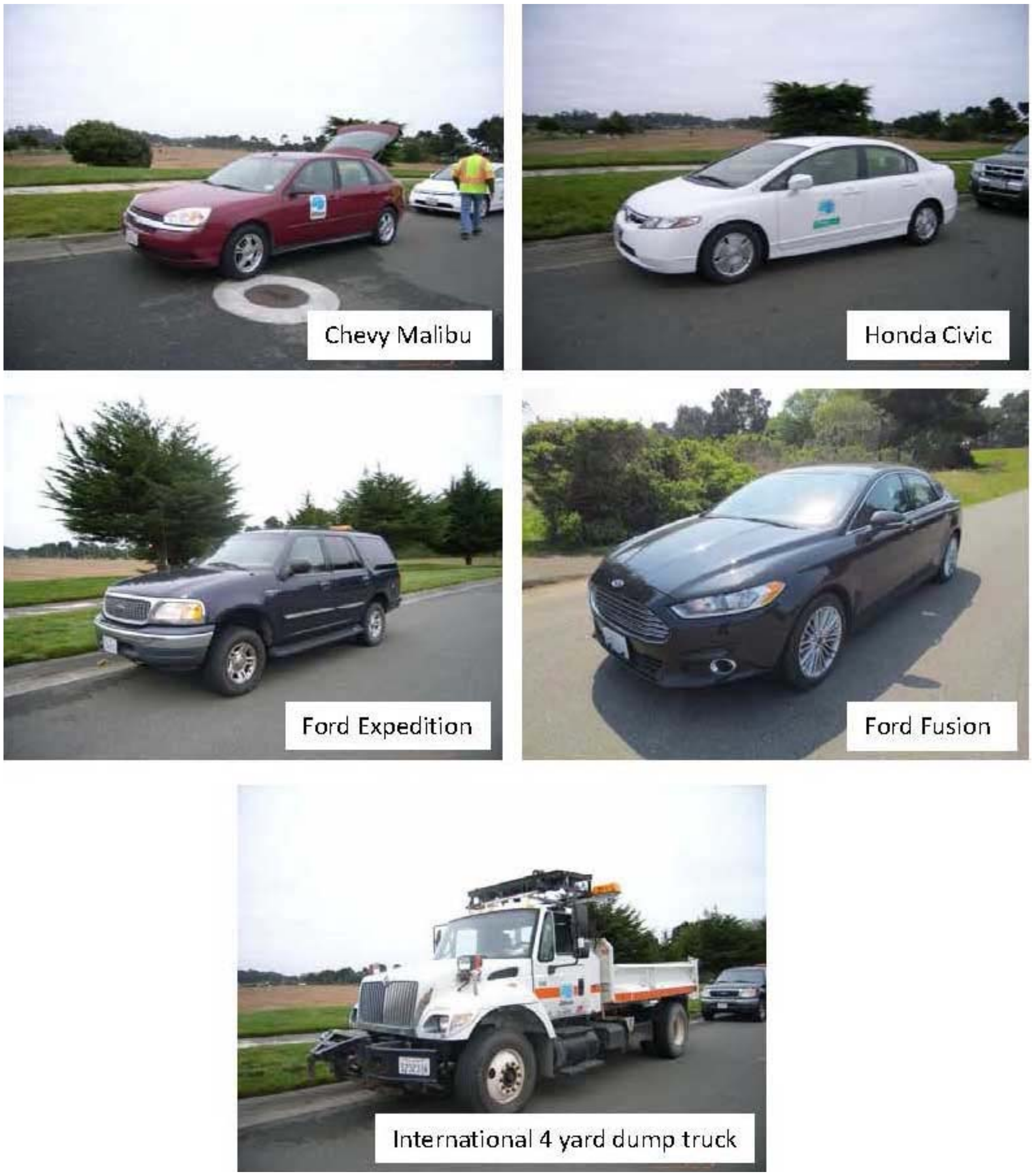


**Figure 17: Photographs of the five test vehicles**

**Table 1: Test Matrix for Mumble Strips (MS), Ground Rumble Strips (RS), and Dots**

| Vehicle | Speed, mph | Measure Type for Each Warning Device Type | | | |
|---|---|---|---|---|---|
| | | Pass-By | Exterior Noise | Interior Noise | Interior Vibration |
| Honda Civic | 60 | MS, RS, Dots | MS, RS | MS, RS | MS, RS |
| Ford Expedition | 60 | MS, RS, Dots | MS, RS | MS, RS | MS, RS |
| 4-Yard Dump | 60 | MS, RS, Dots | | MS, RS | MS, RS |
| Ford Fusion | 60 | MS, RS | MS, RS | MS, RS | MS, RS |
| Chevy Malibu | 60 | MS, RS, Dots | MS, RS | MS, RS | MS, RS |
| Chevy Malibu | 40 | | MS, RS | MS, RS | MS, RS |
| Chevy Malibu | 20 | | MS, RS | MS, RS | MS, RS |

## 3.4 Data Processing

Processing of the results was somewhat different depending on the type of measurement. The pass-by measurements are transitory in nature, requiring identification of the maximum noise level as the vehicle passes by. The on-board measurements, both interior and exterior, in principle are steady state. However, variation in these steady levels results when the test tire path varies in and out of the line of the warning devices.

### 3.4.1 Vehicle Pass-By Measurements

For each pass-by event, a 5-second time history of the overall A-weighted pass-by sound level was obtained with the RTA. Pass-by events were sampled at a rate of $^{1}/_{10}$ second, which is sufficient to capture the maximum level produced by the ⅛ second exponential averaging time. Time histories collected for the Malibu test vehicle traveling on and off the mumble strips are shown in Figure 18. These measurements consisted of seven runs nominally on the strips and six off the strips. For the runs on the strips, the maximum sound levels ranged from 84.3 dBA for Run 1 to 93.1 dBA for Run 27. This range is in part due to the vehicle wandering from the line of the strips and in part due to normal statistical variation in the transient pass-by measurements. For the statistical variation, common practice is average several runs together. For these data, Runs 5, 9, 13, and 21 were averaged. Run 27 was discarded because it alone produced 3.7 to 5.0 dB higher levels than the selected runs. The selected runs had an average of 88.6 dBA. The maximum levels for the pass-bys off the strips were averaged to produce a level of 83.2 dBA. The one-third octave band (⅓ OB) spectra corresponding to the four maximum levels were extracted from the data and are shown in Figure 19. These were averaged to produce an average spectrum for the Malibu on the mumble strips at 60 mph. For reference, a typical spectrum off the strips is also shown in Figure 19. This process was applied to the data obtained for all four vehicles traveling on all three warning devices and traveling off the devices on US Highway 101 and SR 299.

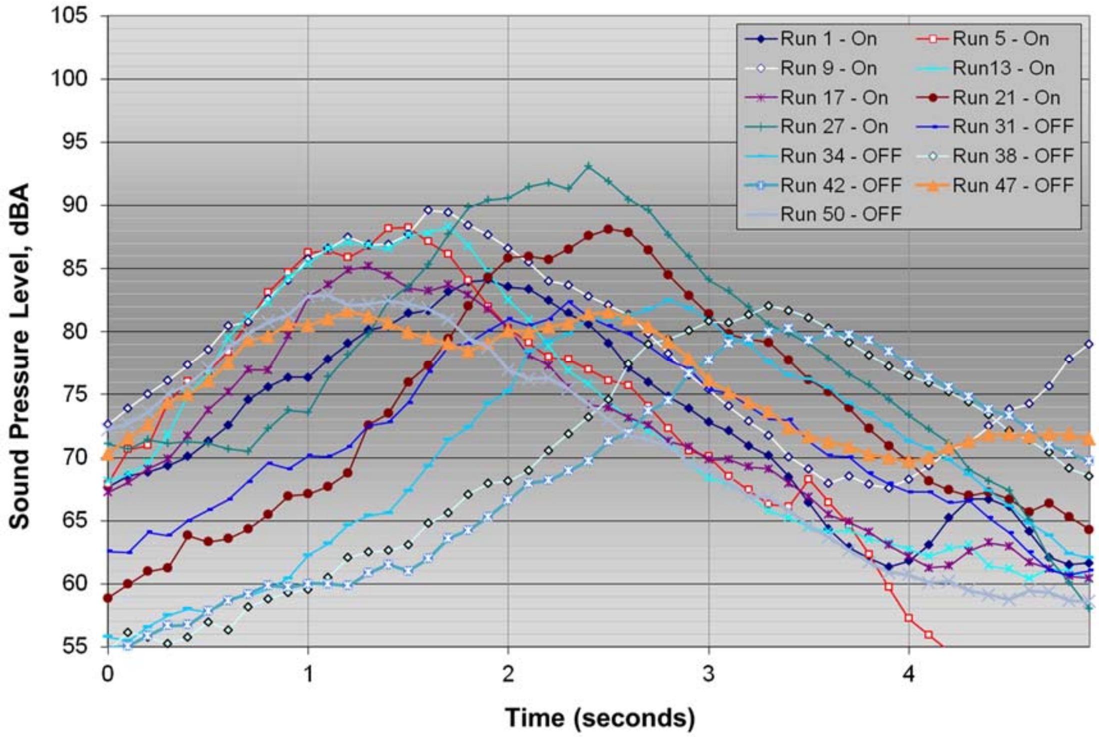


**Figure 18: Pass-by time histories for travel on and off the mumble strips by the Malibu test vehicle**

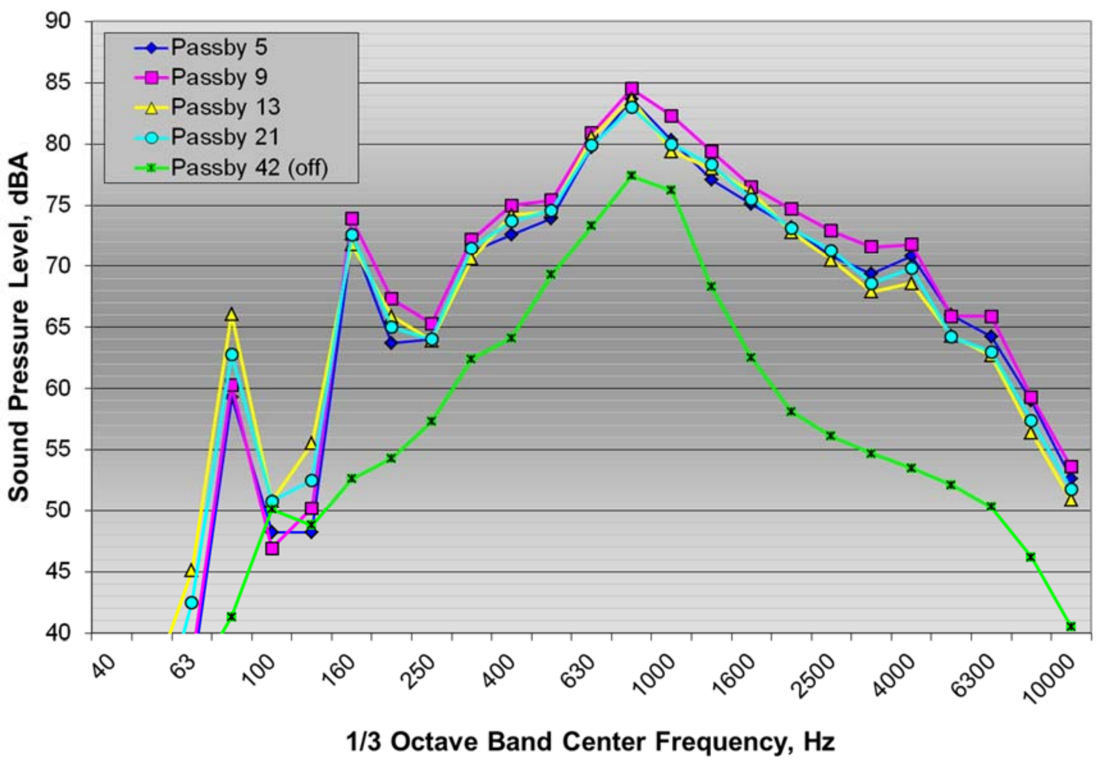


**Figure 19: Spectra at maximum overall A-weighted sound level for multiple pass-bys on the mumble strips and one pass-by off the strips by the Malibu test vehicle**

### 3.4.2 On-Board Measurements

Processing was the same for exterior noise (above the wheel well), interior noise, and vibration measurements taken at the two test locations. These data were also captured for 5 seconds using ⅛ second exponential averaging time and a 1/10 second sampling rate. An example of time histories of the interior noise data measured with the Malibu traveling on and off the mumble strips is shown in Figure 20. The data collected while the Malibu was on the strips clearly illustrate the wandering on and off the strips that can occur during any one run. For these data, typically the run with the highest noise or vibration level was used if there was a period of time when the levels were steady for at least 1 second. The justification for using the highest levels was that these data were most likely to occur when the tire was fully on the strip. For the data shown, Run 12 was selected for a time period from 1.9 to 3.2 seconds. The samples from each of the 0.1-second interval in this range were averaged to determine the overall level of 90.6 dBA for this test condition. For the measurements of the Malibu traveling off the strips, typically a run with a lower noise or vibration level for which there were relatively constant levels over at least a 1-second interval was selected. In the case of Figure 20, Run 12 was used between 2.4 and 3.7 seconds, which produced an average level of 71.5 dBA. To obtain average ⅓ OB spectra, the same averaging process and time interval were producing the results of Figure 21 for the mumble strips and the Malibu test vehicle.

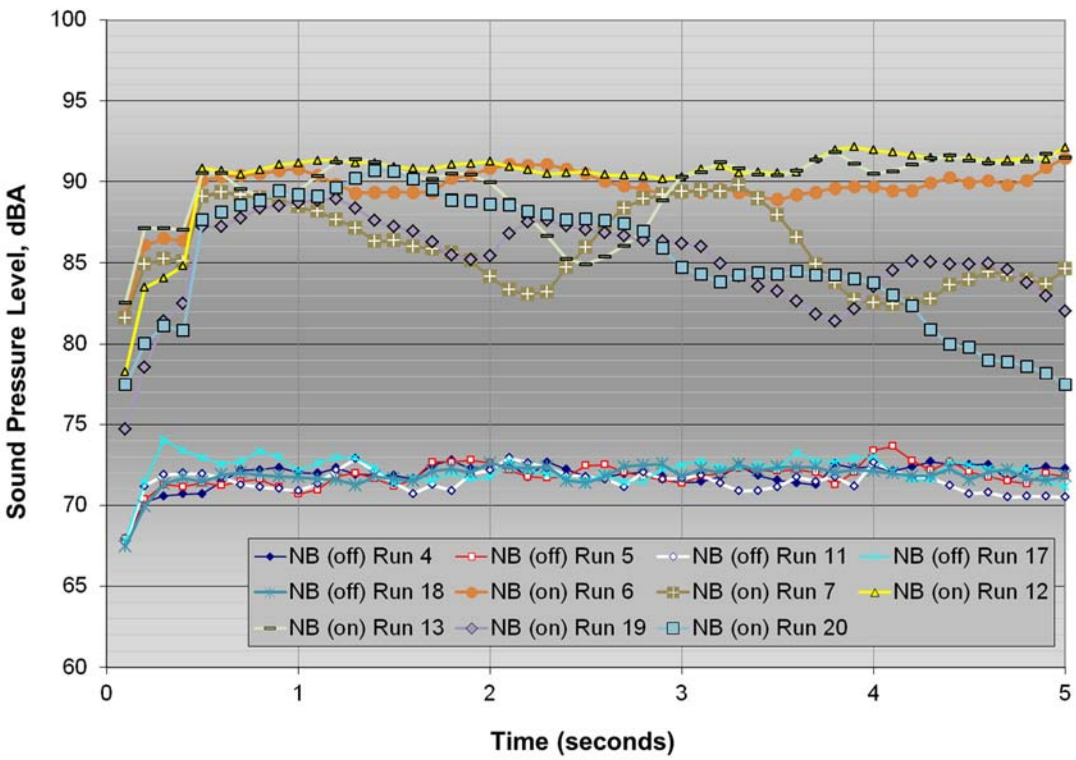


**Figure 20: Interior noise measurement runs on and off the mumble strips by the Malibu test vehicle**

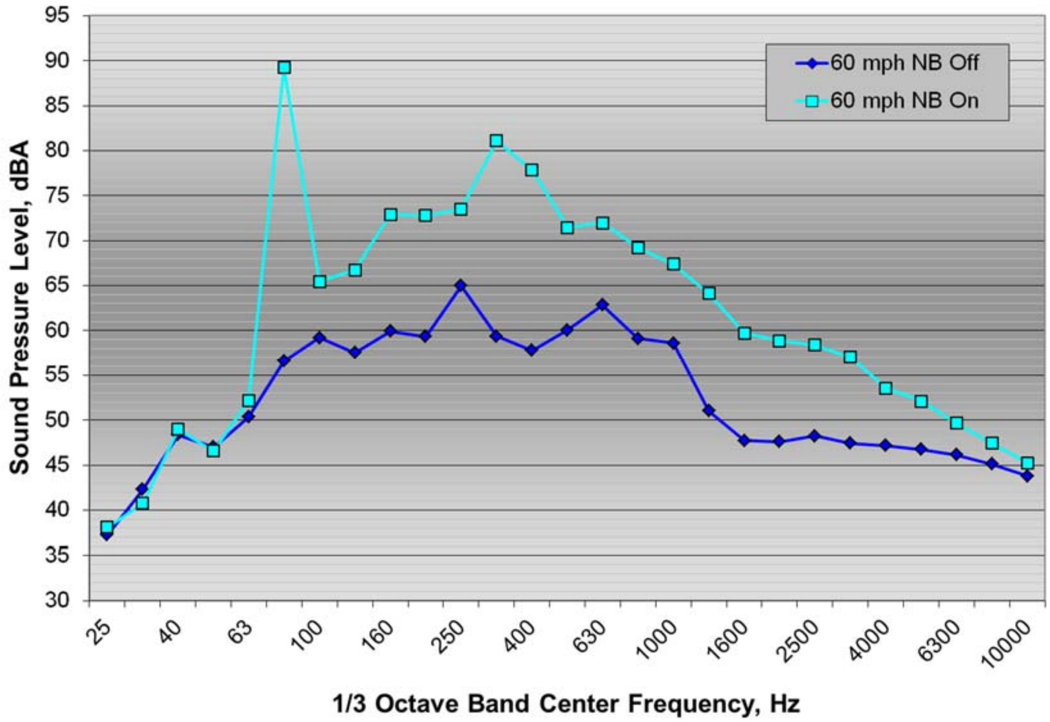


**Figure 21: Interior noise ⅓ octave band spectra for the Malibu test vehicle traveling on and off the mumble strips**

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# Chapter 4 Results of Exterior Noise Measurements

The exterior measurements include both the pass-by data and the on-board exterior noise data collected on the outside of the vehicle at the top of the right rear wheel well (see Figure 14). The goal of the mumble strip design is to reduce the exterior noise. The results for both of these types of measurement are presented and discussed in this chapter.

## 4.1 Pass-By Measurement Results

The overall A-weighted pass-by noise levels for all five test vehicles on the three warning devices (with the exception of the Fusion on the dots) and off the strips of the two highway surfaces are shown in Figure 22. With respect to the ground rumble strips and dots, the mumble strips achieved the goal of producing lower levels of pass-by noise.

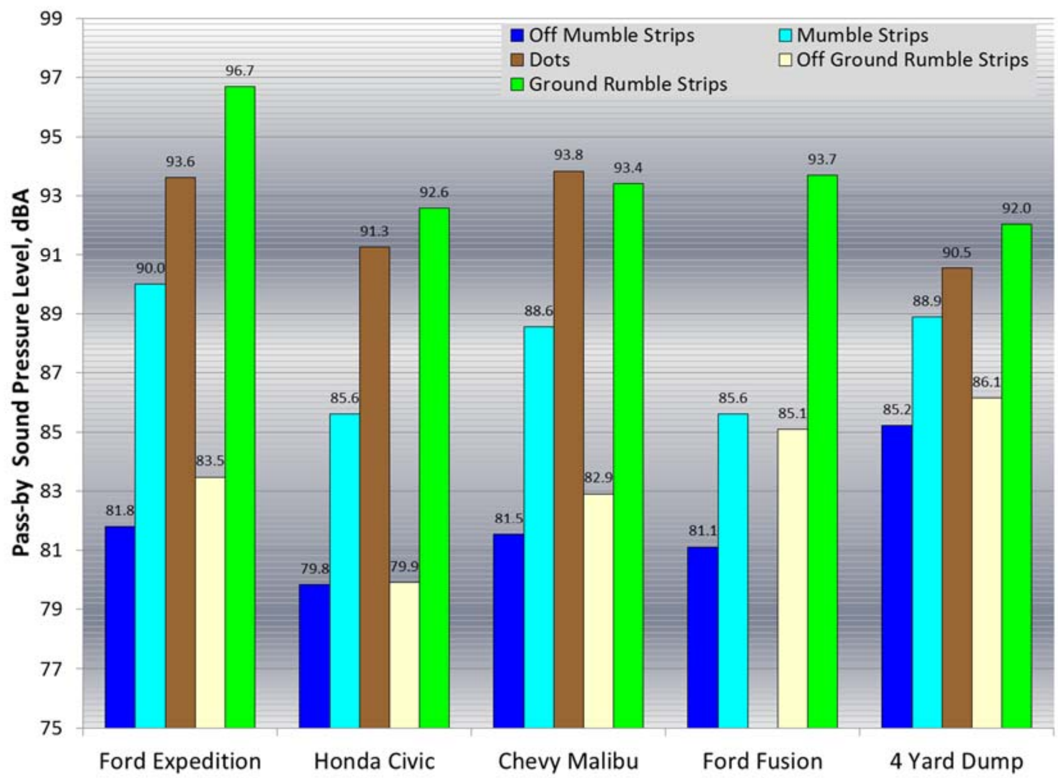


**Figure 22: Overall A-weighted pass-by sound pressure levels for all four test vehicles on three types of warning devices**

For all of the vehicles, levels on the mumble strips are lower than the levels on the other two devices. For the passenger vehicles, the levels on the mumble strips are 6.6 dB lower on average than on those on the ground rumble strips and 4.8 dB lower than on the dots. For the truck, the mumble strips produce differences of 3.2 dB and 1.7 dB relative to the ground rumble strips and dots, respectively. The differences in noise levels of vehicles traveling on warning devices compared with noise levels of vehicles traveling off the warning devices suggest there is still room for improvement in the mumble strips. For the passenger vehicles, the difference is 6.4 dB on average. For the truck, this difference drops to 3.7 dB, but primarily because the off-device pass-by levels are 3.4 to 5.4 dB higher than the passenger vehicle pass-by levels. With higher off-strip levels, the difference between mumble and ground rumble strips for the 4-yard truck is 3.2 dB, which is less than for the passenger vehicles. The overall pass-by noise levels vary from vehicle to vehicle. On the ground rumble strips, the levels are fairly consistent across the vehicles except for the Expedition, which produces noticeably higher levels than do other vehicles (3.0 to 4.7 dB). On the mumble strips, the levels for the Honda and Fusion are noticeably lower than for the other vehicles (3.0 to 4.3 dB).

One-third octave band levels are compared in Figure 23 for the Malibu test vehicle for all of the pass-by measurements on and off the warning devices. Between 250 Hz and 2500 Hz, lower ⅓ OB levels are typically produced on the mumble strips than on the ground rumble strips and dots. The dots produce more noise at higher frequencies above 1000 Hz and at the specific lower frequencies of the 100 and 250 Hz bands. The differences at these lower frequencies for vehicles on the dots and levels for the mumble and ground strips are 17.5 to 26 dB at 100 Hz, and 13.3 to 20.2 dB at 250 Hz. When vehicles travel on the mumble strips, peaks are also seen in the lower frequencies, but at 80 and 160 Hz. Vehicles traveling on the ground rumble strips produce a pronounced peak only at 160 Hz. As Figure 24 indicates, the Honda Civic displays the same trends, with the mumble strips producing lower ⅓ OB levels above 250 Hz. However, when this vehicle travels on the dots, peaks at 100 and 250 Hz are not nearly as pronounced as they are for the Malibu. The Civic's peak at 80 Hz on the mumble strips is more pronounced than the Malibu's peak, and the amplitude is 5.2 dB higher than the Malibu's. The results for the Ford Fusion are quite similar to results for the Honda Civic, as shown in Figure 25. The most prominent deviation is at 250 Hz, where there is a peak in the Fusion results that does not appear in the Civic spectrum. As seen in Figure 26, the Expedition produces similar trends in the higher frequencies; however, the Expedition traveling on mumble strips produces a pronounced peak of 74.9 dBA at 80 Hz, or 7.6 dB higher than the Civic produces at 80 Hz.

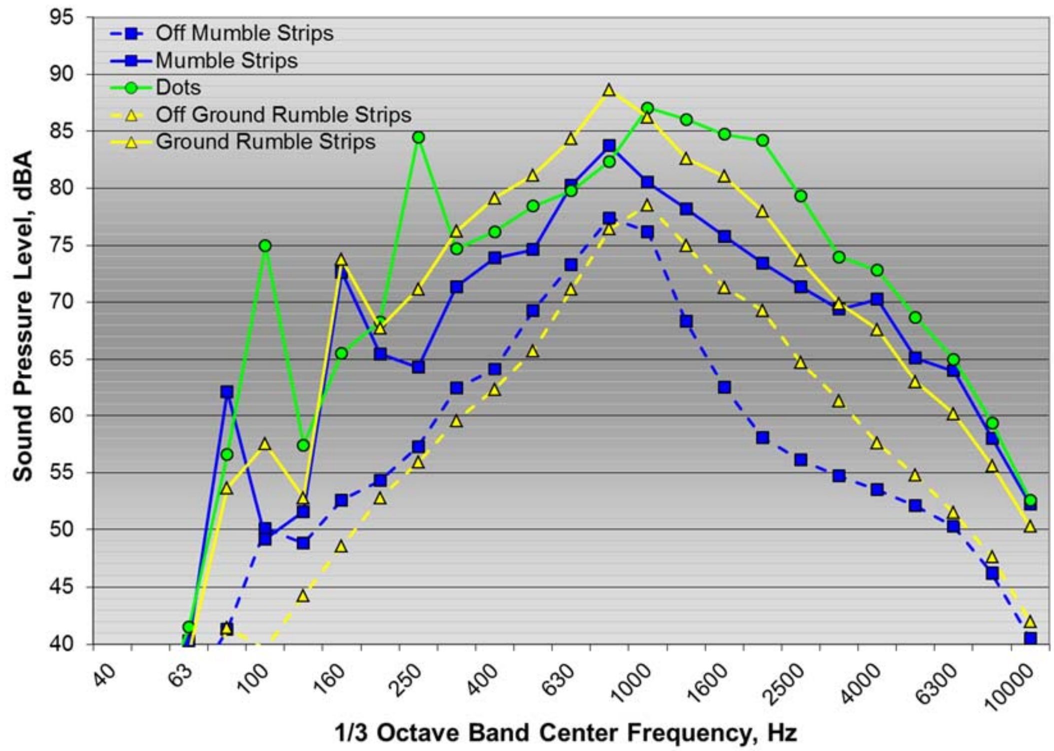


**Figure 23: ⅓ octave band pass-by spectra for Malibu test vehicle on (solid lines) and off (dashed lines) mumble strips, dots, and ground rumble strips**

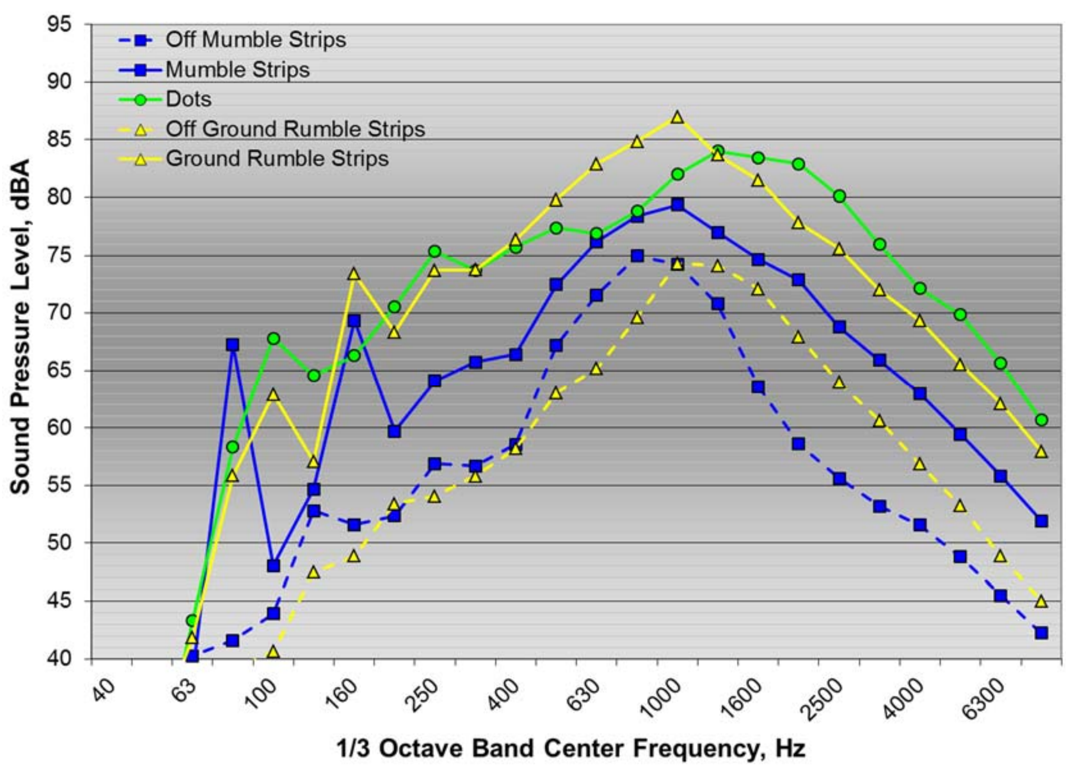


**Figure 24: ⅓ octave band pass-by spectra for Civic test vehicle on (solid lines) and off (dashed lines) mumble strips, dots, and ground rumble strips**

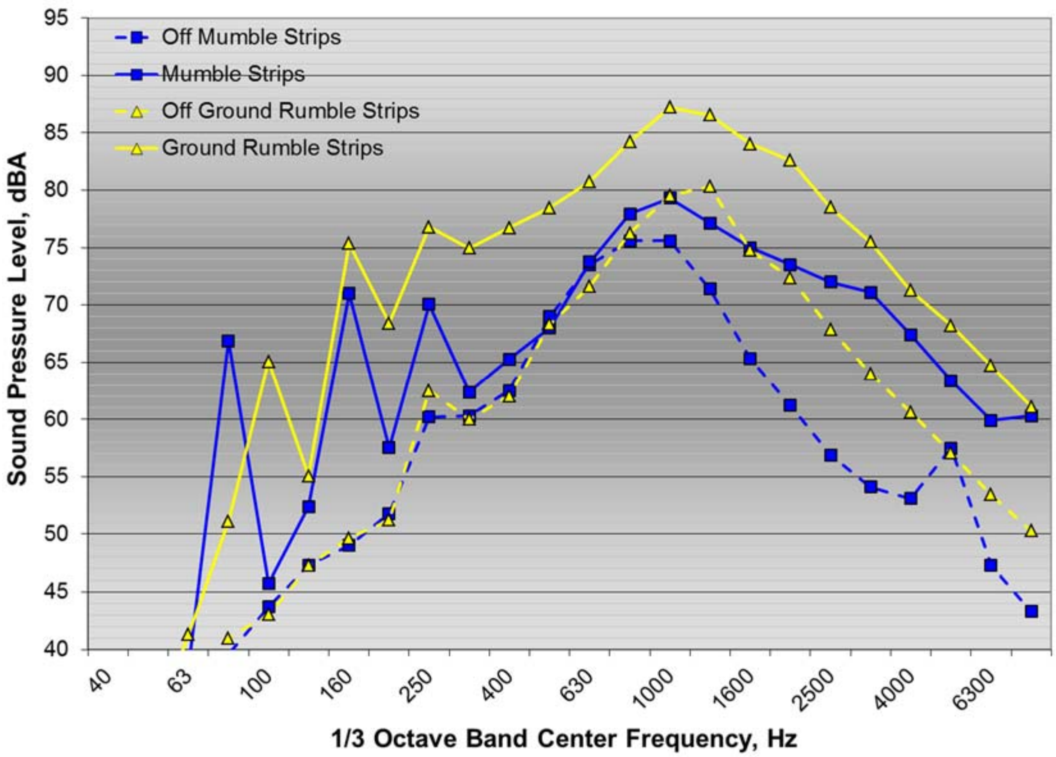


**Figure 25: ⅓ octave band pass-by spectra for Ford Fusion test vehicle on (solid lines) and off (dashed lines) mumble strips and ground rumble strips**

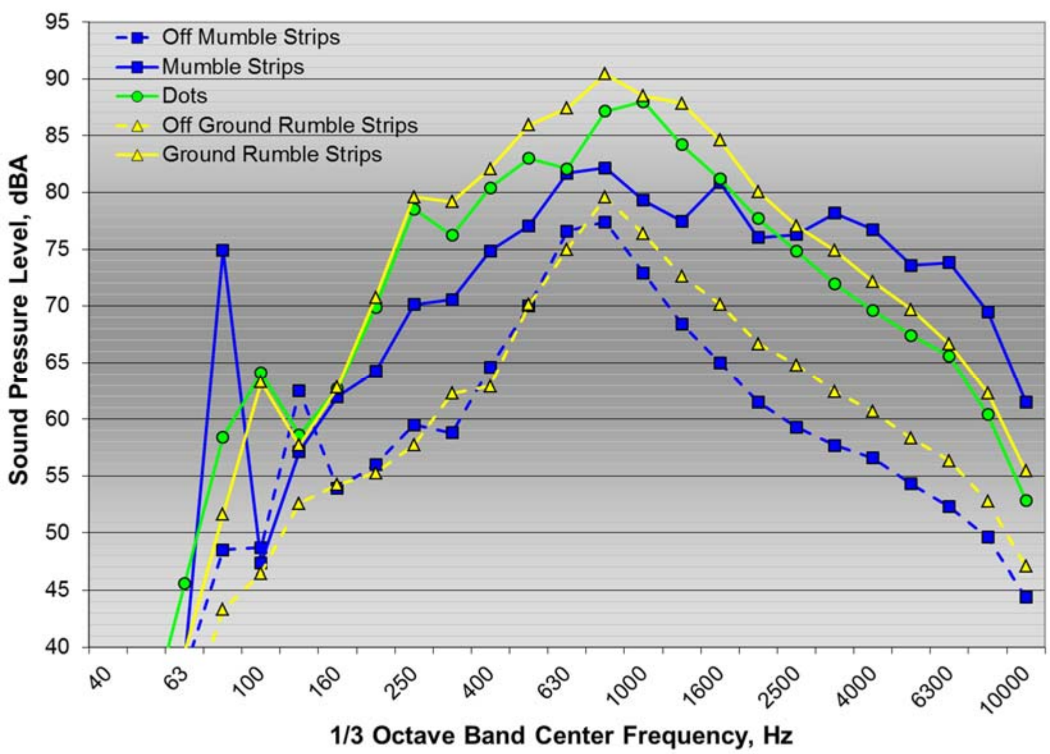


**Figure 26: ⅓ octave band pass-by spectra for Expedition test vehicle on (solid lines) and off (dashed lines) mumble strips, dots, and ground rumble strips**

For the dump truck, the higher frequency trends still old, but the differences in the warning devices is greatly reduced, as shown in Figure 27. In the lower frequencies, pronounced peaks are seen at 80 and 160 Hz when the dump truck travels on the mumble strips.

Some of the frequency dependences noted for Figures 23 through 27 become more apparent if the spectra for four vehicles are considered together for each type of device. For the mumble strips, the peak at 80 Hz is apparent on all vehicles although with a substantial range in sound level (12.8 dB), as shown in Figure 28. At 60 mph (88 feet/second), the 14-inch (1.167-foot) wavelength corresponds to a frequency of 75.4 Hz, which falls directly in the 80 Hz ⅓ OB; thus, each vehicle is driven at this frequency. Because the radiation efficiency of tires is very poor at these low frequency, the sound produced is likely from other vehicle parts, such as body panels, responding to the vibrational input (see Chapter 7). This could account for the large difference in sound levels among the different vehicles. For the first harmonic of the mumble frequency at 160 Hz, peaks are seen for all vehicles except the Ford Expedition. The lack of response for the Expedition may be due to better road isolation for this full-frame vehicle or less effective sound radiation from its larger body panels. Between 200 and 1000 Hz, there is as much as a 10 dB difference among the light vehicles, with the Fusion being the quietest in this range except at 250 Hz. In this frequency range, the differences may still be due to differences in panel response or differences in vehicle isolation. Above 1250 Hz, the sound levels for the Expedition are consistently higher than for the other vehicles and also significantly higher than the off-strip pass-by levels (see Figure 26). In these higher frequencies, it is possible that the vibration input creates some nonlinear rattle or other noises.

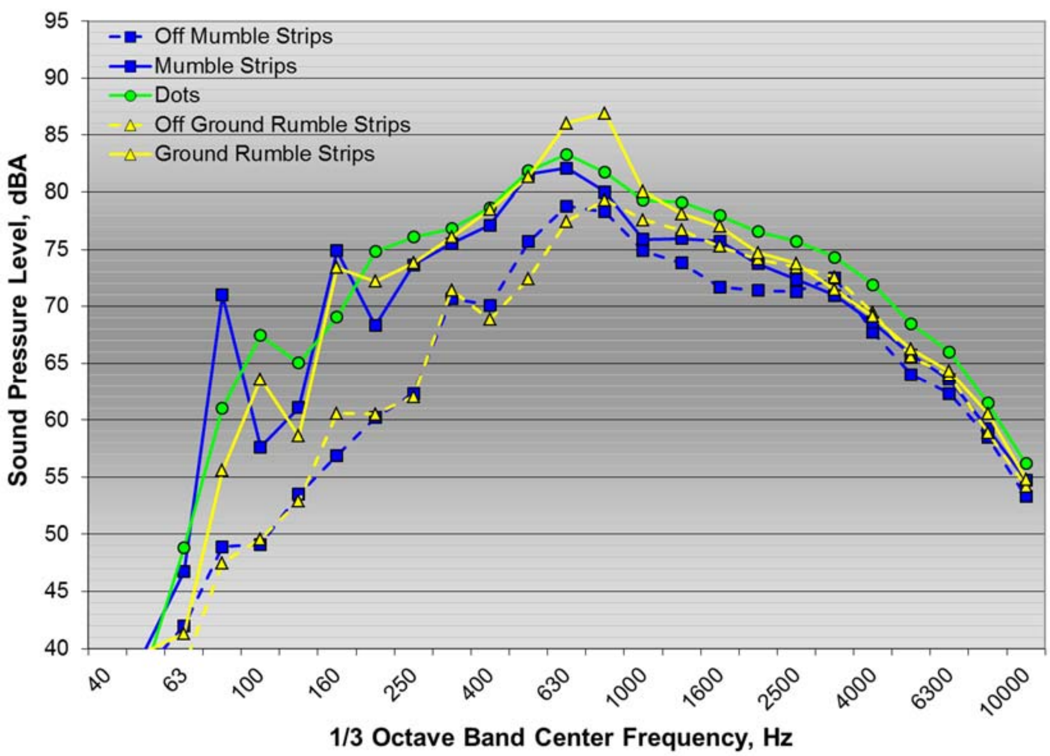


**Figure 27: ⅓ octave band pass-by spectra for 4-yard dump truck test vehicle on (solid lines) and off (dashed lines) mumble strips, dots, and ground rumble strips**

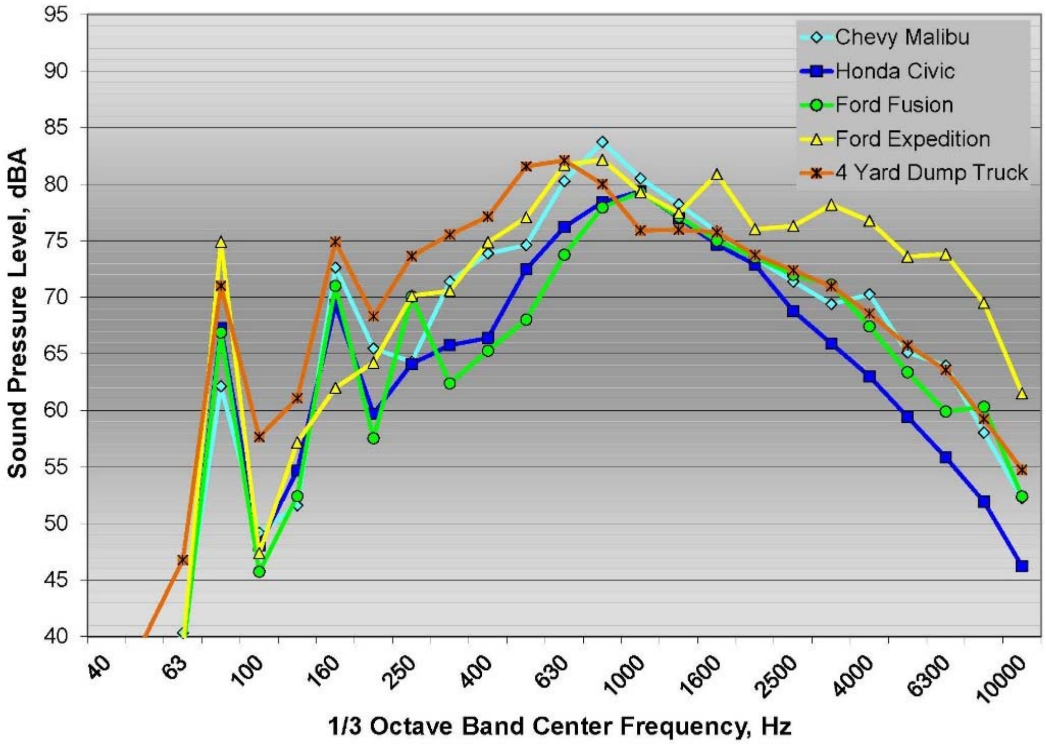


**Figure 28: ⅓ octave band pass-by spectra on mumble strips for all five test vehicles**

Figure 29 provides a comparison of sound levels from vehicles traveling on the ground rumble strips. On these devices, the differences among vehicles are somewhat less than the differences when the vehicles travel on the mumble strips. All five vehicles display a small peak in sound level in the 100 Hz ⅓ OB. At 60 mph, the 12-inch spacing of the strips has a repetition rate of 88 Hz, which lies at the border between the 80 and 100 Hz ⅓ OBs; therefore, the acoustic energy is split between the two bands. Although the ground strips repeat at a rate of 88 Hz, the transits in the profile from cylindrical to flat occur in a shorter distance. This will introduce more high-frequency content than the more pure sinusoidal profile of the mumble strips. Because the ground strip has more high-frequency content, the acoustic energy at the 88 Hz repetition rate is lower than it is for mumble strips in the 80 Hz band. The design intent of the mumble strip is to move more energy to lower frequency by eliminating transitions that generate higher frequency inputs. The harmonic of the repetition rate occurs at 176 Hz, which falls into the 160 Hz band, and all test vehicles except the Expedition produce a small peak at this frequency (Figure 28).

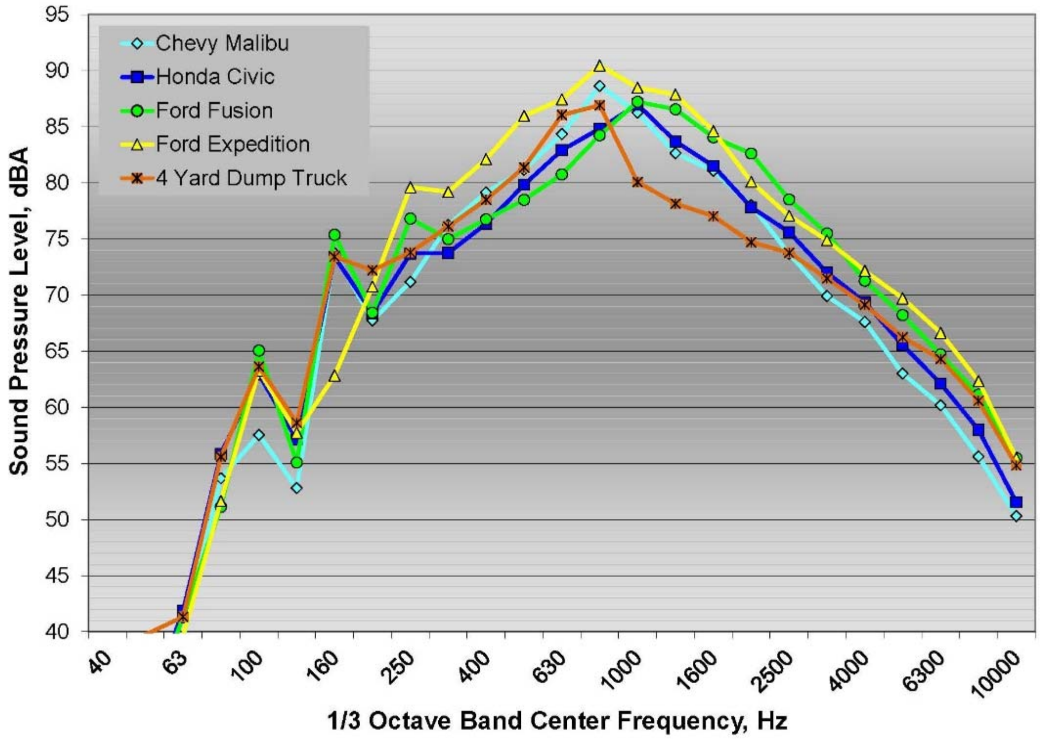


**Figure 29: ⅓ octave band pass-by spectra on ground rumble strips for all five test vehicles**

The dots have the same spacing as the ground rumble strips and a peak occurs in 100 Hz band for all of the vehicles, as shown in Figure 30. Unlike the ground rumble strips, the dots do not display a peak at the first harmonic of the repetition rate. The Malibu does have a definite peak in the 250 Hz band that would coincide with the second harmonic at 264 Hz. The Expedition and Civic both have a hint of a blip at this frequency, which suggests that there is some input at this frequency and that the Malibu actually responds to it more than do the other vehicles.

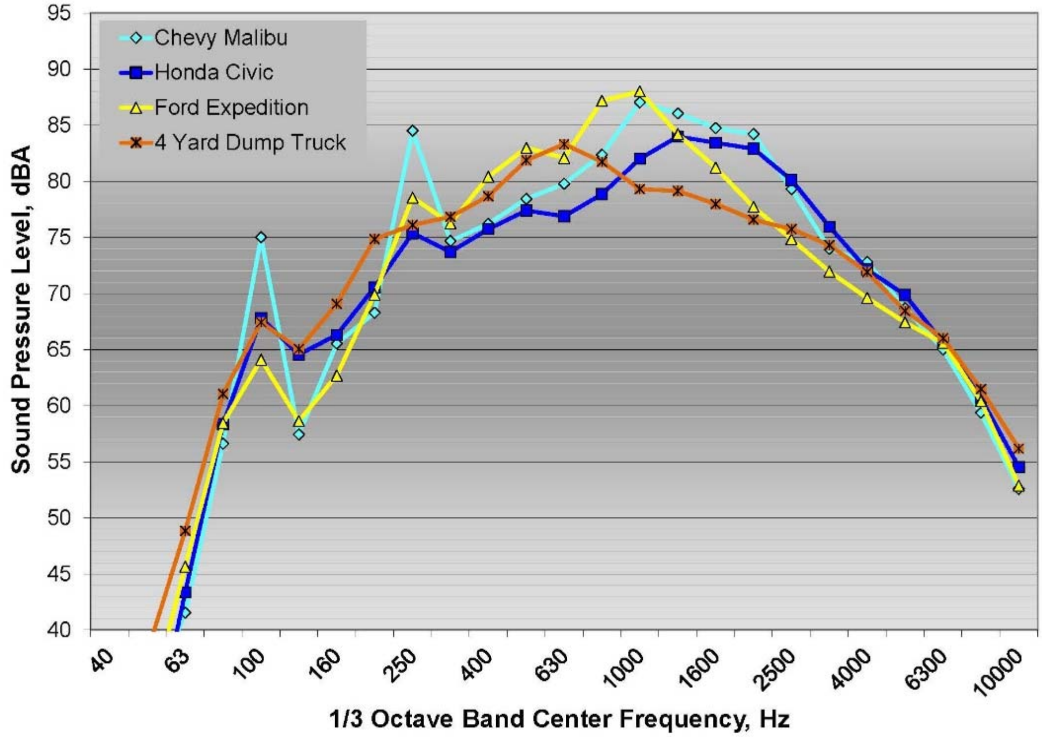


**Figure 30: ⅓ octave band pass-by spectra on dots for four test vehicles**

Although the mumble strips were successful in reducing the overall A-weighted pass-by levels, the spectra depicted in Figure 27 do introduce some possible concern. As shown, there is a pronounced peak in the 80 Hz band produced by the wavelength of the sinusoidal profile ranging in level from about 62 to 75 dBA when A-weighted. At this frequency, the A-weighting filter shape applies an attenuation of 22.5 dB so that un-weighted levels range from 84.5 to 97.5 dB. At this frequency, the sound will be less attenuated by barrier effects, atmospheric effects, and exterior to interior noise reduction by buildings than sound at frequencies around 1000 Hz. As a result, the perception of the mumble strips maybe greater than what is suggested by the overall A-weighted level reduction compared with the ground rumble strips.

## 4.2 On-Board Exterior Noise Results

The overall A-weighted exterior sound levels measured on-board the Expedition, Civic, Malibu, and Fusion test vehicles are shown in Figure 31 as measured at the top of the right rear wheel well (see Figure 14 in Chapter 3). Except for the Civic on the mumble strips, there is at least a 10 dB signal-to-noise ratio between the levels measured on the strips and off the strips, implying that this measurement is of some use in the evaluating the strips. Comparing the pass-by levels of Figure 22 to Figure 31 reveals that there are some similarities and some differences between the two measurements. For the Expedition, Fusion, and Civic, the difference between the mumble and rumble strips are similar to the pass-by results. For the Malibu, this is not the case as the difference is only 0.8 dB compared to 4.8 dB as measured with the pass-bys. Also the differences between the on and off the mumble strips for the Civic and Fusion are smaller (2.7 and 2.9 vs. 5.8 dB) for the on-board exterior noise measurement. These differences between the pass-by and on-board are to be expected as the pass-bys measure total noise from all parts of the car while the on-board measurement is quite localized. Also, the on-board sound pressure measurement is definitely in the acoustic near-field of source especially at lower frequency and will measure both propagating and non-propagating acoustic energy.

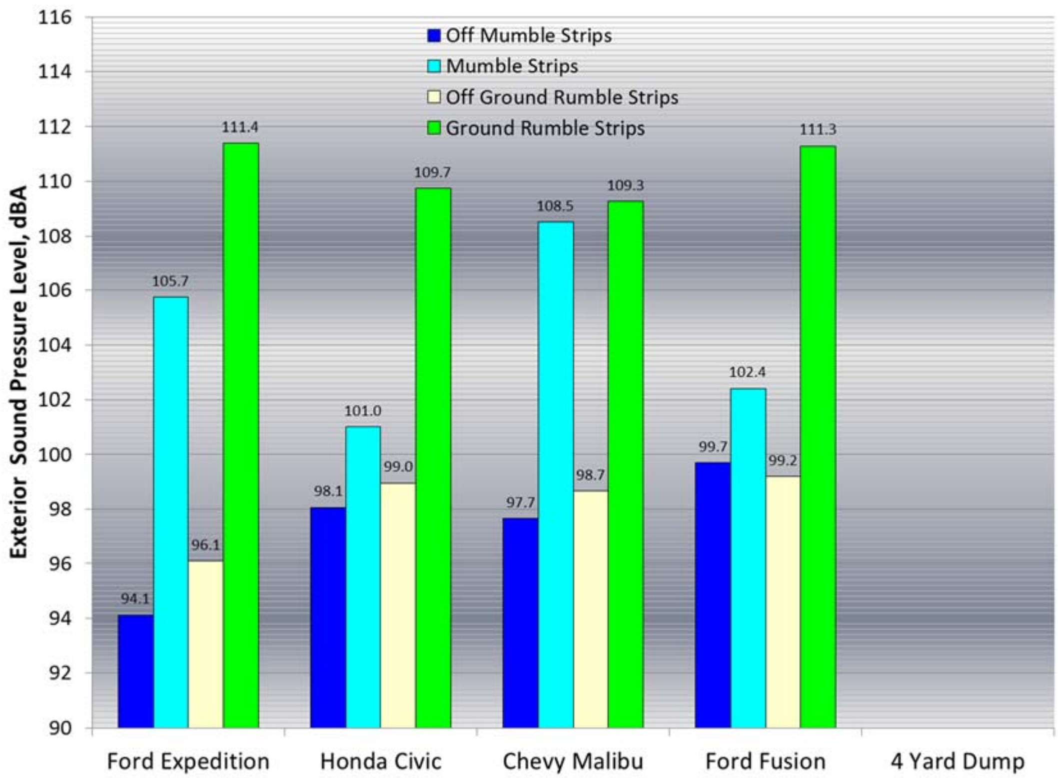


**Figure 31: Overall A-weighted on-board exterior sound pressure levels for four test vehicles on mumble and ground rumble strips**

The on-board ⅓ OB results for the mumble strips for four test vehicles are shown in Figure 32 for comparison to Figure 28. Comparing the on-board measurement and the pass-by results does show that trends are similar between the two types of data. The strip repetition rate and harmonic are clearly shown both. However, the amplitudes at 80 Hz show a different rank ordering with the Malibu being about 18 dB greater than the Fusion or Civic in the on-board results and both the Malibu and Fusion being about 5 dB higher than the Malibu in the pass-by results. This may be indicative of differences in the proximity to the sound radiating surfaces or differences in response to front axle versus rear axle inputs. A comparison of the spectra for the ground rumble strips for pass-by (Figure 29) and on-board measurements as shown in Figure 33 also identifies some similarities and differences. For the on-board measurements, the levels in the frequencies below the 315 Hz band are relatively higher compared to the higher frequencies than they are for the mumble strips. Also for the Expedition and Malibu, there is relatively more energy in the 80 Hz band than in the 100 Hz band. For the Fusion, the levels in both the 80 and 100 Hz bands are lower than the other three vehicles by about 10 dB. This trend is not seen in the pass-by spectrum (Figure 29) where the levels at 80 Hz are about the same for all of the vehicles except the Malibu.

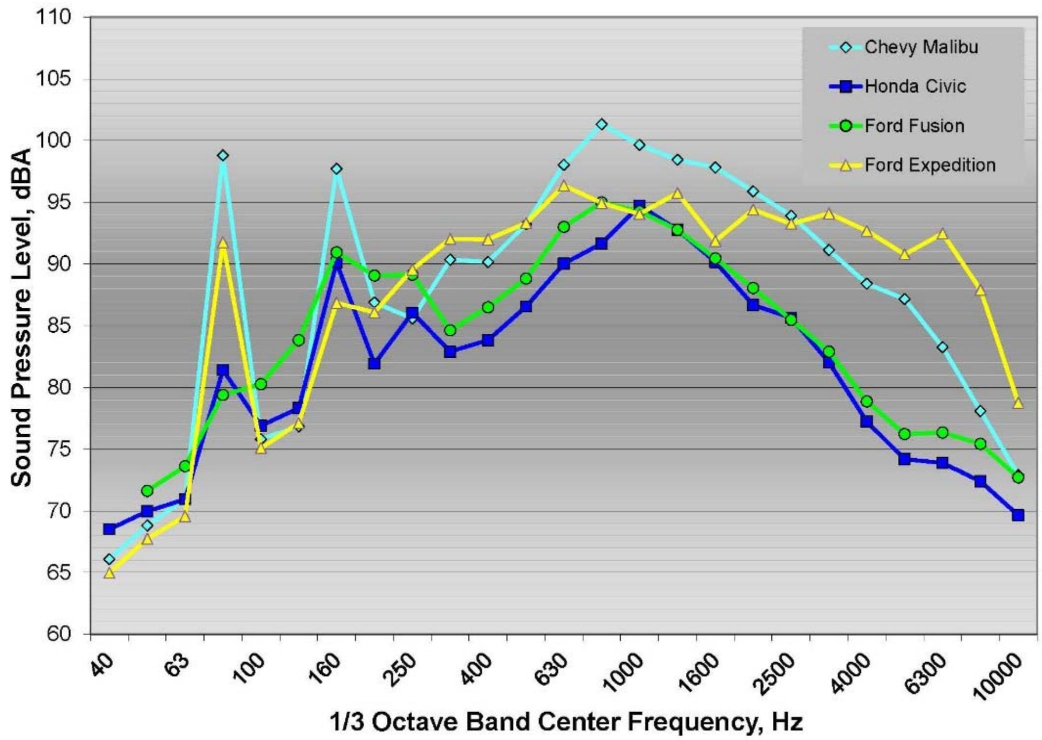


**Figure 32: ⅓ octave band on-board exterior spectra on mumble strips for four test vehicles**

Although the on-board measurements were successful in demonstrating the differences between the mumble strips and ground rumble strips, the tests did not accomplish the intent of isolating the tire noise contribution to the total exterior noise. In the 2015 testing, a method for measuring OBSI in a manner similar to the conventional method of AASHTO TP 76 was developed and is discussed in Chapter 7, *Additional Evaluations*, Section 7.2.

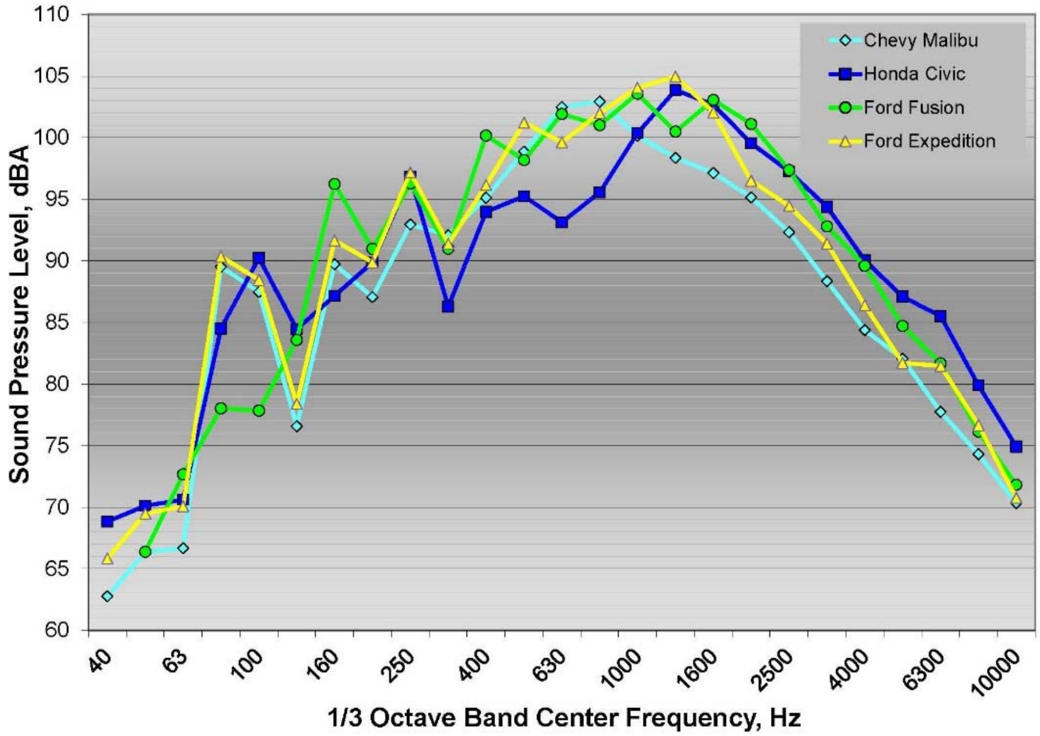


**Figure 33: ⅓ octave band on-board exterior spectra on ground rumble strips for four test vehicles**

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# Chapter 5 Results of Interior Measurements

The interior measurements include the noise data collected at the right front passenger head location (mid cab for the truck) and acceleration data collected on the right front seat track and steering column. These measurements are intended to quantify the level of aural and tactile warning that the vehicle operator receives when the vehicle begins to wander off the lane of travel. The results of these measurements are presented in this chapter.

## 5.1 Interior Noise Measurements

Overall A-weighted interior noise levels are presented in Figure 34 for the five test vehicles traveling at 60 mph on and off the mumble strips and ground rumble strips. For the four passenger vehicles, both types of warning devices produce levels more than 11 dB greater than the levels off of the strips. Interior noise in passenger vehicles traveling on the mumble strips averages 14.4 dB greater than the noise in vehicles traveling off the strips. For the ground rumble strips, the average difference is 13.9 dB. These test results indicate that, for these vehicles, the mumble strips produce a similar level of audio warning as the rumble strips. In three out of the four passenger vehicle cases, the mumble strips actually produce higher interior noise levels than the rumble strips. For the fourth passenger vehicle case, the Honda Civic, the mumble strips produce less interior noise than the ground stripes; however, the difference between on and off the mumble strips is greater than that for the Ford Fusion. For the dump truck, the difference between on and off the strips is not great, 2.6 dB for the mumble strips and 7.6 dB for rumble strips. Although the interior noise levels for the truck are higher than for the Expedition, the interior noise levels off the strips are 8.5 to 10.2 dB higher than for the Expedition.

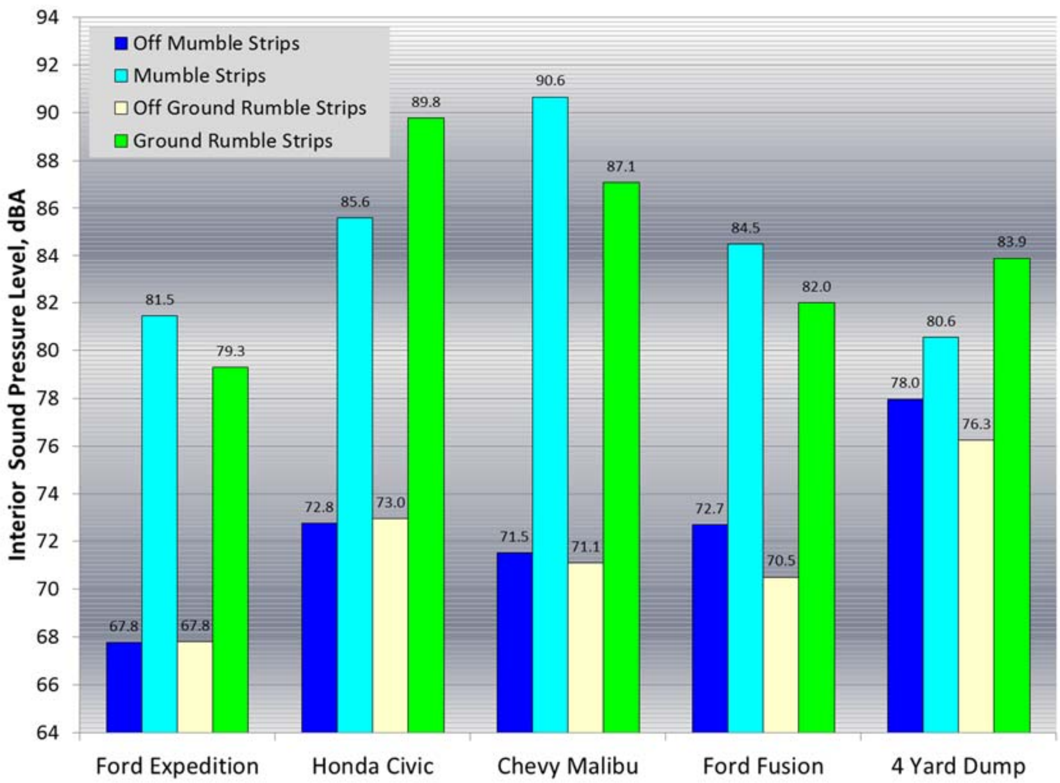


**Figure 34: Overall A-weighted interior sound pressure levels for all four test vehicles on and off mumble and ground rumble strips**

In the ⅓ OB measurements of interior noise, instrumentation noise contaminated some of the higher frequency levels for some of the vehicles. This contamination was the result of both on strip and off strip measurements being made in one pass. To accommodate both measurements in one pass, the RTA gain was set to capture data while the vehicle was traveling on warning strip data without overloading, which left insufficient dynamic range to capture some of the higher frequencies. These contaminated data have been removed for the appropriate data plots. In Figure 35, the interior noise spectra for the Malibu traveling on and off the mumble strips and ground rumble strips indicates that there is a 10 dB difference between on strip and off strip from 80 Hz up to about 800 Hz, as would expected from the overall levels. At 80 Hz, the difference between on strip and off strip is 32.6 dB for the mumble strip and 25.5 dB for the ground rumble strip. Subjectively, the difference in noise is very noticeable inside the car when the tires go onto either type of warning device. The spectral comparison for the Civic also displays large differences on and off the strips, as shown in Figure 36. For the mumble strips, this difference is as large as 22.3 dB. For the ground rumble strips, the maximum difference is 26.3 dB. Again, the difference between travel on and off both types of strips is very noticeable in the car. The Fusion spectra shown in Figure 37 indicates that, although there are large differences when the vehicle is traveling on and off both types of strips, the differences are not as striking as they are for the Malibu and Civic. For the Expedition shown in Figure 38, the frequency bands between 160 and 400 Hz show slightly less difference for on strip and off strip compared with the other three passenger vehicles, likely due more isolation in the Expedition. However, in the 80 and 100 Hz bands, increases of 20 to almost 30 dB are produced during travel on the strips. The interior noise spectra for the 4-yard dump truck are shown in Figure 39. As suggested by the overall levels of Figure 34, the differences in the ⅓ OB levels during travel on and off the mumble strips are small, with greatest difference of about 4 dB occurring at 80 Hz. The differences for the ground rumble strips are larger, with bands producing separations of more than 10 dB.

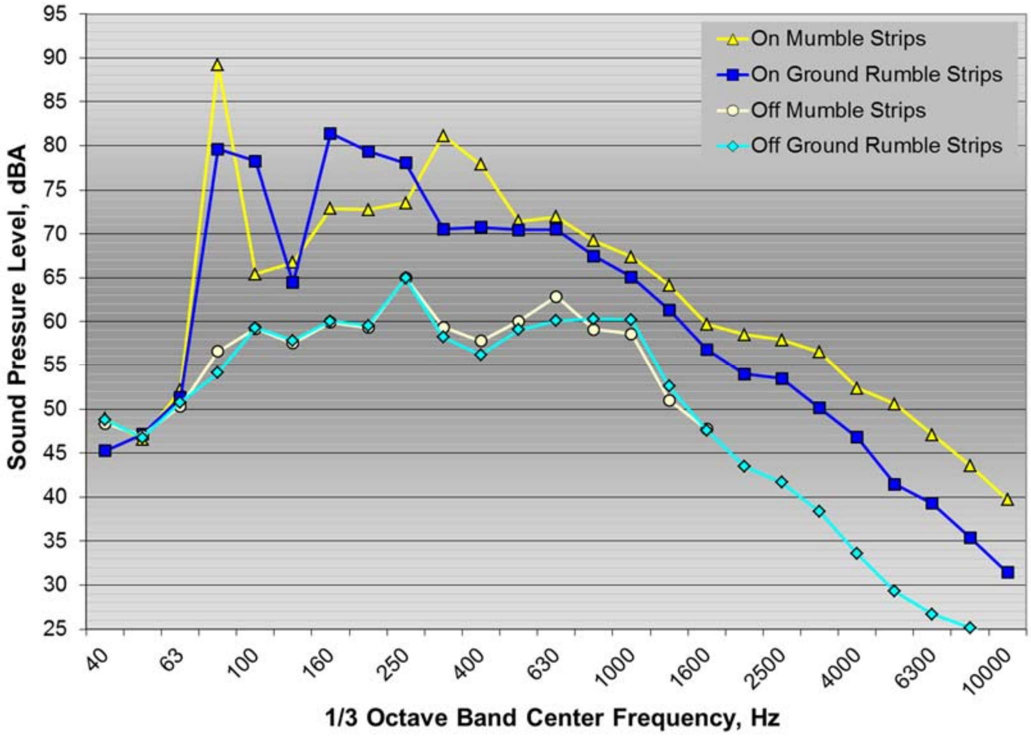


**Figure 35: ⅓ octave band interior noise spectra for Malibu test vehicle on and off mumble strips and ground rumble strips**

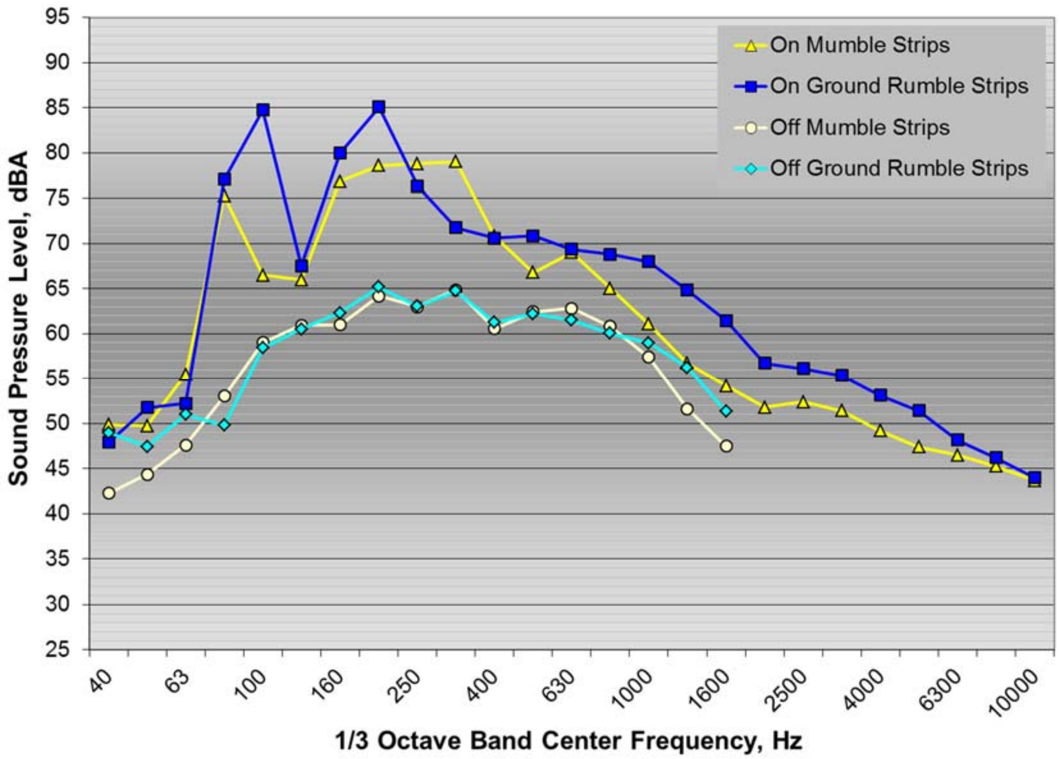


**Figure 36: ⅓ octave band interior noise spectra for Civic test vehicle on and off mumble strips and ground rumble strips**

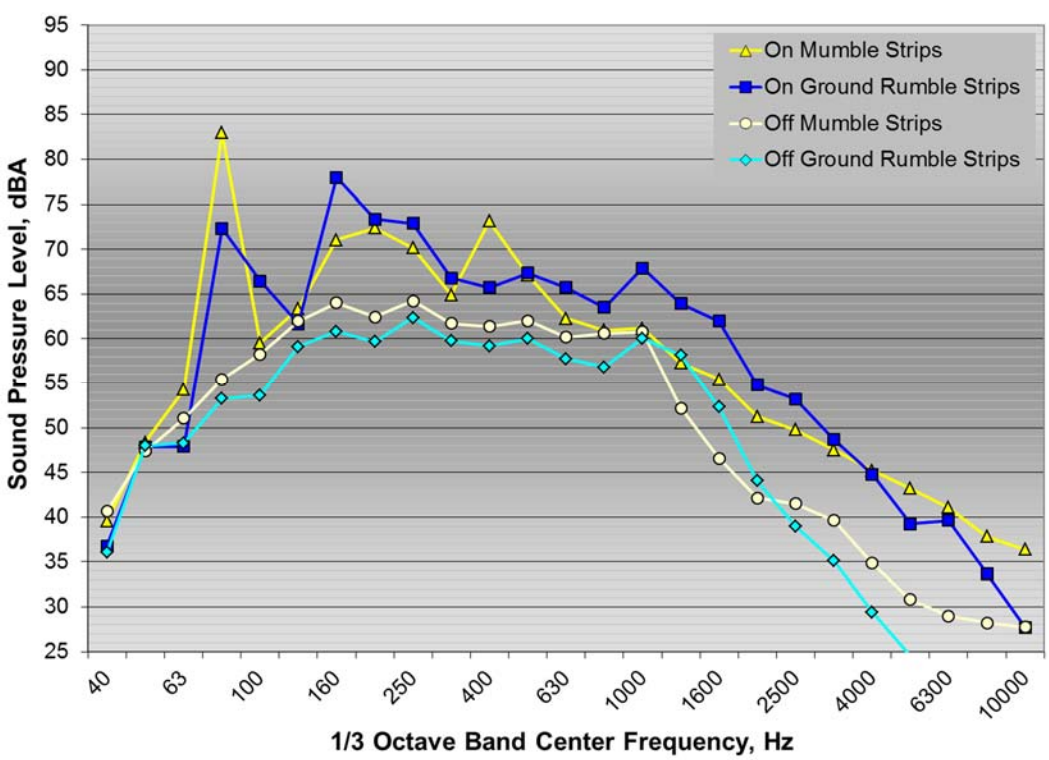


**Figure 37: ⅓ octave band interior noise spectra for Fusion test vehicle on and off mumble strips and ground rumble strips**

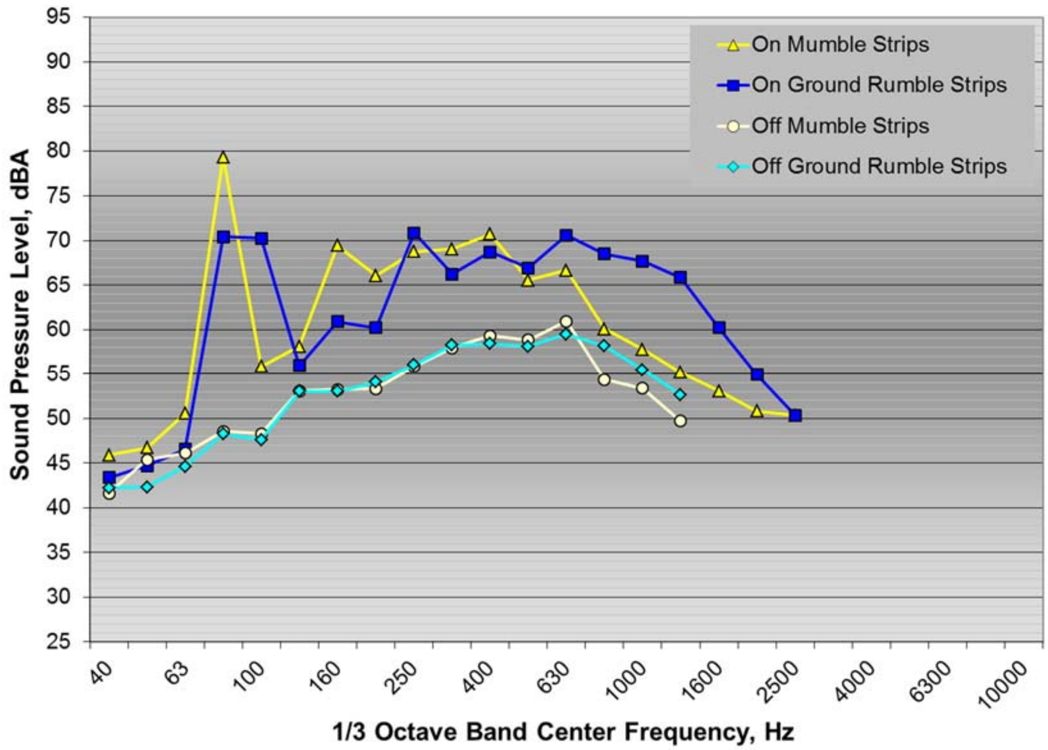


**Figure 38: ⅓ octave band interior noise spectra for Expedition test vehicle on and off mumble strips and ground rumble strips**

Figure 40 provides a comparison of the interior levels for all vehicles on the mumble strips. Compared with the passenger vehicles, the dump truck levels are 7.1 to 19.3 dB lower in the 80 Hz band, which is the repetition rate of the sinusoidal mumble strips. In the pass-by results (Figure 28 in Chapter 4), the truck produces a distinct peak at this frequency. The absence of a peak in the truck interior data may be related to the location of the interior noise microphone, which was centered in the cab. At this point in the interior space, a null in sound pressure level would be expected due to standing waves inside the cab in the transverse direction. The first order null would occur for a dimension corresponding to ½ of an acoustic wavelength. Assuming the cab is about 7 feet across, the 14-foot wavelength would correspond to about 80 Hz. This may contribute to the absence of a pronounced peak at 80 Hz and for the small difference in interior levels during travel on and off the mumble strips, as shown in Figure 40. For the other vehicles, the interior data are consistent with the pass-by and the exterior results (Figure 32). For the Expedition, Fusion, and Malibu, the peak at 80 Hz is still apparent in the interior spectrum, as indicated in Figure 40; however, the harmonic at 160 Hz is not apparent. For the Civic, the level at 80 Hz is the lowest of all of the passenger vehicles, but it is the highest from 160 to 250 Hz by 4 to 6 dB. The lower level at 80 Hz and the higher levels from 160 to 250 Hz may also be indicative of resonances associated with either the vehicle's interior acoustical space or the body structure. In the higher frequencies, above about 400 Hz, the interior levels are relatively more attenuated than in the lower frequencies. In the higher frequencies, the path of noise into the vehicle interior tends to be airborne with typically more attenuation than the structure-borne paths of the lower frequencies. This shift from higher frequencies on the outside of the vehicle to lower frequency inside is quite pronounced for the ground rumble strips comparing the results of Figure 41 with Figure 29 in Chapter 4. Figure 41 also displays some differences in the response of some of the vehicles. Unlike the mumble strips, there typically are higher levels in both the 80 and 100 Hz bands due the higher repetition rate of the ground rumble strips. And unlike the other vehicles, the Civic produces higher levels in the 100 Hz band than in the 80 Hz band, with another peak in the 200 Hz band. These behaviors are not as pronounced in exterior on-board results (Figure 33 in Chapter 4) and may be due to interior acoustic cavity modes.

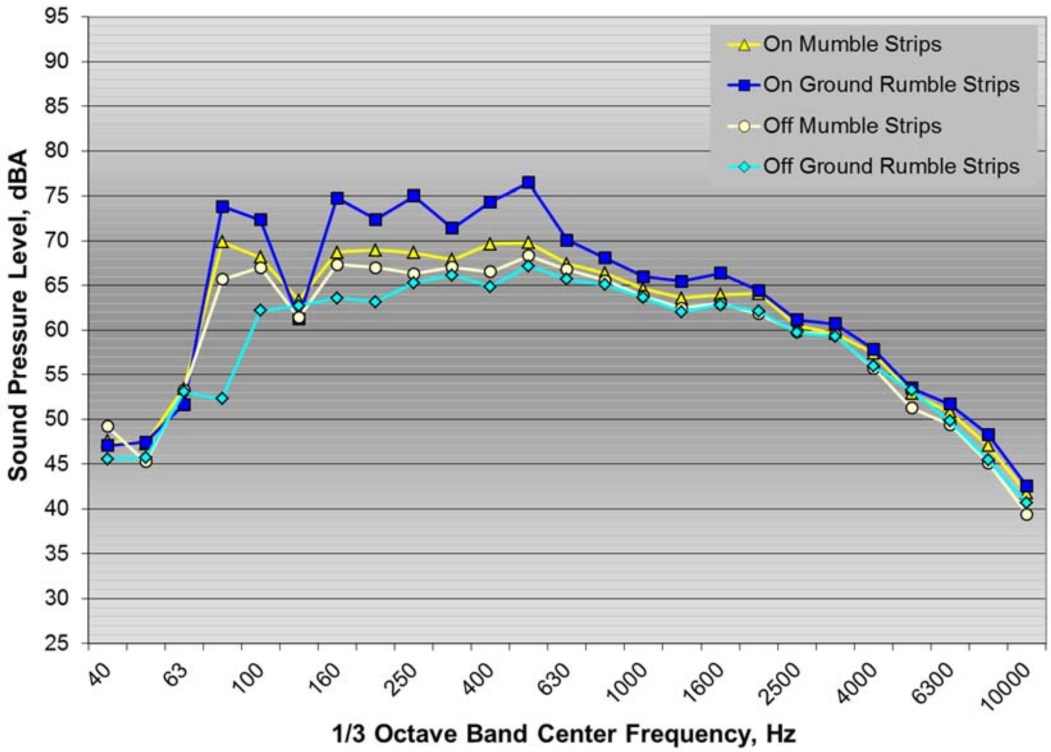


**Figure 39: ⅓ octave band interior noise spectra for 4-yard dump truck test vehicle on and off mumble strips and ground rumble strips**

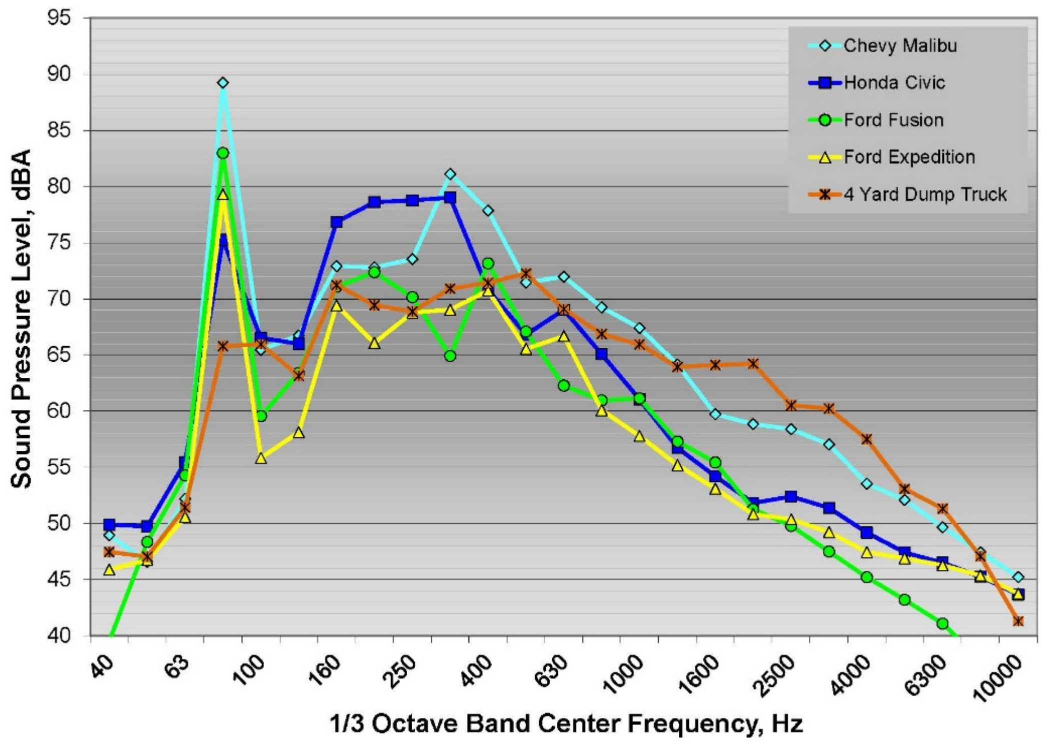


**Figure 40: ⅓ octave band interior noise spectra for all five test vehicles on mumble strips**

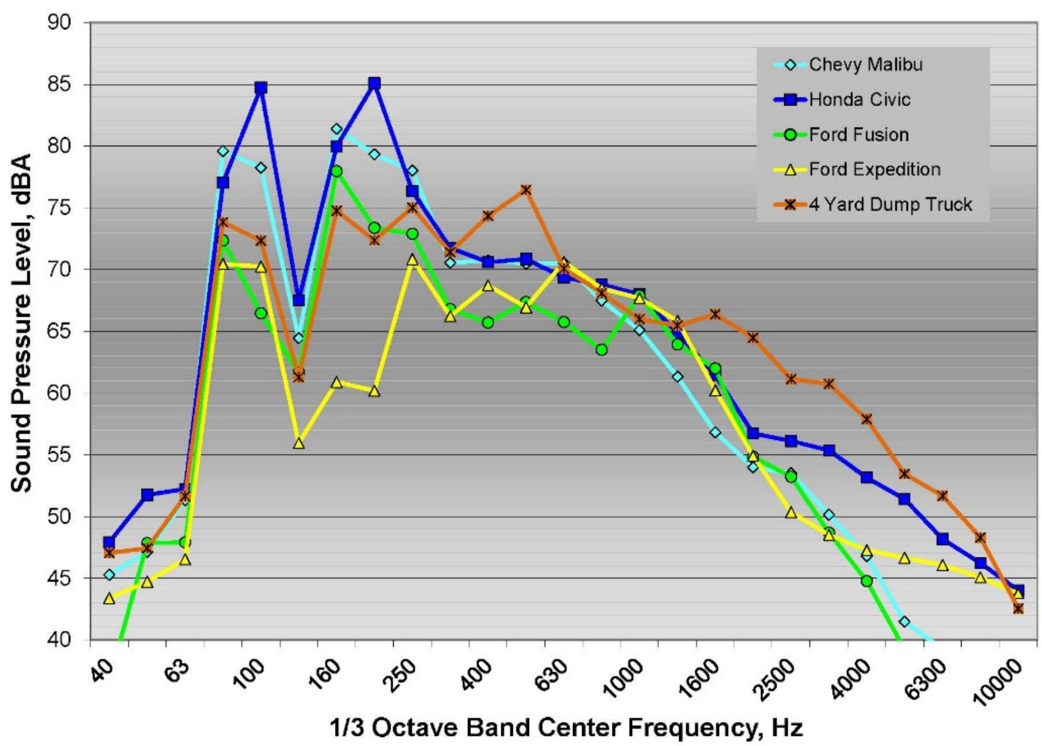


**Figure 41: ⅓ octave band interior noise spectra for all five test vehicles on ground rumble strips**

## 5.2 Acceleration Measurements

Overall un-weighted acceleration levels for the seat tracks of the five test vehicles on and off the mumble strips and ground rumble strips are shown in Figure 42. Similar to the interior noise levels, the seat track acceleration levels are more than 10 dB greater when a passenger vehicle is traveling on either type of strip than when traveling off either type of strip. Also, like the interior noise results, the difference in vibration level for the dump truck on and off the strips is much smaller than the difference for the passenger vehicles. For the dump truck, the difference is only 2.0 dB on the mumble strips and 4.9 dB on the ground rumble strips. Also similar to the interior results, the Civic displays significantly lower levels on the mumble strips than on the ground rumble strips, although the difference between on the strips and off the strips remains high.

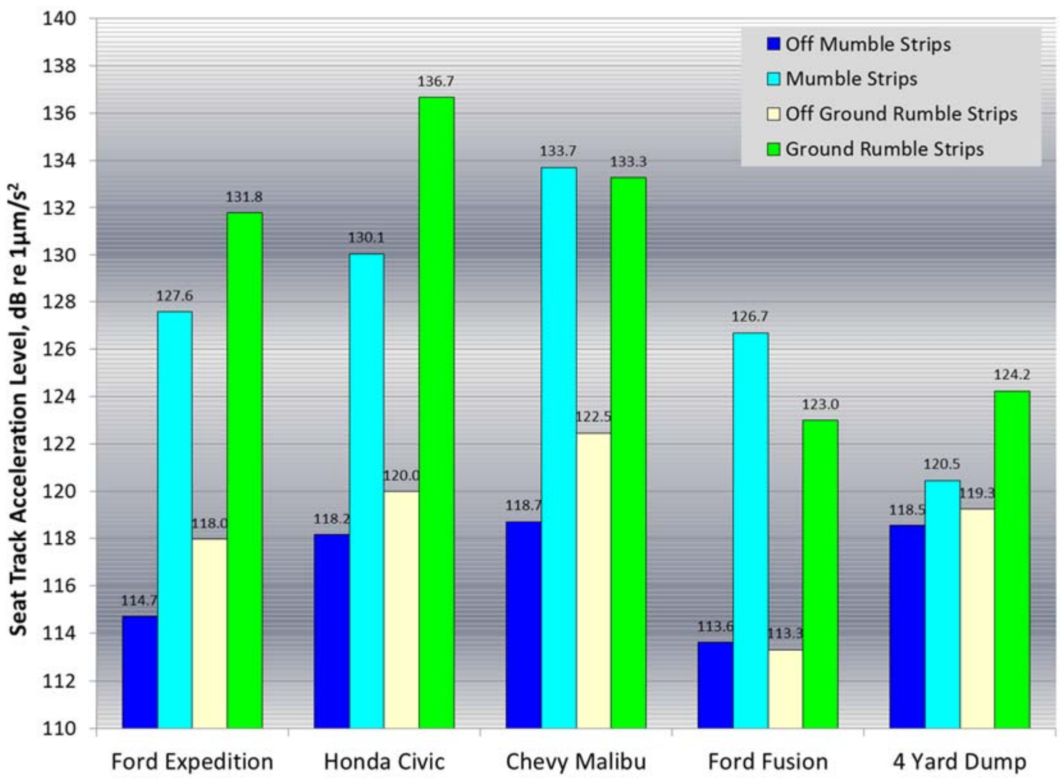


**Figure 42: Overall seat track acceleration levels for all five test vehicles on and off mumble strips and ground rumble strips**

Seat track acceleration spectra for all five vehicles on the mumble strips are shown in Figure 43. The influence of the fundamental repetition rate and its first harmonic are clearly seen in the 80 Hz and 160 Hz bands for all five vehicles. For the passenger vehicles, the response at 80 Hz is very pronounced and the amplitudes are within about 5 dB of each other. For the dump truck, the 80 Hz level is considerably lower (15 to 20 dB); however, peak is 10 to 15 dB higher than in the adjacent 63 and 100 Hz bands for this vehicle, indicating the 80 Hz repetition is still prominent. There could be a number of explanations for the lower response of the truck at 80 Hz, including the possibility of more designed isolation from road inputs, the structure at the seat track being much more stiff than the passenger vehicles thereby reducing the response at this location, or that the dual tires on the rear axle are too wide to be fully engaged into the mumble strip. Between 160 Hz and 630, the responses of Expedition are both lower than the other passenger vehicles and generally closer in level to those of the dump truck. Subjectively, the Expedition is more isolated from the road than the other passenger vehicles, which may account for its reduced response. Among the passenger cars, the Fusion displays lower vibration levels at 160 Hz and above. This is particularly apparent at 800 Hz and above, where differences of up 15 dB are seen.

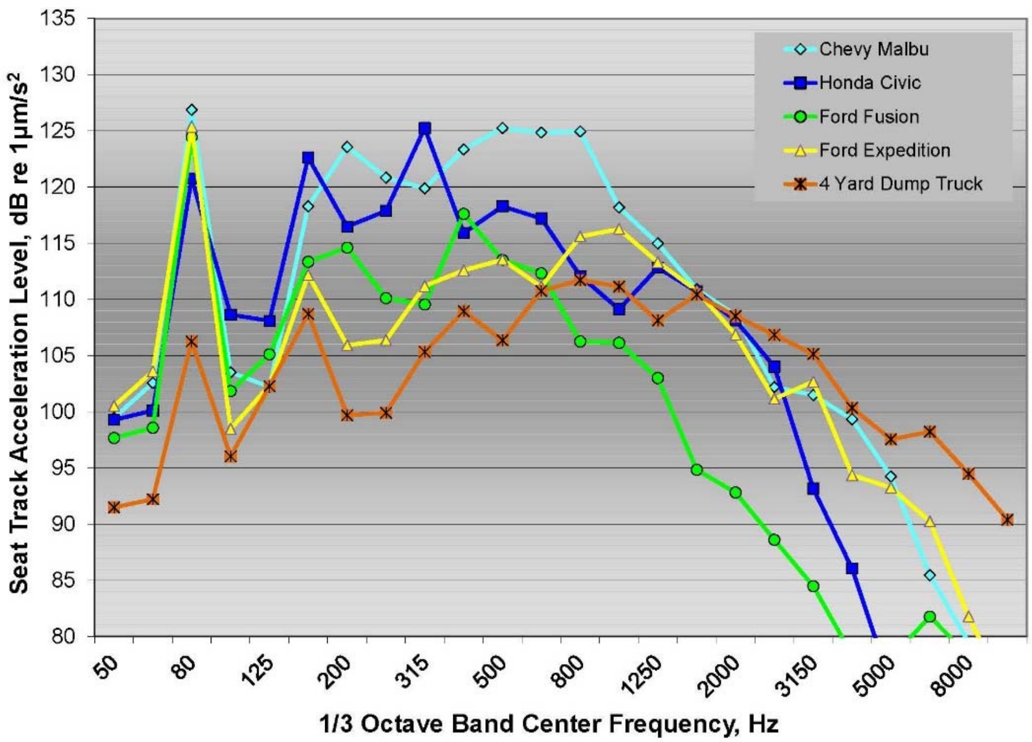


**Figure 43: ⅓ octave band seat track acceleration spectra for all five test vehicles on mumble strips**

When the passenger vehicles travel on the ground rumble strips, the repetition rate falls between the 80 and 100 Hz bands, producing increased response in the passenger vehicle acceleration levels at the seat track location in both of these bands. As shown in Figure 44, the response of the Civic is notable in these frequencies as the response is 10 dB to almost 20 dB higher than any other vehicle. For the first harmonic at 160 Hz, the response for the Civic is also higher than for other vehicles; the levels for the Malibu are within about 5 dB of levels for the Civic. These results suggest that the Civic is not as effective as other vehicles at isolating the inputs from the ground rumble strips. The Civic also is not as effective at isolating inputs from the ground rumble strips compared with inputs from the mumble strips. The Expedition has a unique response at the seat track location while traveling on the ground rumble strips in the frequency range from 800 to 1600 Hz. There is a hint of this response on the mumble strips; however, the higher frequencies generated by the profile of the ground rumble strips may exaggerate this behavior for this vehicle. Between 80 and 630 Hz, the responses of the Expedition, Fusion, and dump truck are remarkably similar given the disparity of the vehicle designs.

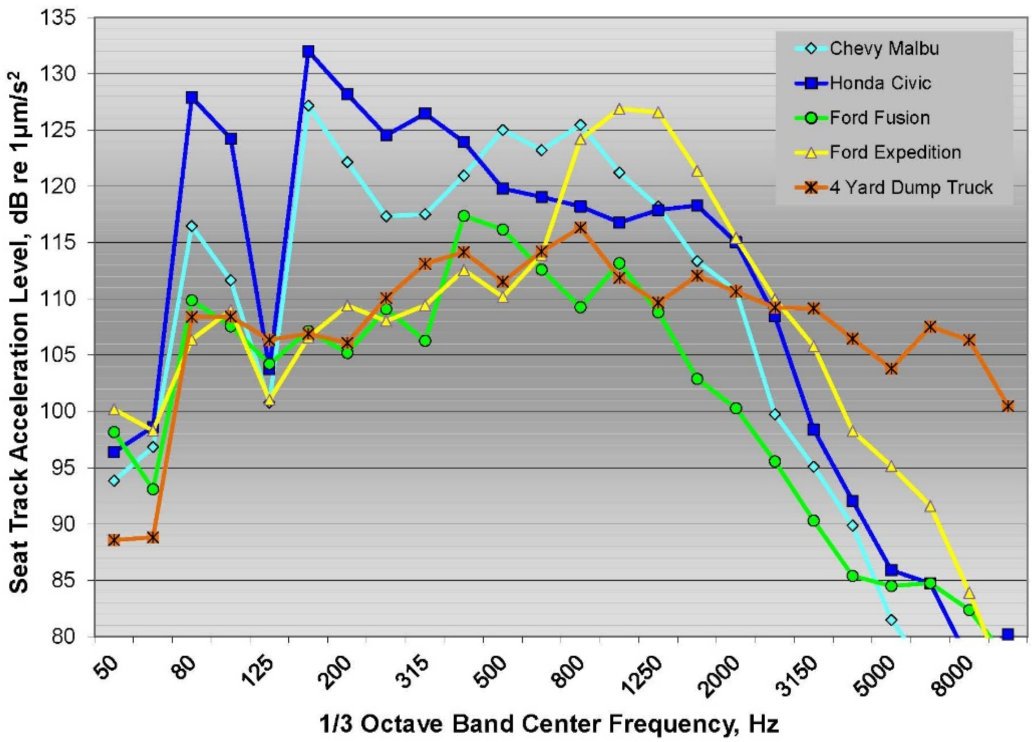


**Figure 44: ⅓ octave band seat track acceleration spectra for all five test vehicles on ground rumble strips**

Overall un-weighted acceleration levels for the steering columns of the five test vehicles are shown in Figure 45. Results for the steering columns are somewhat different than for the seat tracks. For the steering columns, the levels when the vehicles are traveling on the mumble strips are actually higher than those when the vehicles are on the ground rumble strips. For the dump truck, the difference at the steering column when the vehicle is on and off the strips is greater than the difference at the seat track, particularly for the mumble strips which produced a 7.2 dB difference at the steering column. Further, travel on the ground rumble strips produces differences from travel off the rumble strips of only 5.0 dB for the Expedition and 9.1 dB for the Civic. When the passenger vehicles are on the mumble strips, the differences are at least 12 dBgreater than when the vehicles are off the mumble strips.. The spectra results for the steering column measurement on the mumble strips, shown in Figure 46, are somewhat more complicated than the results for the seat track (see Figure 43). The four passenger vehicles all show the fundamental repetition rate in the 80 Hz band. However, unlike its response at the seat track location, the response of the dump truck at the steering column is comparable to that of the passenger vehicles, although the dump truck does not display a peak at this frequency. The other vehicles also display some unique behaviors that could be due resonances in the steering column itself or the structure paths leading to the steering column mounting points. At 80 Hz, the response of the Fusion is 5 to 10 dB greater than the other passenger cars. For the Civic, the response at 315 Hz is 10 to as much as 30 dB higher than the other vehicles. This response is centered at the second harmonic of the mumble strip repetition rate, which does appear in the seat track data for this vehicle. However, the response is about 10 dB greater for the steering column at 315 Hz than at the first harmonic at 160 Hz. A resonant response is also indicated in the Expedition results at 250 Hz. The 10 to 15 dB peak in this band does align with the second harmonic of the repetition rate; however, this harmonic is not seen in the seat track data. The Malibu also displays a peak in the 630 Hz band, although it is not as pronounced as that for the Civic and Expedition. Above 800 Hz, the response of the Fusion is consistently higher than the other vehicles by 5 to 15 dB. This is the opposite trend than what was noted for the seat track position, where the Fusion is much lower than the other vehicles (Figure 43). Based on results at the both the high frequency levels and at 80 Hz, the Fusion's steering column appears to be more responsive than those of the other vehicles. For the dump truck, the response from 63 to 500 Hz at the steering column is considerably (10 dB or more) higher than at the seat track location and is from about to 10 dB to as much as 20 dB higher than the Expedition in the 100 to 1000 Hz range. As for the Fusion, these results indicate some amplification or nonlinear response in the steering column of the truck.

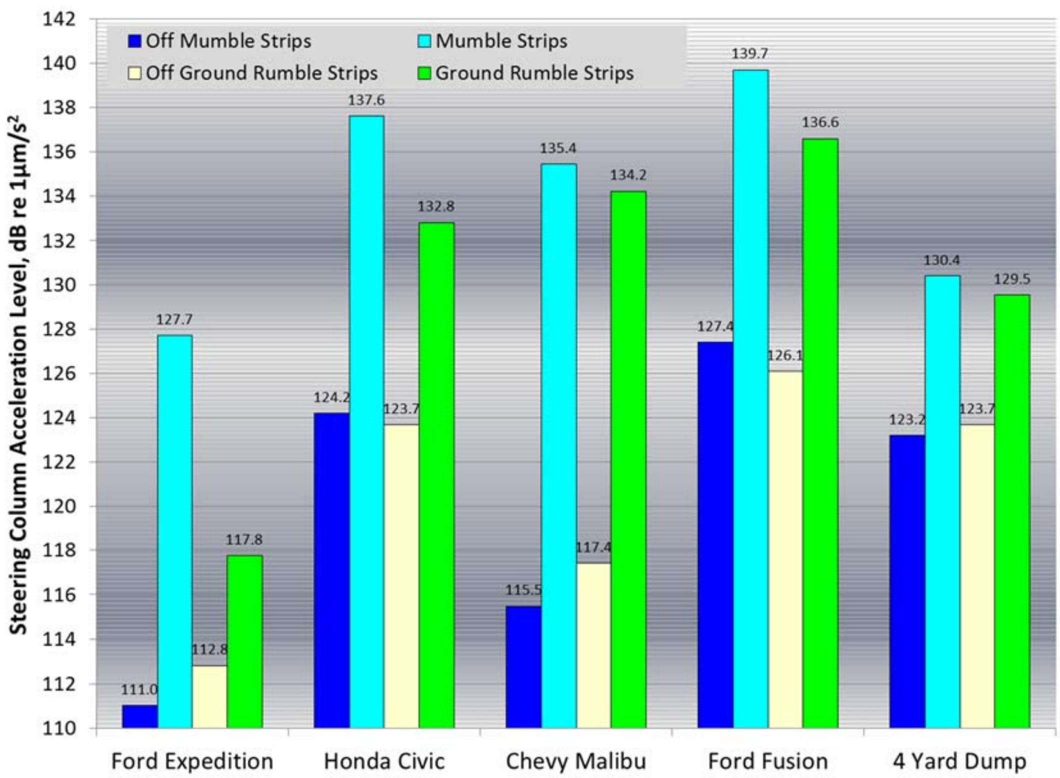


**Figure 45: Overall steering column acceleration levels for all five test vehicles on and off mumble strips and ground rumble strips**

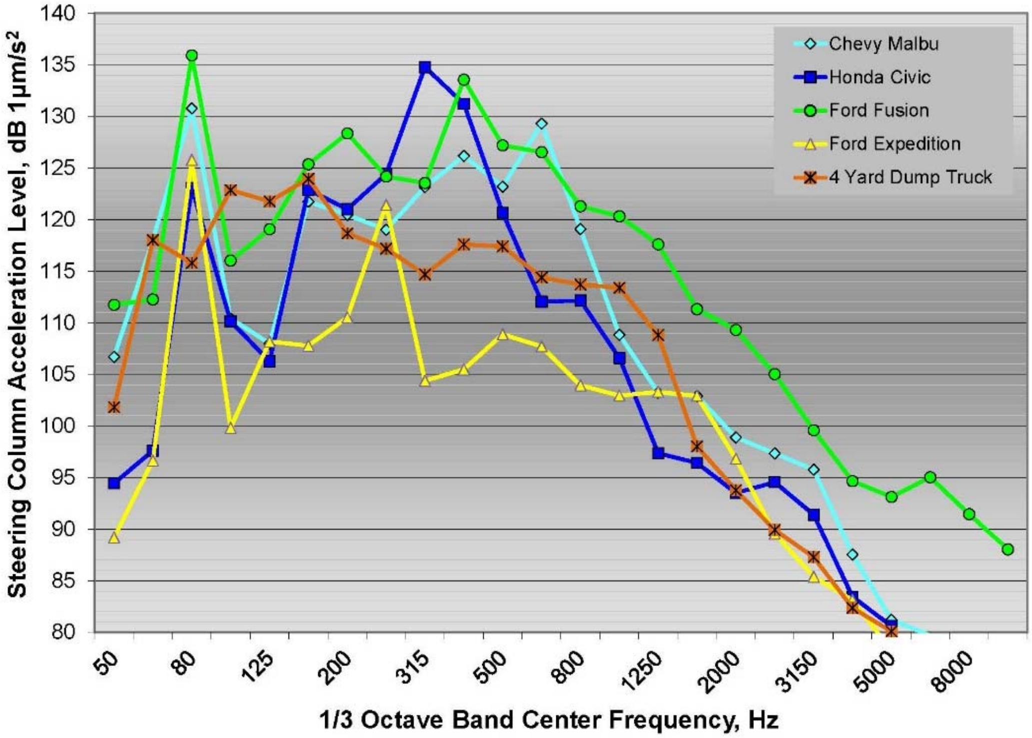


**Figure 46: ⅓ octave band steering column acceleration spectra for all four test vehicles on mumble strips**

Figure 47 shows that, for the steering column acceleration levels on the ground rumble strips, the response of the dump truck is again elevated compared with the other vehicles. This result is similar to the result when the dump truck was on the mumble strips. The relative response of the Expedition traveling on the ground rumble strips compared with the other vehicles is again low, as it was for the mumble strips. However, when the Expedition is on the ground rumble strips, the response at the strip repetition rate and its harmonic is much lower than it is for the other vehicles. Consistent with the mumble strip steering column response, the levels for the Fusion are consistently greater than for the other vehicles above 1000 Hz.

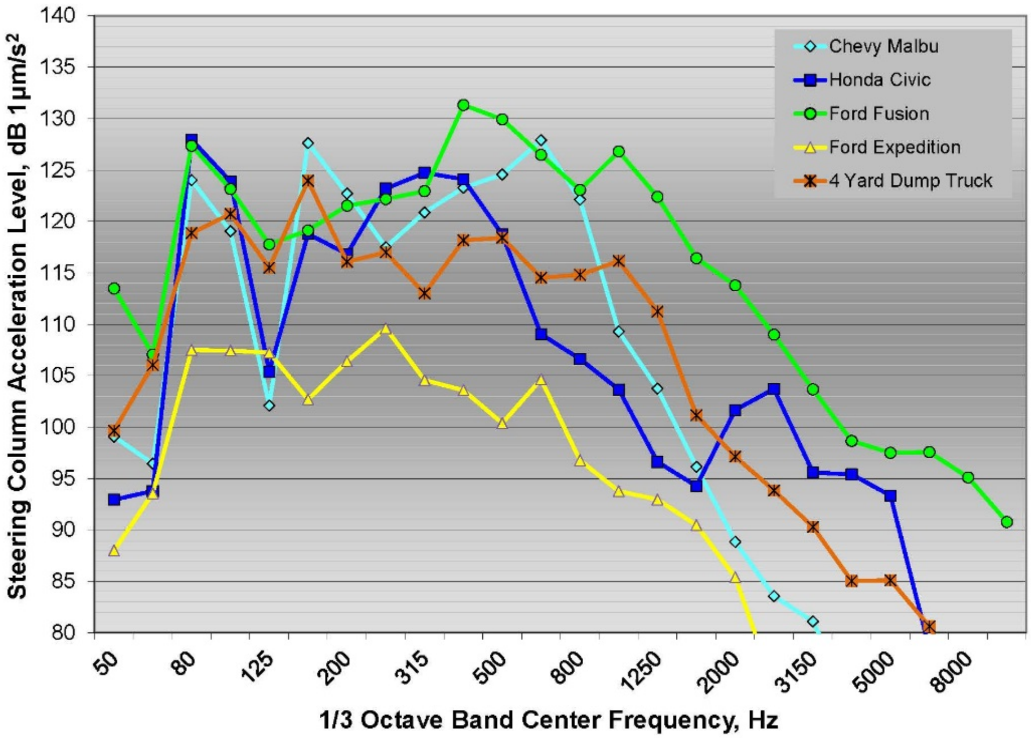


**Figure 47: ⅓ octave band steering column acceleration spectra for all five test vehicles on ground rumble strips**

In general, the vibration response to the mumble strips and ground rumble strips across the five vehicles indicates some similarities that are related to the input from the different warning device designs. This is most clearly seen in the seat track data. As with the interior noise results, the vibration responses, especially at the steering column, also display characteristics that are unique to each vehicle.

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# Chapter 6 Speed Dependence

For the Malibu test vehicle, the noise and vibration measurements were also made at speeds of 20 and 40 mph while traveling on and off the warning strips. In this chapter, these data are compared with the 60 mph results of exterior on-board noise, interior noise, the interior vibration.

## 6.1 Exterior and Interior Noise

The overall interior and on-board exterior noise levels for the Malibu at all three test speeds are plotted in Figure 48 for the mumble strips and ground rumble strips. For the interior and exterior data and the two types of strips, the levels increase uniformly with increasing speed. However, the increases with speed are greater for the mumble strips than for the ground rumble strips. For interior noise, the more rapid rate of the increase for the mumble strips results in the levels being slightly lower (3.4 dB) than for the ground rumble strips at 20 mph and slightly higher (3.5 dB) at 60 mph. At 40 and 60 mph, the mumble strips actually produce more interior noise than the ground rumble strips. Compared with the levels when the Malibu is off the strips, the interior levels on both strips are at least 10 dB greater for all cases except for the mumble strips at 20 mph, where the difference is 8.3 dB. The exterior noise levels when the Malibu is on the mumble strips are substantially lower (13.6 dB) than when the vehicle is on the ground rumble strips, while at 60 mph the levels are similar. These results imply that, at the lower speeds, the mumble strips perform quite well in reducing overall A-weighted exterior noise affecting the wayside levels while still maintaining an adequate interior noise level for driver attention.

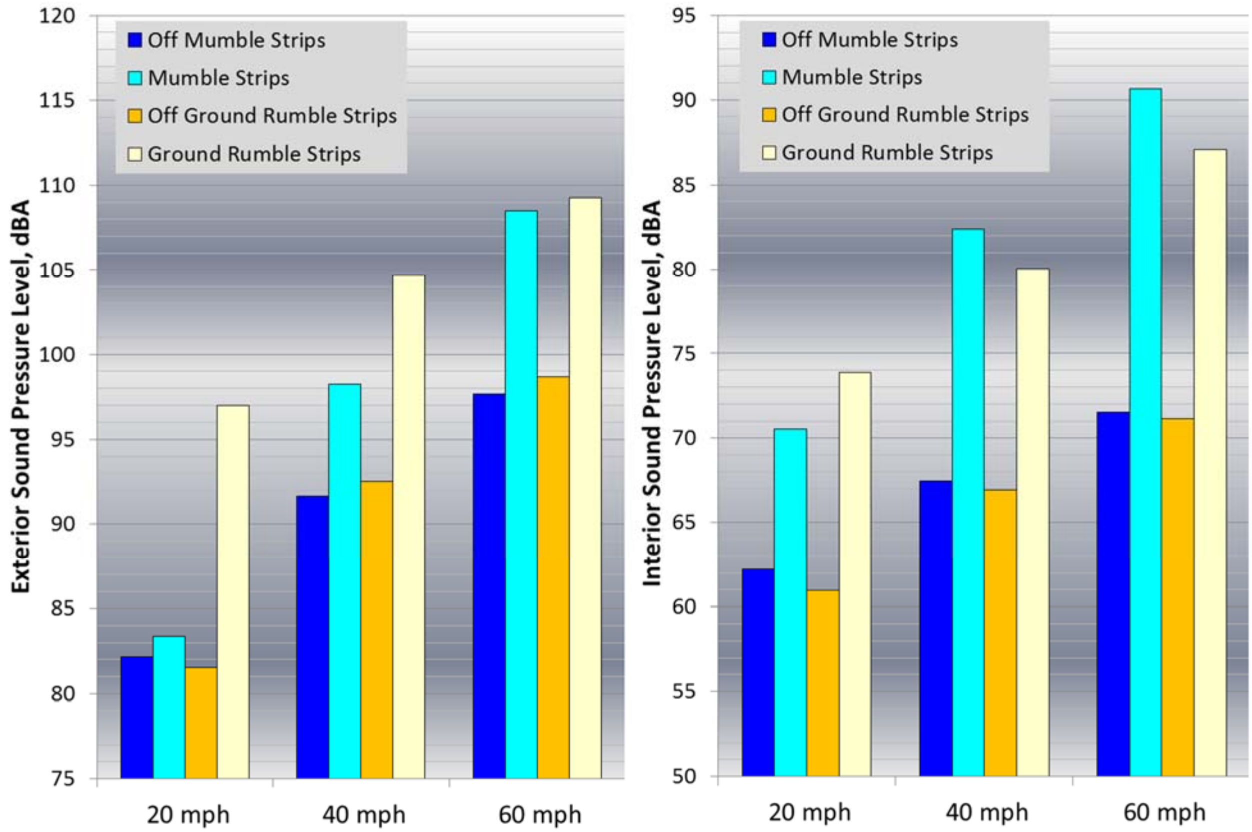


**Figure 48: Overall A-weighted on-board exterior (left) and interior (right) sound pressure levels for Malibu test vehicle on and off mumble strips and ground rumble strips at 20, 40, and 60 mph**

Figures 49 displays exterior noise spectra for the mumble strips. In these data, the upward frequency shifts of the sinusoidal repetition rate and harmonics are readily apparent. At 20 mph, the rate is 25.1 Hz and shows a peak in the 25 Hz band with a second harmonic at 50 Hz and a third at 75 Hz that is contained in the 80 Hz ⅓ OB. At 40 mph, the fundamental rate is twice as high as at 20 mph and this is indicated by the peak in the 50 Hz band while the first harmonic is in the 100 Hz band. There is little evidence, however, of the second harmonic that would occur in the 160 Hz band. For 60 mph, the 80 Hz fundamental is apparent, as is the first harmonic at 160 Hz; however, the second harmonic is only slightly indicated in the 315 Hz band. Some differences are apparent between the exterior and interior results shown in Figure 50. For 20 mph in the interior results, the fundamental frequency is about as prominent as it is in the exterior data; however, the first harmonic shows only a small peak and the second harmonic is not seen at all. At 40 mph in the interior, the fundamental frequency at 50 Hz is more pronounced than it is in the exterior data, and the second harmonic at 160 Hz in the interior is quite prominent, especially compared with the exterior data. At 60 mph, the first harmonic of the rumble strip repetition rate is not very apparent in the 160 Hz band of the interior data compared with its prominence in the exterior results. In general, comparing the interior and exterior results of Figure 49 and 50 indicates that the relationships between these data are complex and not simply noise reductions from exterior to interior noise. The interior results are likely influenced by the modal characteristics of the interior space and by energy transmitted through the suspension and body structure.

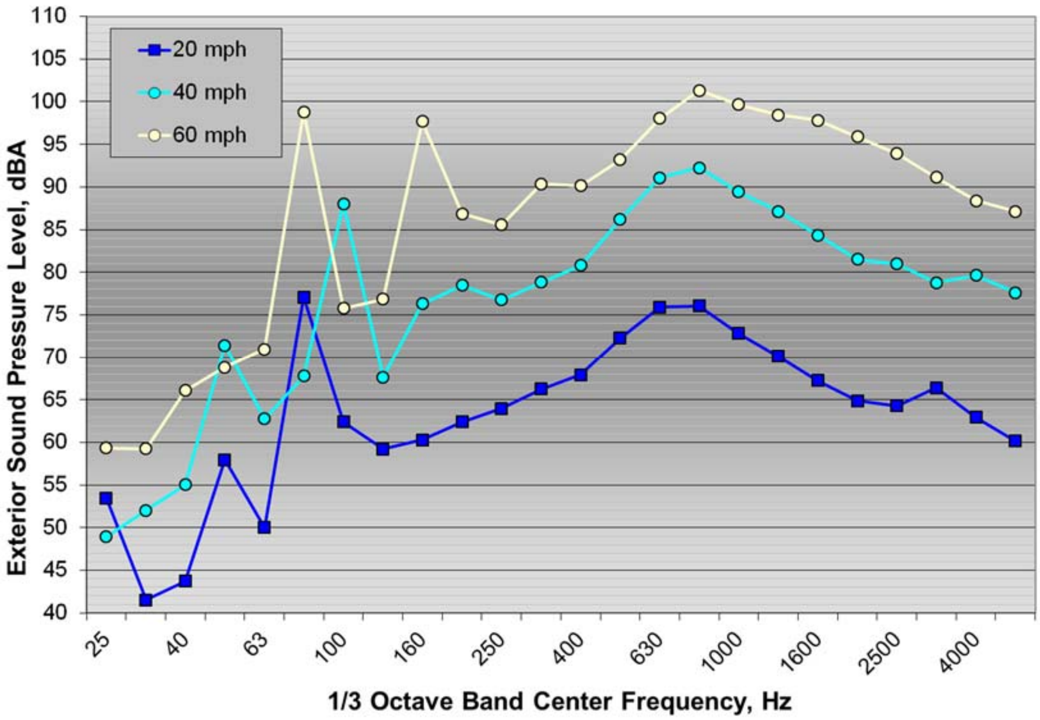


**Figure 49: ⅓ octave band on-board exterior noise spectra on mumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

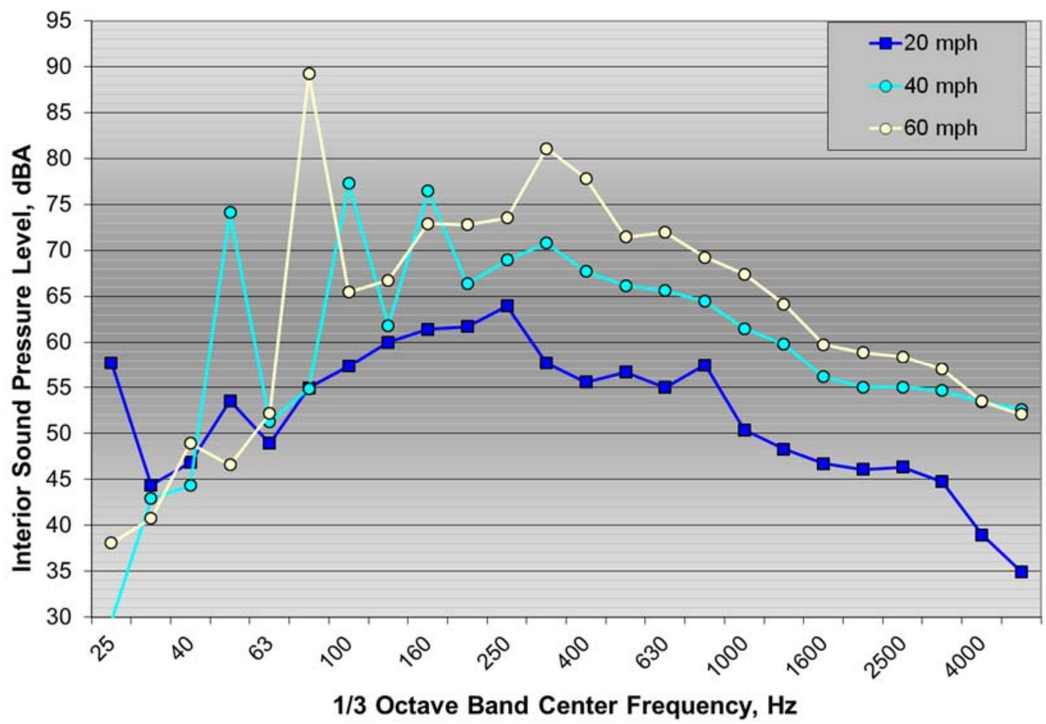


**Figure 50: ⅓ octave band interior noise spectra on mumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

The relationships between the exterior and interior data for the ground rumble strips are more complex than for the mumble strips. Comparisons of the exterior and interior spectra for the three speeds on the ground rumble strips are provided in Figures 51 and 52. For the ground rumble strips, the fundamental repetition rate should be about 29 Hz for 20 mph (31.5 Hz ⅓ OB), 59 Hz for 40 mph (63 Hz band), and 88 Hz for 60 mph (80 and 100 Hz bands) and the harmonics multiples of these. For these data, peaks corresponding to these frequencies are more difficult to identify and some of the peaks occur in the exterior spectra and not in the interior and vice versa. In Figure 51 for the exterior data, the fundamental and first harmonic peaks at 20 mph are shifted higher than expected and are unexplained. Maintaining the vehicle at speed and on the strips was particularly difficult at this speed and may be the cause of this shift. The interior data depicted in Figure 52 shows that the peak occurs in the 31.5 Hz band, as expected.

## 6.2 Vehicle Vibration

Overall, unweighted acceleration levels for 20, 40, and 60 mph for the Malibu seat track and steering column positions are shown in Figure 53. In all cases the acceleration levels measured for the mumble and ground strip exceed the off-strip levels by at least 10 dB except for 40 mph on the seat track where the differences are only about 9 dB. The levels both on and off the strips increase with speed in a fairly consistent manner and levels on either device type are approximately the same. Based on these overall levels, both types of devices should provide sufficient and equal input to the vehicle operator when the vehicle wanders off-road throughout this speed range.

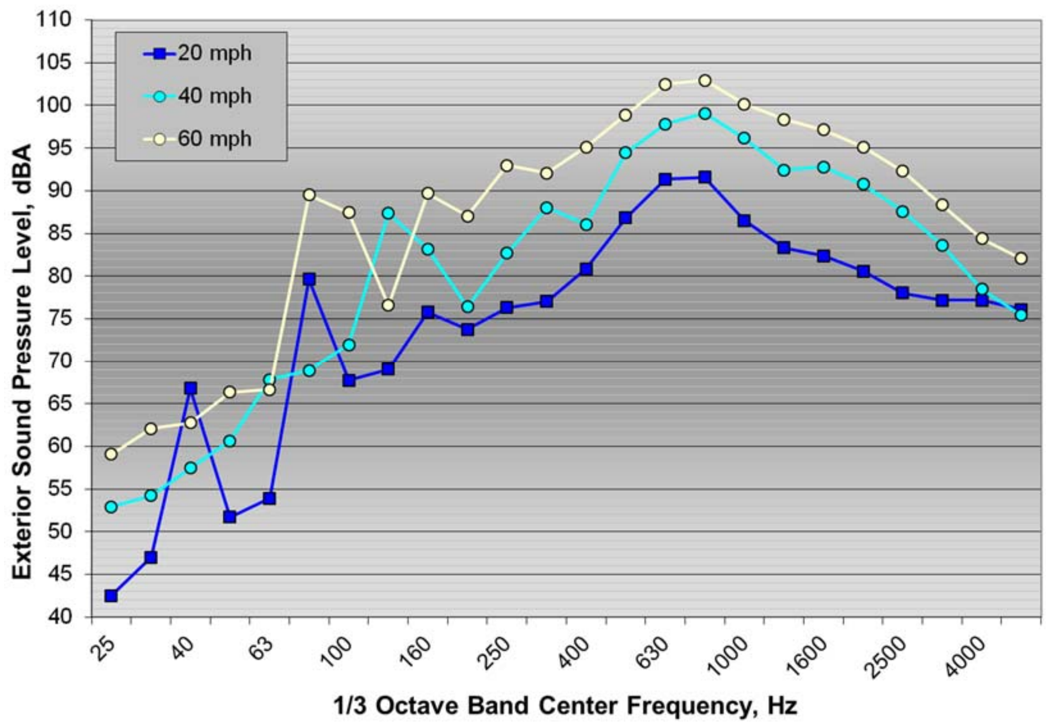


**Figure 51: ⅓ octave band on-board exterior noise spectra on ground rumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

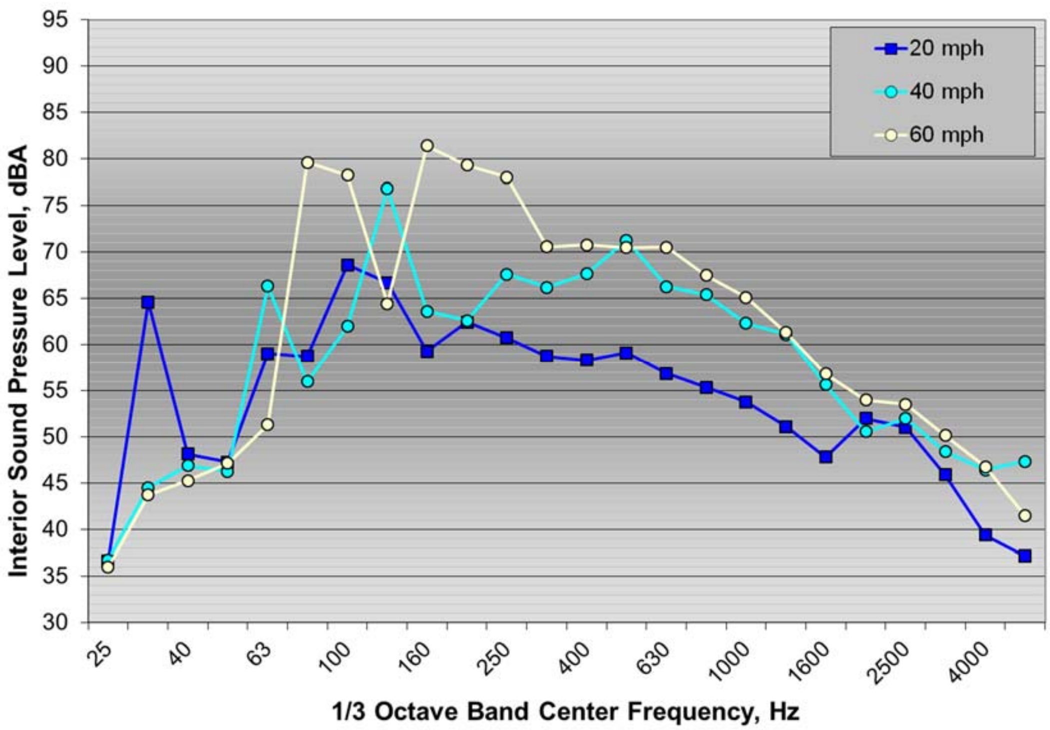


**Figure 52: ⅓ octave band interior noise spectra on ground rumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

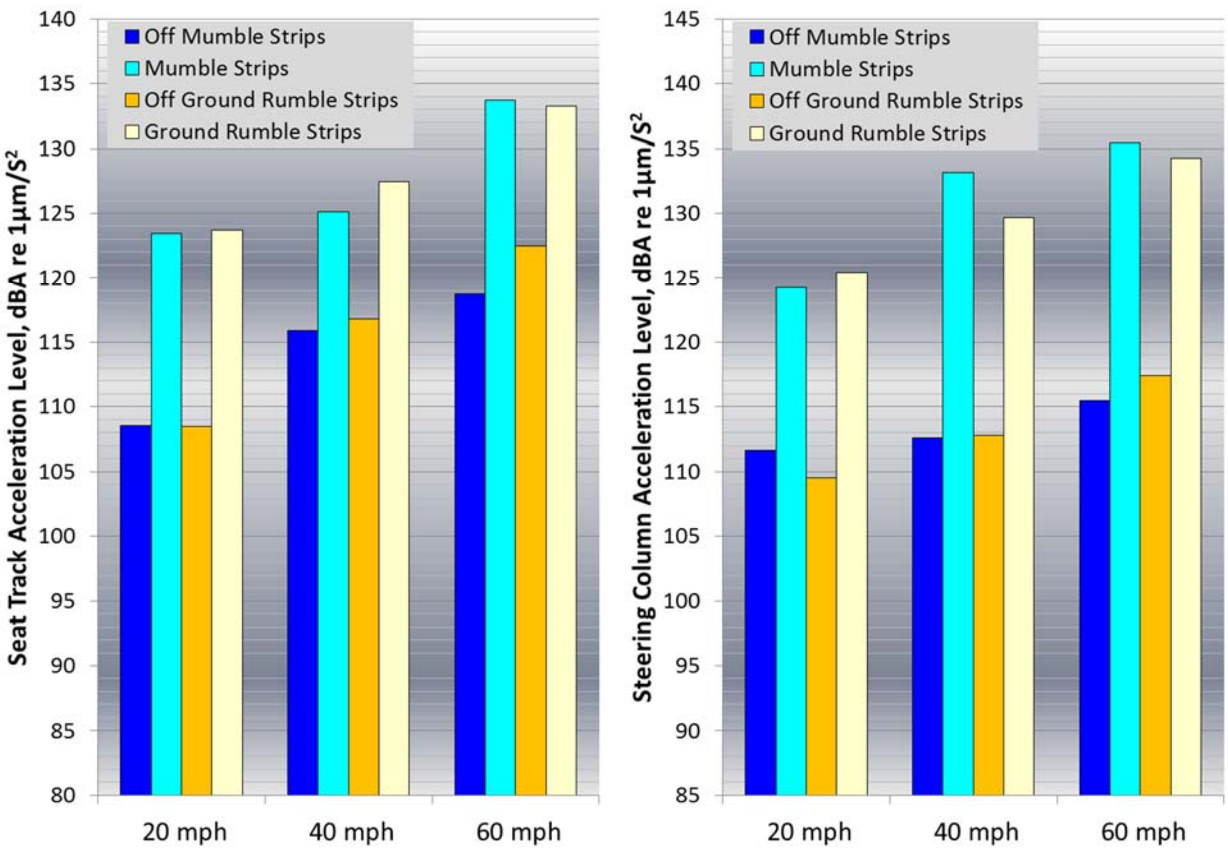


**Figure 53: Overall seat track (left) and steering column acceleration levels for Malibu test vehicle on and off mumble strips and ground rumble strips at 20, 40, and 60 mph**

Seat track accelerations in ⅓ octave bands for the three test speeds on the mumble strips are shown in Figure 54. The repetition rates and their harmonics for the sinusoidal mumble strip are apparent up to about 125 Hz. For the 20 and 60 mph data in particular, the fundamental repetition rates are quite pronounced with 40 mph fundamental repetition rate in the 50 Hz band being clearly identifiable, but 8 to 12 dB lower in level than 20 and 60 mph, respectively. Above 160 Hz, the differences between the speeds become more broad-band and display a relatively uniform increase with speed. The trends for the steering column response shown in Figure 55 are somewhat more complex. The fundamental repetition rate seen for all speeds, but again less pronounced at 40 mph. For the 20 mph results, the harmonics are not apparent while for the 40 and 60 mph results, they are identifiable, but not as pronounced as in the seat track results. Above 160 Hz, the steering column spectra are not uniformly separated with speed as they are for the seat track and some of the levels at 40 mph are higher than at 60 mph. The transmission path to the steering column is less direct than to the seat track and nonlinearities in the path and response of the steering column may be affecting the response at this measurement point. In any case, the response level at the steering column is substantial and should be readily detectable by the vehicle operator.

The trends for the ground rumble strips as shown in Figures 56 and 57 for the seat track and steering column, respectively, are similar to trends for the mumble strips. For seat track position

(Figure 54), the fundamental repetition rates for the three speeds are apparent in the 31.5, 63, and 80 Hz bands. For 20 and 60 mph, harmonics are also apparent. At 40 mph, a peak at the first harmonic (120 Hz) is not noticeable although the level in the 125 Hz band is about 10 dB greater than the 100 Hz band. As for the mumble strips (see Figure 54), the acceleration levels increase markedly for the 160 Hz band which may be overshadowing the first harmonic peak at 40 mph. As was noted for the seat track response on the mumble strips, this acceleration measurement position on the ground rumble strips also produces more broad-band levels above 160 Hz and increase rather uniformly with speed. For the steering column measurement position, the characteristics of the response and magnitude are quite similar to the seat track position except above 500 Hz where the differences between the 40 and 60 mph results become considerably smaller than it does for the seat track. This same behavior was noted for the mumble strips also and may be due to nonlinearities for the steering column response also.

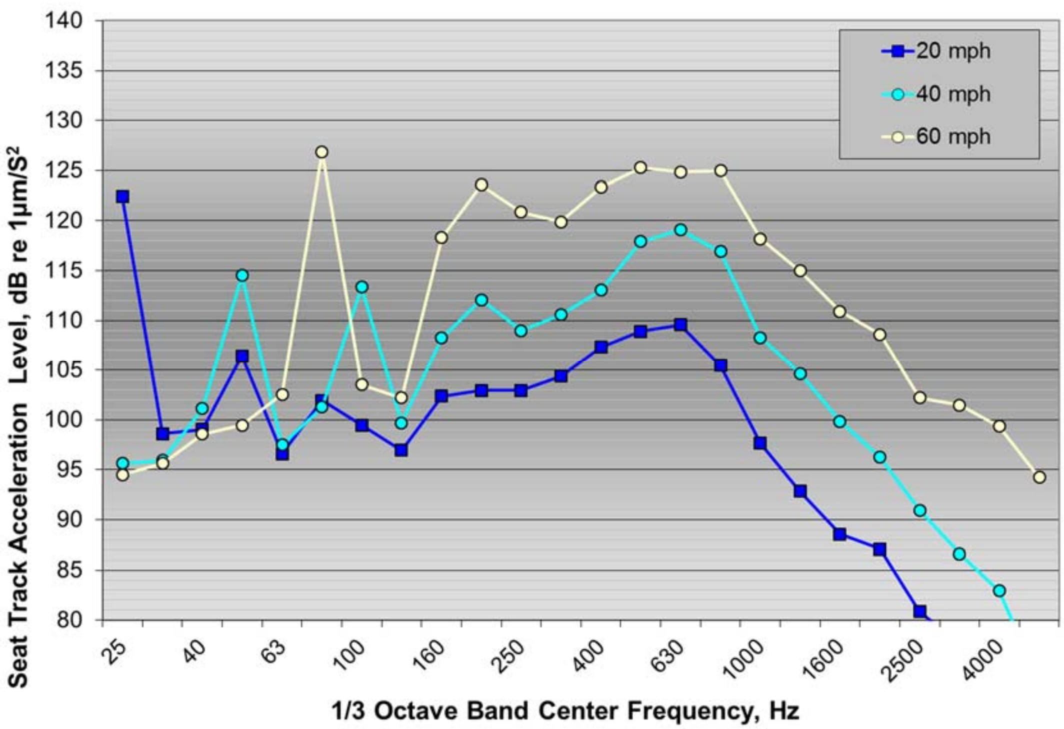


**Figure 54: ⅓ octave band seat track acceleration level on mumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

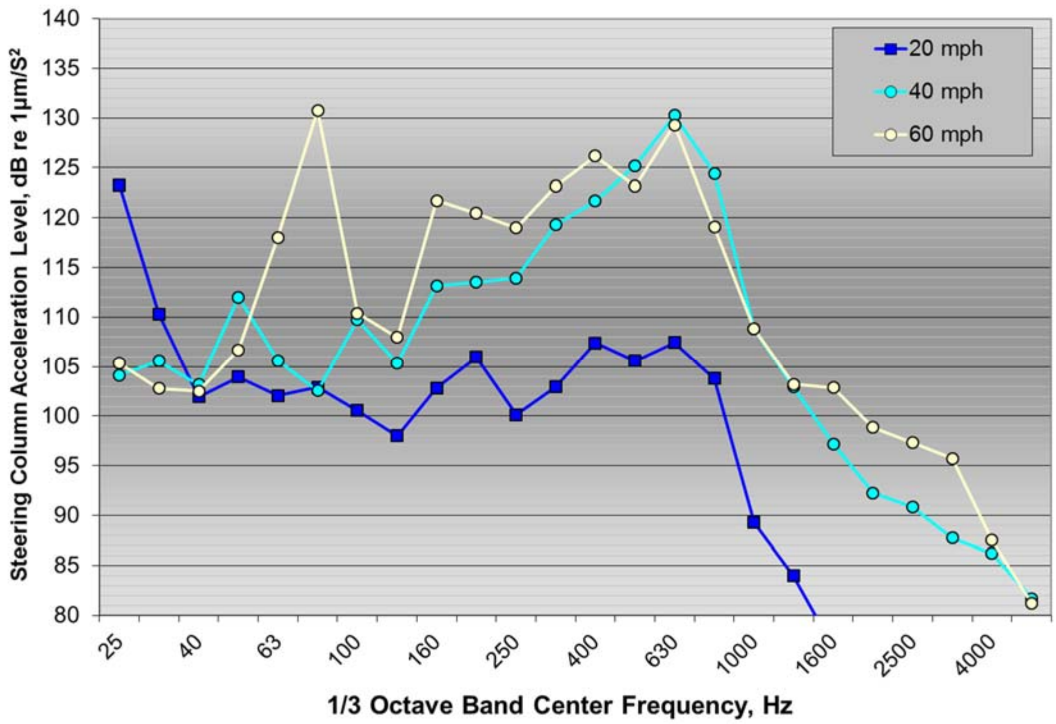


**Figure 55: ⅓ octave band steering column acceleration level on mumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

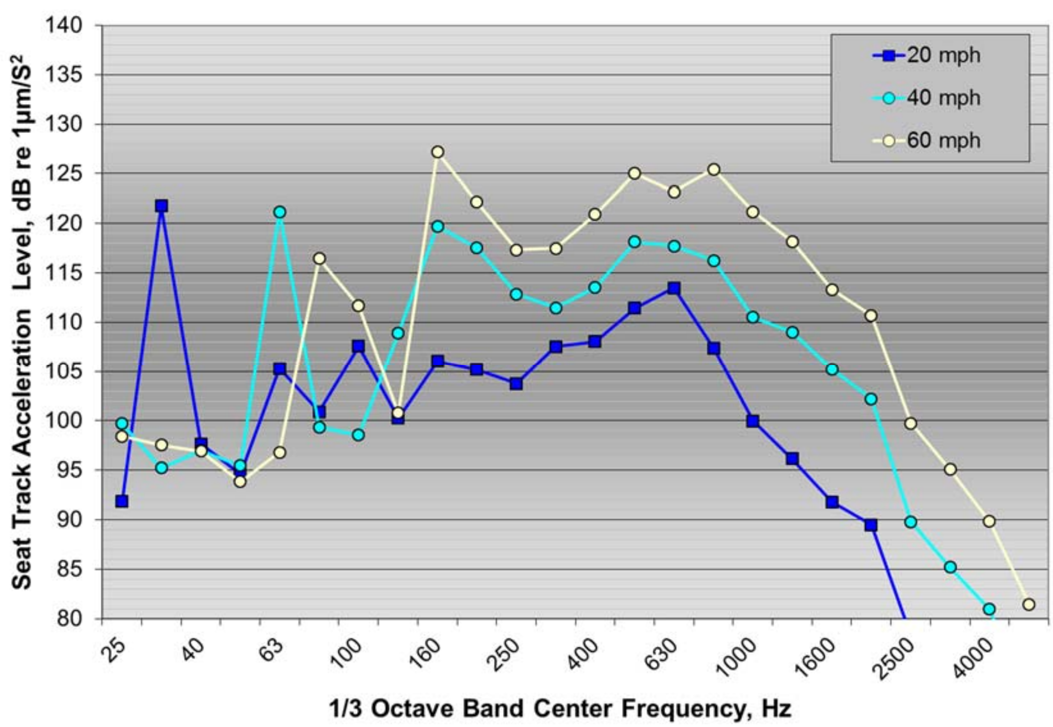


**Figure 56: ⅓ octave band seat track acceleration level on ground rumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

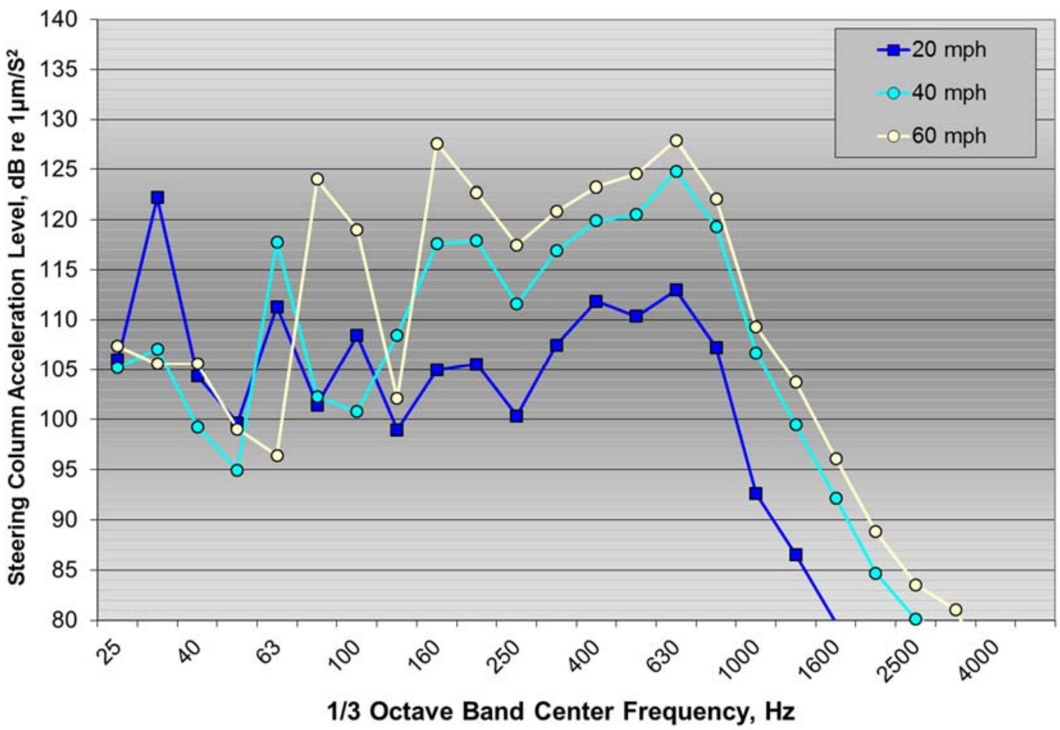


**Figure 57: ⅓ octave band steering column acceleration level on ground rumble strips for the Malibu test vehicle at 20, 40, and 60 mph**

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# Chapter 7 Additional Evaluations

Additional tests on the Ford Fusion in April 2015 afforded the opportunity to expand the number of vehicles used to evaluate the mumble strip performance and address some other issues identified in the 2012 testing. These tests measured the effect of tire and wheel design on warning strip performance, and the vibration of exterior body panels in response to the mumble strips and ground rumbles strips. The tests also provided an attempt to again measure sound intensity of the tires using the OBSI method. The purpose of measurements was to determine whether the exterior pass-by noise on the strips was generated by sound radiation from the body panels or directly from the tire.

## 7.1 Influence of Tires

The Ford Fusion test vehicle came equipped with Goodyear Eagle $LS_2$ (GDY) tires, which are significantly different than the SRTT required in the AASHTO TP 76 OBSI test procedure and on the Chevrolet Malibu in 2012. The GDY tire is a low profile design compared to the more tradition SRTT as shown in Figure 58. The measurement program defined in Chapter 3 was implemented for the Fusion on a full of set of both tire types.

**Figure 58: SRTT (left) and GDY test tire (right)**

The overall A-weighted sound pressure levels measured on the outside of the Fusion with the GDY tires and SRTT are shown in Figure 59. These data indicate some differences in the way the two tires perform on each of the strips. For both the pass-by and exterior noise, the GDY tires produce lower levels than the SRTT on mumble strips by about 5 dB. On the ground rumble strips, the levels for the two tires are about the same. The differences between on and off of the strips is also consistently less for the GDY tire than for the SRTT. From the ⅓ OB levels shown in Figure 60, the GDY tire is consistently lower in the bands from 315 Hz up to 10,000Hz for the mumble strips. On the ground rumble strips, the SRTT only produces higher levels only at 80, 630, and 800 Hz. The exterior noise results plotted in Figure 61show the trends that are somewhat different than the pass-bys. With the SRTT, the levels at the repetition rates of the two strips (80 and 100 Hz) are higher, 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 for the GDY tires above 315 Hz. Similarly, the levels above 1250 Hz are consistently higher for the GDY tires than for the SRTT on the ground rumble strips.

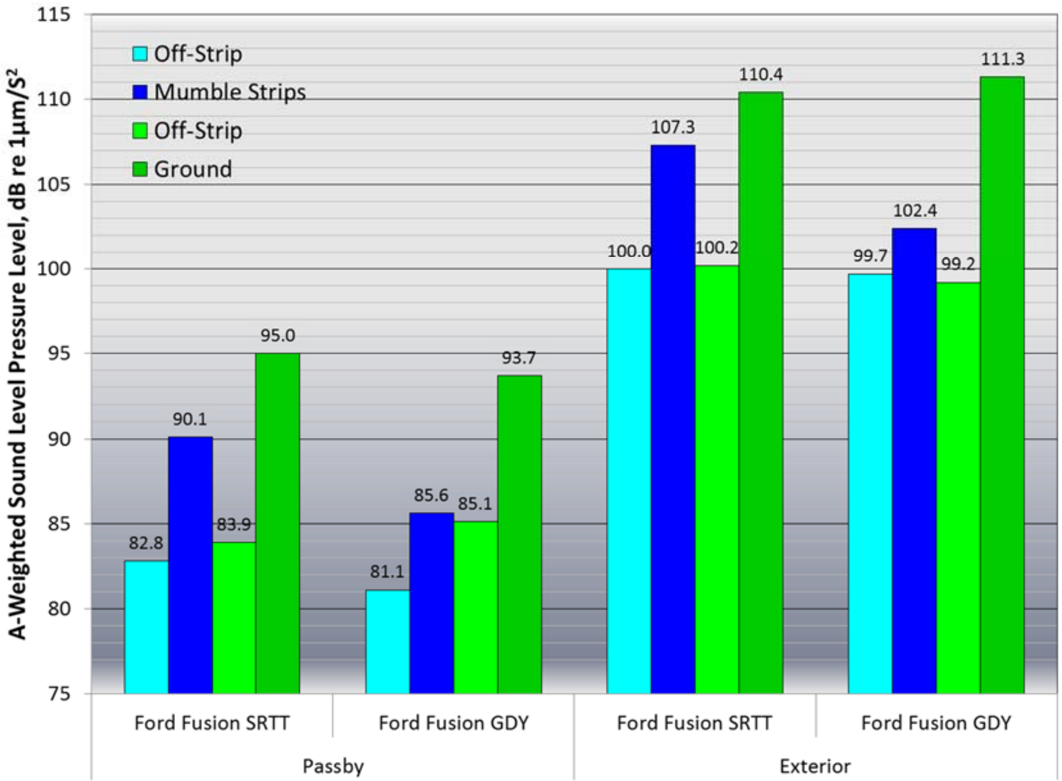


**Figure 59: Overall A-weighted pass-by and exterior sound pressure levels for GDY tires and SRTT**

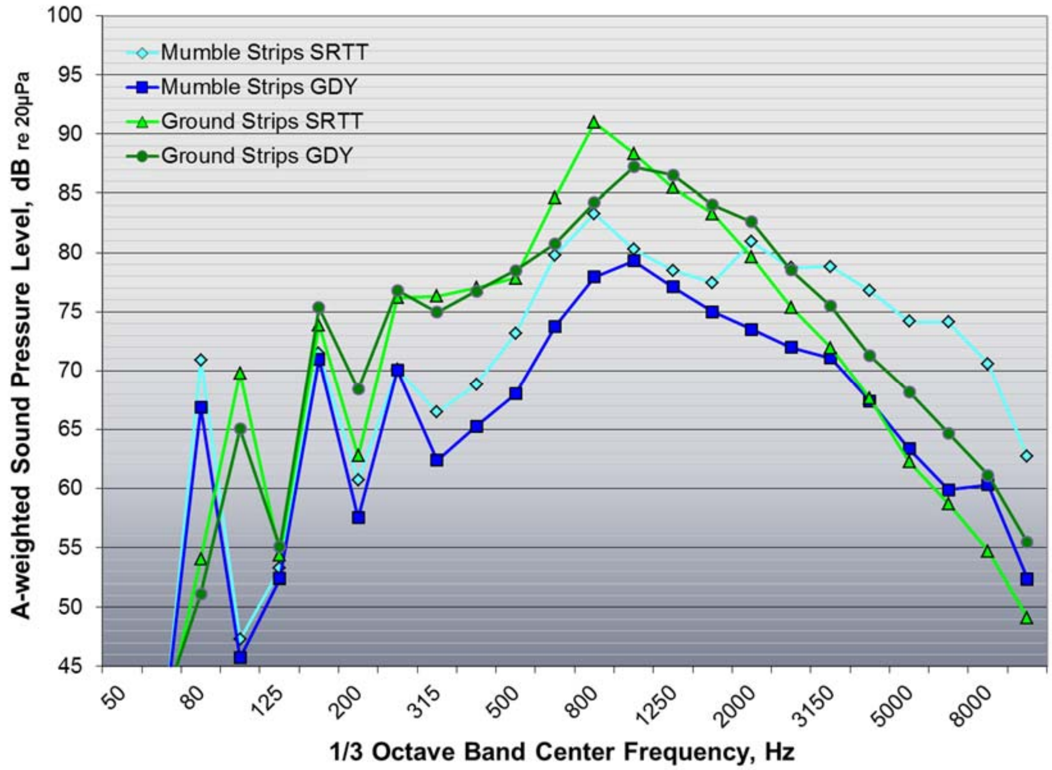


**Figure 60: ⅓ octave band pass-by sound pressure levels measured with GDY tires and SRTT**

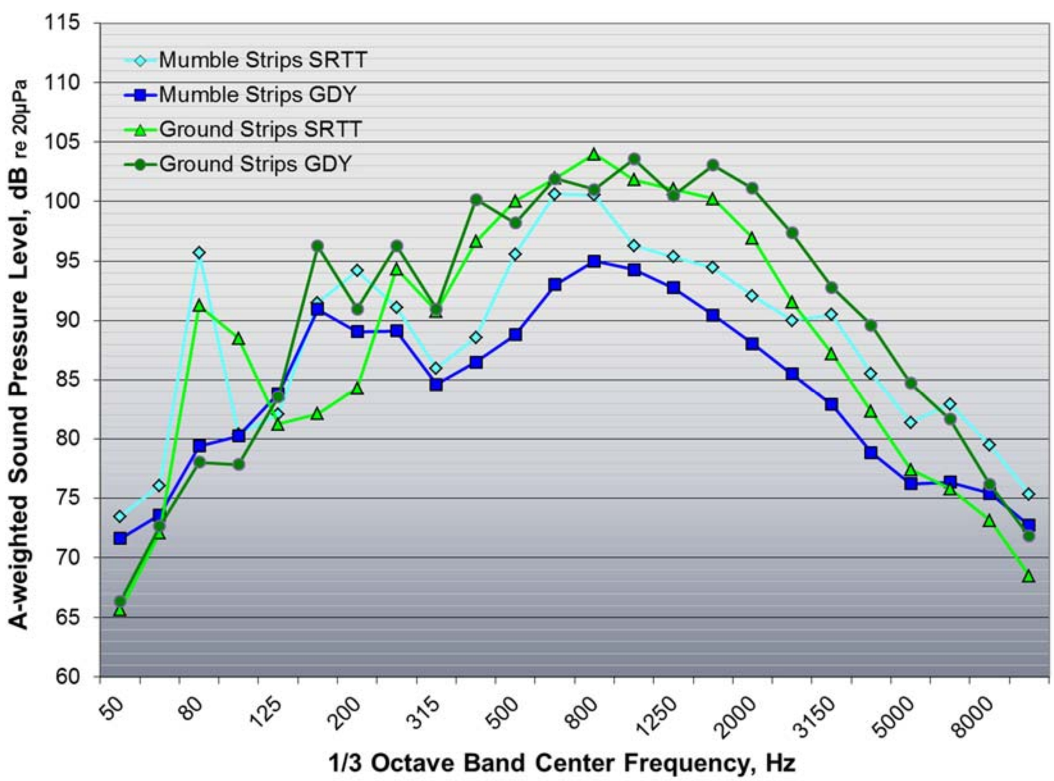


**Figure 61: ⅓ octave band exterior sound pressure levels measured with GDY tires and SRTT**

The overall response levels for the interior of the Fusion with the two tire sets are shown in Figure 62. For the interior noise and both vibration measurements, the SRTT produces higher levels (2.5 to 7.1 dB) of response on both strips than does the GDY tire. The difference when the vehicles is on the trips compared with being off the strips also tends to be slightly higher for the SRTT. In the ⅓ OB interior noise levels shown in Figure 63, the 80 Hz band shows up prominently for both tires on the 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 rumble 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 62 being higher for GDY tire and being slightly higher (1.7 dB) than those of the SRTT on the ground rumble strips.

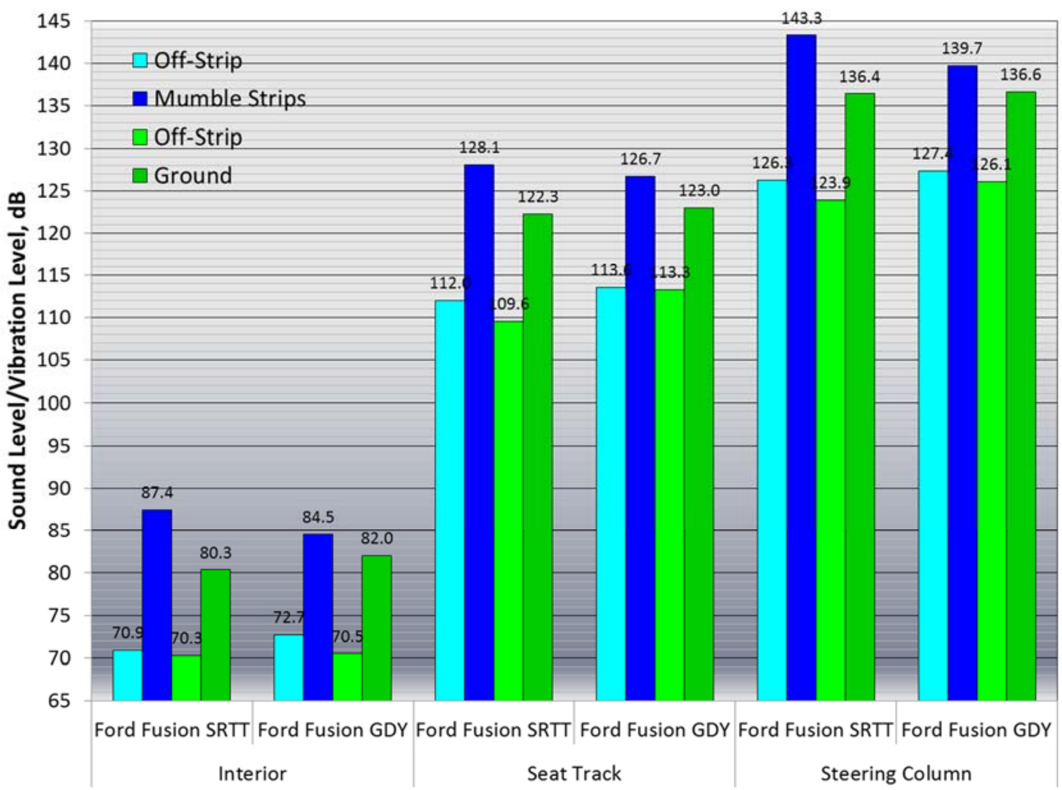


**Figure 62: Overall A-weighted interior sound pressure and unweighted vibration levels for GDY tires and SRTT**

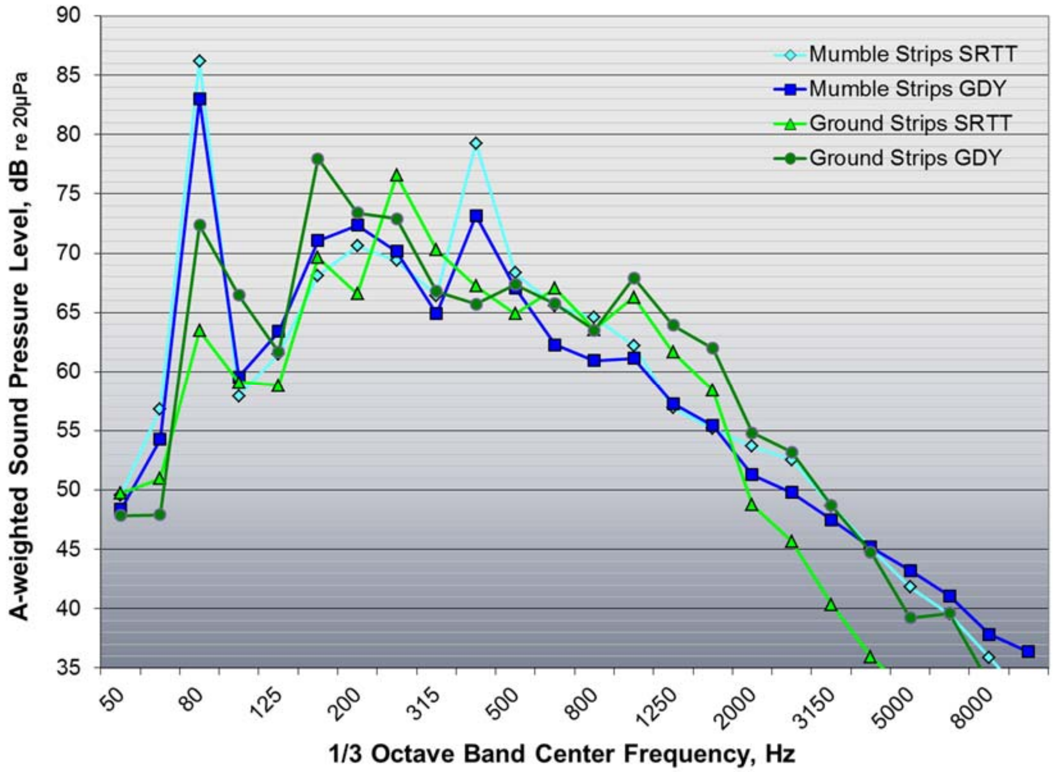


**Figure 63: ⅓ octave band interior sound pressure levels measured with GDY tires and SRTT**

Figure 64 provides comparisons of the seat track accelerations for the two warning strips and two tires. On the mumble strips, although the overall levels for the SRTT and GDY tires are within 1.4 dB (Figure 62), the spectral distributions created by the tires are substantially different. For the GDY tires, 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 rumble 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 62, the acceleration levels for the steering column as shown in Figure 65 are considerable higher than those for the seat track for both tires and on both types of strips. On the ground rumble 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.

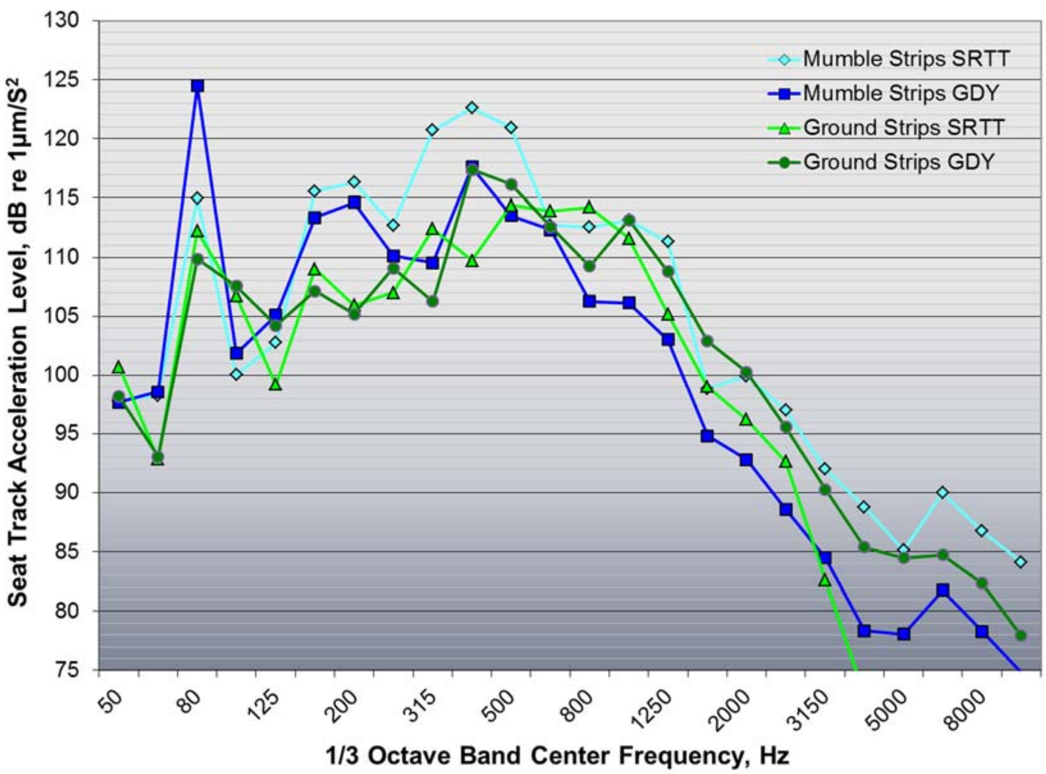


**Figure 64: ⅓ octave band seat track acceleration levels measured with GDY tires and SRTT**

Additional results for the two test tires are provided in the appendix. These results include comparisons of ⅓ octave bands levels measured when either tire is on or off the strips.

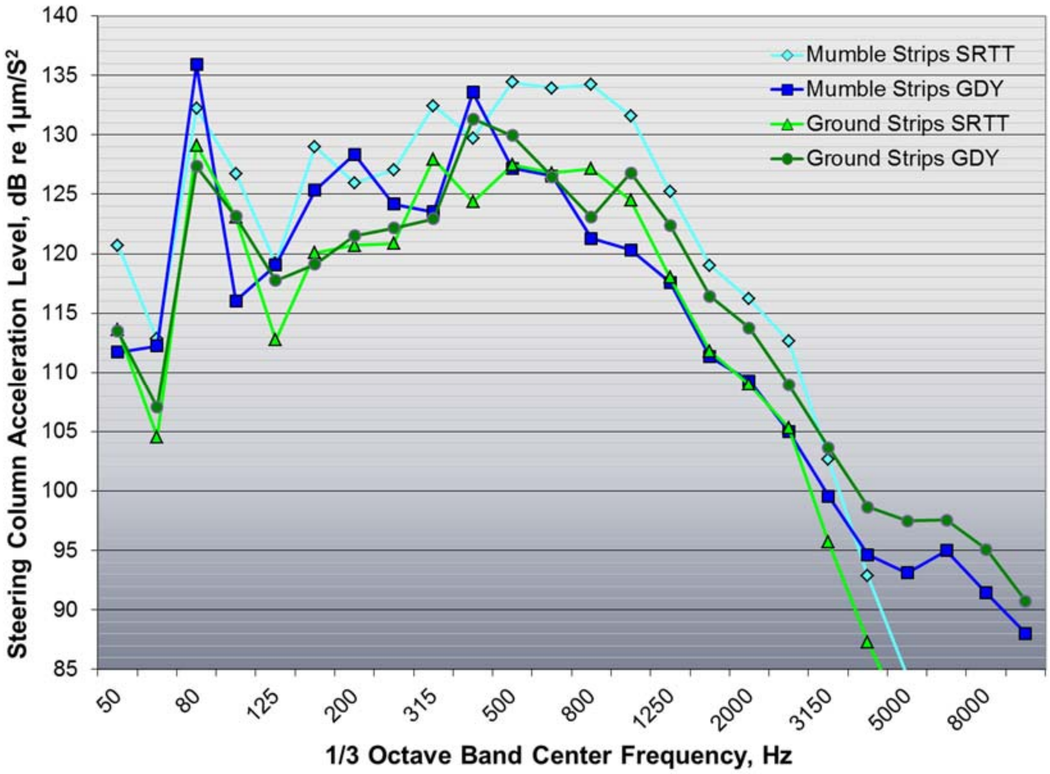


**Figure 65: ⅓ octave band steering column acceleration levels measured with GDY tires and SRTT**

## 7.2 OBSI Measurements

During the 2012 testing, OBSI on the mumble strips was attempted using the fixture commonly used for conducting these measurements under the AASHTO TP 76 test method, as shown in Figure 66. During the attempt, it was found that the probes supported by the plastic vertical rods began to vibrate wildly. As result, the attempts were aborted due to concerns for the equipment. Prior to the April 2015 tests, the fixture was redesigned in an effort to minimize the motion of the probes. The resultant fixture is shown in Figure 67. In this design, the rods were eliminated and a cross bar was rigidly attached to the lower end of the fixture. On-road trials determined that attachment of the spacer holding the microphones and preamplifiers to the fixture could result in acceleration levels sufficient to damage the preamplifiers. To combat this, isolation was added between the metal fixture and blocks holding the preamplifiers as shown in Figure 67. With this modification, it was found that the preamplifiers could survive the inputs from the rumble strips. In the modified fixture design, the spacing between the microphones was increased to 32mm to more accurately capture the low frequency sound created by the mumble strips.

For the OBSI measurements in all cases, it was found that the sound intensity was negative up to about 315 Hz. This indicates the at the OBSI points, the sound intensity vector is directed toward the tire. This behavior is often seen when measuring at discrete points in the near field of an extended source such as a vibrating panel. In such cases, the sound radiated by the source needs to be averaged over the entire surface of the panel, or in this case, the tire, in order to determine the outgoing sound power. Such measurements would be better suited using array techniques where many points near the surface of the tire could be measured at once.

**Figure 66: Conventional OBSI fixture**

**Figure 67: Modified OBSI fixture for rumble strip and mumble strip measurements installed (left) and with added probe holder isolation (right)**

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. Figure 68 provides a comparison of the sound pressure levels from the probes for the two tires on the two strips. These data capture the behaviors 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 rumble strips. Generally, the results in Figure 68 show trends at 200 Hz that are similar to those of the exterior microphone data shown in Figure 61. 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 all at 80 Hz. Further, in the 80 and 100 Hz bands, the SRTT on the ground rumble strips produce noticeably higher exterior noise levels than do the GDY tires (Figure 61). For the OBSI location, these results are switched, with the GDY tires producing higher levels (by about 7 dB) for the exterior location (Figure 68). 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 with the other types of data.

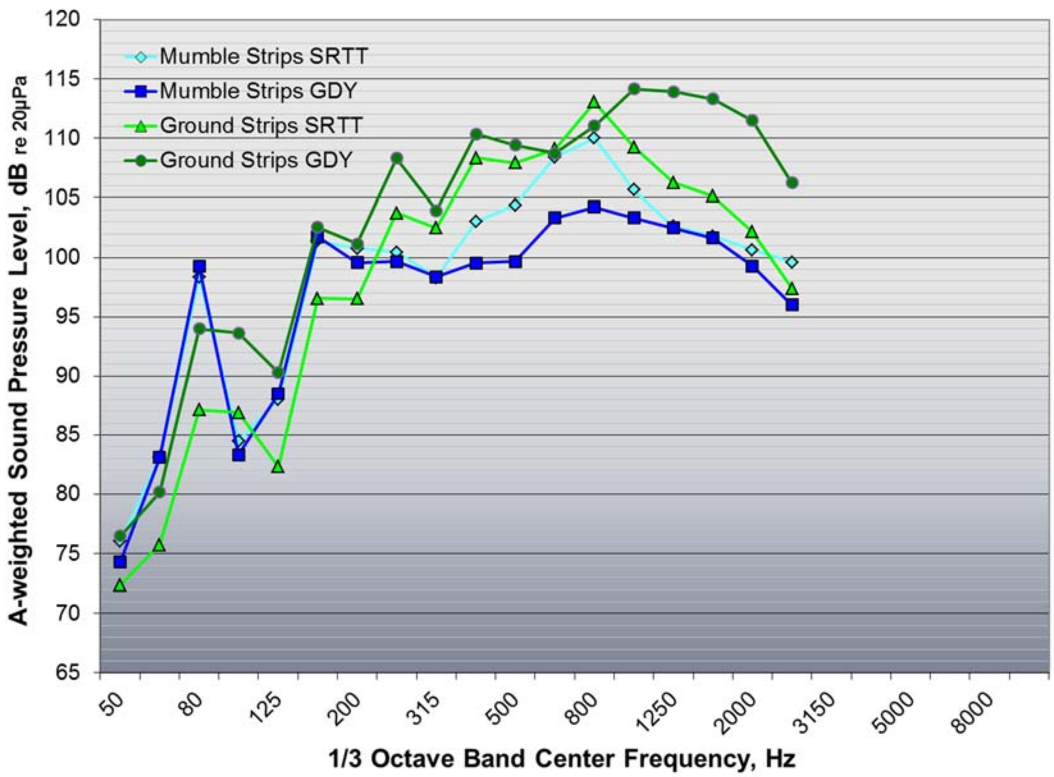


**Figure 68: ⅓ octave band sound pressure levels measured by the OBSI probes for the GDY tires and SRTT**

## 7.3 Exterior Body Panel Vibration Measurements

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 sufficient 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. As a step to evaluating this possibility, the acceleration levels of three major body panels were measured: the right rear fender, the rear door, and the front fender. The same 5.8 gr accelerometer used for the steering column was used for these measurements located as shown in

Figure 69. The overall acceleration levels for the three panels and two tires when the vehicles is on and off the two types of strips are shown in Figure 70. As with the interior acceleration and sound pressure level data, the panel acceleration levels display a large difference when the vehicle is on the strips and off the strips, with an average difference of 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 69: Body panel acceleration measurement points: front fender (upper left), rear door (upper right), and rear fender (lower center)**

Although the results of Figure 70 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 shown in Figure 71. For the pass-by measurements, the increase in sound level on and off the mumble strips was less than for the ground rumble strips. For the panel vibration, the differences for the mumble are greater than for the ground rumble strips. Because behavior is the opposite of the pass-by results, it is not clear that the differences in pass-by performance are determined 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.

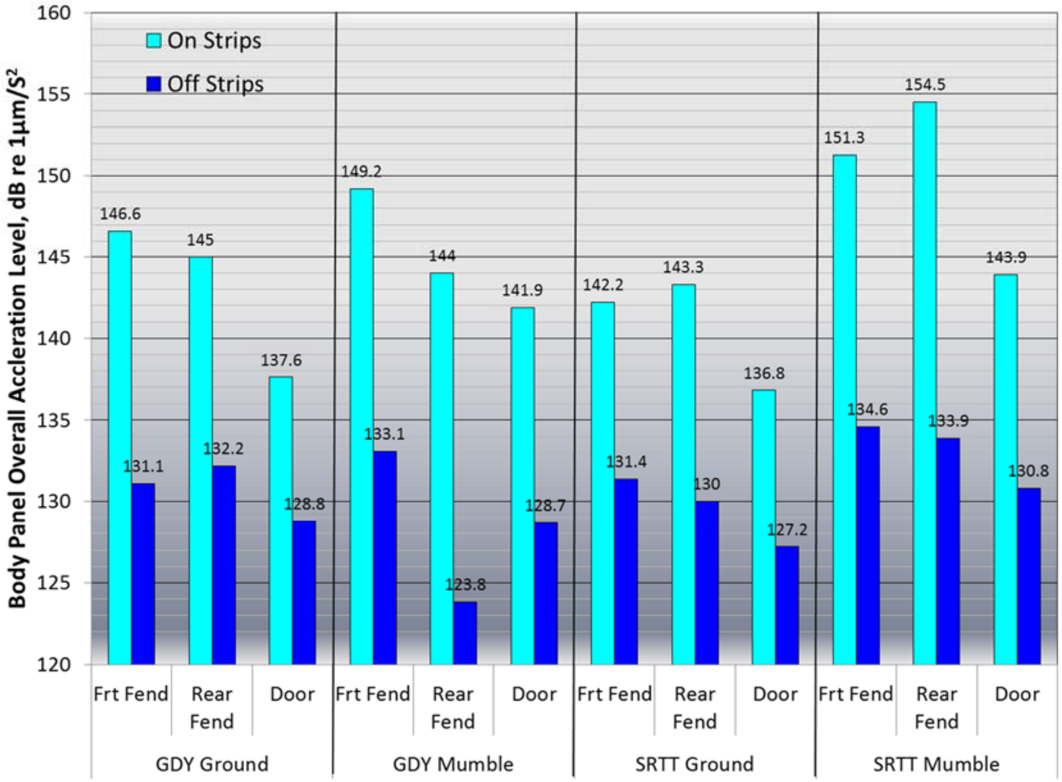


**Figure 70: Overall panel acceleration levels on and off warning strips**

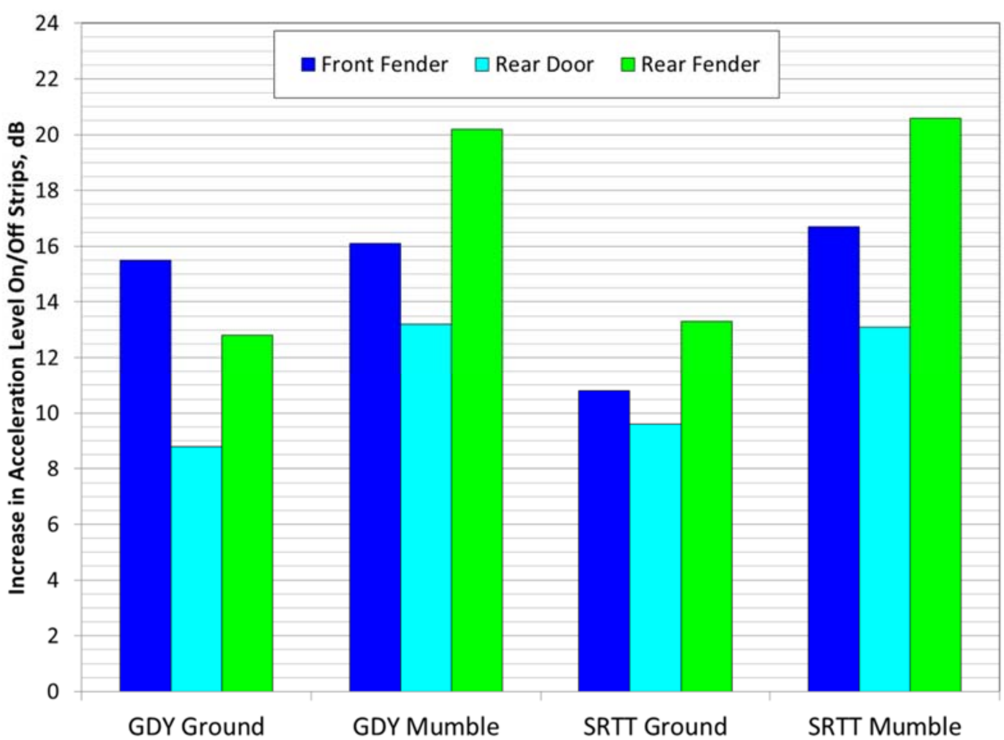


**Figure 71: Overall panel acceleration differences for on and off the ground rumble strips and the mumble strips**

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# Chapter 8 Summary and Conclusions

## 8.1 Performance of the Mumble Strips

In general, the experimental mumble strips performed as intended. For a range of passenger vehicles, the mumble strips reduced the higher frequency noise typically generated by conventional warning devices, lowering the overall A-weighted exterior pass-by levels by 6.2 dB. For a 4-yard dump truck, pass-by levels were lowered by only 3.2 dB due to levels from the truck off the strips. The sinusoidal design of mumble strips did produce lower frequency narrow band sounds at frequencies dependent on vehicle speed; however, these lower frequencies generally had no effect on the overall A-weighted sound levels. The relative annoyance of these lower frequency sounds should be evaluated if more widespread use of the mumble strip design is contemplated.

Inside the test vehicles, the mumble strip disturbance levels to warn operators and occupants of a vehicle wandering out of the lane of travel were generally about the same or greater as levels provided by conventional warning strips. The difference in interior A-weighted noise levels when a vehicles is on and off the mumble strips averaged about 13 dB for the passenger vehicles versus about 14 dB for conventional ground rumble strips. For the dump truck, the noise level differences were lower for both mumble strips (2.6 dB) and ground rumble strips (7.6 dB). Differences in vibration levels inside the vehicles while traveling on and off the strips were similar to differences in interior noise. For seat track acceleration, the on/off difference in un-weighted level was more than 13 dB when passenger vehicles were on the mumble strips or ground rumble strips. Similar to the interior noise differences, the change in seat track vibration levels for the truck on the mumble strips (1.9 dB) was lower than when the truck was the ground rumble strips (5.0 dB). For the steering column, this trend as reversed as the mumble strips produced a 7.2 dB difference compared to 5.8 dB for the ground rumble strips. In all of the vehicles, the subjective disturbance to the operator and occupants created by the mumble strips seemed more than adequate to warn of excursions out of the travel lane at 60 mph. One test car was also measured at speeds of 20 and 40 mph. At these speeds, the disturbance of the mumble strips also was objectively and subjectively adequate, while the exterior levels were reduced compared with the conventional ground rumble strips.

Some variation in the exterior noise and interior disturbance was found for the vehicles, even among the passenger vehicles. This variation was observed when vehicles were on either the mumble strips or ground rumble strips. Some of this variation was related to the response of each vehicle to the repetition rate of the strips and the harmonics of this rate. Especially at lower frequencies, the individual responses appeared to be controlled in part by acoustic and structural modes of the different vehicles. Tire design is another variable affecting all aspects of vehicle response, both interior and exterior, as shown by data for the two different tires tested on the Fusion. The variation in results of different vehicles could also be the result of other parameters, such as vehicle weight, wheelbase, and general body isolation.

For the mumble strips, a key unknown factor is how the lower frequency pass-by noise is produced. In the range from 40 to 160 Hz, it is known that the tire itself is not an efficient radiator of sound and OBSI sound pressure level and that the exterior measurements do not consistently correlate to the pass-by measurements. It was thought that sound radiation from exterior body panels may be a factor as driven by vibration inputs transmitted into the vehicle through the suspension. Although the body panels do vibrate to a level consistent with radiating a significant level of noise, the trends in results for the two warning strip designs are not the same for pass-by and exterior panel vibration for individual panels. At 80 Hz, the acoustic wavelength is about 14 feet. The sizes of the panels are about 2 to 3 feet. As a result, the sound field produced by the entire vehicle could be quite complex and involve participation of multiple panels with some unknown phase relationships. Given the amplitude of the lower frequency narrow-band levels generated by the mumble strip design, understanding how this energy is generated and actually radiated may be an important issue to understand before wider implementation of this warning device concept.

## 8.2 Evaluation Methods

All of the measurements provided useful and different information for the evaluation of the mumble strips and rumble strips in general. The inclusion of multiple test vehicles of different categories should be considered as a necessity in performing the evaluations. Measuring pass-by noise levels is a necessary part of the testing. The exterior noise measurement at the top of the right rear wheel well was somewhat useful, but results were somewhat ambiguous. Measuring OBSI below 400 Hz is not useful because the sound intensity is negative, directed into the tire. However, sound pressure measured at the OBSI locations may be of some use. Measurement of exterior panel vibration may be relatable to low frequency pass-by noise (below 400 Hz); however, further investigation will be needed to establish this relationship. The relationship of data captured at isolated points on the exterior of the vehicle to pass-by noise is not well defined because the isolated points are in the very near acoustic field of the source, especially at low frequency. Further, these measurements do not separate tire noise from other sources of radiated sound on the vehicle. The use of sound pressure level measurements at the OBSI locations should be examined further in future evaluations. To address sound radiation from the vehicle exterior and body panels, vibration of these panels should be measured simultaneously at more points to capture the phase relationships of the vibrations. Such data could then be combined with theoretical methods, such as Boundary Element Modeling, to determine the nature of the low-frequency sound radiation. Understanding the sound radiation may lead to designs of warning strips that result in even lower pass-by sound levels. .

Interior noise measurements were also very useful in quantifying interior disturbance for warning the operator and occupants. Because of the potential of standing acoustic waves in the interior cavity, it would be advisable to use more than one microphone location or to be certain that the microphone position chosen will not be located in a null point of any potential standing waves. Because of standing waves and cavity modes of the interior, acoustic measures such unweighted or C-weighted levels are not a surrogate for vibration measurements.

Vibration measurements at the seat track and on the steering column both provided useful information, especially when used together. The seat track location is typically on the body structure and, because of its stiffness, provides a measurement point that should not be influenced by local structural modes. The steering column will be affected by local modes and the attachment details of the steering column to the structure. However, this position is indicative of the amount of vibration that an operator with hands on the steering wheel would experience. As noted for the 4-yard dump truck, the difference between on and off of the mumble strips was greater at the steering column position than at any other vibration or noise response point. From the operator's viewpoint, the steering column data should provide the best indication that there is sufficient input to warn of excursions out of the lane of travel. In future vibration measurements, an additional tri-axial accelerometer near the spindle that supports the hub and wheel assembly of the test tire would also be useful. This measurement would give an indication of the input of the warning device to the suspension and would not be complicated by the suspension modes between the input and the response at the seat track. To understand the effect of the transfer paths from the spindle to the seat track and steering column response points, transfer mobilities (velocity response/force input) between the spindle and these locations could also be measured.

Heavy trucks could particularly benefit from transfer path analysis. When the test dump truck was on the mumble strips, only the steering column vibration produced a difference greater is than 3 dB compared with travel off the strips. This limited difference in results for on- and off-strip travel may be due to cab isolation designed particularly to address lower frequency vibration in order to reduce driver fatigue (Wang et al. 2017). As a result, the most direct path for providing warning to the operator may be through the steering column. Because of cab isolation, attempting to modify the mumble strip design to improve operator warning based on interior noise and seat track vibration may have minimal benefit at the expense of producing greater pass-by levels.

This measurement program leads to some consideration for proper evaluation methods criteria development. At a minimum, the evaluation methods should include pass-by, interior noise, and interior vibration measurements. There is no substitute for vibration measurements, which should be taken at seat track and steering column locations. Given the variation in level of response for each vehicle, absolute noise and vibration level criteria for rumble performance is not viable. Criteria should be based on levels measured when a vehicle on and off the strips. This may require further stipulation if the levels of tire-pavement noise are high off the strips because of a noisy pavement. Although trends between vehicles were similar, warning strip evaluation should be done with several vehicles of different design. Of the three passenger cars tested, the Civic appeared to have unique response that may be due to its weight, wheelbase, suspension design, or interior acoustics. More testing, especially with smaller, lighter weight cars, should be done. Given the influence of vehicle and tire designs, standard methods of evaluating warning strip noise and vibration are needed. Without this standardization, transportation agencies will likely be chasing warning strip designs that are not quieter and do not provide the necessary amount of driver warning.

## 8.3 Design Recommendations

The mumble strip design was successful in its goals of reducing higher frequency noise and the overall A-weighted sound level. The disturbance created by the mumble strips appeared to be easily sufficient to provide operator warning. However, the mumble strip concept does generate narrow band lower frequency noise content that could be of concern to nearby residents. From the results of these measurements, it appears that it may be possible to optimize the mumble strip design to lower the exterior noise corresponding to the fundamental and harmonics for the strip repetition rate while maintaining adequate interior warning. From this evaluation, decreasing the depth or peak-to-peak amplitude of the mumble strip sinusoidal may be one way to lower the exterior noise and maintain sufficient interior warning. This modification should reduce the tire input by reducing the variation in contact patch geometry. It is suggested that this modification be considered incrementally by reducing the $^{5}/_{16}$ inch depth used here to ¼ inch. Exterior noise might also be reduced by slightly increasing the wavelength of the sinusoidal shape. As a first step, the wavelength could be increased to 16 inches, which would correspond to 66 Hz at 60 mph.

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# Chapter 9 Glossary

The definitions that follow were taken largely from the Caltrans Technical Noise Supplement (Caltrans 2013).

**Accelerometer:** An electroacoustic transducer that transforms the motion of surface or objective into equivalent electric waves.

**A-Weighted Sound Level:** Expressed in dBA. Frequency-weighted sound pressure level approximating the frequency response of the human ear. It is defined as the sound level in decibels measured with a sound level meter having the metering characteristics and a frequency weighting specified in the American National Standards Institute Specification for Sound Level Meters, ANSI S 1.4–1983. The A-weighting de-emphasizes lower frequency sound sounds below 1,000 Hz (1 kHz) and higher frequency sounds above 4 kHz. It emphasizes sounds between 1 and 4 kHz. A-weighting is the most commonly used measure for traffic and environmental noise throughout the world.

**Decibel:** A decibel is one-tenth of a bel. It is a measure on a logarithmic scale that indicates the squared ratio of sound pressure to a reference sound pressure (unit for sound pressure level) or the ratio of sound power to a reference sound power (unit for sound power level). See also "Sound Pressure Level" and "Sound Power Level."

**Dynamic Range:** The range in sound levels, in decibels, through which a source or receiver can emit or receive sound. For example, the dynamic range of a sound level meter typically ranges from 20 to 140 dB.

**Filter:** A device for separating components of a signal based on their frequency. It allows components in one or more frequency bands to pass relatively unattenuated and attenuates components in other frequency bands.

**Frequency:** The number of oscillations per second of a periodic wave sound and of a vibrating solid, expressed in units of hertz, formerly cycles per second (cps). 1 Hz = 1 cps = 1 oscillation per second. The value is the reciprocal (1/x) of the period of oscillations in seconds. The symbol for frequency is *f*.

**Frequency Band:** An interval of the frequency spectrum defined between an upper and lower cutoff frequency. The band may be described in terms of these two frequencies or (preferably) by the width of the band and the geometric mean frequency of the upper and lower cutoff frequencies (e.g., an octave band "centered" at 500 Hz).

**Frequency Spectrum:** The description of a sound wave's resolution into components of different frequency and usually different amplitude and phase.

**Fundamental Frequency:** The frequency with which a periodic function (e.g., sound wave) reproduces itself, sometimes called the first harmonic. See also "Harmonic."

**Harmonic:** A sinusoidal (i.e., pure-tone) component whose frequency is a whole-number multiple of the fundamental frequency of the wave. If a component has a frequency twice that of the fundamental frequency, it is called the second harmonic.

**Hertz (Hz):** Unit of frequency, formerly called cycles per second. 1 Hz = 1 cycle per second. See also “Frequency.”

**Level:** In acoustics, the value of a logarithm of the ratio or ratio squared of that quantity *t* a reference quantity of the same kind in decibels. The base of the logarithm is commonly 10. The reference quantity and kind of level must be specified (e.g., sound pressure level of 60 dB RE: 20 μPa, sound power level RE: $10^{-12}$ watts).

**Lmax:** The highest sound pressure level in a specific time period.

**Meter Response:** Measure of the quickness with which the needle of an analog sound level meter or the display of a digital sound level meter follows changes in the actual sound level.

**Microphone:** An electroacoustic transducer that transforms sound waves into equivalent electric waves.

**Natural Frequency:** Frequency of free oscillation of a system (i.e., the frequency at which a system vibrates when given an initial excitation and allowed to vibrate freely without constraints).

**Near Field:** The part of a sound field, usually within about two wavelengths of the lowest sound frequency from a sound source, in which the dimensions of the sound source have an important effect and where there is no simple relationship between sound level and distance.

**Octave:** The interval between two sounds having a frequency ratio of 1:2; (e.g., 500 to 1,000 Hz; 440 to 880 Hz).

**Octave Band:** A frequency band in which the interval between the upper and lower cutoff frequency is one octave. As with all frequency bands, the octave band is usually described by its center frequency. Octave bands are centered by preferred frequencies described by ISO R 266. An example is the 500-Hz octave band. See also “Frequency Band.”

**One-Third Octave:** The interval between two sounds having a frequency ratio of the cube root of 2 (approximately 1.26). Three contiguous one-third octaves cover the same frequency range as an octave.

**One-Third Octave Band:** A frequency band in which the interval between the upper and lower cutoff frequency is one-third of an octave. As with all frequency bands, the one-third octave band is usually described by its center frequency. Three contiguous octave bands make up one octave band. As with octave bands, one-third octave bands are centered by preferred frequencies described by ISO R 266. For example, three one-third octave bands centered at 400, 500, and 630 Hz make up the 500-Hz octave band. See also "Frequency Band."

**Overall Level:** The sound pressure level that includes all the energy in all frequency bands of interest.

**Real Time Analyzer (RTA)** is an audio device that measures and displays the frequency spectrum of an electrical signal from a transducer such as a microphone or accelerometer.

**Resonance:** The relatively large amplitude of sound or vibration produced when the frequency of the source of the sound or vibration "matches" (i.e., synchronizes) with the natural frequency of vibration of an object. See also "Natural Frequency."

**Root Mean Square:** The square root of the mean of the squares of a set of instantaneous positive, negative, or zero pressure amplitudes. The root mean square value is calculated by squaring the pressure values at each instant, adding them, dividing the total by the number of values, and taking the square root of the result. The squaring of both the positive and negative values ensures a positive result. A root mean square sound pressure is directly correlated with sound energy.

**Sine Wave:** A sound wave, audible as a pure tone, in which the sound pressure is a sinusoidal function of time.

**Sound:** A vibratory disturbance created by a moving or vibrating source in the pressure and density of a gaseous, liquid medium or in the elastic strain of a solid that is capable of being detected by hearing organs. Sound may be thought of as mechanical energy of a vibrating object transmitted by pressure waves through a medium to the ears. The medium of main concern is air. Unless otherwise specified, sound will be considered airborne, not structureborne, earthborne, etc.

**Sound Intensity:** The average rate of sound energy transmitted in a specified direction through a unit area normal to this direction at a point considered.

**Sound Level:** Frequency-weighted sound pressure level measured using metering characteristics and frequency weighting, such as A, B, or C, specified in the ANSI Specification for Sound Level Meters.

**Sound Level Meter:** An instrument used for measuring sound levels in a specified manner. It generally consists of a microphone, amplifier, output display, and frequency weighting networks

**Sound Power:** The total amount of energy radiated into the atmosphere per unit of time by a source of sound.

**Sound Power Level:** The level of sound power, averaged over a period of time, the reference being $10^{-12}$ watts.

**Sound Pressure Level:** Ten times the logarithm to the base 10 of the ratio of the time mean-square pressure of a sound, in a stated frequency band to the square of the reference sound pressure in gasses, of 20 μPa. Sound pressure level represents only unweighted root mean square levels. The unit is decibels. See also “Root Mean Square.”

**Steady-State Sound:** Sounds for which average characteristics remain constant in time (e.g., sound of an air conditioner, fan, or pump).

**Transducer:** A device capable of being actuated by waves from one or more transmission systems or media, and supplying related waves to one or more other transmission systems or media (e.g., microphones, loud speakers, accelerometers, seismometers).

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# Appendix A Supplemental Data

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# Appendix A Supplemental Data

This appendix contains additional data plots referenced in the main body of the report. Figures A1 through A12 present overall levels comparing the performance of northbound mumble strips (primary test direction) with the southbound strips and comparing the eastbound ground rumble strips (primary test direction) with westbound strips. These data include the exterior noise, interior noise, seat track acceleration, and steering column acceleration levels for each test vehicle at 60 mph and for the Malibu test vehicle at 20 and 40 mph as well as 60 mph. On average, there is very little difference (0.2 dB) among the levels of sound and acceleration measured in opposing directions; however, in one case, the difference was as large as 3.4 dB. For the April 2015 measurements with the Ford Fusion, data from only one direction of travel was acquired. Figures A13 through A20 present the ⅓ octave band acceleration levels for the same four vehicles on and off the mumble strips and ground rumble strips for the seat and steering column measurement points. Figures A21 through A36 present the ⅓ octave band noise and acceleration levels measured when the Ford Fusion was on and off the mumble strips and ground rumble strips with the SRTT and Goodyear test tires.

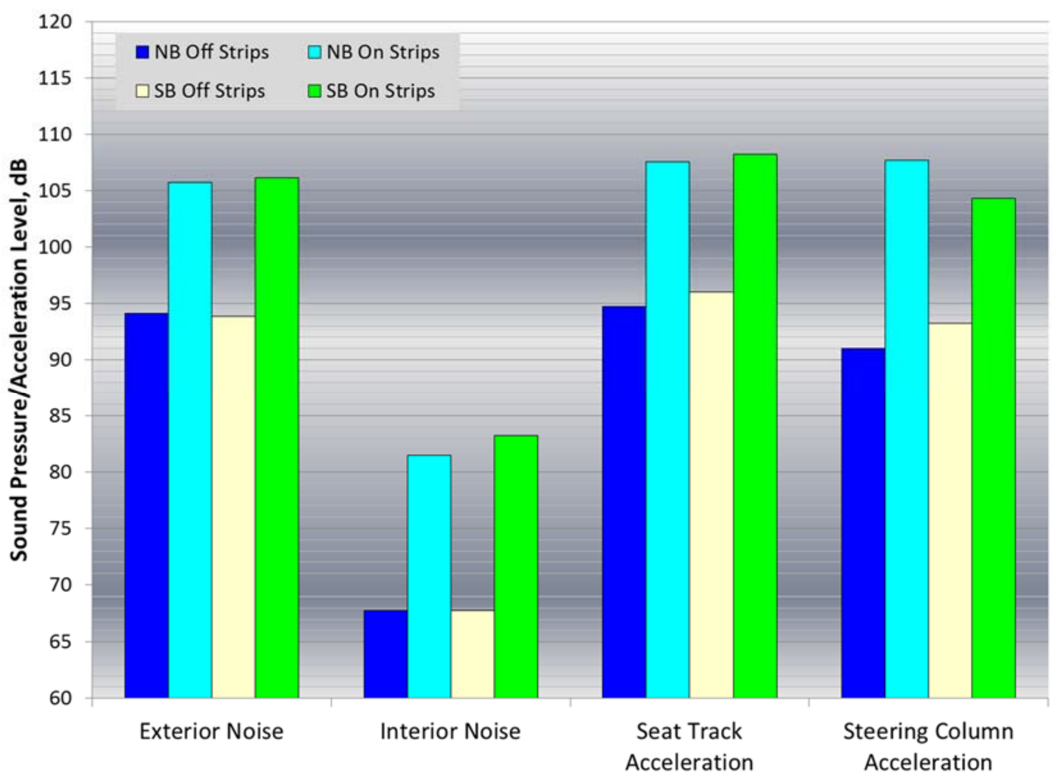


**Figure A1: Overall noise and acceleration levels for Expedition test vehicle traveling at 60 mph both on and off mumble strips and both northbound and southbound**

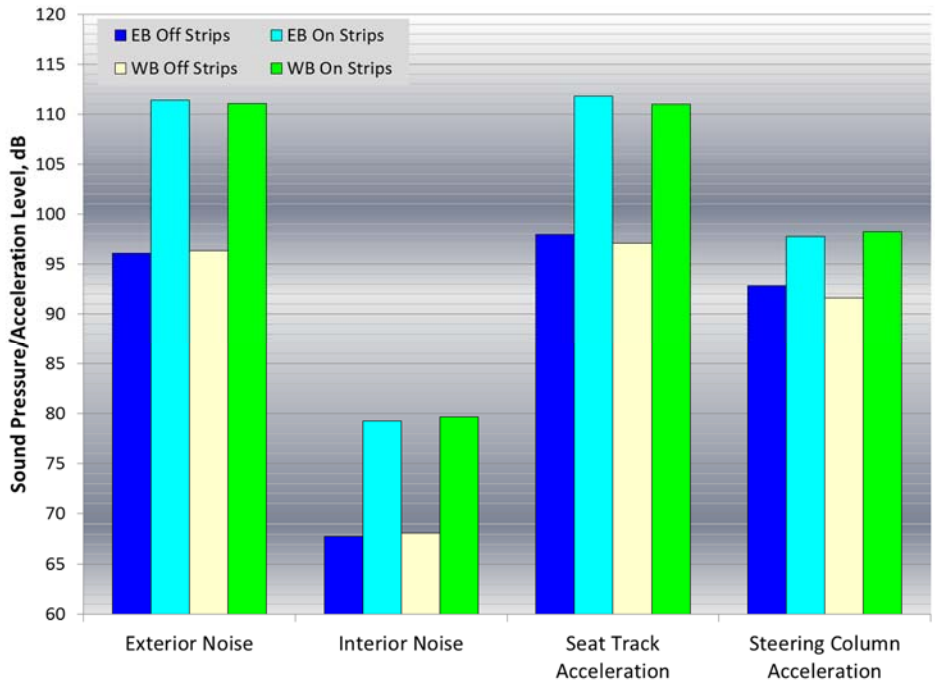


**Figure A2: Overall noise and acceleration levels for Expedition test vehicle traveling at 60 mph both on and off ground rumble strips and both eastbound and westbound**

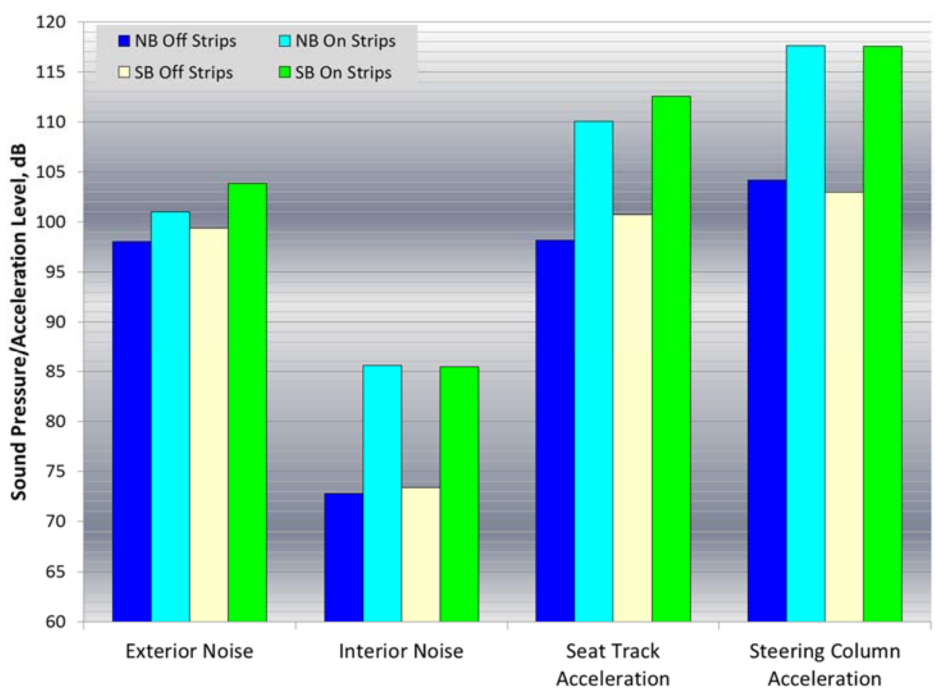


**Figure A3: Overall noise and acceleration levels for Civic test vehicle traveling at 60 mph both on and off mumble strips and both northbound and southbound**

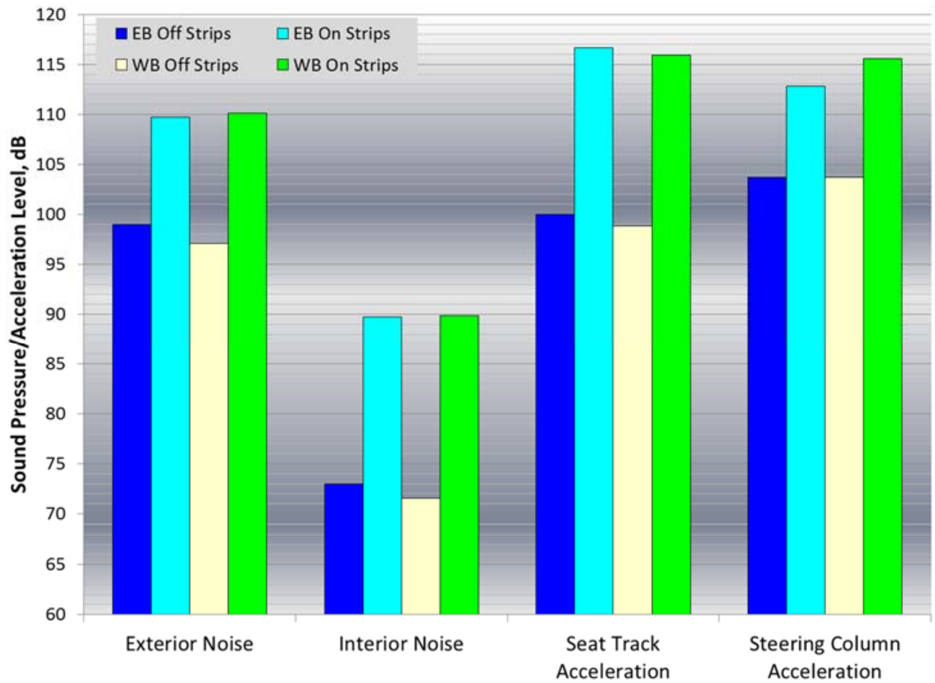


**Figure A4: Overall noise and acceleration levels for Civic test vehicle traveling at 60 mph both on and off ground rumble strips and both eastbound and westbound**

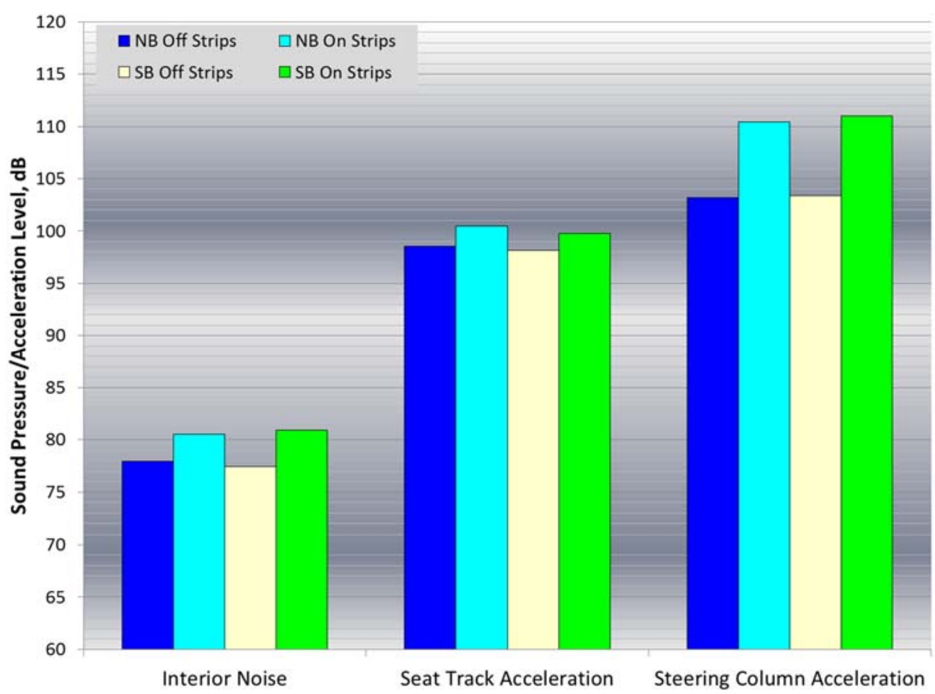


**Figure A5: Overall noise and acceleration levels for 4-yard dump truck test vehicle traveling at 60 mph both on and off mumble strips and both northbound and southbound**

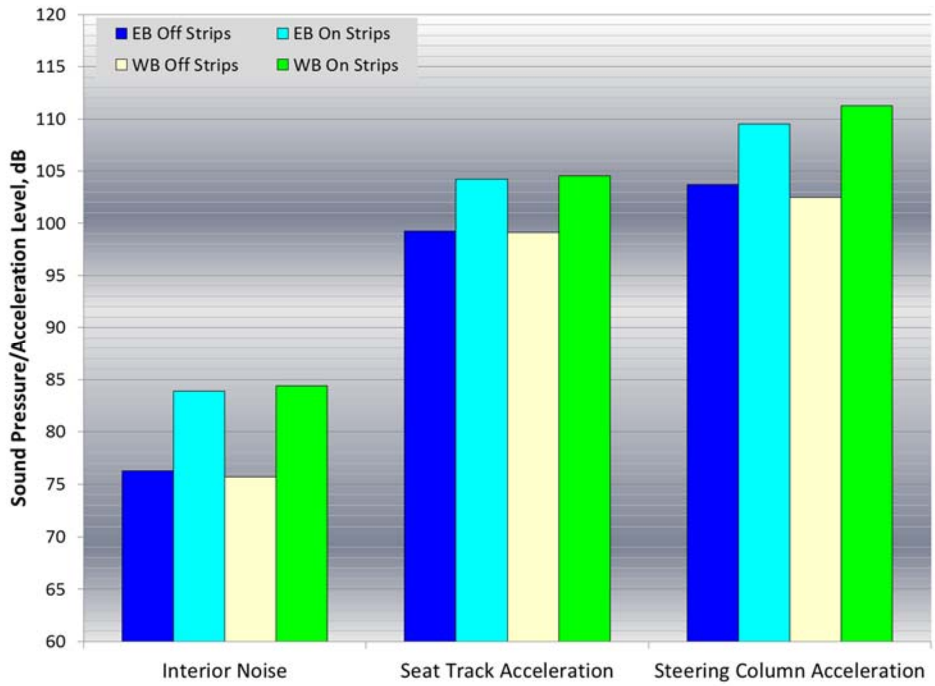


**Figure A6: Overall noise and acceleration levels for 4-yard dump truck test vehicle traveling at 60 mph both on and off ground rumble strips and both eastbound and westbound**

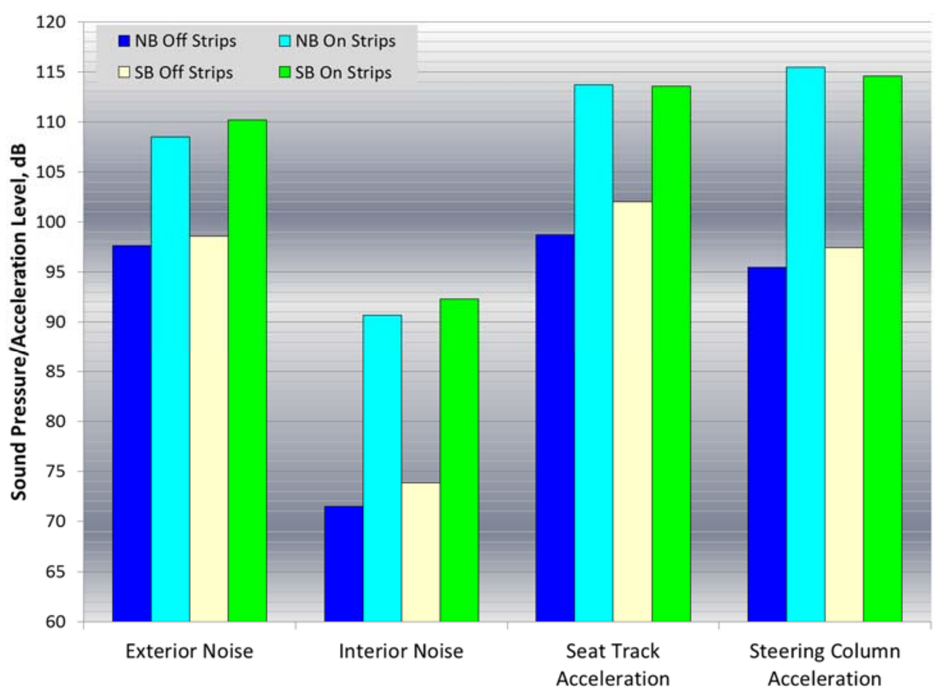


**Figure A7: Overall noise and acceleration levels for Malibu test vehicle traveling at 60 mph both on and off mumble strips and both northbound and southbound**

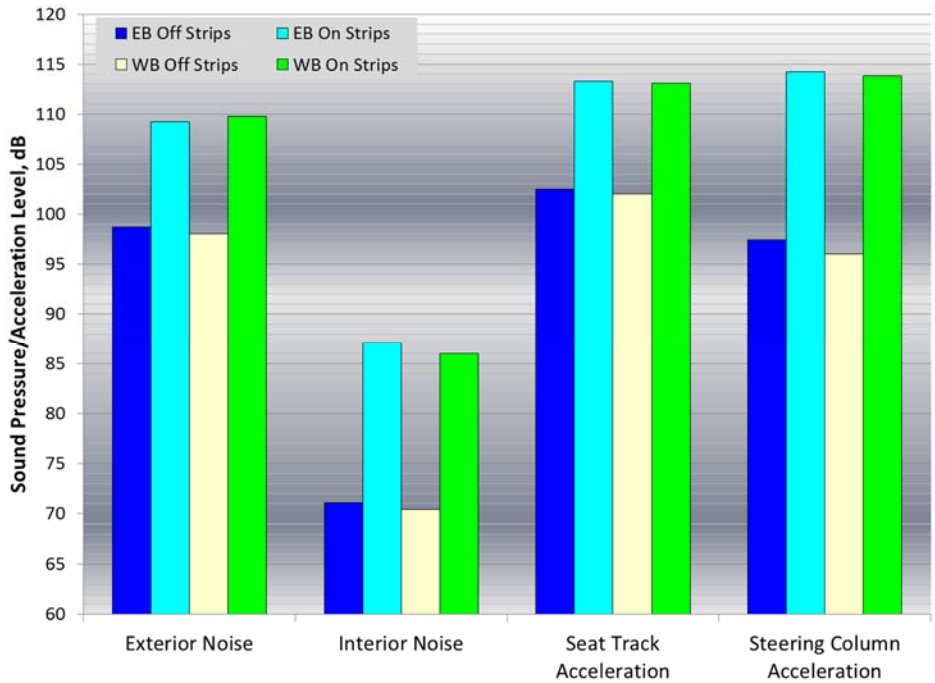


**Figure A8: Overall noise and acceleration levels for Malibu test vehicle traveling at 60 mph both on and off ground rumble strips and both eastbound and westbound**

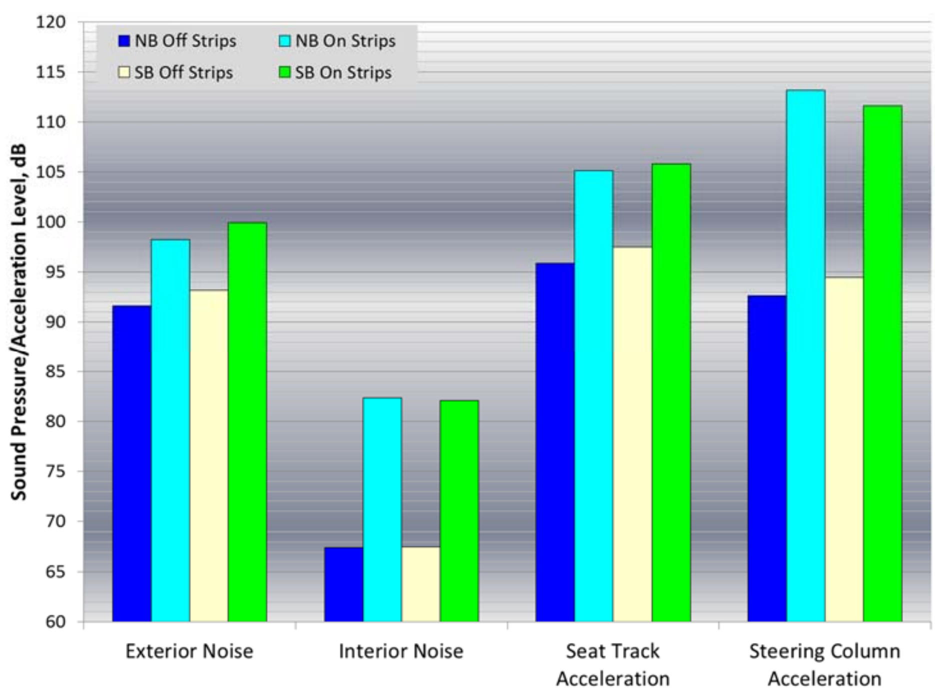


**Figure A9: Overall noise and acceleration levels for Malibu test vehicle traveling at 40 mph both on and off mumble strips and both northbound and southbound**

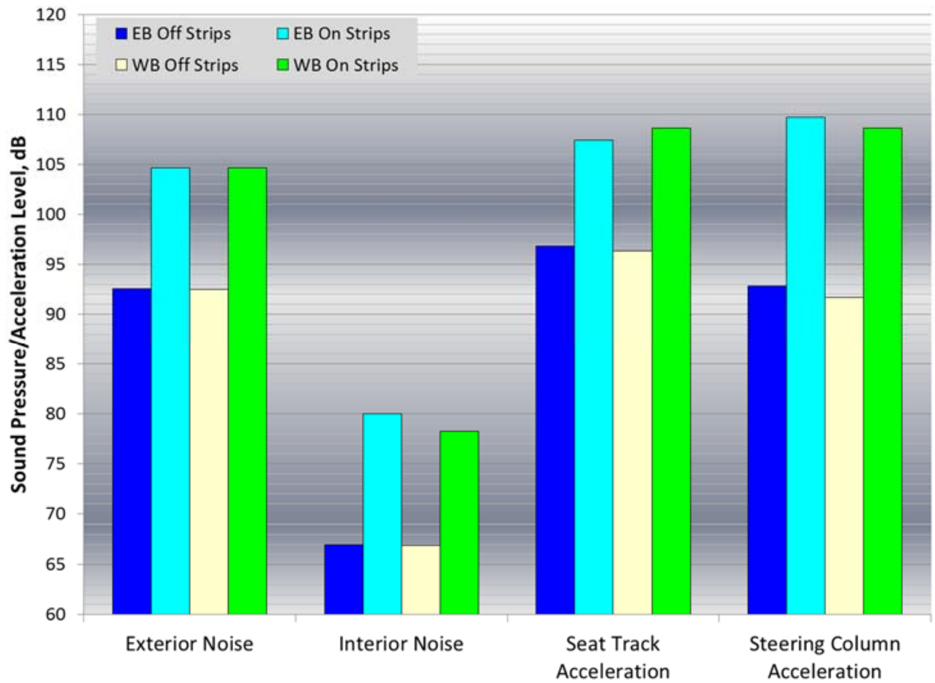


**Figure A10: Overall noise and acceleration levels for Malibu test vehicle traveling at 40 mph both on and off ground rumble strips and both eastbound and westbound**

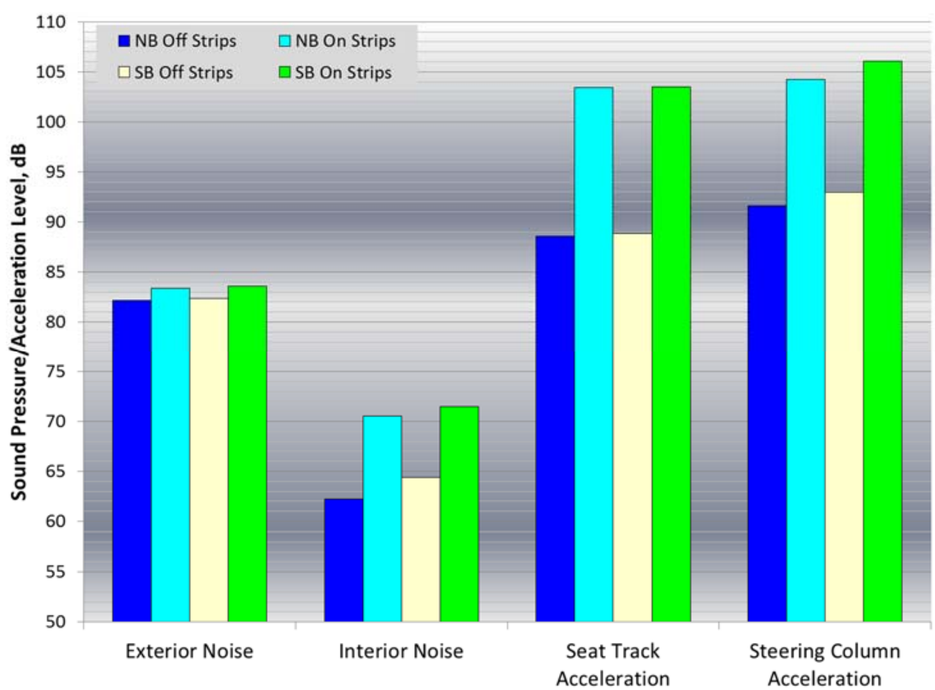


**Figure A11: Overall noise and acceleration levels for Malibu test vehicle traveling at 20 mph both on and off mumble strips and both northbound and southbound**

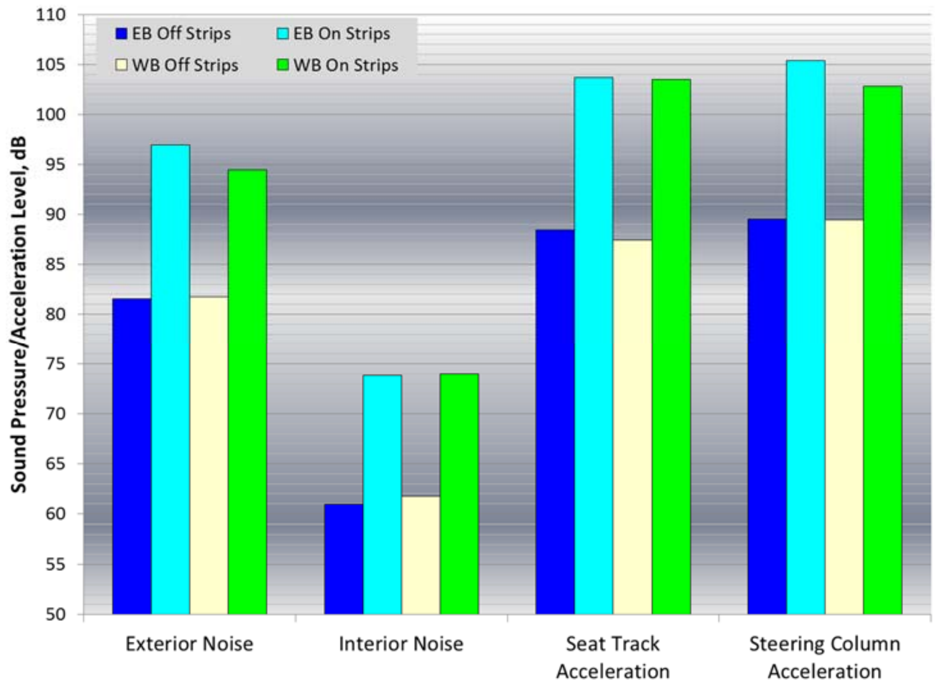


**Figure A12: Overall noise and acceleration levels for Malibu test vehicle traveling at 20 mph both on and off ground rumble strips and both eastbound and westbound**

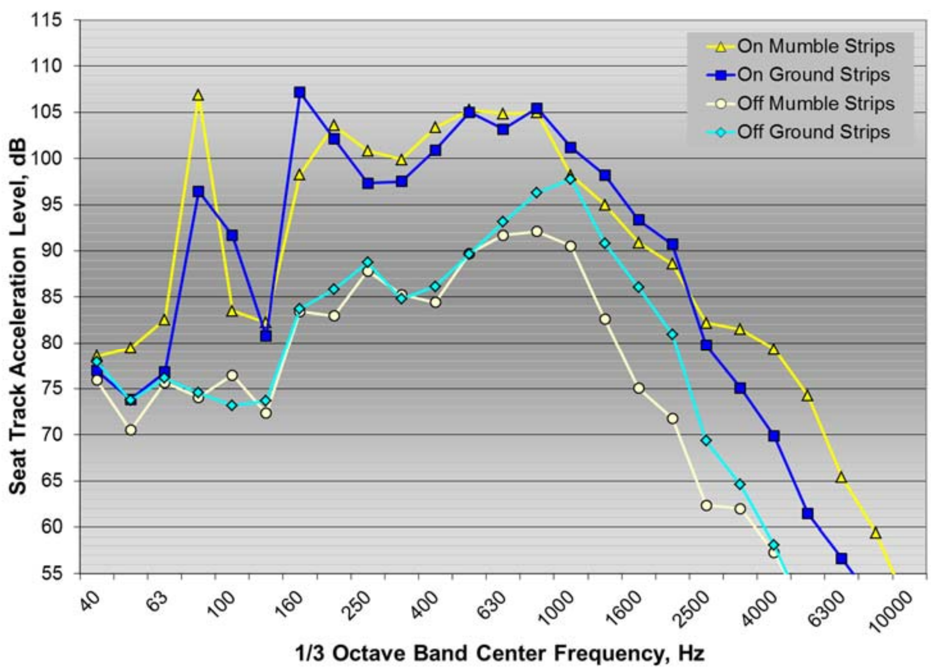


**Figure A13: ⅓ octave band seat track acceleration spectra for Malibu test vehicle on and off mumble strips and ground rumble strips at 60 mph**

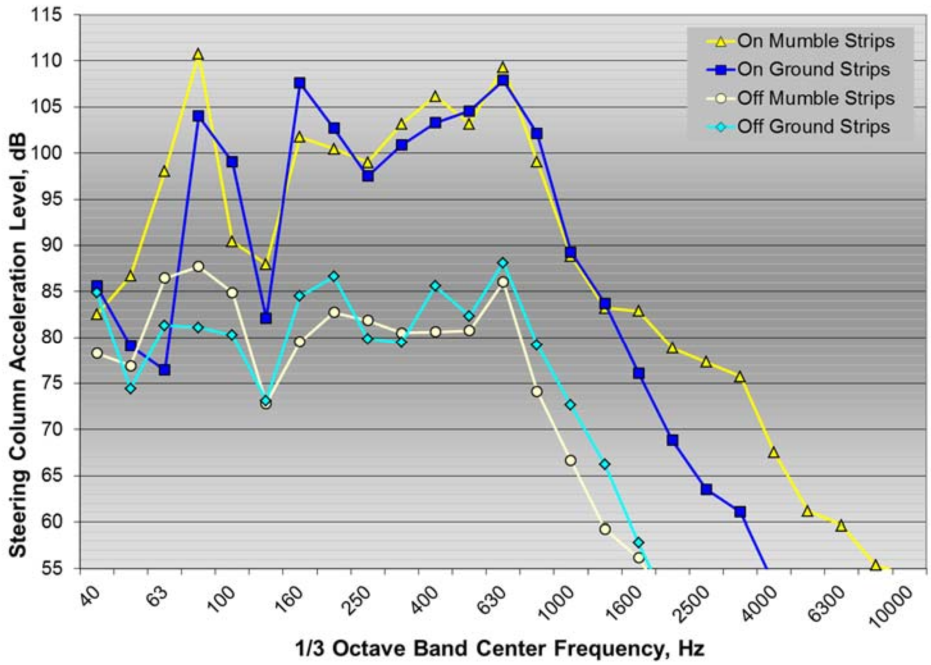


**Figure A14: ⅓ octave band steering column acceleration spectra for Malibu test vehicle on and off mumble strips and ground rumble strips at 60 mph**

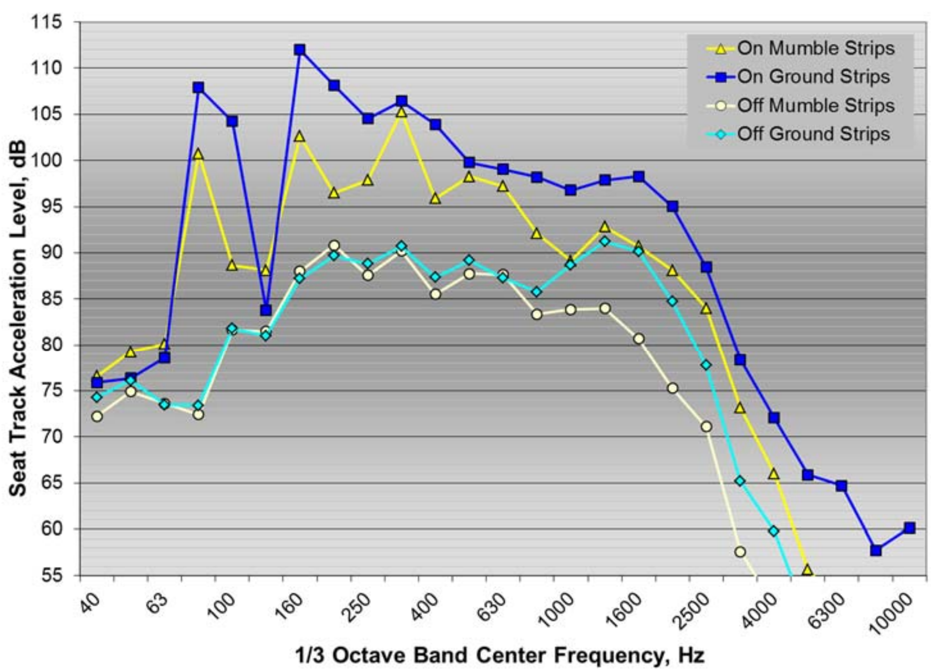


**Figure A15: ⅓ octave band seat track acceleration spectra for Civic test vehicle on and off mumble strips and ground rumble strips at 60 mph**

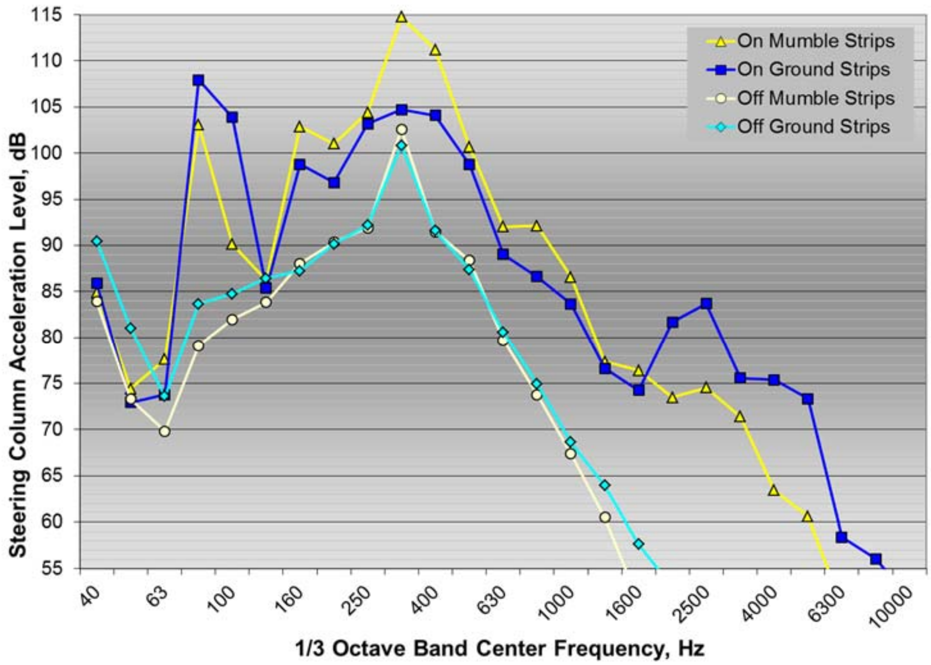


**Figure A16: ⅓ octave band steering column acceleration spectra for Civic test vehicle on and off mumble strips and ground rumble strips at 60 mph**

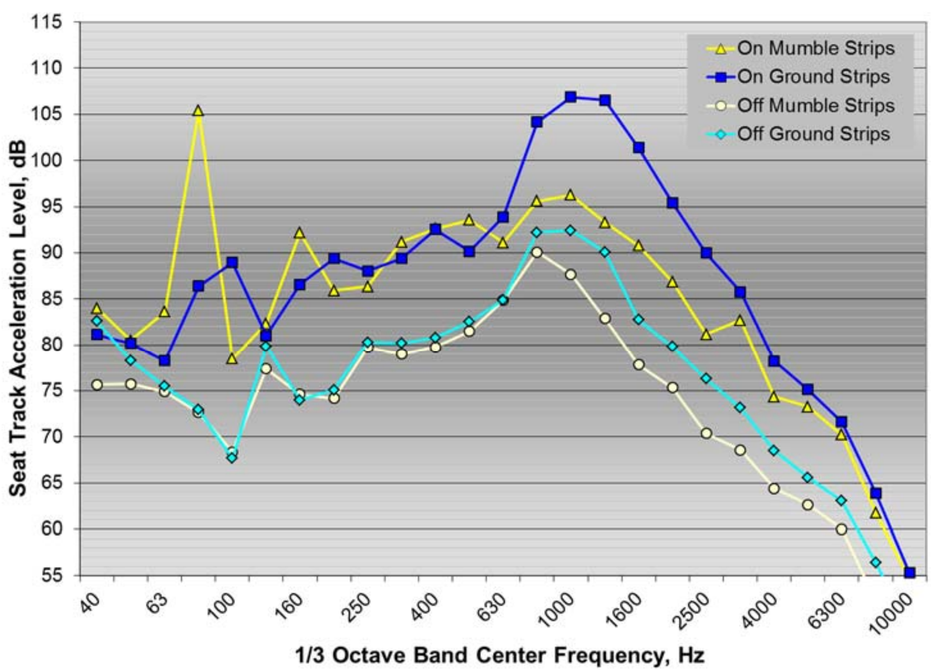


**Figure A17: ⅓ octave band seat track acceleration spectra for Expedition test vehicle on and off mumble strips and ground rumble strips at 60 mph**

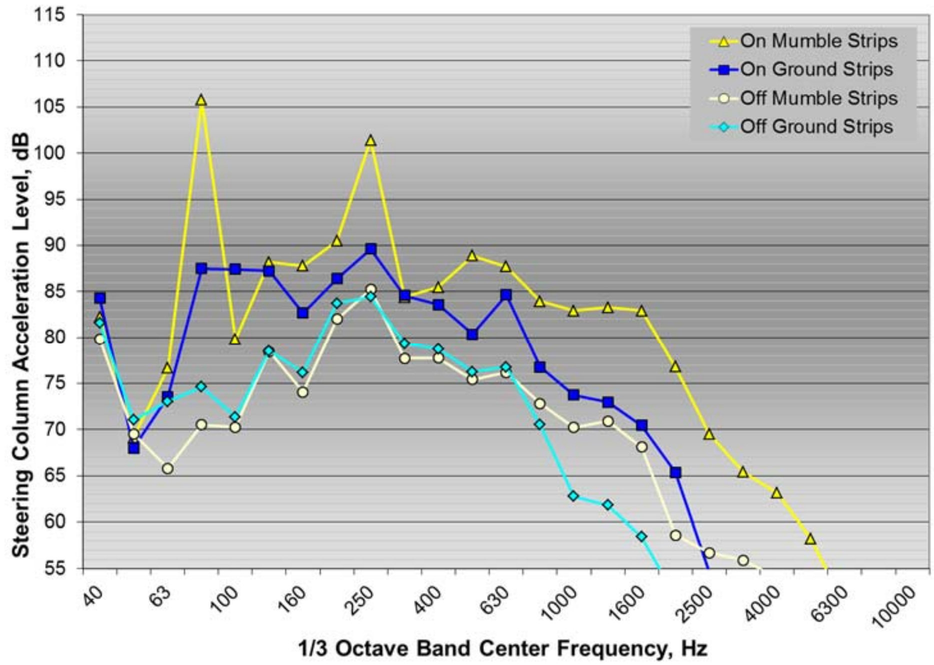


**Figure A18: ⅓ octave band steering column acceleration spectra for Expedition test vehicle on and off mumble strips and ground rumble strips at 60 mph**

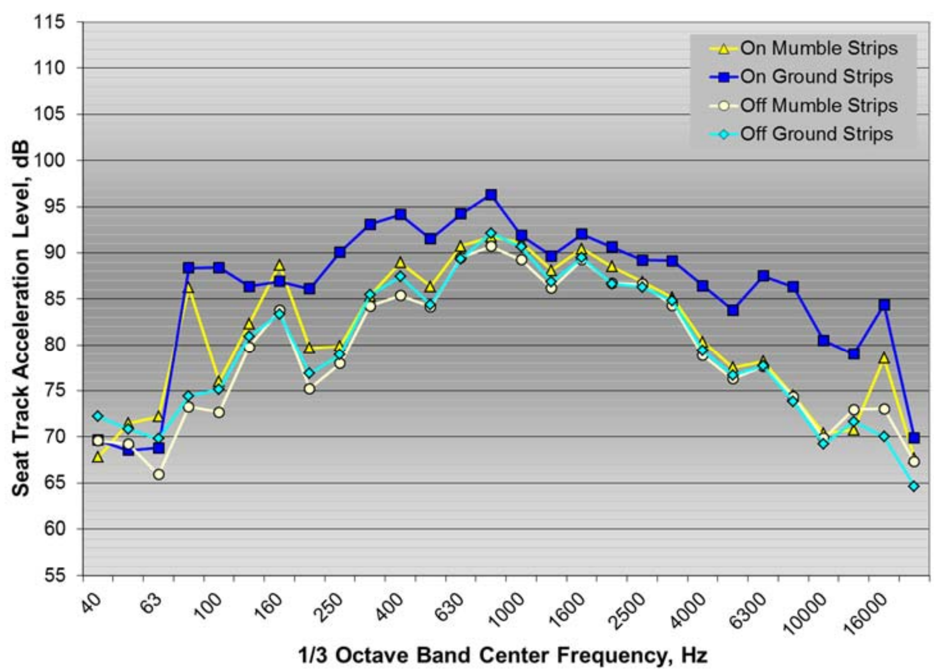


**Figure A19: ⅓ octave band seat track acceleration spectra for 4-yard dump truck test vehicle on and off mumble strips and ground rumble strips at 60 mph**

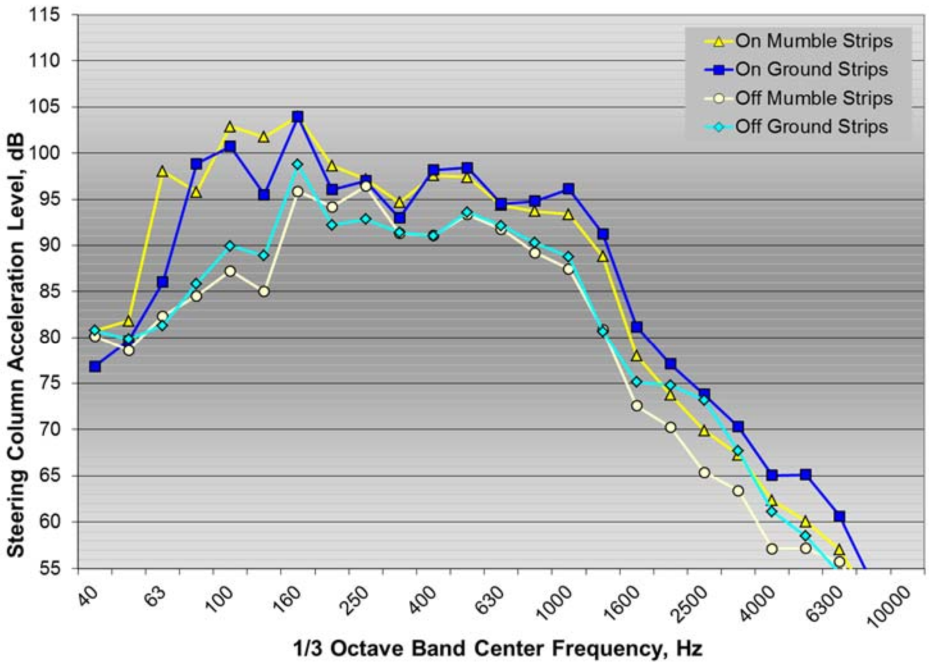


**Figure A20: ⅓ octave band steering column acceleration spectra for 4-yard dump truck test vehicle on and off mumble strips and ground rumble strips at 60 mph**

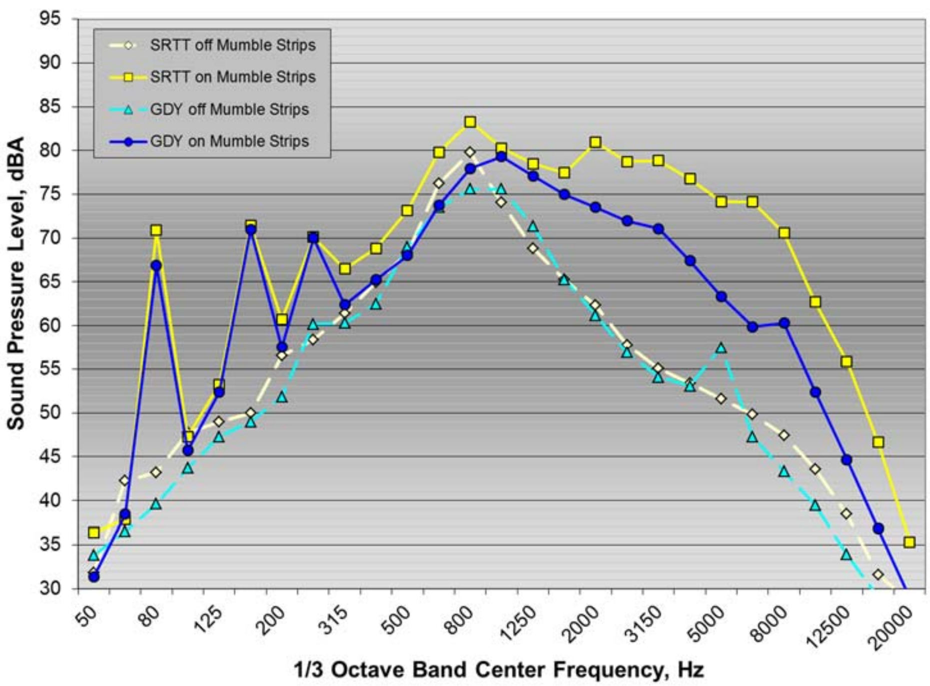


**Figure A21: ⅓ octave band pass-by noise spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

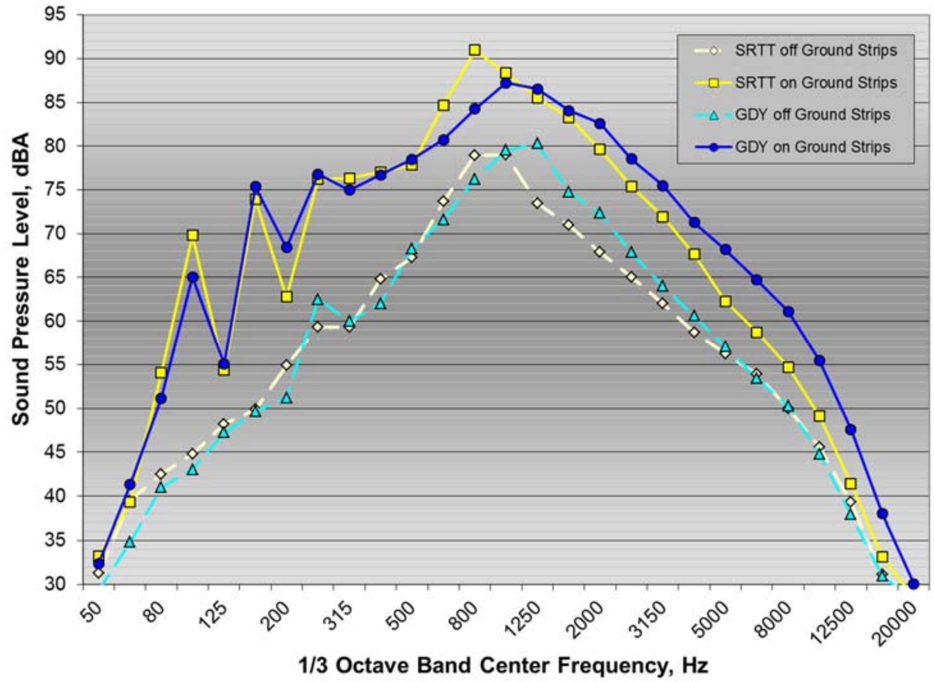


**Figure A22: ⅓ octave band pass-by noise spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

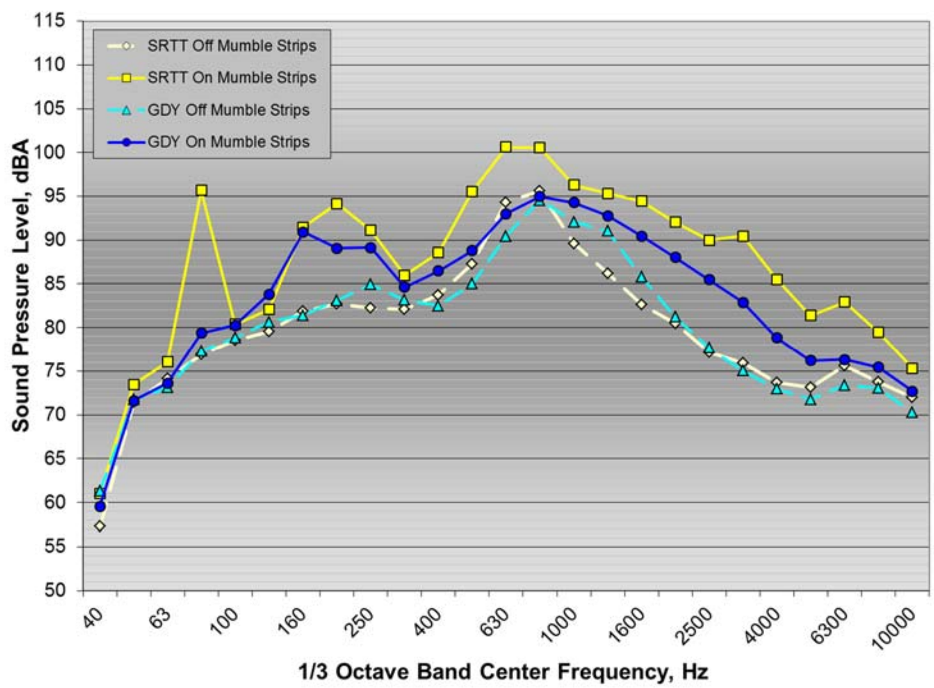


**Figure A23: ⅓ octave band exterior noise spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

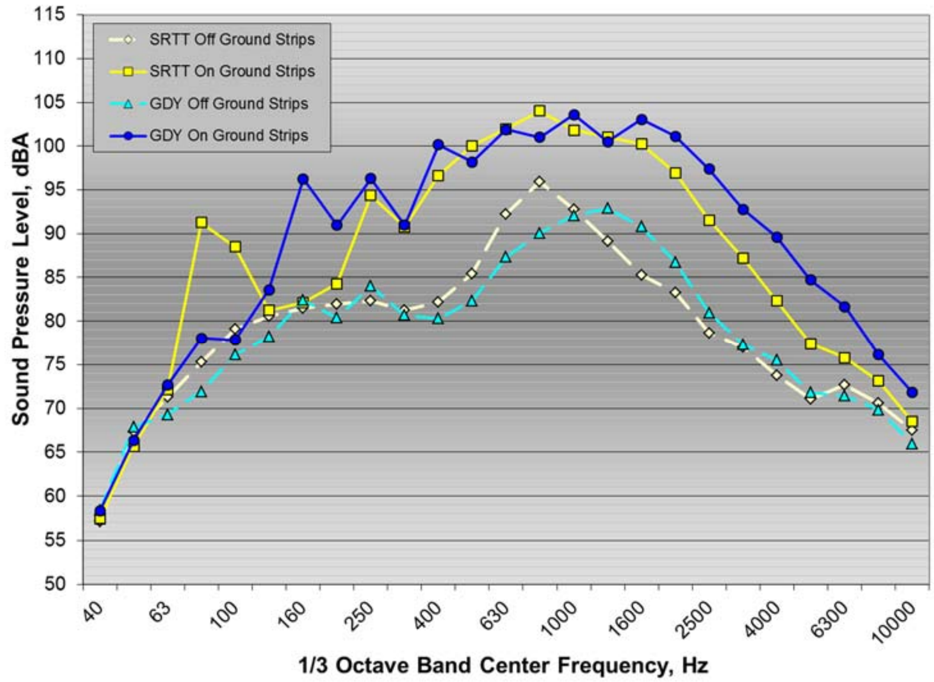


**Figure A24: ⅓ octave band exterior noise spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

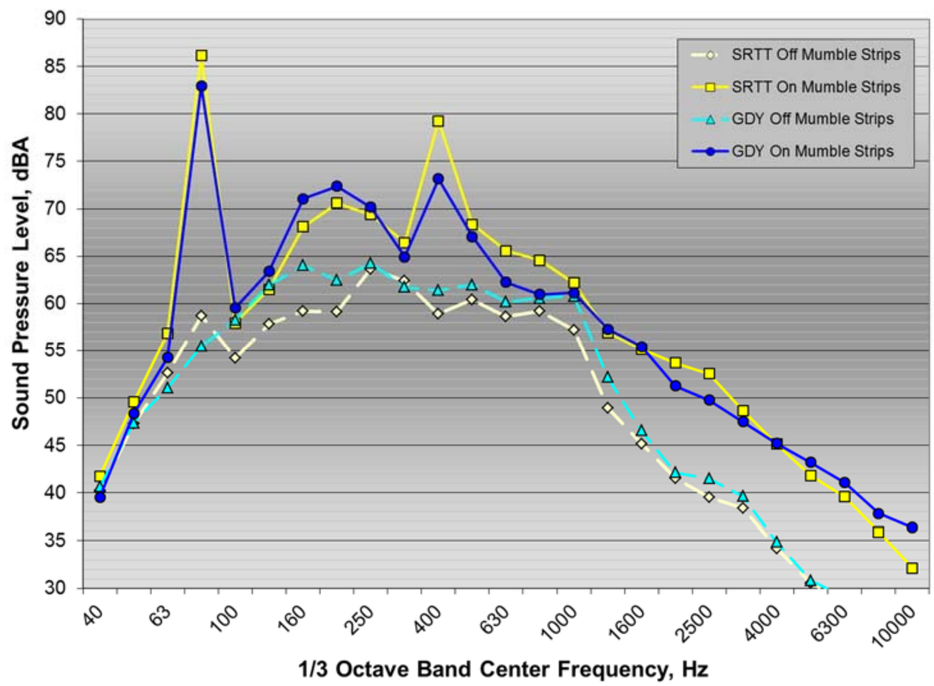


**Figure A25: ⅓ octave band interior noise spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

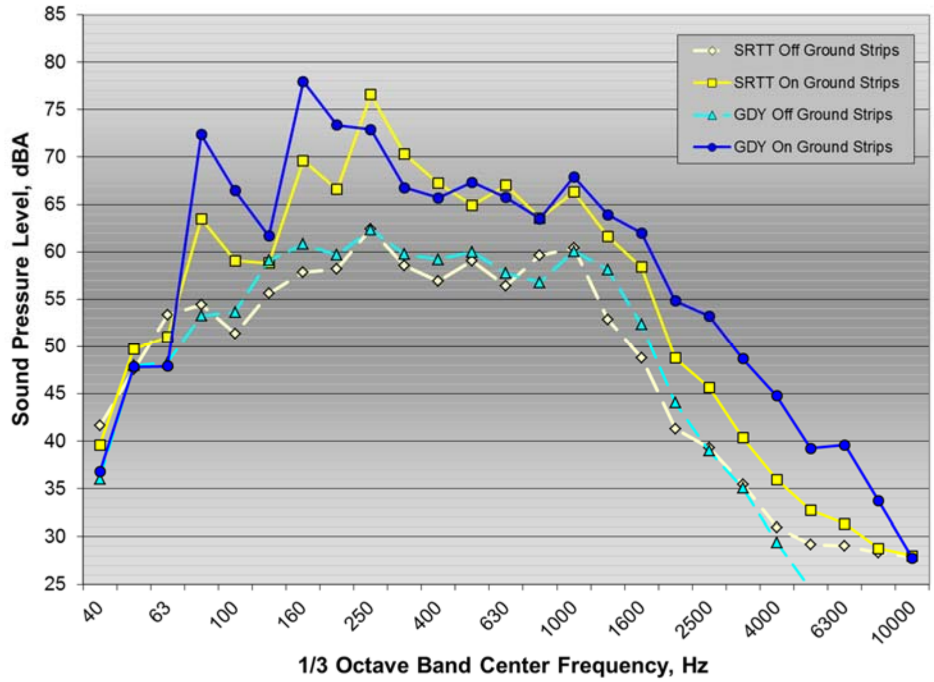


**Figure A26: ⅓ octave band interior noise spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

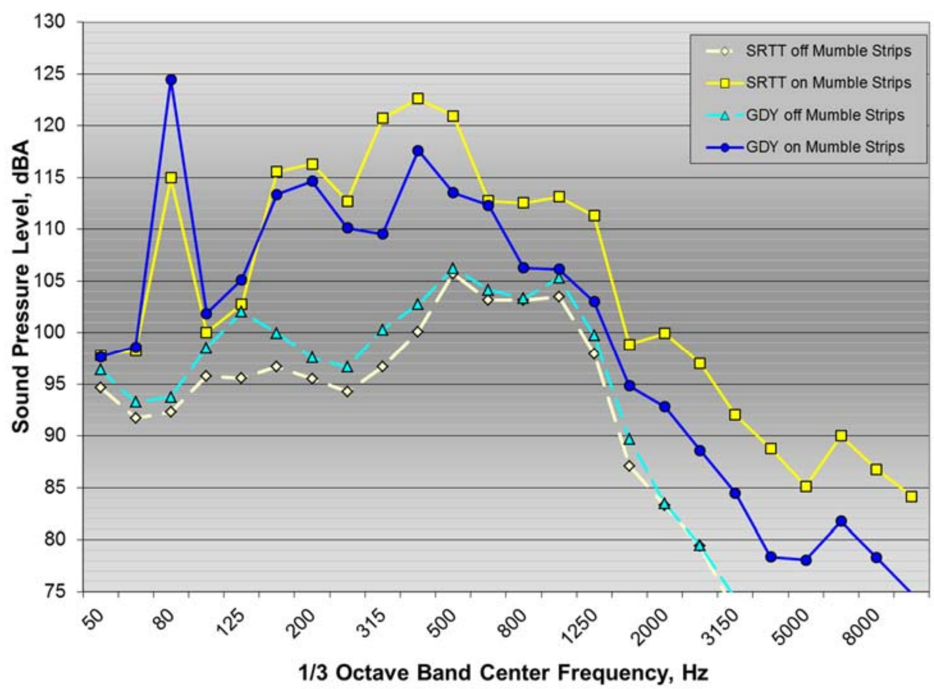


**Figure A27: ⅓ octave band seat track acceleration spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

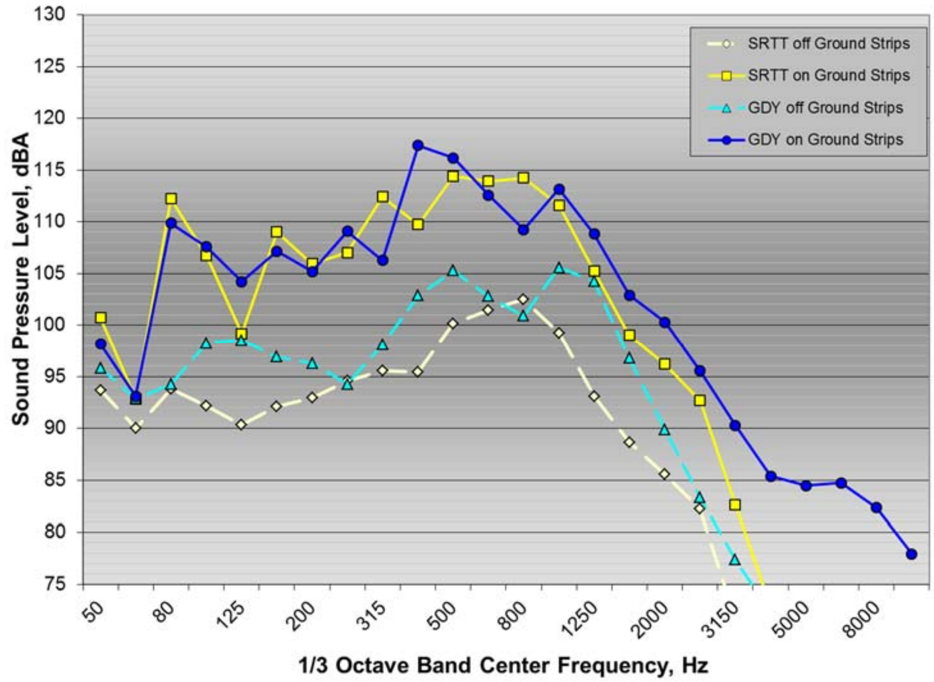


**Figure A28: ⅓ octave band seat track acceleration spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

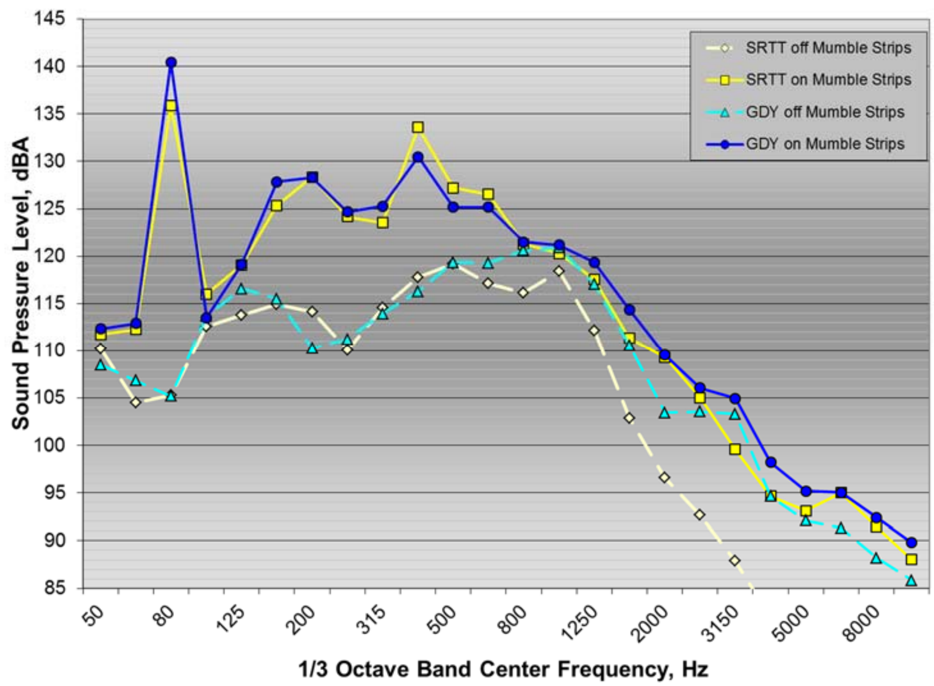


**Figure A29: ⅓ octave band steering column acceleration spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

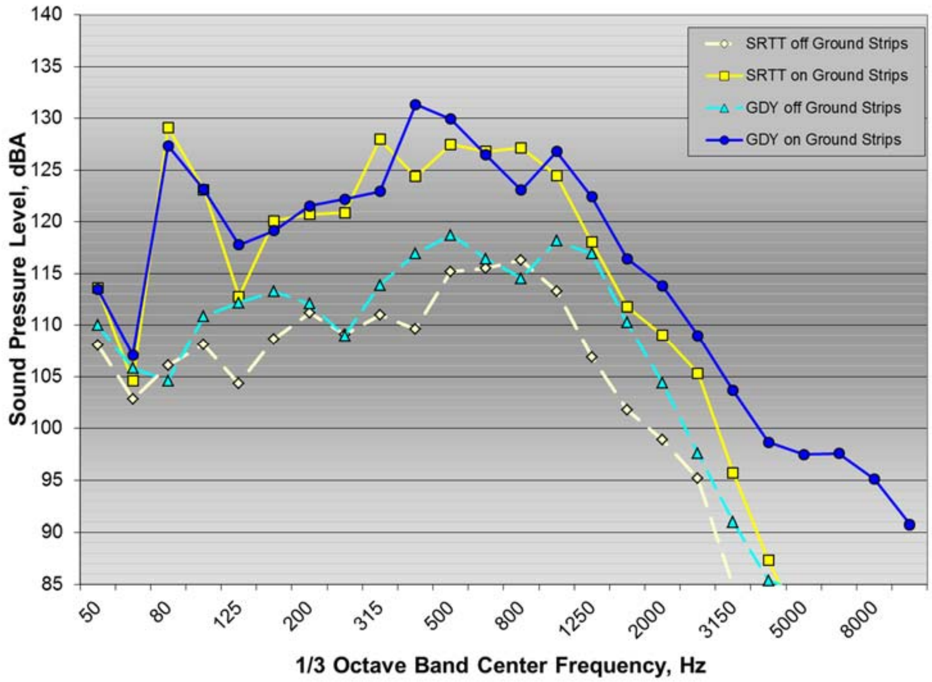


**Figure A30: ⅓ octave band steering column acceleration spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

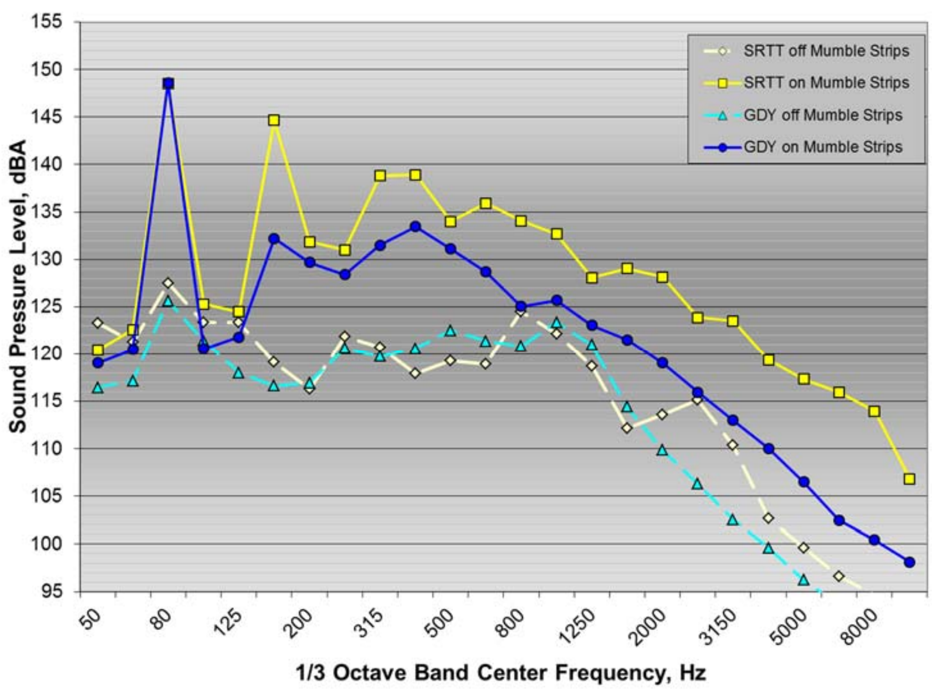


**Figure A31: ⅓ octave band front fender acceleration spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

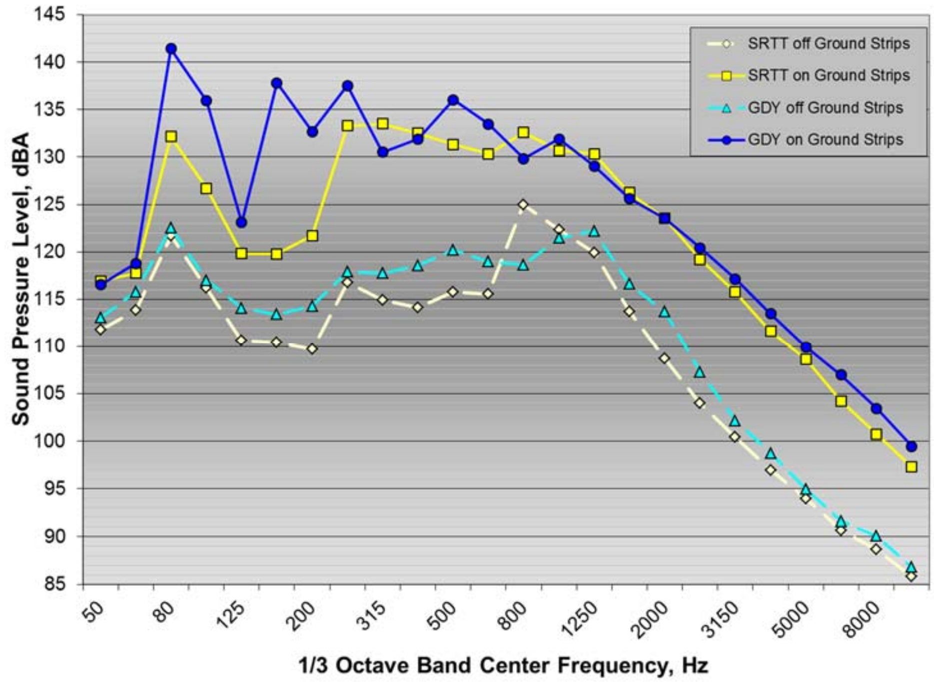


**Figure A32: ⅓ octave band front fender acceleration spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

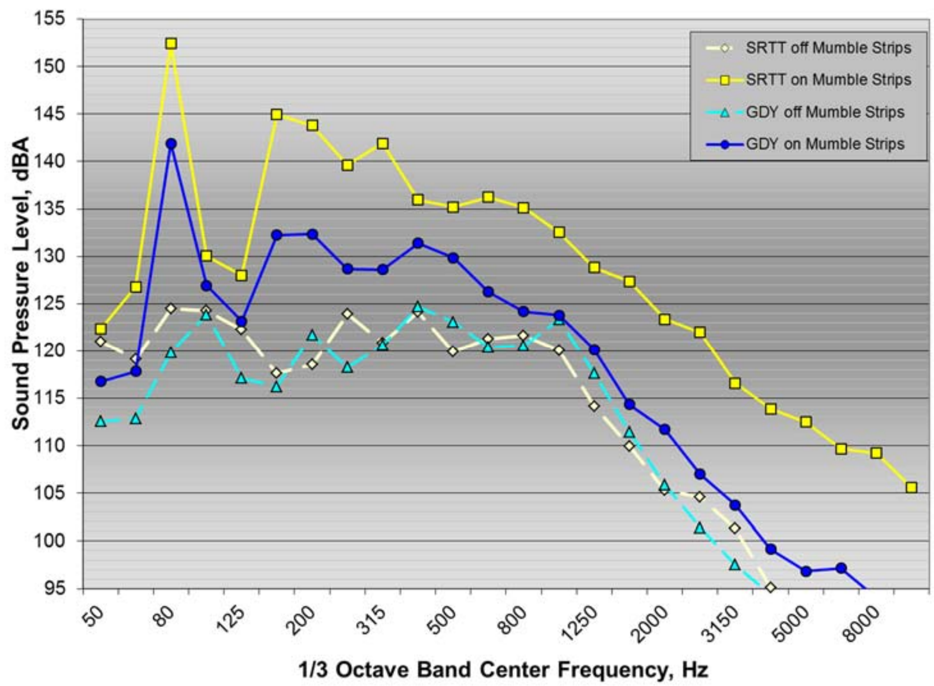


**Figure A33: ⅓ octave band rear fender acceleration spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

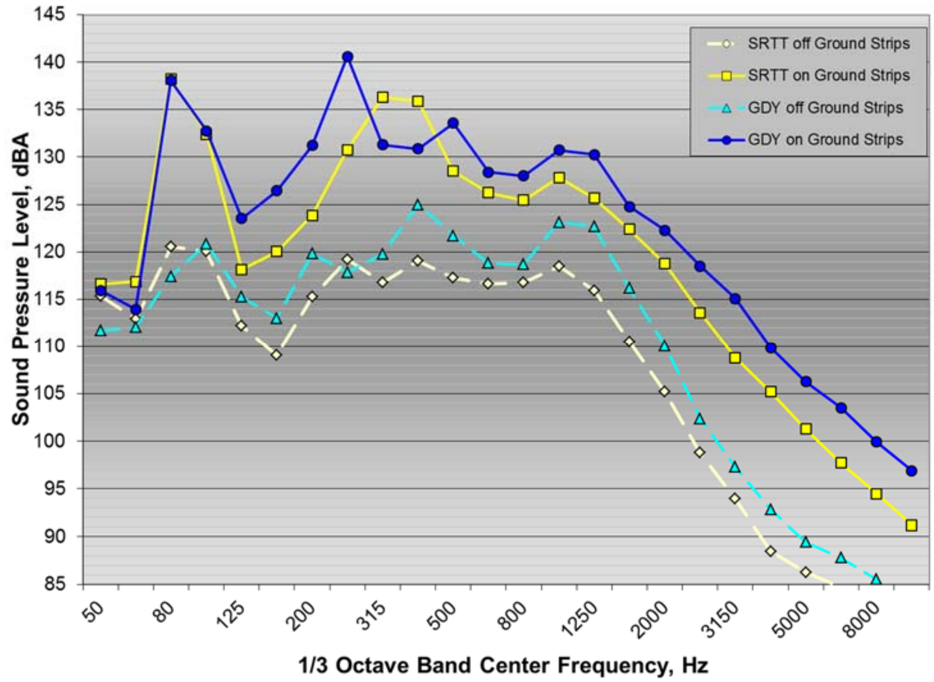


**Figure A34: ⅓ octave band rear fender acceleration spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

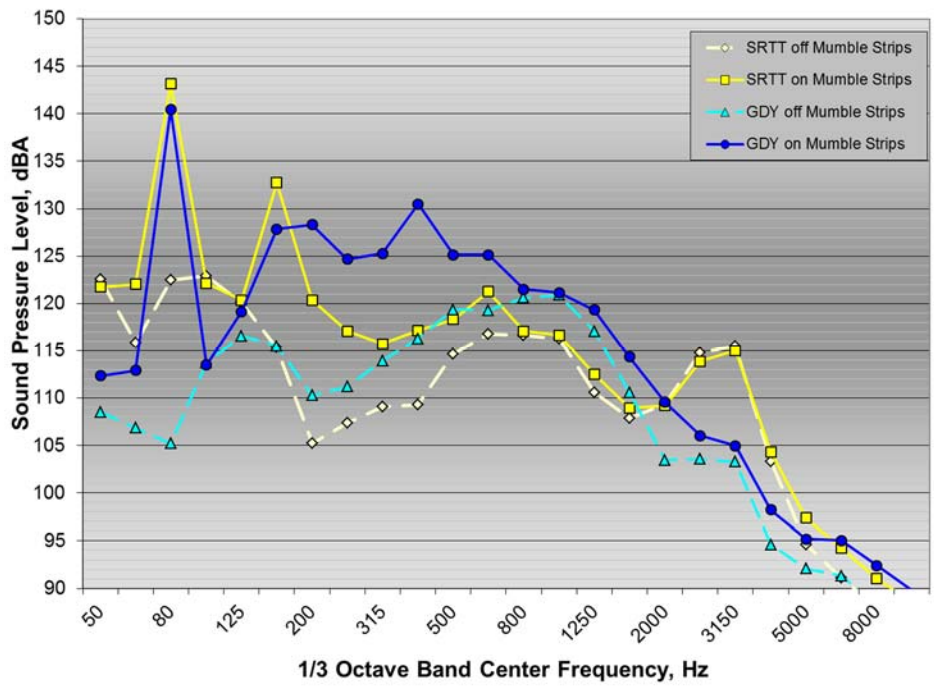


**Figure A35: ⅓ octave band rear door acceleration spectra for Ford Fusion test vehicle on and off mumble strips with SRTT and Goodyear test tires**

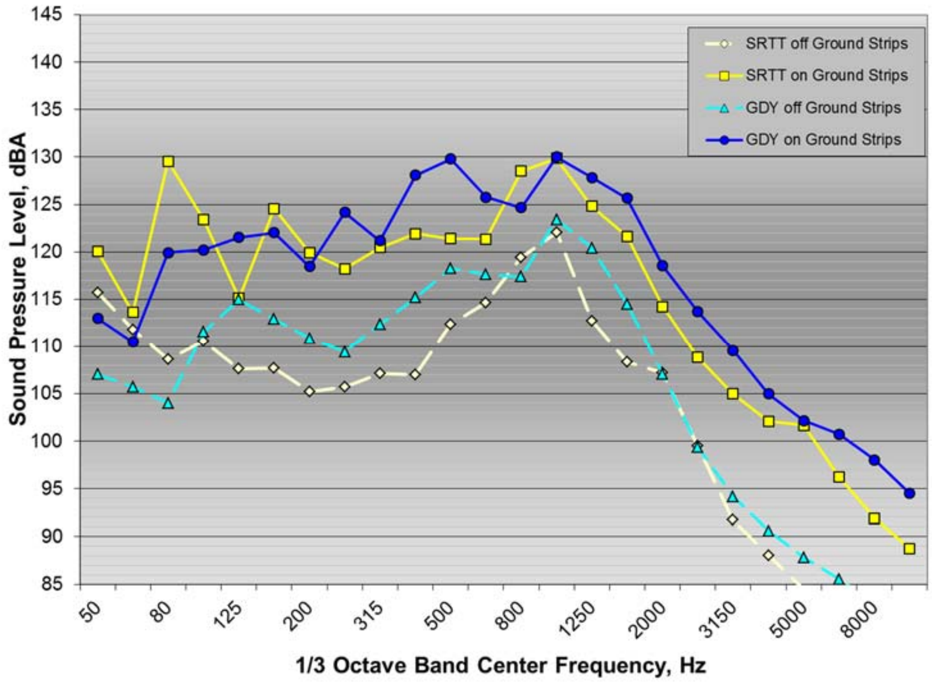


**Figure A36: ⅓ octave band rear door acceleration spectra for Ford Fusion test vehicle on and off ground rumble strips with SRTT and Goodyear test tires**

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