NCHRP Project 15-68(01)

EFFECTIVE LOW-NOISE RUMBLE STRIPS

APPENDIX B:
TEST PROGRAM DEVELOPMENT

Prepared for
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Paul Donavan and Carrie Janello

Illingworth & Rodkin, Inc.
Cotati, California

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APPENDIX B

TEST PROGRAM DEVELOPMENT

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INTRODUCTION

This appendix contains the NCHRP Rumble Strip Project test program development, completed in 2018 and 2019.

MEASUREMENT PROGRAM

The measurements were conducted in Northern California in the vicinity of Arcata using rumble strips which were the subject of previous research as reported by the California Department of Transportation (Caltrans).[1] The measurements were conducted from October 15 through 25, 2018. Eight vehicles were tested ranging from small subcompact cars to large, full-frame sport utility vehicles (SUV). The measurements included conventional pass-by testing using the procedures of American Association of State Highway Transportation Officials (AASHTO) TP-98 test procedure, interior noise, and interior vibration measurements on and off the strips. The details of program are provided in the remainder of this section.

Description of Rumble Strips

The rumble strips were of two types: partial cylindrical ground conventional strips and continuously ground sinusoidal strips or "mumble" strips. The mumble strips were specifically designed to reduce overall A-weighted pass-by noise levels while maintaining sufficient disturbance inside a vehicle to provide warning to the vehicle operator of a roadway departure (RwD). The mumble strips were located on U.S. Highway 101 and the conventional strips on California State Route 299 about 10 miles apart, as shown in Figure B-1.

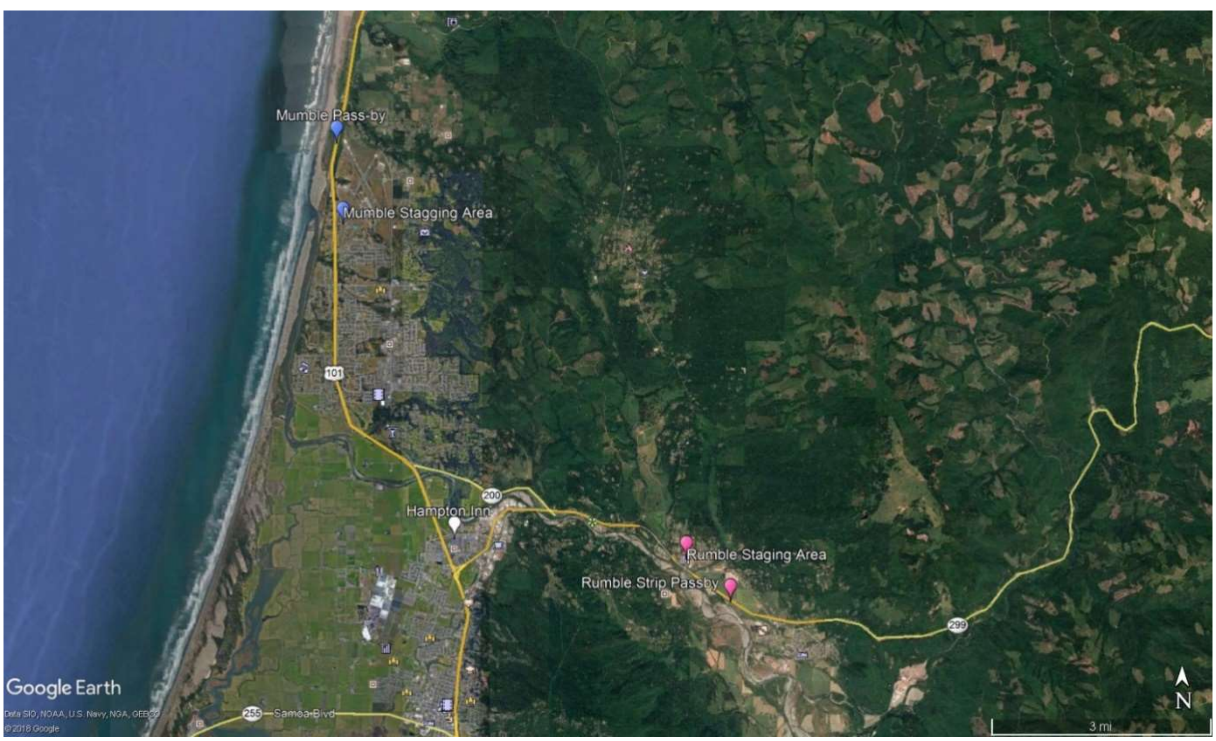


Figure B-1: Mumble and Conventional Rumble sites near Arcata, CA

The conventional ground strips are shown in Figure B-2. These are produced by grinding a partial indention in the pavement with a cylindrical grinding head, lifting the head out of contact and grinding another indention at a fixed spacing further along the road. For the strips shown in Figure B-2, the spacing of the cylindrical indentions was 12 inches. The width of each

Figure B-2: Photographs of ground rumble strips on State Route 299

indention in the direction of travel was nominally 4 inches with a depth of 5/16 inches and width perpendicular to the direction travel of 12 inches. The intervening unground or flat spot was nominally 8 inches in length. This type of strip design is common in California and known to produce noise complaints from residences in the vicinity of the highway when RwDs occur.

The sinusoidal mumble strips are shown in Figure B-3. These are produced by continuously grinding the surface from 0 displacement into the surface to 5/16 inches into the surface using a sinusoidal cam to drive the cylindrical grinding head. The peak-to-peak distance (or wavelength)

Figure B-3: Photographs of mumble strips installed on U.S. Highway 101

is 14 inches. The width perpendicular to the direction travel is 12 inches. At 60 miles per hour (mph), these strips have a passage rate of 0.013 seconds (wavelength in inches divided by speed in inches/second (in/s)), producing a frequency of about 75 hertz (Hz) (the inverse of the passage rate). For cylindrically ground strips, the frequency content is more complex. The repetition rate of the indentations is 0.011 seconds producing 88 Hz at 60 mph; however, the alternating indentations and flat spots generate inputs to the tire that occur more often, generating higher frequency components.

Test Vehicles

Eight vehicles were tested and are identified and pictured in Figure B-4. In Table B-1, the vehicles are listed with tire size, tire diameter, wheelbase, and ratio of wheelbase to strip spacing. The tires diameters ranged from 24 to 33½ inches. The mumble strip design was based on an assumed tire deflected radius (distance of the axle to the pavement) of about 12 inches.

Test Car 1

Test Car 2

Test Car 3

Test Car 4

Test Car 5

Test Car 6

Test Car 7

Test Car 8

Figure B-4: Photographs of Test Vehicles

Table B-1: Test Vehicles with Tire Sizes and Wheelbases

Test Car	Tire Size	Tire Dia.(in.)	Wheelbase (in.)	WB/Spacing Conventional	WB/Spacing Mumble
Test Car 1	185/65R15	24	102	8.5	7.3
Test Car 2	185/65R15	24	102	8.5	7.3
Test Car 3	235/45R18	26	112	9.3	8.0
Test Car 4	215/55R17	26	112	9.3	8.0
Test Car 5	225/55R17	26	105	8.8	7.5
Test Car 6	235/55R17	26	106	8.8	7.5
Test Car 7	225/65R17	26	121.5	10.1	8.7
Test Car 8	265/65R18	33.5	127	10.6	9.1

Based on the mumble strip design philosophy, larger radius tires may generate higher pass-by levels as the radius of curvature of the tire becomes larger than that of the mumble strip. Also shown in Table B-1 is the ratio of the wheelbase to nominal spacing of each type of strip. For ratios near a whole number, the input to the front and rear suspension is in phase with the tires being driven upward or downward at the same time. For ratios ending near 0.5, the inputs are out of phase such that one tire is being driven up while the other is down. These relationships may have implications for the vibration response of the different vehicles.

For acoustic response, the geometry of the interior space of the vehicle is significant as it relates to interior cavity modes and measurement at fixed locations in the cabin. This is particularly important for lower frequencies where standing waves (cavity modes) create spatial maximum and mum sound pressure levels at anti-node and node points.[2] The interior dimensions for each of the test vehicles are reported in Table B-2. In comparing the sedans to the SUVs, it should be noted that there are significant differences. The SUVs have more box-like interiors for which the first modal frequency (f_1) can be defined by $f_1 = c/2L$, where c is the speed of sound and L is the dimension between the walls in a given direction. At the walls, the sound pressure level is maximum while halfway between the walls, the sound pressure level is at a mum.

Table B-2: Test Vehicle Interior Dimensions

Test Car	Windshield/Backlite (Inches)	Door-to-Door (Inches)	Floor to Roof (Inches)
Test Car 1	115	54	47.5
Test Car 2	110	60	44
Test Car 3	122	61	46
Test Car 4	115	60	46
Test Car 5	111	56	50.5
Test Car 6	125	60	48
Test Car 7	148	67	48
Test Car 8	151	64	47

For the second mode, the sound pressure level is also maximum at the walls, but there are two locations between the walls where the sound pressure level is at a mum: $L/4$ and $3L/4$. When three dimensions are considered, the sound field becomes more complex; however, there are still locations where the sound pressure level is at a mum. Sedans have less well-defined forward/aft ends due to the angle of the windshield and the backlite making the estimation modal response more uncertain. For these interiors, accurate determination can be precisely determined using acoustical finite-element analysis;[2] however, approximations can be made using the rectangular box analysis. In Table B-3, the frequencies of the first and second cavity modes in the three directions are provided for the test vehicles. Inspecting the photographs of Figure B-4, visually, it appears that the operator's head position will be in a region about midway between the windshield and the backlite for the sedans (near the B-pillar) when the seat is at or near the full back position. At this location, the operator's ear would be close to the node of the first fore/aft mode. For the sedans, seat movement was between 9.5 and 10 inches. For the SUVs with more vertical tailgates, the operator seat position is typically at about one-third of the distance between the windshield and the tailgate. For these designs, the operator ear position would be away from the node of the first mode and possibly closer to the node of the second mode. In the lateral direction, the node of the first mode would be in the center of the vehicle and generally away from the operator's ears; however, the node of the second mode would be close to the operator's head. A similar situation occurs for the vertical direction.

Table B-3: Test Vehicle Fore/Aft, Lateral, and Vertical Modal Frequencies

Test Car	**Frequency, Hz Fore/Aft**		**Frequency, Hz Lateral**		**Frequency, Hz Vertical**	
	1st Mode	**2nd Mode**	**1st Mode**	**2nd Mode**	**1st Mode**	**2nd Mode**
Test Car 1	59	118	125	251	143	285
Test Car 2	62	123	113	226	154	308
Test Car 3	56	111	111	222	147	295
Test Car 4	59	118	113	226	147	295
Test Car 5	61	122	121	242	134	268
Test Car 6	54	108	113	226	141	282
Test Car 7	46	92	101	202	141	282
Test Car 8	45	90	106	212	144	288

Pass-by Noise Measurements

The vehicle pass-by measurements were made following the procedure defined by the AASHTO TP-98 procedure with some exceptions.[3] For the purposes of this evaluation, only the test vehicles were measured, as opposed to vehicles occurring randomly. The distance to centerline of vehicle travel was maintained at 25 feet; however, the measurement microphone was physically offset for the pass-by measurements on the rumble strips, as the vehicles were no longer in the center of the nearest lane of travel. This was accomplished by using two microphones each at the proper distance with the data taken from the appropriate microphone corresponding to whether the vehicle was on or off the rumble strip. Photographs of the measurement arrangement for Test Car 3 on the conventional ground rumble strips and the sinusoidal mumble strips are shown in Figure B-5. The vehicles were operated at

Conventional Ground Strips

Sinusoidal Mumble Strips

Figure B-5: Photographs of pass-by measurements at rumble strip sites

constant speeds of 60 and 45 mph both for on and off the strips. At least three pass-bys were made for each condition. The quality of the pass-by was judged by the instrument operator in the field as to whether the vehicle was fully on or fully off the rumble strips. The pass-bys were also judged as to whether noise from other vehicles possibly contaminated the pass-by noise level.

Pass-bys not meeting these criteria were repeated as needed. Interior noise and vibration measurements were also made inside the vehicle during the pass-bys.

Sound level versus time was obtained for each pass-by using a Larson Davis 3000 Real Time Analyzer (RTA). The RTA acquired data in a "by-time" mode in which the exponentially fast response (one-eighth second average) was sampled every one-tenth of a second for a duration of 5 seconds. The RTA was triggered manually as the vehicle approached. The sound pressure level was measured using a Larson Davis LD 2560 ½-inch diameter random incidence microphone and LD 426A30 microphone preamplifiers. Field calibration was done with a LD CAL200 Precision Acoustic Calibrator producing 94 dB at 1,000 Hz. The pass-by signals were also recorded on Roland R-05 solid state recorders if addition analysis was required. The air temperature ranged from 48 to 62 degrees Fahrenheit during the days of the measurements and conditions varied from sunny to overcast. Measurements were only made under dry pavement conditions.

Interior Noise Measurements

Interior noise in vehicles would potentially vary substantially due to the trim designs of the different makes and models. The size of the passenger cabin would also vary, depending on the vehicle classification. One of the goals for the interior measurements was to develop a repeatable and equivalent testing procedure across all vehicle types. A total of six microphone positions were considered for initial Task 4 testing, five of which were hung from the front unoccupied passenger seat, while the sixth microphone was hung from the ceiling on the driver's side of the vehicle.

The microphone positions were based on measurements from the seat back and the seat base when the seat was adjusted for a five-foot, ten-inch male driver. For the driver's side microphone, the driver adjusted the seat to a comfortable driving position, and the microphone was hung from the ceiling of the vehicle such that the sensor was positioned within 1 inch of the driver's outboard ear (DE). During road testing, the driver leaned slightly away from the microphone to avoid hitting the microphone. On the unoccupied passenger side, the five microphone locations used during testing are shown in Figure B-6.

The first step to identify the proper microphone locations is to adjust the seat back angle of the passenger side seat. Once properly adjusted, the same angle will be used for all five microphone locations. The optimal seat back angle was determined for a five-foot, ten-inch male passenger based on riding comfort, and a device was manufactured in the field to measure the angle of the seat back with respect to the vertical plane. This device was used for all eight test vehicles to ensure repeatability. The device, which is shown in Figure B-7, measures approximately a 19-degree angle from the vertical plane.

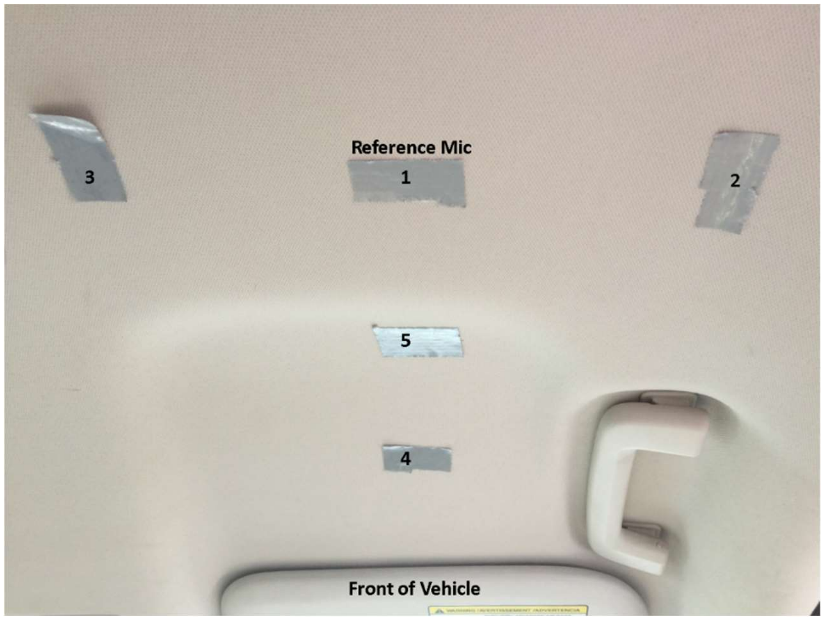


Figure B-6: Interior microphone positions from the ceiling of the front passenger seat


Figure B-7: Device fashioned in field to measure the 19-degree angle of the seat back

Below is a brief description of how each microphone location was measured:

- Reference Microphone (Microphone #1) – The reference microphone position is along the centerline of the passenger position when the seat is adjusted as far back as possible along the seat track. After adjusting the seat back angle, as described above, the passenger seat was adjusted as far back from the dash as each vehicle would allow. To determine the centerline of the passenger and the passenger seat, the center point between the holes in which the headrest rods attach to the seat back was determined, as shown in Figure B-8. Once the centerline is determined, the reference microphone was hung 7 inches in front of the seat with respect to the center of the holes of the headrest. This is the distance corresponds to where the ear of an average male passenger would be as shown in Figure B-9.

Figure B-8: Determine the center point between the two headrests

Figure B-9: For the average male passenger, the ear is located approximately 7 inches from the center of the headrest holes

The height of the microphone would also have to be with respect to the average male passenger ear height. As shown in Figure B-10, this height was estimated to be approximately 29 inches from bottom seat pad at the point nearest to the seat back.

Measured from the base of the seat near the seat back

Approximately 29 inches, vertically, to ear

Figure B-10: Microphone height is based on the height of the average male passenger's ear

- Microphone #2 – The second microphone shown in Figure B-6 is at the passenger's outboard ear position when the seat is adjusted as far back as possible along the seat track. For repeatability purposes in setting up this test, the distance from the centerline of the holes in the headrest to the ear of the average male passenger was estimated to be approximately 4 to 5 inches, as shown in Figure B-11. For microphone #2 position in each vehicle, 5 inches towards the passenger side door was measured from the reference microphone position in order to stay consistent with the DE position of within 1 inch of the driver's ear, as well as providing a bit more separation between from the reference microphone. This microphone was also 7 inches forward from the center of the headrest holes. The microphone height would be the same as the reference microphone.

- Microphone #3 – The third microphone shown in Figure B-6 is at the passenger's inboard ear position when the seat is adjusted as far back as possible along the seat track. Similar to microphone #2, microphone #3 was measured 5 inches towards the center of the vehicle cab from the reference microphone position. The height would be the same as the previous microphones.

Figure B-11: From the center point between the headrest holes, the microphone was positioned 5 inches outward

- Microphone #4 – The fourth microphone shown in Figure B-6 is along the centerline of the passenger position when the seat is adjusted as close to the dashboard as possible along the seat track. Using the same 19-degree seat back angle, the seat is adjusted as close to the dashboard as possible. The two extreme seat track positions were used in Task 4 testing for two reasons: repeatability purposes and to better understand the interior noise difference when the seat is adjusted as the maximum range of positions. For the eight vehicles tested in Task 4, the distance from the forward seat track position to the rear seat track position ranged from 7.5 to 10 inches. Depending on the position along the seat track, the passenger could potentially be exposed to substantially different noise levels in each vehicle. Microphone #4 was positioned 7 inches forward from the center of the holes of the headrest along the centerline between the holes of the headrest, similar to the reference microphone. The height would be the same as the previous microphones.

- Microphone #5 – The final microphone shown in Figure B-6 is along the centerline of the passenger position halfway between the reference microphone and microphone #4. The height would be the same as the previous microphones.

Two-channel Larson Davis 3000 RTA were used to measure interior noise data. The RTA acquired data in a “by-time” mode in which the exponentially fast response (one-eighth second average) was sampled every one-tenth of a second for a duration of 8 seconds. The RTA was triggered manually just before the pass-by measurement site was approached. The sound pressure level was measured using a Larson Davis LD 2560 ½-inch diameter random incidence microphone and LD 426A30 microphone preamplifiers. Field calibration was done with a LD CAL200 Precision Acoustic Calibrator producing 94 dB at 1,000 Hz. Each run was also recorded on Roland R-05 sloid state recorders if addition analysis was required. During testing, the vehicle's air conditioning system and radio were turned off so as not to contaminate the measurements.

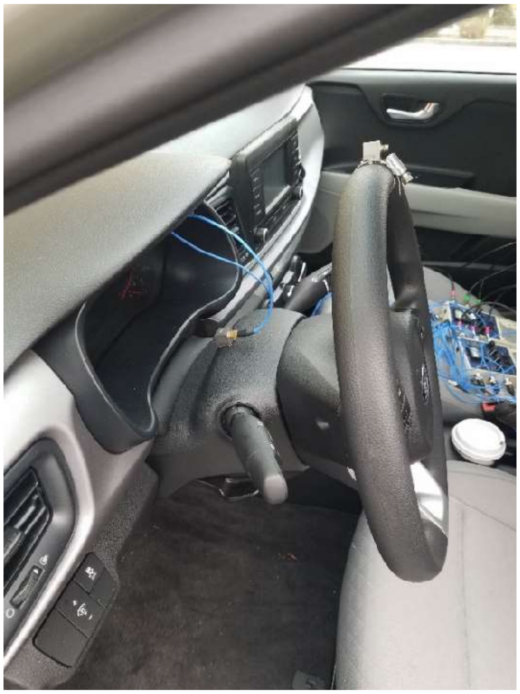
Since two RTAs were used to acquire the interior noise data, only four channels could be acquired at once. Therefore, two different test configurations were used for interior noise measurements, increasing the total number of pass-by runs made for each vehicle.

Vehicle Vibration Measurements

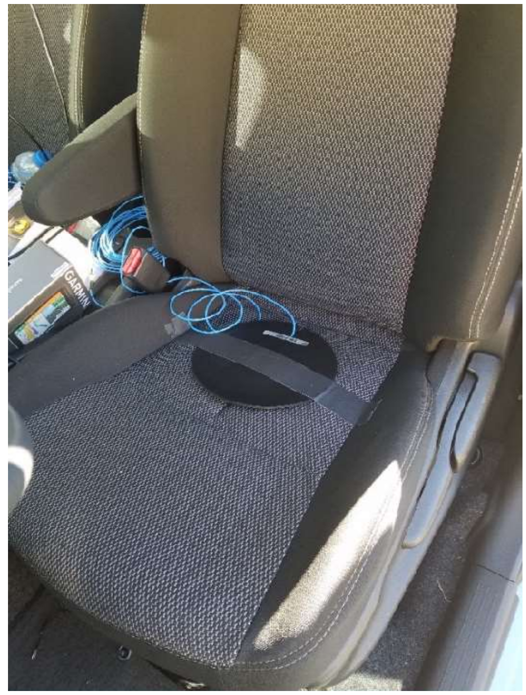
Vibration levels on and off the rumble strips were measured at six locations on each test vehicle. At all locations, tri-axial accelerometers were used to measure nominally in the vertical, lateral, and fore/aft directions, resulting in 18 channels of data. The locations were:

- Seat track – passenger side,
- Seat sensor – under the vehicle operator,
- Steering column,
- Steering wheel,
- Right front spindle, and
- Right rear spindle.

Photographs of the typical installation of the accelerometers are shown in Figure B-12 for operator input monitoring locations. Figure B-13 shows the seat track mounting for the aft end of the seat track and for the forward location for another vehicle. Figure B-14 shows typical installation of front and rear spindle locations. For all installations except the seat sensor, PCB 356A15 tri-axial accelerometers were used. These have a sensitivity of 100mV/g (10.2mV/m/s^2) and weigh 0.37oz (10.5gr). The PCB 356B41 seat sensor contained an accelerometer of the same sensitivity with overall weight of 9.6oz (272gm). The signals from each sensor were conditioned by a 3-channel PCB 480B21 ICP sensor signal conditioner. The location of the seat track accelerometer varied somewhat from vehicle to vehicle. In all cases, it was on the outboard track of the passenger seat rail. However, to find an accessible rigid mounting point, the accelerometer was located on the forward end of the track or the rear end of the track. The seat sensor was always in the same location. The steering column accelerometer was attached to the plastic cover over the actual steering column. For the steering wheel, it was found that the wheels were covered with vinyl, leather, or similar material that was not conducive to mounting the accelerometer securely with hot glue as was done for the seat track and steering column. As a result, a hose clamp was securely fitted to the steering wheel and the accelerometer could be attached to it. To mize interference with the operator, the cable from the accelerometer zip-tied to the wheel with sufficient slack that the wheel could be turned enough to complete low speed turnaround maneuvers. Mounting on the front and rear spindles was more problematic.

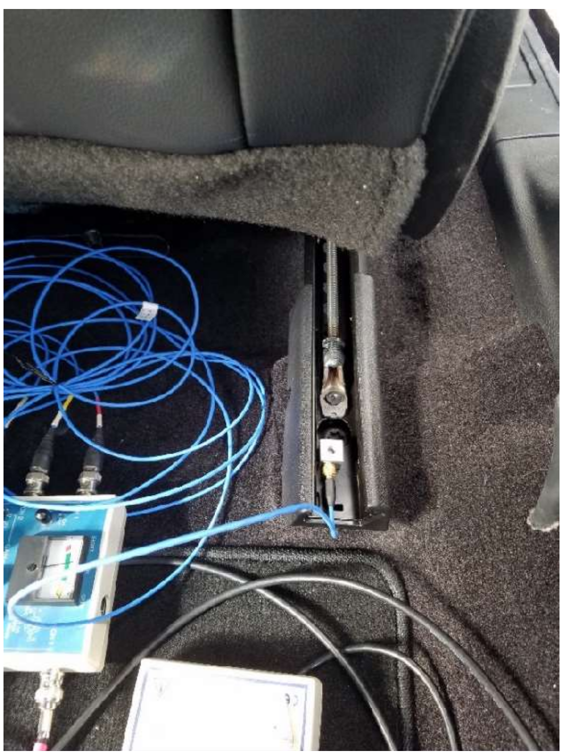


Steering column and wheel

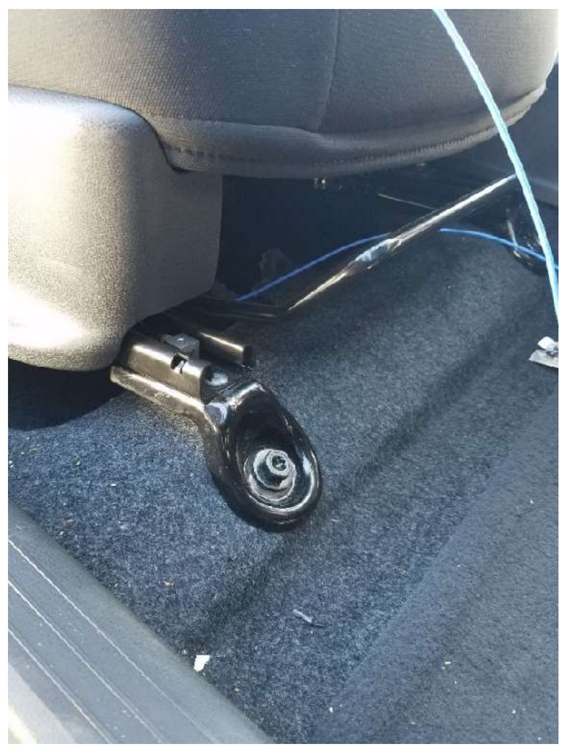


Seat pad

Figure B-12: Accelerometer locations for operator inputs

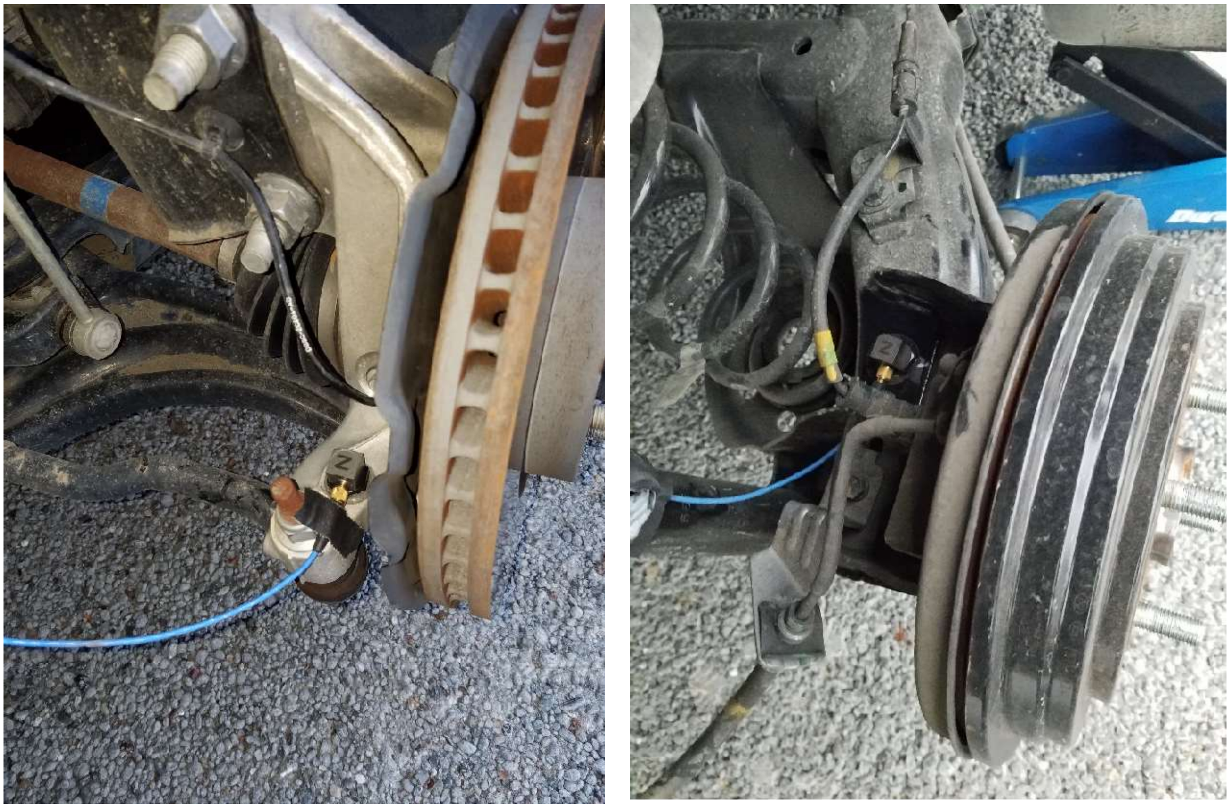


Aft end of track – Test Car 4



Forward end of track – Test Car 1

Figure B-13: Typical seat track accelerometer mountings different vehicles



Front spindle Test Car 4 *Rear spindle Test Car 2*

Figure B-14: Typical accelerometer locations on front and rear spindles

It was typically not possible to mount directly on the spindle and route the cable in the absence of a vehicle hoist. However, it was possible to attach it to a control arm that directly connected to the spindle so that no isolators were located between the spindle and point of the measurement. It was found that careful routing of the cable out of the wheel well was needed to eliminate the possibility of the cable contacting the tire or other moving parts while the vehicle was operating. It was also found that epoxy was needed to reliably secure the accelerometer base plate to the suspension component. Photographs of the spindle installations for all eight test vehicles are provided at the end of this Appendix.

The vibration data was acquired with a 16-channel analog-to-digital convertor. The sampling rate was set to 12.8 kHz. Recording was manually triggered as the vehicle approached the test section of the roadway and data was collected continuously through the test section. The signals were monitored and stored on a laptop computer during acquisition for later processing. In post-processing the data was reduced to 0.25 second root mean square (RMS) averages with 1/3 octave band frequency data from 2 Hz to 5000 Hz. To capture all 18 of the channels of data, two measurement configurations were required. For each of the rumble strips, measurements were completed in one configuration and then repeated in the second configuration similar the interior noise data.

Ground Vibration Measurements

Ground vibration was acquired on October 22 and 23, 2018 during pass-bys of four of the test vehicles: Test Car 3, Test Car 6, Test Car 7, and Test Car 5. Caltrans also provided pass-bys of a 4-yard dump truck fitted with a mobile barrier, as shown in Figure B-15 both on and off the two rumble strip designs. The vibration measurements were made at

Figure B-15: Caltrans 4-yard dump with mounted barrier

four distances from the roadway, close and parallel to the microphone line used for the noise pass-by measurements, as shown in Figure B-16 for the mumble strips and Figure B-17 for the conventional ground strips. The middle accelerometers were at the same distance as the pass-by microphones.

Figure B-16: Ground vibration accelerometers installed at the mumble strip pass-by site

A third accelerometer was closer to the highway than the 25-foot off-strip distance, and a fourth accelerometer was beyond the 25-foot on-strip distance; the distances were 15 and 30 feet from the rumble strip, in order to establish a doubling-of-distance vibration propagation drop-off rate, if needed.

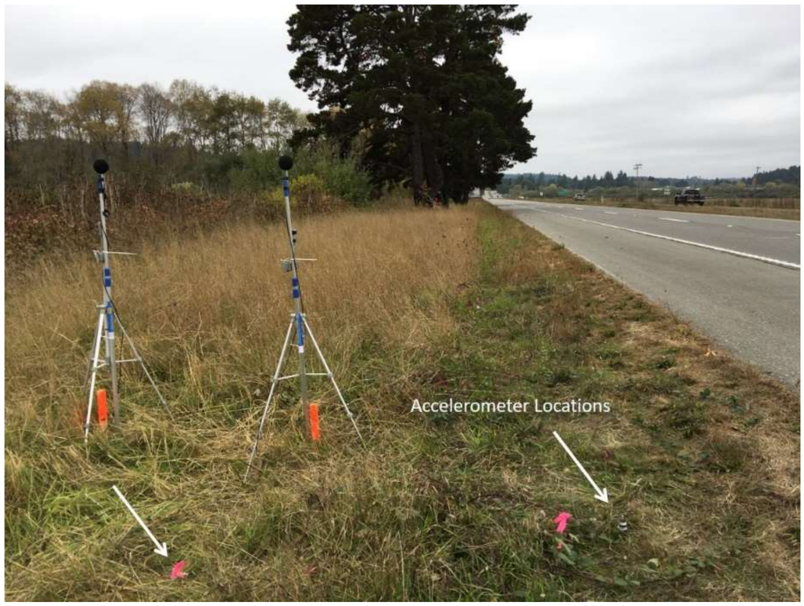


Figure B-17: Ground vibration accelerometers installed at the conventional rumble strip pass-by site

Since the ground vibration data were collected at the same time as pass-by noise data, all the same vehicle operational parameters apply, with data captured at speeds of 60 and 45 mph both for on and off the strips. The pass-bys were also judged as to whether vibration from other vehicles possibly contaminated the pass-by vibration level. Pass-bys not meeting these criteria were repeated as needed. Ambient vibration data were also captured to help interpret/evaluate the pass-by data.

The vibration data were acquired with a 4-channel DAQ system (Data Translation), along with four PCB 393B05 seismic accelerometers. The sampling rate was set to 1,198 Hz. Recording was manually triggered as the vehicle approached the test section of the roadway and ran through the duration of the pass-by event. The signals were monitored and stored on a laptop computer during acquisition for later processing.

MEASUREMENT RESULTS

Pass-by Noise

Data Processing

To process the pass-by data, each individual time history was reviewed to confirm that a pass-by was "clean" with no interference from other vehicles. The field notes were also reviewed, which noted cases where the vehicle may not have been fully on the rumble strips. For those events that were confirmed to be acceptable, the highest level during the pass-by was identified. This was done for vehicles both on and off the strips. Typically, at least four valid pass-bys were identified for each condition, and the levels for these events were averaged together to produce the reported level for that condition. A typical event was then selected for each condition to use in spectral comparisons.

Results

Pass-by measurements were made at both the conventional ground strip site and the mumble strip site for all eight vehicles and at both 45 and 60 mph. Figure B-18 shows the overall A-weighted pass-by noise levels measured for each vehicle at 60 mph. For each vehicle, the overall levels shown in Figure B-18 are the average for all valid pass-by runs. All data collected at 45 mph is presented in next section.

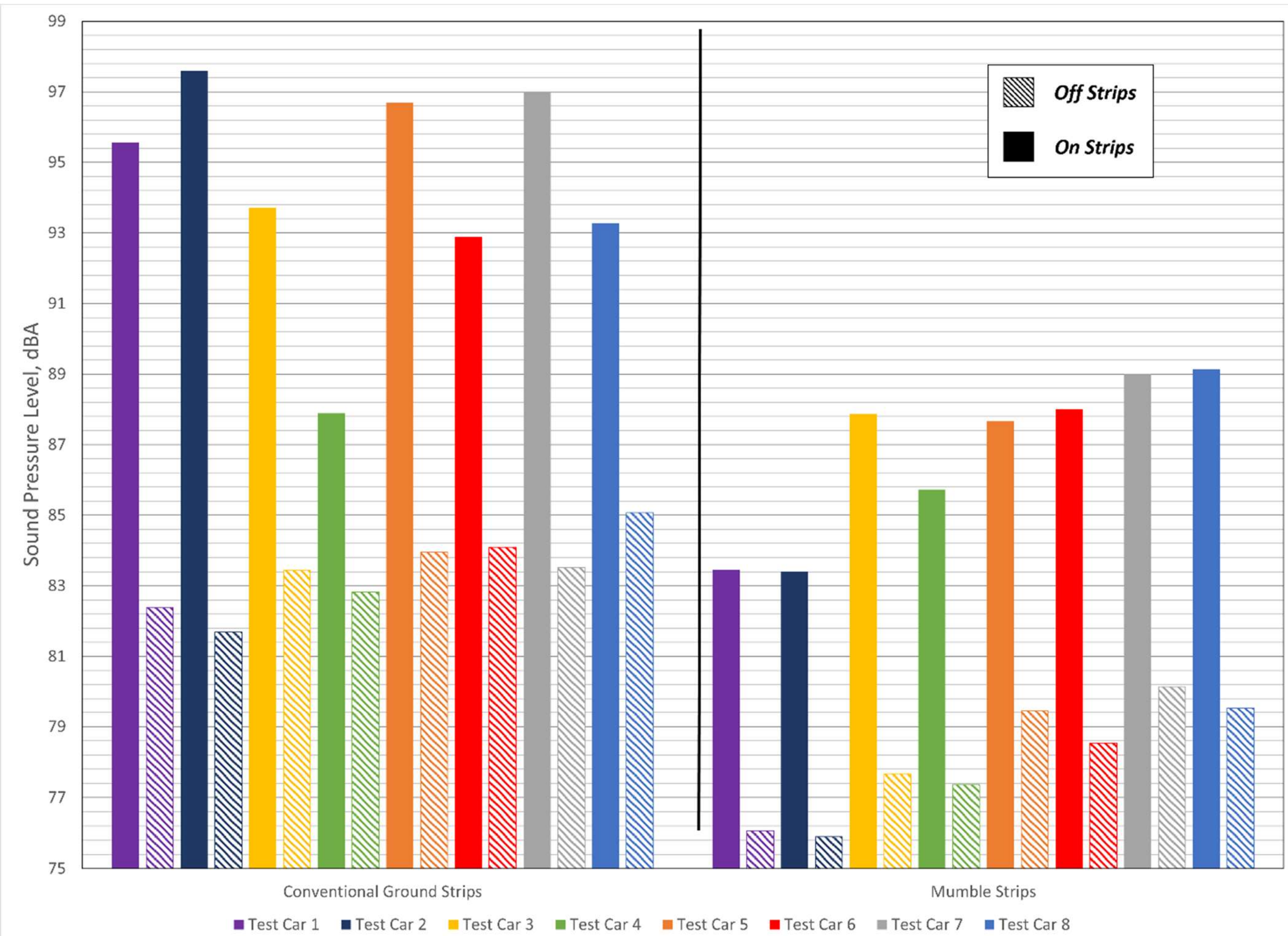


Figure B-18: Overall A-weighted pass-by sound pressure levels for all eight test vehicles on conventional ground rumble strips and mumble strips

For each of the test vehicles, pass-by noise levels were lower on the mumble strips than on the conventional ground rumble strips. At the mumble strip site, overall noise levels ranged from 83.4 to 89.1 dBA, while overall noise levels ranged from 87.9 to 97.6 dBA at the conventional ground rumble strip site. This figure shows higher variability on the conventional ground strips

(9.7 dBA) than on the mumble strips (5.7 dBA), with the overall pass-by levels on the conventional ground strips being consistently higher than on the mumble strips for every test vehicle. Breaking down the test vehicles by type and size, four distinct groupings are represented by two vehicles each: 1) the larger sports utility vehicle (SUV) and van, which have longer passenger cabins (Test Car 8 and Test Car 7), 2) crossover SUVs (Test Car 6 and Test Car 5), 3) sedans (Test Car 4 and Test Car 3), and 4) compact cars (Test Car 2 and Test Car 1). On the conventional ground strips, the overall pass-by results varied within each grouping by 0.6 to 3.8 dBA, while on the mumble strips, the difference in overall levels between both vehicles included in each grouping was 0.3 dBA or less. This limited sampling of vehicles indicates that vehicle-to-vehicle variation for pass-by noise levels could be better on the mumble strips.

In comparing the two tests sites for each vehicle, the greatest difference in overall pass-by level was measured using Test Car 2, with the conventional ground strips resulting in levels over 14.2 dBA higher than the mumble strips. The smallest difference was measured with Test Car 3, which resulted in a noise level difference of about 2.2 dBA between the two sites.

Figure B-19 shows the overall noise levels for each grouping averaged together. The average for the compact cars resulted in the highest overall noise levels on the conventional ground strips. Considering the smaller frames and weight of these vehicles, these pass-by results are somewhat surprising. In contrast, the compact cars have the lowest average overall level on the mumble strips. The difference of this group average is about 13.1 dBA between the two sites. For the other three groupings, the overall noise level at the conventional ground site was 4.0 to 7.0 dBA higher than the mumble strips. In total, the average for all eight vehicles at the conventional ground site was 7.5 dBA higher than the mumble strips.

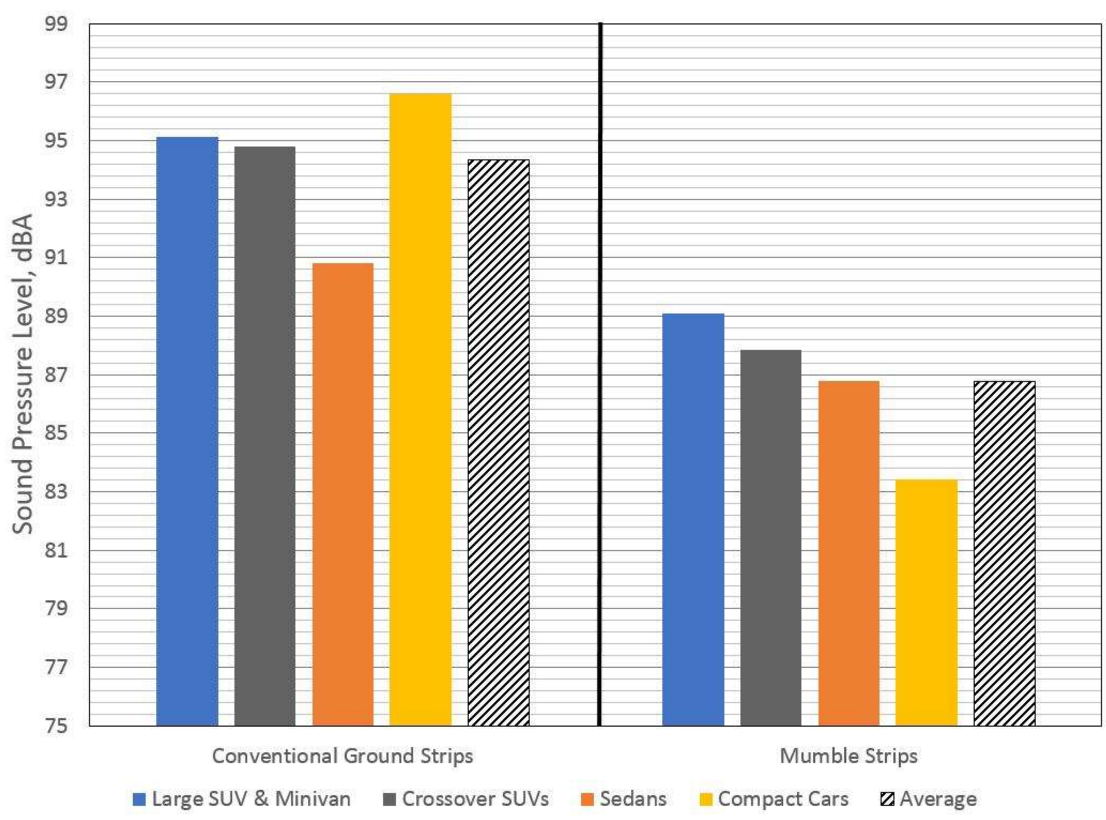


Figure B-19: Average overall A-weighted pass-by sound pressure levels for four groups, paired by vehicle type and size

Figure B-20 shows the differences between on and off strips at both test sites and for all test vehicles. Additionally, the average difference for all vehicles is also shown for at the conventional ground and mumble strip sites. The overall noise level difference between on and off strips ranged from 5.1 to 15.9 dBA along the wayside on the conventional ground strips, while the differences ranged from 7.5 to 10.2 dBA on the mumble strips. The vehicle-to-vehicle variation in noise level differences were more consistent at the mumble strip site producing an average of 8.7 dBA. In contrast, the on/off differences on the conventional ground strips averaged of 11.0 dBA.

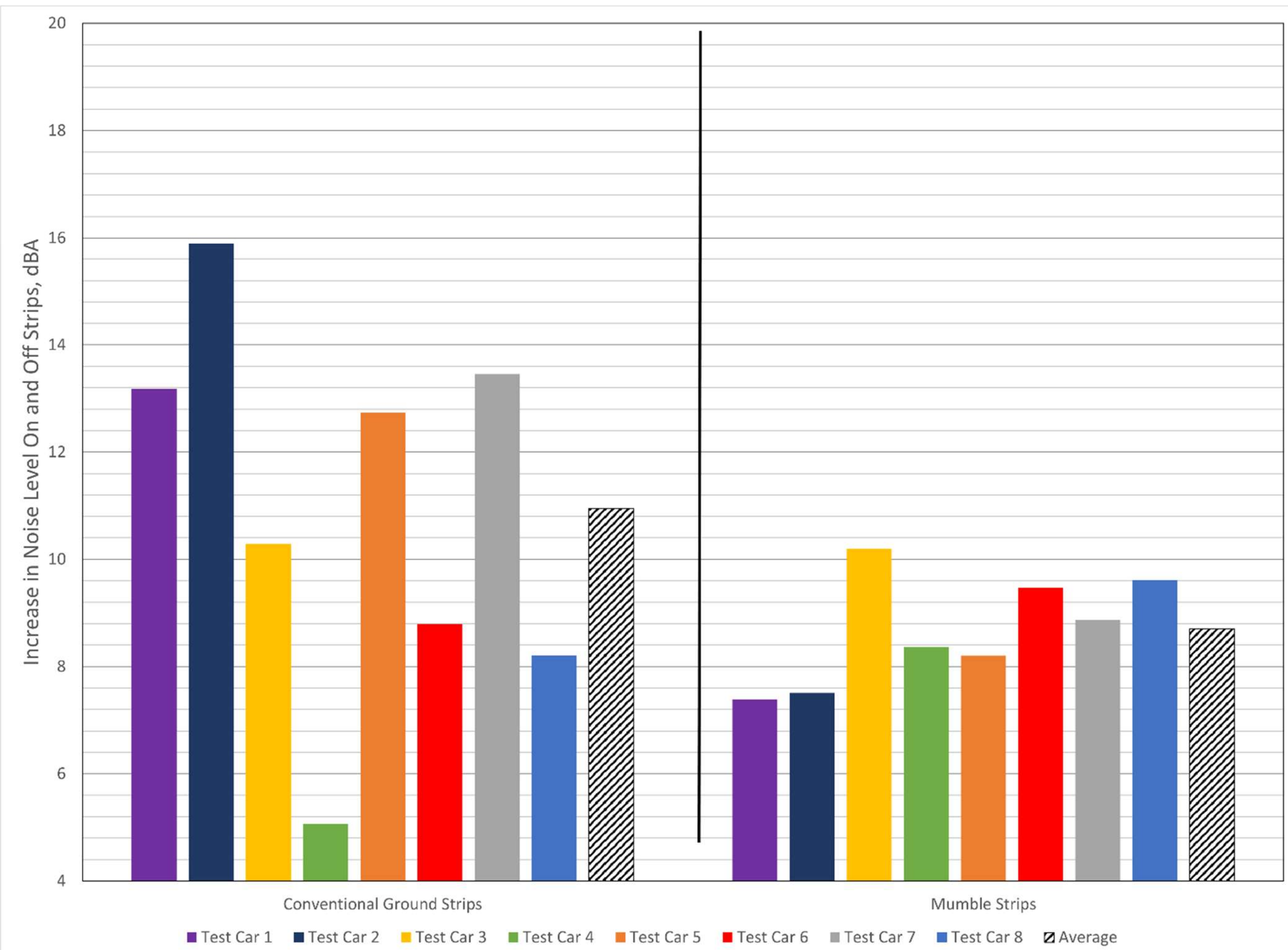


Figure B-20: Overall pass-by noise level differences between on and off strips at the conventional ground rumble strips and mumble strips sites for all test vehicles

Test Car 8 and Test Car 7, which are averaged together as the large SUV and van group shown Figure B-19, have on/off differences varying by 5.2 dBA on the conventional ground strips as shown in Figure B-20. The two sedans (Test Car 3 and Test Car 4) average in Figure 4.1.2 also show on/off differences varying by 5.2 dBA in Figure 4.1.3. The on/off differences between the two Crossover SUVs (Test Car 6 and Test Car 5) varies by 3.9 dBA at this site, and the compact cars vary by 2.7 dBA. In contrast, each of these groupings have on/off differences on the mumble strips that vary by 1.8 dBA or less between the two vehicles in each pair.

When averaged together, the on/off differences for each pairing at both sites is shown in Figure B-21. On the conventional ground strips, the compact cars have an average on/off difference of 14.5 dBA, while the other three groupings have on/off differences of 7.7 to 10.8 dBA. The on/off difference for the compact cars on the mumble strips is about 7.4 dBA, while the other three groupings range from 8.8 to 9.3 dBA. On average, all eight test vehicles had on/off differences of 8.7 dBA on the mumble strips and 11.0 dBA on the conventional ground strips.

This may indicate that the mumble strip design would not only reduce the noise propagating to noise-sensitive receptors residing on the wayside of roadways with shoulder warning devices but also that the mumble strip design would result in noise levels less dependent on vehicle type and/or size. Typically, people are more sensitive to noises that are abnormal or inconsistent than to repetitive or recurring noise.

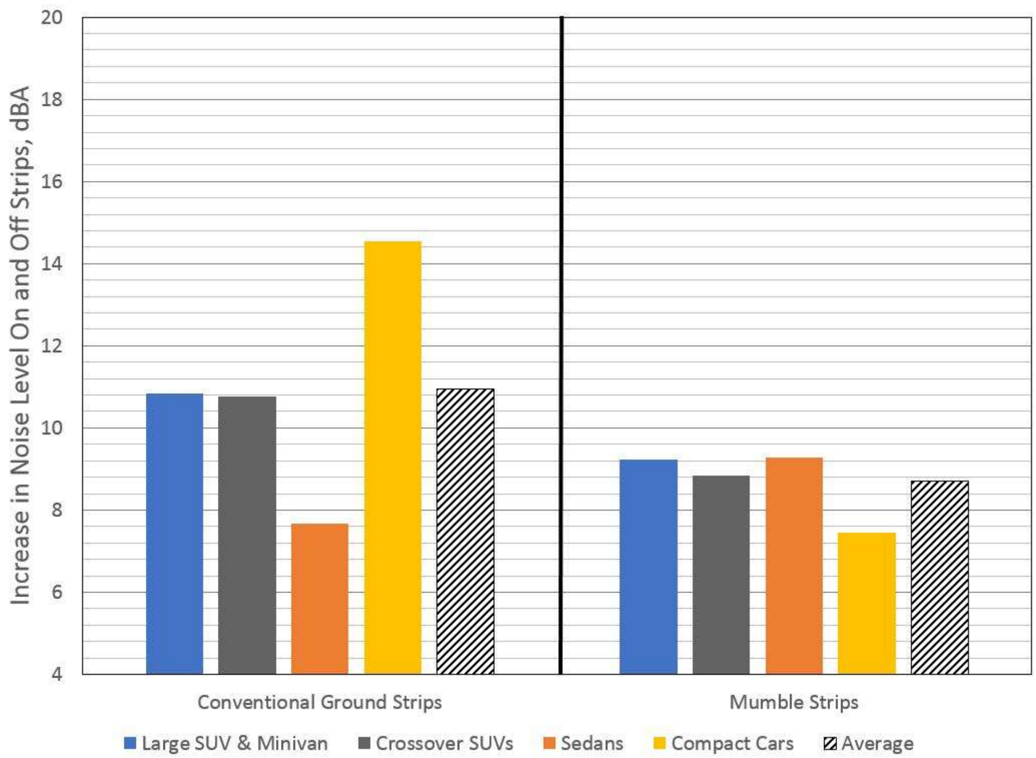


Figure B-21: Average overall difference between on and off strips at both test sites for four groups, paired by vehicle type and size

One-third octave band levels are shown in Figures B-22 and B-23 for each vehicle, on and off strips, measured at the conventional ground rumble strip site and mumble strip site, respectively. In each figure, the dashed lines represent pass-by measurements made off strips, while the solid lines represent pass-by measurements on the strips. The conventional ground strips typically excite noise levels at the 80 and 100 Hz frequency bands, while mumble strips typically excite noise levels at 80 Hz only. From the figures, noise levels at the conventional rumble strips site were an average of 13.1 dB higher than the mumble strips at 100 Hz but an average of 11.5 dB lower at 80 Hz. It also appears that 200 and 1,000 Hz, the noise levels on the mumble strips are not significantly higher than the off strips spectra results; however, the conventional ground strips are an average of 10 dBA higher than the off strips spectra.

Figure B-24 compares the spectra on the conventional ground strips and mumble strips for the four groupings of vehicles described above. As shown in this figure, noise levels measured between 200 and 1,600 Hz are lower on the mumble strips than on the conventional ground strips for each group.

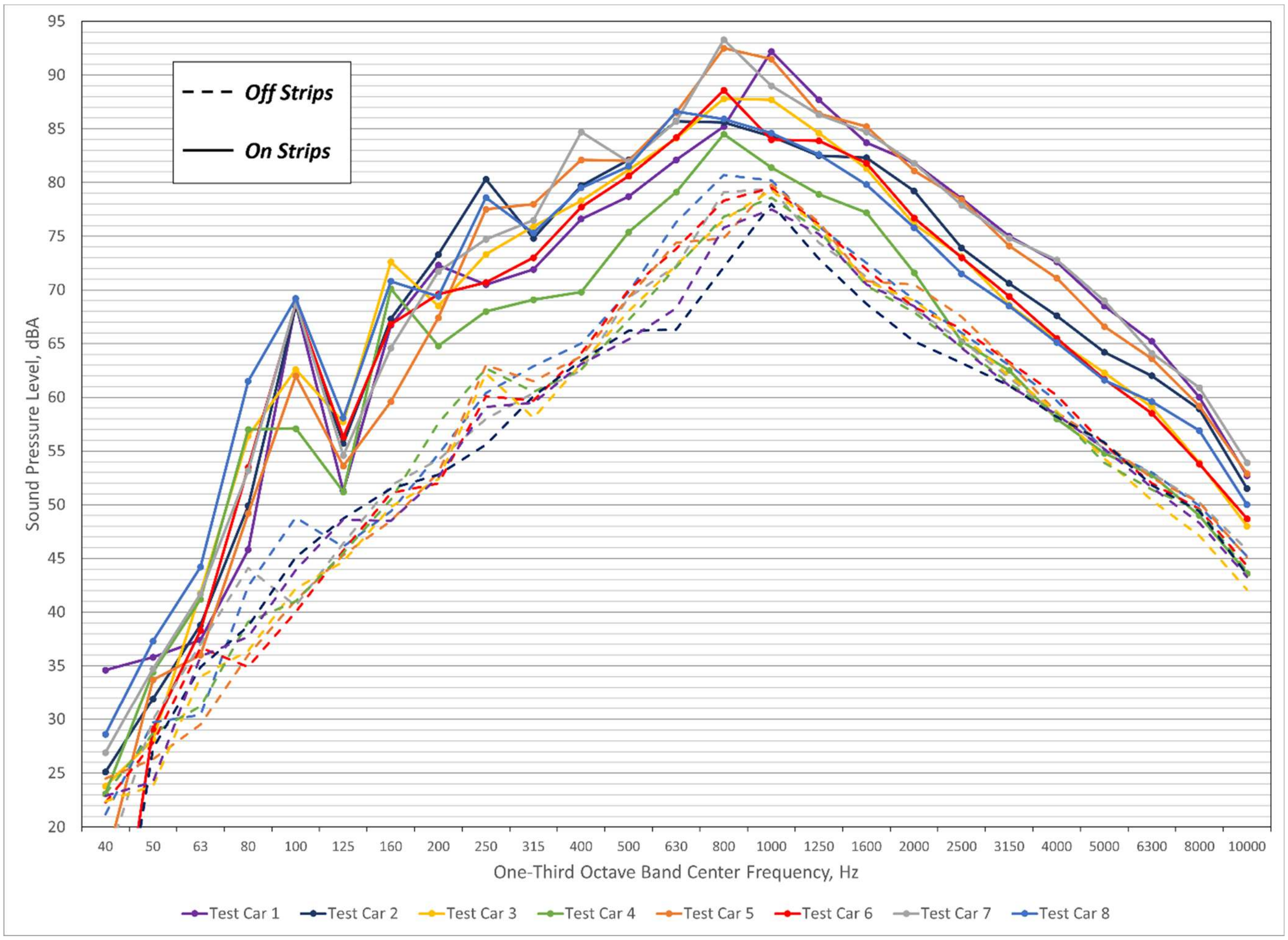


Figure B-22: A-weighted one-third octave band spectra for all eight test vehicles on and off conventional ground strips

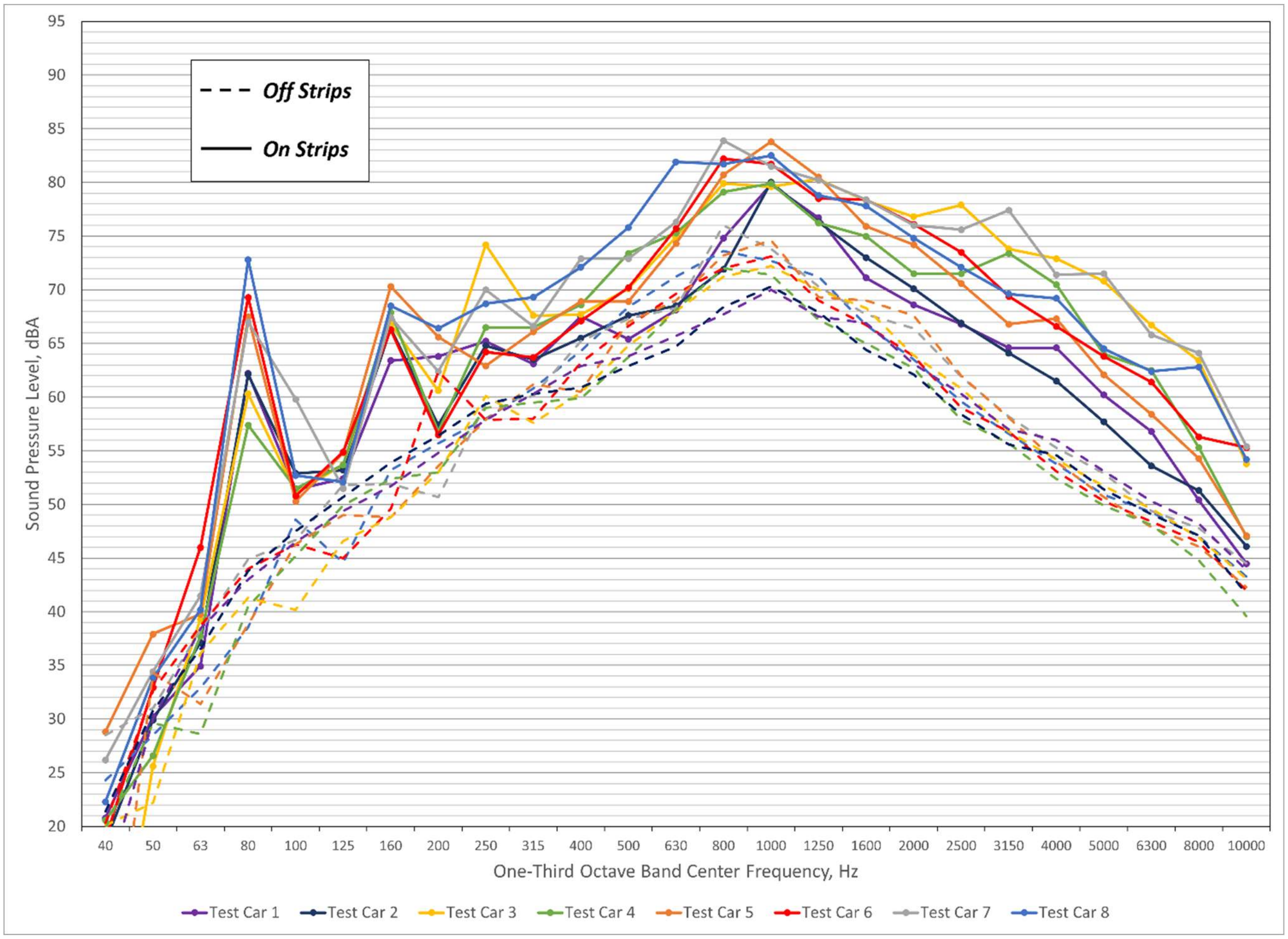


Figure B-23: A-weighted one-third octave band spectra for all eight test vehicles on and off mumble strips

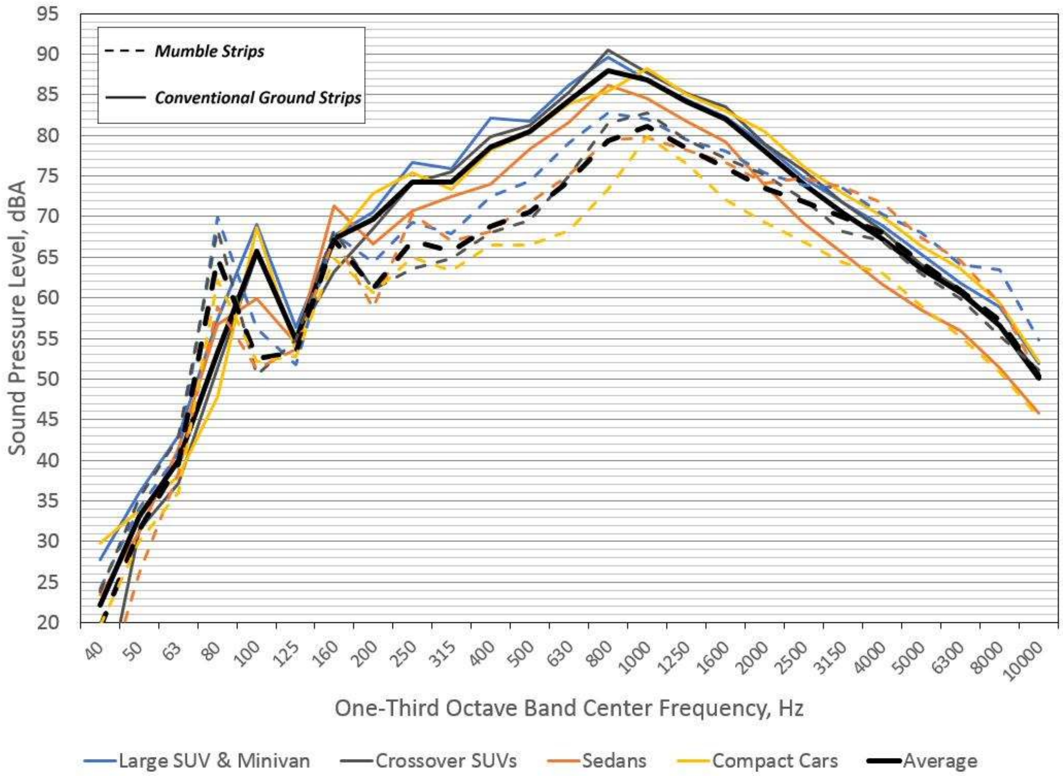


Figure B-24: Average pass-by A-weighted one-third octave band spectra for four groups, paired by vehicle type and size

Speed Dependence

Pass-by data was taken at 45 mph speeds for Test Car 8, Test Car 6, Test Car 4, Test Car 3, Test Car 2, and Test Car 1 (all but Test Car 5 and Test Car 7). The overall pass-by levels on and off the strips at both sites are shown in Figure B-25. Similar to the overall pass-by results at 60 mph, the noise levels taken on the mumble strips are slightly more consistent from vehicle-to-vehicle, with overall levels being lower on the mumble strips for each vehicle. On the mumble strips, pass-by levels ranged from 77.6 to 82.5 dBA, for a total difference of 4.9 dBA. On the conventional ground strips, the overall noise levels ranged from 87.0 to 92.9 dBA, for a total difference of 5.9 dBA. The data taken at 60 mph resulted in overall levels ranging from 83.4 to 89.1 dBA on the mumble strips (total difference of 5.7 dBA), while on the conventional ground strips, overall levels ranged from 87.9 to 97.6 dBA (total difference of 9.7 dBA). On the mumble strips, the overall noise levels at 60 mph were 4.1 to 7.1 dBA higher than at 45 mph. On the conventional ground strips, the overall noise levels at 60 mph were 0.9 to 9.8 dBA higher than at 45 mph, except in Test Car 6, which had the same overall level at both speeds.

Since Test Car 7 and Test Car 5 were not tested at 45 mph, averages for the large SUV and van and crossover SUVs groups could not be calculated. Using the single vehicle overall levels to represent the respective groupings at 45 mph, the overall levels for groupings are shown in Figure B-26, as compared to the 60 mph grouping data. With lower overall averages in each grouping, the compact cars are more than 3 dBA lower than the other groupings on the mumble strips at both travel speeds. The slower speed also results in more consistency in the average overall level for the other three groupings on the mumble strips. While the average overall level for compact cars changes from being the highest level of all the groupings at 60 mph, at 45 mph, it has the lowest level on the conventional ground strips. Test Car 6 at 45 mph resulted in pass-by levels less than 2 dBA lower than the crossover SUV grouping at 60 mph; however, due to the limited sample size and the age of Test Car 6, more testing would have to be completed to draw any conclusions.

Figure B-27 summarizes the difference between on and off strips at each site when traveling at 45 mph. As shown in Figure B-27, the pass-by measurements for each vehicle resulted in levels 8.5 to 13 dB higher on the rumble strips than off, while levels were 5.5 to 9 dB higher on the mumble strips than off. On average, the on/off strip difference for each test vehicle was 10.5 dB on the conventional rumble strips and 3 dB on the mumble strips. On the conventional strips, noise on/off differences for each vehicle varied. For Test Car 8, for instance, both traveling speeds resulted in on/off differences of about 8 dBA, while Test Car 6 had an on/off difference about 4 dBA higher at 45 mph than at 60 mph. Both sedans had a greater on/off difference at 45 mph than at 60 mph on the conventional ground strips, while both compact cars had lower on/off differences at 45 mph than at 60 mph. In contrast, all vehicles except Test Car 2 resulted in lower on/off differences at 45 mph than at 60 mph on the mumble strips, and Test Car 2 had on/off differences at 45 mph that were 0.3 dB higher than at 60 mph, which is virtually immeasurable.

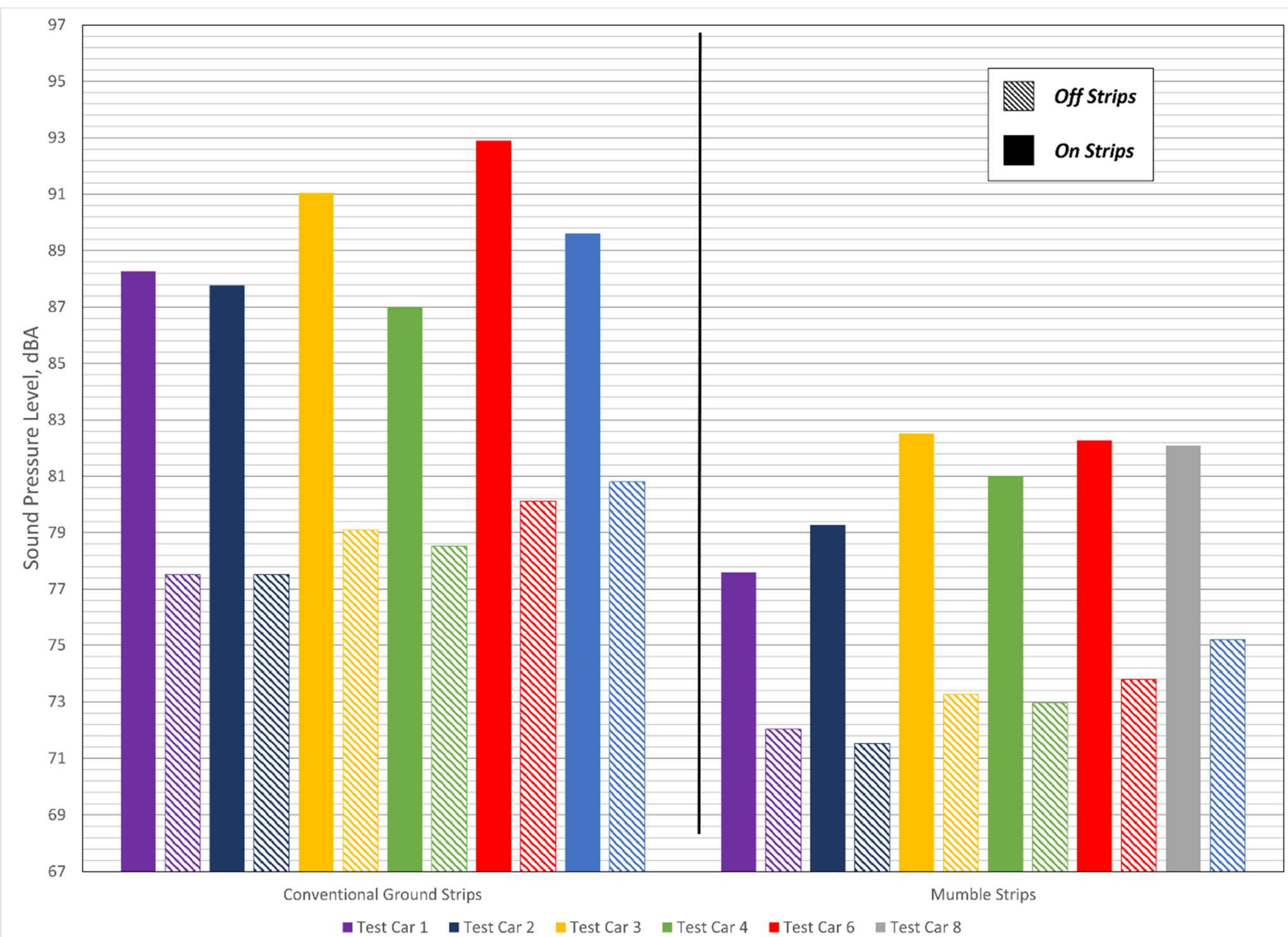


Figure B-25: Overall A-weighted pass-by sound pressure levels for the all test vehicles on conventional ground rumble strips and mumble strips (45 mph)

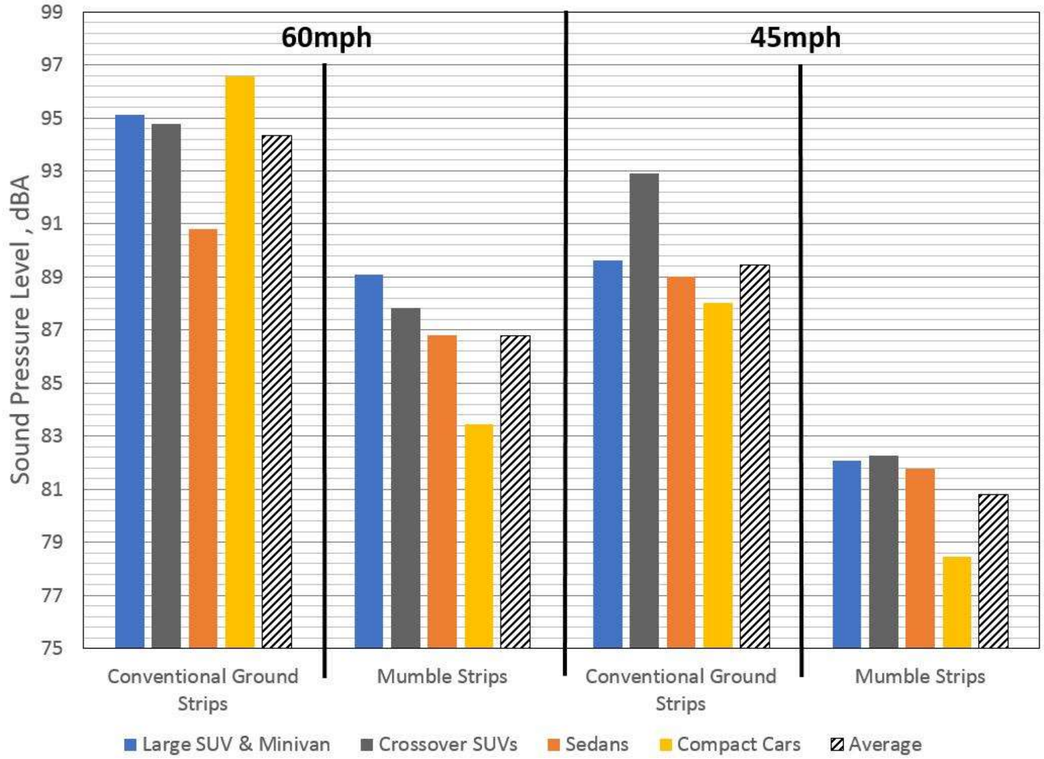


Figure B-27: Average overall A-weighted pass-by sound pressure levels for four groups, paired by vehicle type and size (60 mph vs. 45 mph)

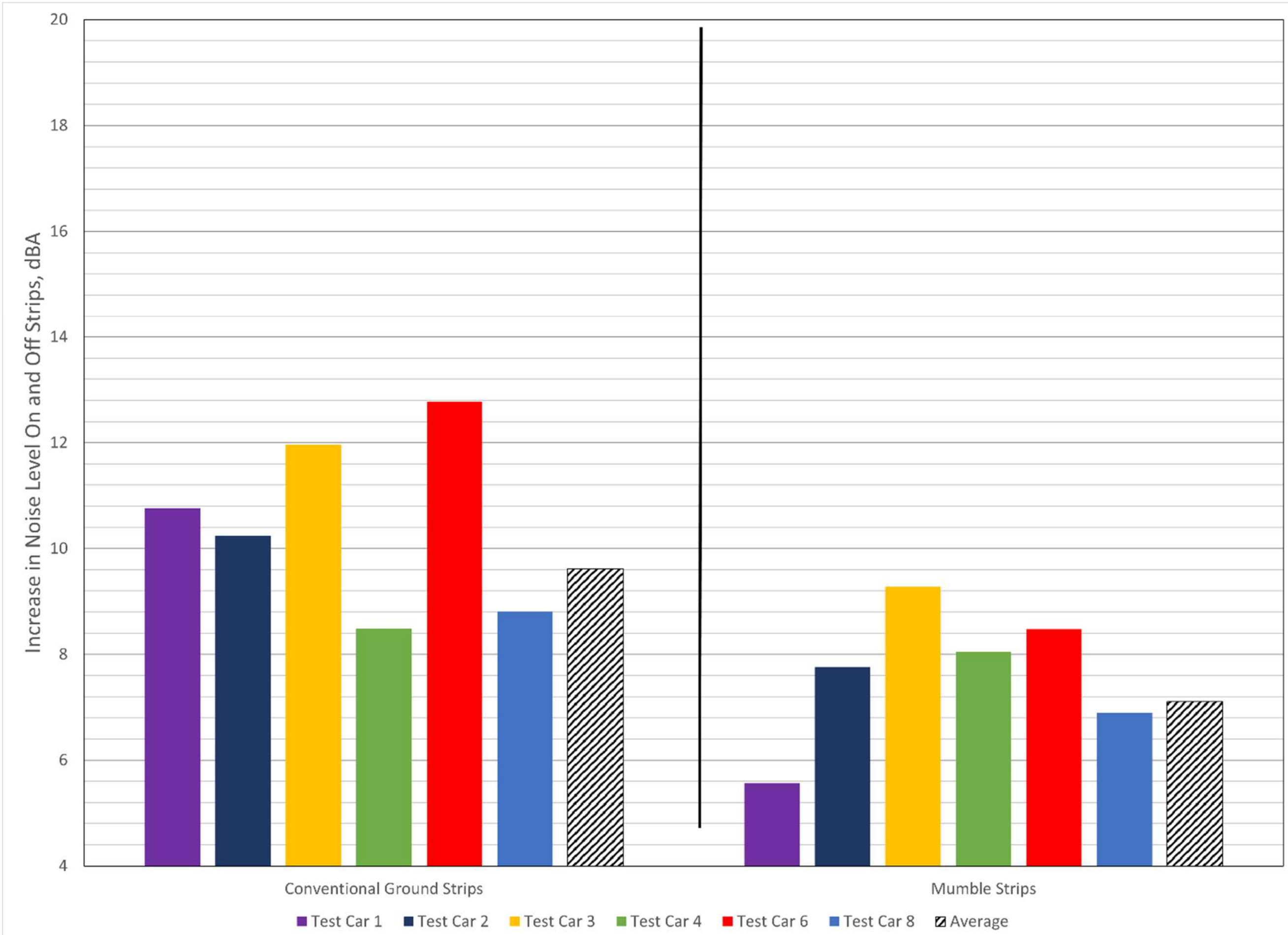


Figure B-28: Overall pass-by noise level differences between on and off strips at the conventional ground rumble strips and mumble strips sites for all test vehicles (45 mph)

Figure B-29 shows the average differences for each of the pairings at 45 mph, compared to 60 mph. For each group except large SUV and van, on/off differences at 45 mph and 60 mph were within 1.0 dBA of each other on the mumble strips. While 2.3 dBA was the variation between the on/off differences of the large SUV and van group, only one vehicle was tested at 45 mph, and this small sample size may skew the results. More data would need to be taken to better define this group at 45 mph. On the conventional ground strips, on/off differences varied by 2.0 to 4.0 dBA, and unlike the mumble strip data, the 60 mph differences were not always greater. This indicates further inconsistency in noise level data taken on the conventional ground strips.

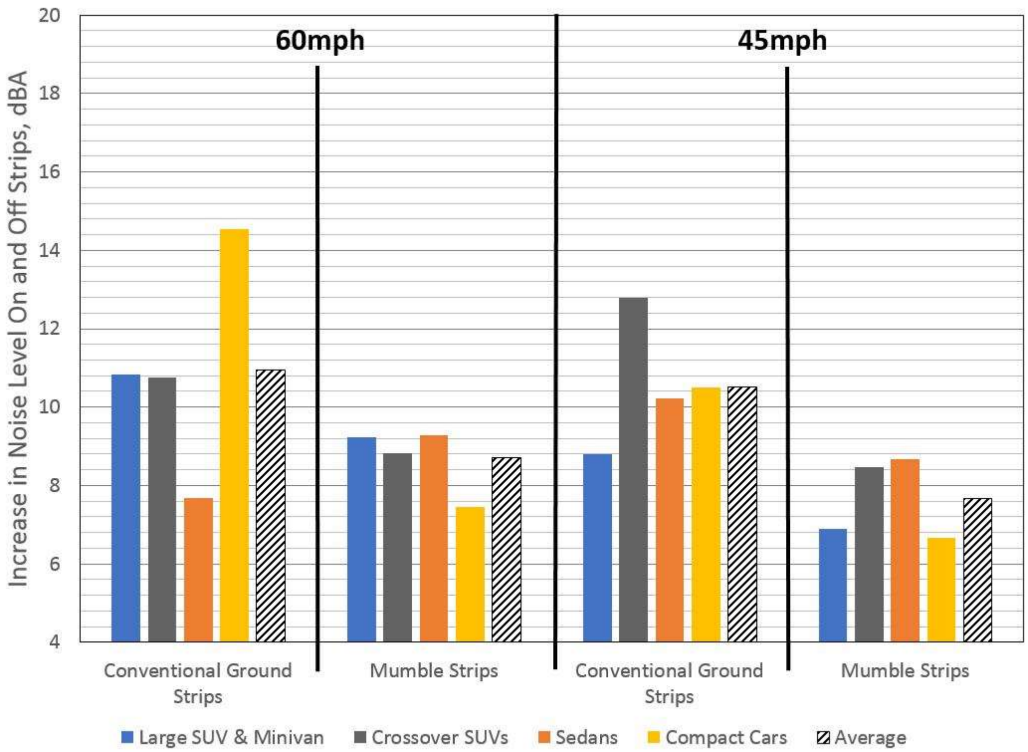


Figure B-29: Average overall pass-by noise level differences between on and off strips at the conventional ground rumble strips and mumble strips sites for four groups, paired by vehicle type and size (60 mph vs. 45 mph)

Figures B-30 and B-31 show the one-third octave band spectra for each test vehicle, on and off strips for the mumble and conventional ground strips, respectively. For most test vehicles, there are peaks at 63 and 125 Hz for measurements on the mumble strips. These spectra also show noise levels up to 10 dB higher than off strips between 500 and 2,000 Hz. However, for the other frequency bands, on strips data was slightly above off strips. In comparison, the spectra measured at the conventional ground strips site shows noticeably higher levels throughout the frequency spectra for all vehicles except Test Car 2, which has high ambient measurements at frequency bands below 315 Hz.

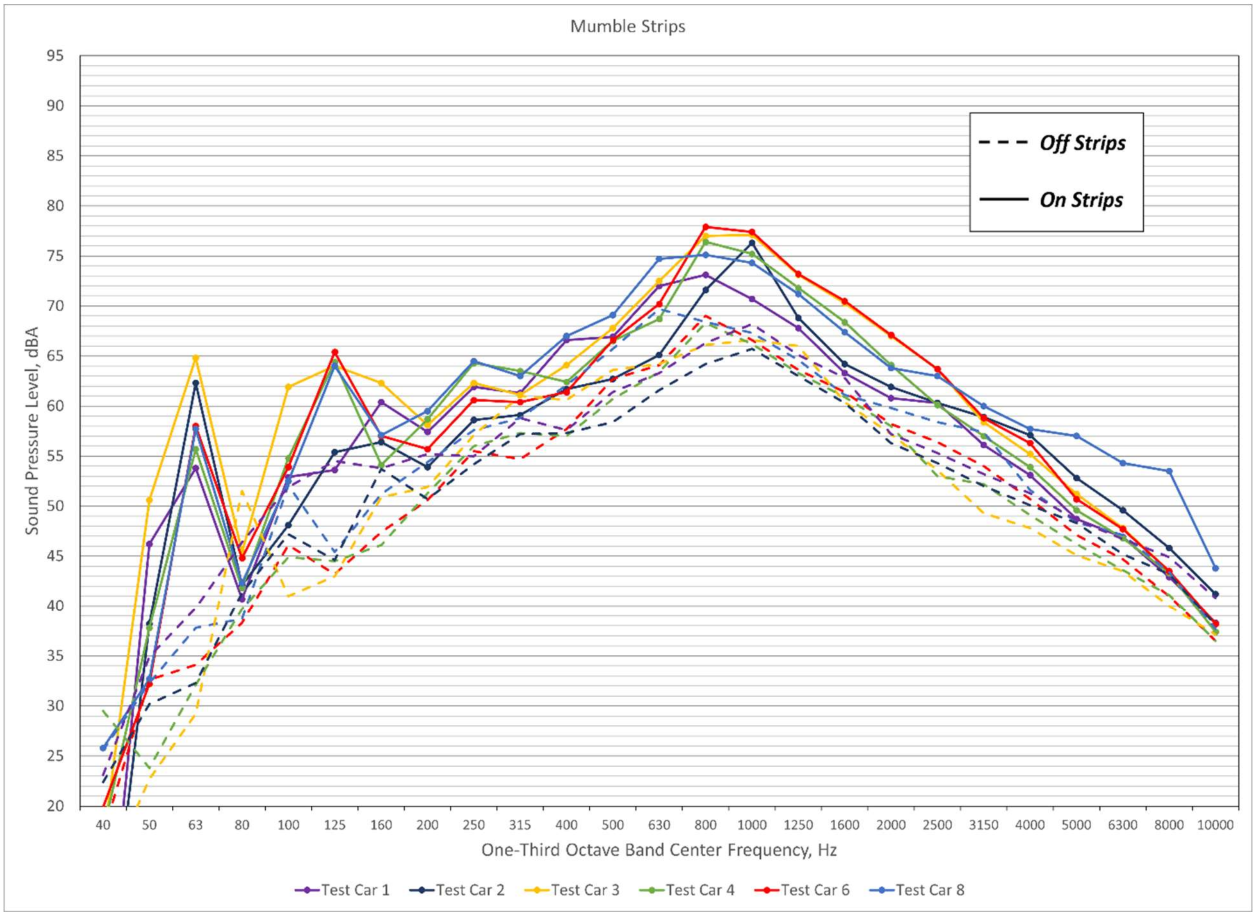


Figure B-30: A-weighted one-third octave band spectra for all eight test vehicles on and off mumble strips (45 mph)

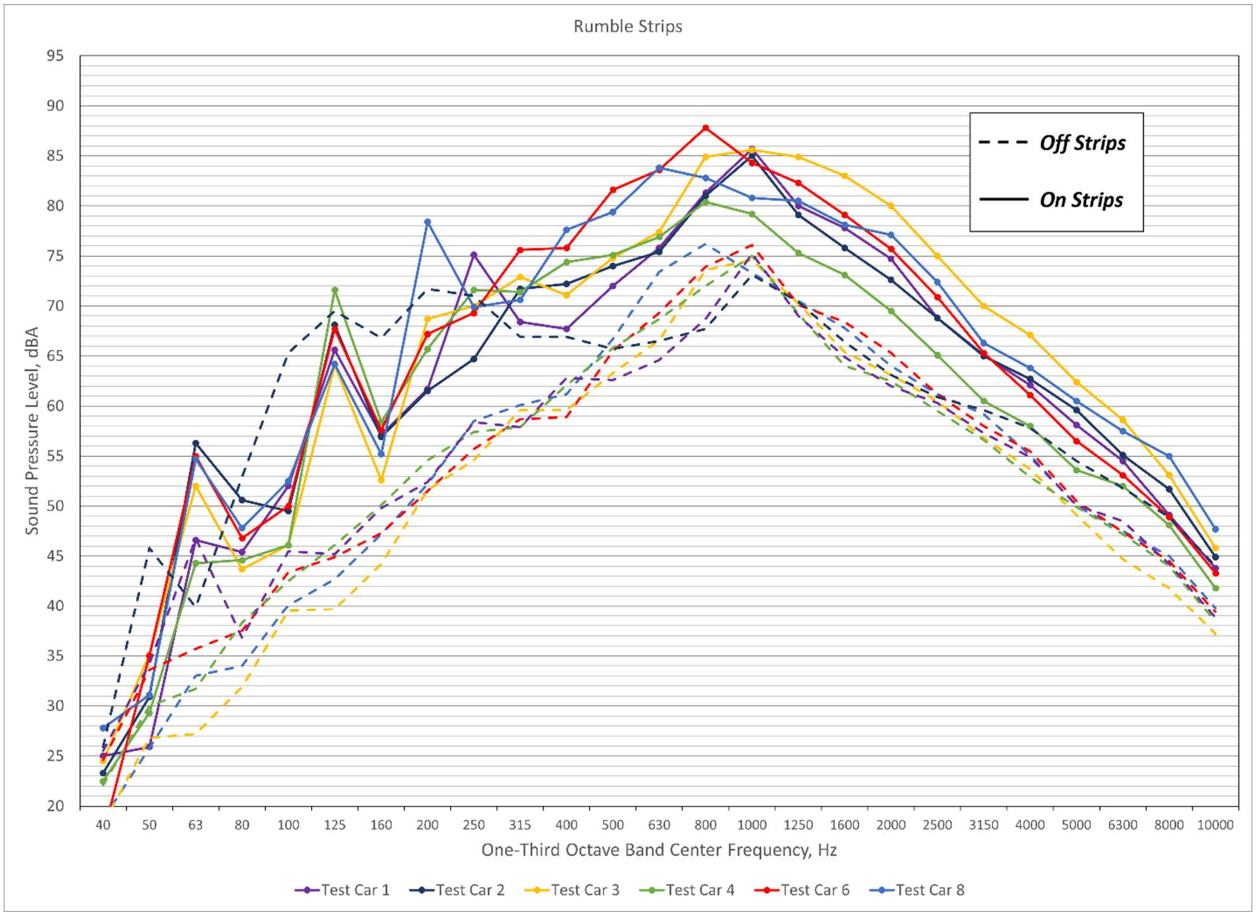


Figure B-31: A-weighted one-third octave band spectra for all eight test vehicles on and off conventional ground strips (45 mph)

Figure B-32 shows the conventional ground strips and mumble strips for the four groupings of vehicles described above. As shown in this figure, noise levels measured at 160 Hz and above are lower on the mumble strips than on the conventional ground strips for each group. However, the 63 Hz peak appears to be higher on the mumble strips than on the conventional ground strips.

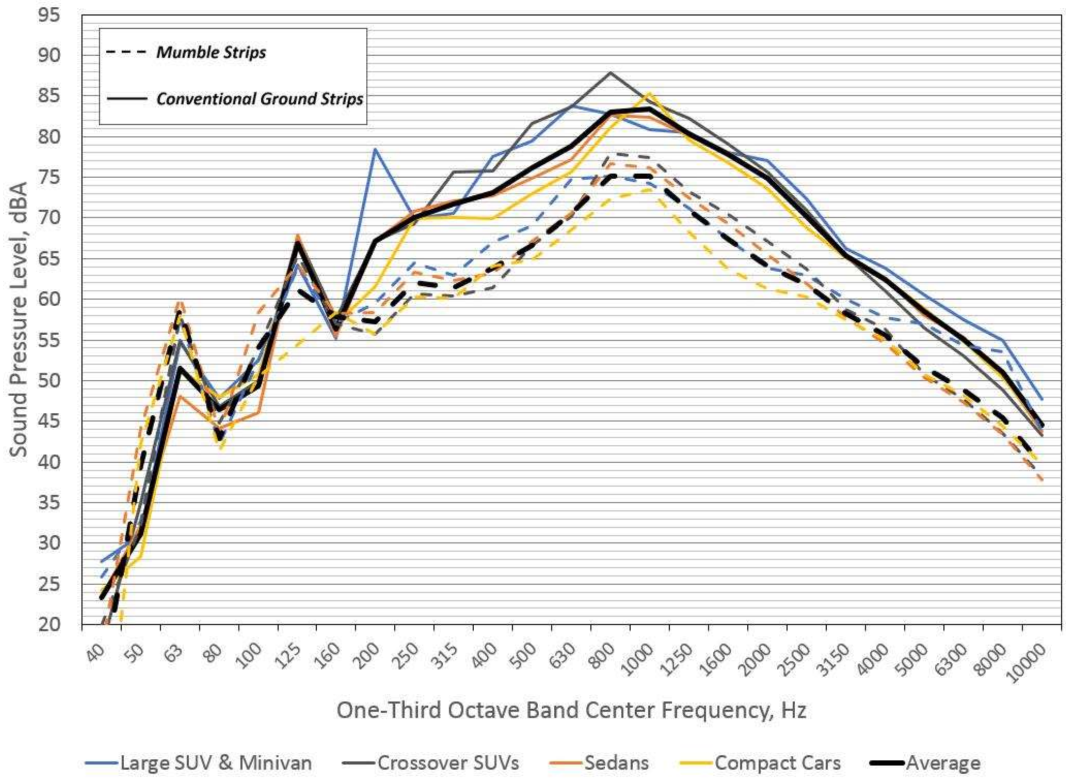


Figure B-32: Average pass-by A-weighted one-third octave band spectra for four groups, paired by vehicle type and size (45 mph)

Comparison to Previous Results

In 2012 and 2015, testing was completed at both the mumble strip and conventional ground strip sites for Caltrans.[4] Noise testing included both pass-by and interior measurements. The pass-by setup was the same as used in 2018. In 2012, an Expedition, Honda Civic, and Malibu were tested, while a Camry was tested in 2015 with two different tires (Standard Reference Test Tire [SRTT] and Goodyear Eagle LS_2). The following section compares the 2018 pass-by noise measurement results to these previous studies.

Figure B-33 shows the overall pass-by levels on the mumble strips for each of the 2018 groupings compared to the 2012 and 2015 results. The overall levels measured during the Expedition pass-bys in 2012 were about 1 dBA higher than Test Car 8 on the mumble strips and less than 3 dBA higher than all 2018 SUV and van measurements. The Honda Civic had pass-by levels about 2 dBA higher than the two compact cars in 2018 and were about equivalent to the Test Car 3 pass-by levels on the mumble strips. The Malibu was less than 1 dBA higher than the 2018 Test Car 4, which had pass-by levels equivalent to the average of the Camry pass-by levels from 2015. For all test vehicles in the Caltrans and NCHRP studies, the pass-by levels on the mumble strips ranged from 83 to 90 dBA.

On the conventional ground strips shown in Figure B-34, overall pass-by levels for all vehicles in the Caltrans and NCHRP studies ranged from about 88 to 98 dBA. The 2012 Expedition measurement on the conventional ground strips was equivalent to the Test Car 5 pass-by in 2018 and about 3.5 dBA higher than Test Car 8. While the Malibu had similar levels to the 2018 Test

Car 4, the Honda Civic was 3 to 5 dBA lower than the 2018 compact cars. The 2015 Camry with the Goodyear tire had about the same pass-by levels as the 2018 Test Car 4 on the conventional ground strips, while the 2015 Camry with the SRTT tire was less than 2 dBA higher.

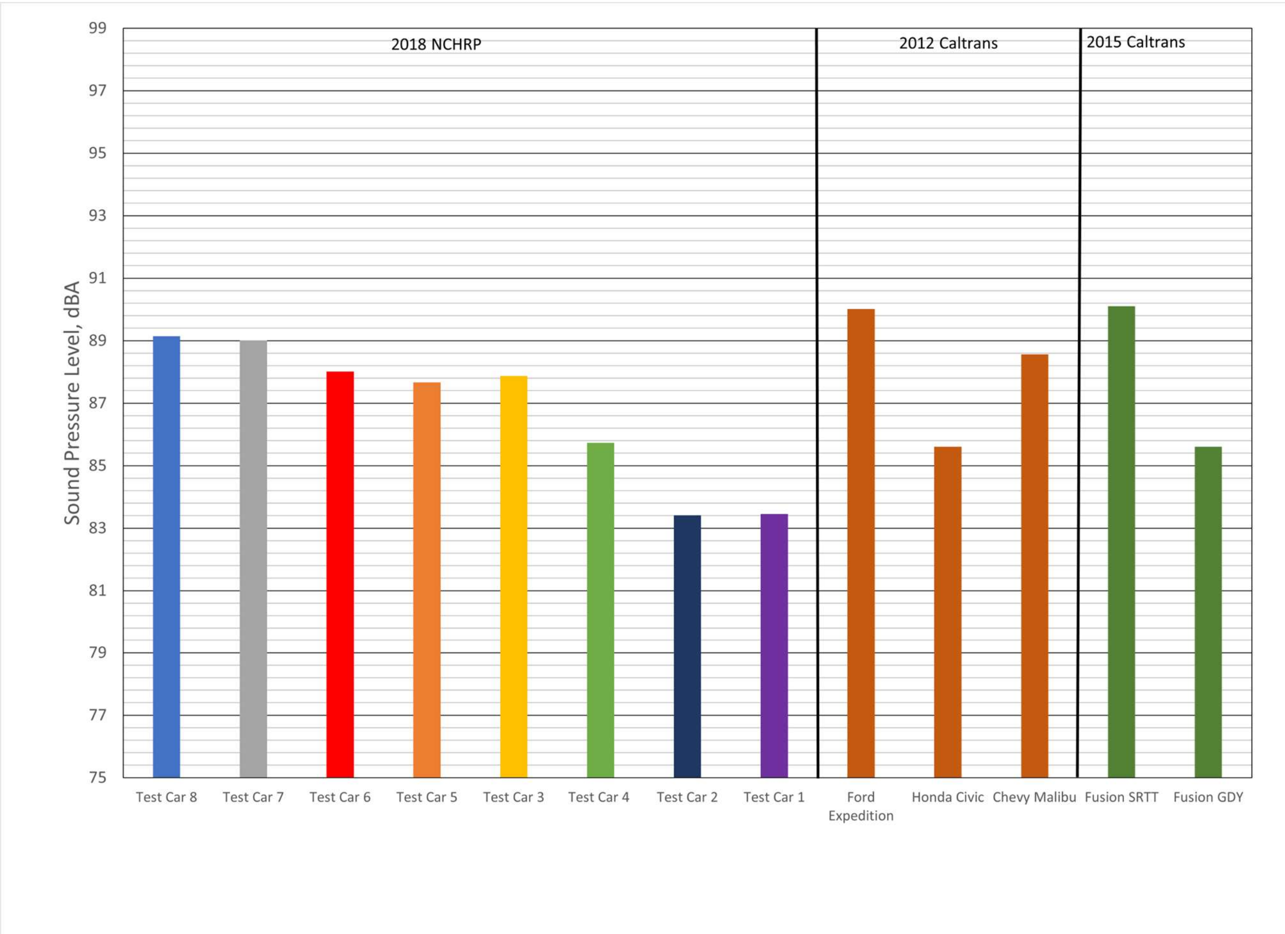


Figure B-33: Overall pass-by noise levels at the mumble strip site when compared to results of previous Caltrans studies

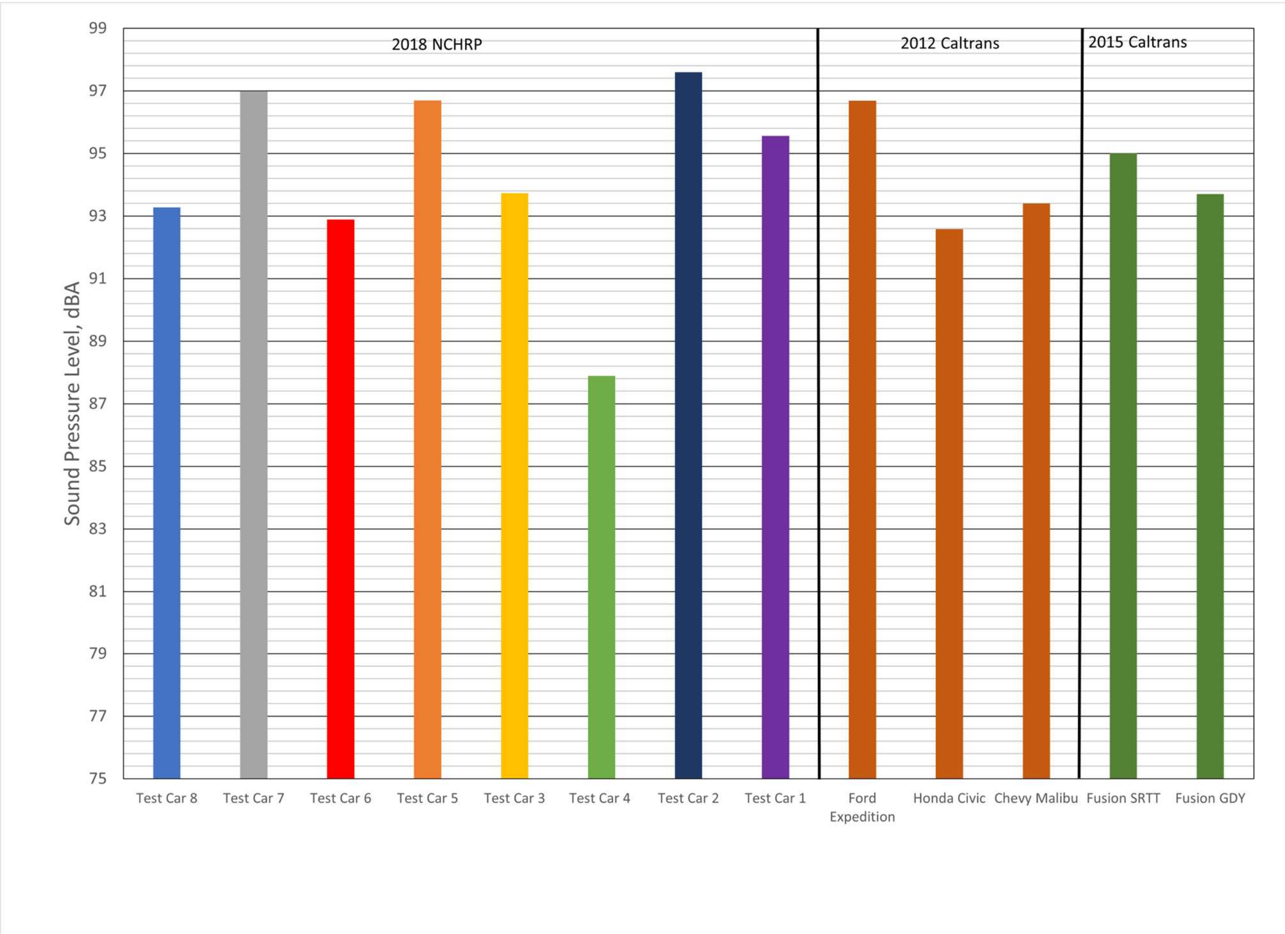


Figure B-34: Overall pass-by noise levels at the conventional ground strip site when compared to results of previous Caltrans studies

The on/off differences of the overall pass-by levels for the Caltrans data in 2012 and 2015 are compared to the 2018 NCHRP data in Figures B-35 (on the mumble strips) and B-36 (on the conventional ground strips). The pass-by differences on and off the mumble strips range from about 4 to 10 dBA across all test vehicles. The data collected in 2012 and 2015 for the previous Caltrans studies resulted in lower on/off differences for each vehicle when compared to 2018 vehicles of similar types. On the conventional ground strips, however, the on/off differences showed more variation, ranging from 5 to 16 dBA. The Expedition on the conventional ground strips had a difference from off strips equivalent to that measured in 2018 for Test Car 5 and was about 5 dBA higher than the on/off difference of Test Car 8. While the Honda Civic was less than 1 dBA lower than Test Car 1, it was more than 3 dBA lower than Test Car 2. The on/off differences for the Malibu was equivalent to the 2018 Test Car 4 but more than 5 dBA higher than Test Car 3. On the conventional ground strips, the 2018 Test Car 4 was less than 1 dBA lower than the 2015 Camry with SRTT and about 2 dBA higher than Test Car 4 with Goodyear.

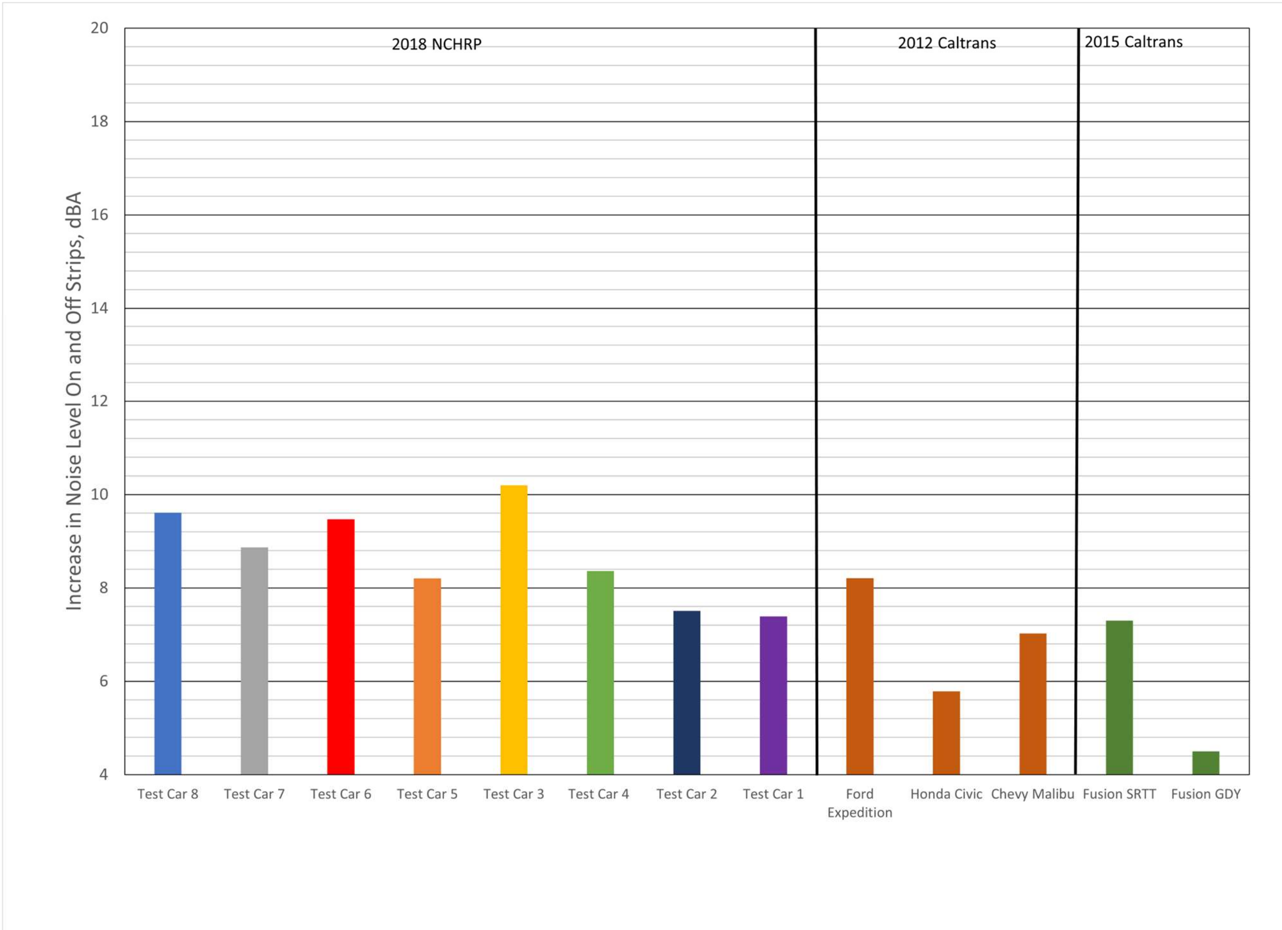


Figure B-35: Overall pass-by noise level differences between on and off strips at the mumble strip site when compared to results of previous Caltrans studies

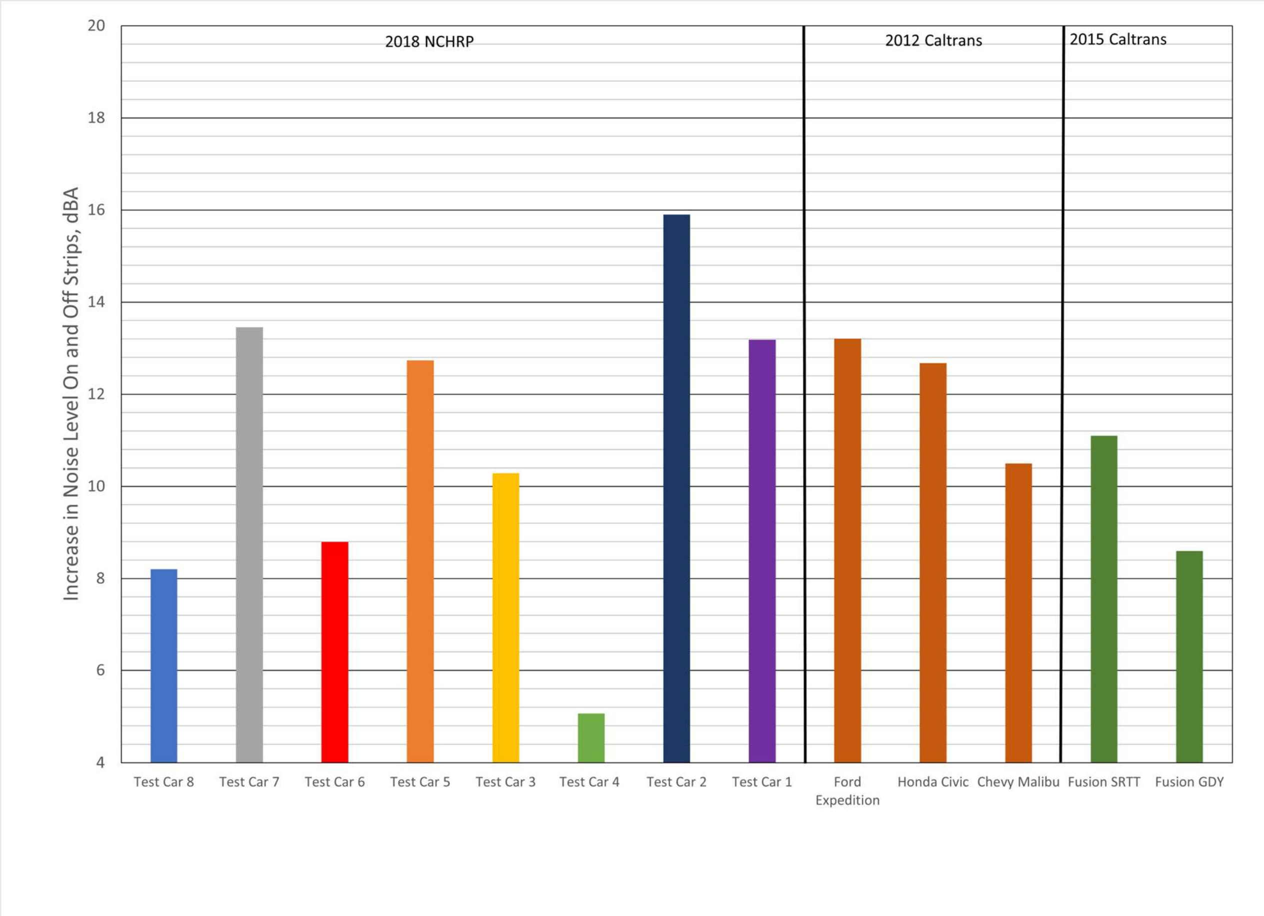
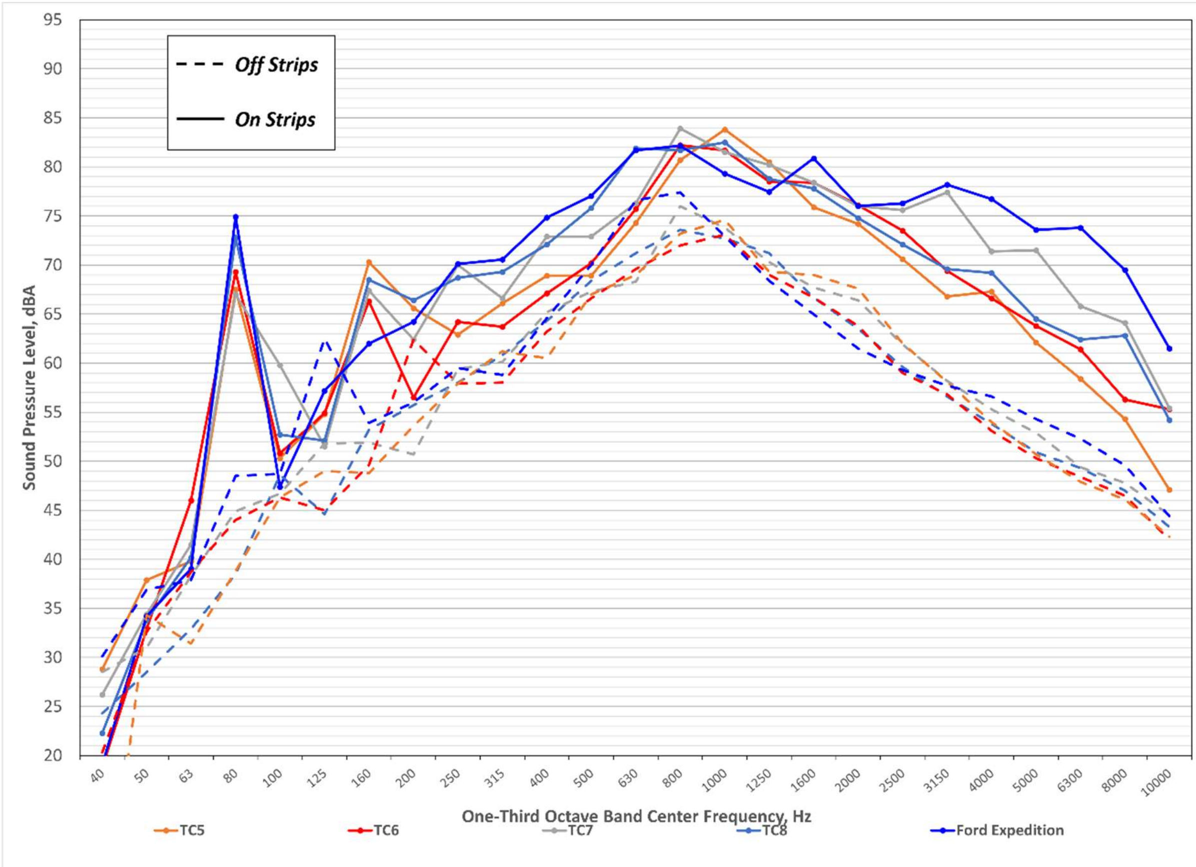
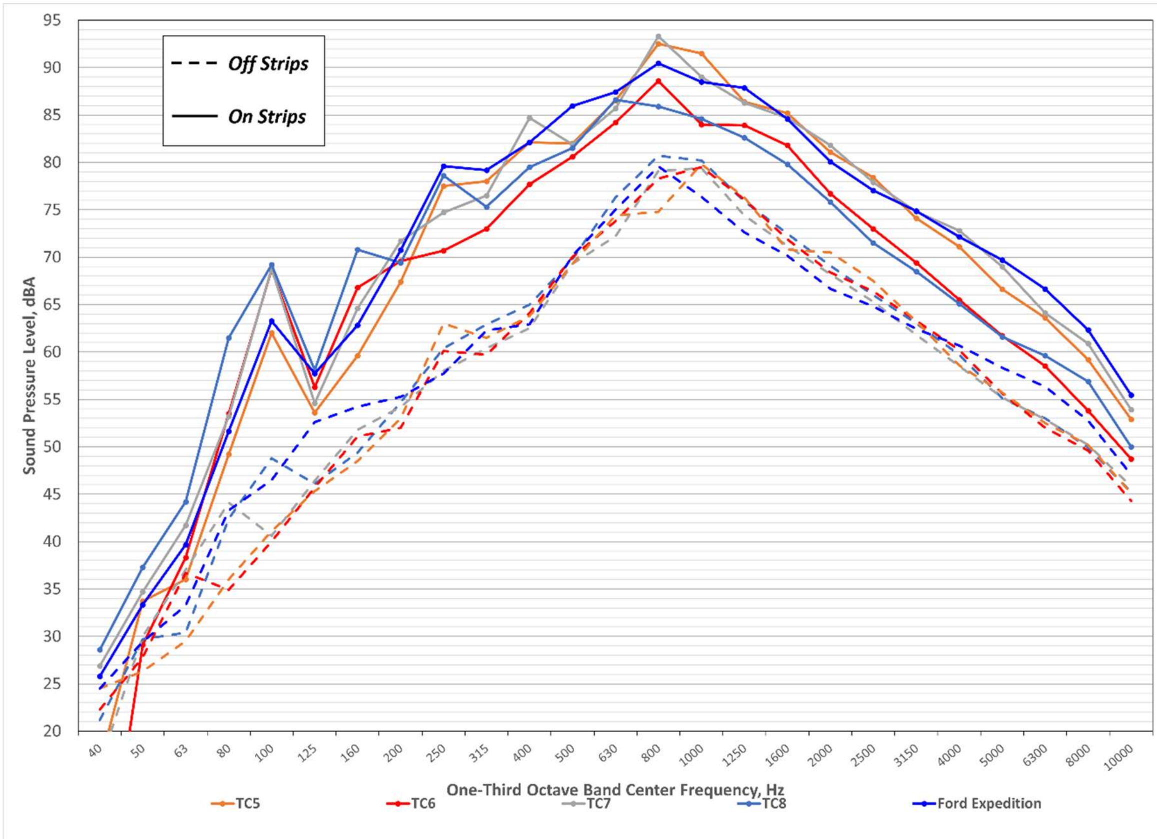


Figure B-36: Overall pass-by noise level differences between on and off strips at the conventional ground strip site when compared to results of previous Caltrans studies

Figure B-37 shows the one-third octave band spectra for the SUVs and minivans of 2018, compared to the 2012 Expedition, on the mumble and conventional ground strips. On both test sites, the general trends, on and off the strips, are similar. However, there is less vehicle-to-vehicle variation at the 80 Hz peak on the mumble strips (67.5 to 75 dBA) than at the 100 Hz peak on the conventional ground strips (57.7 to 69.2 dBA). There is also less noticeable gap between the on and off strips spectra between 200 and 630 Hz on the mumble strips than on the conventional ground strips.



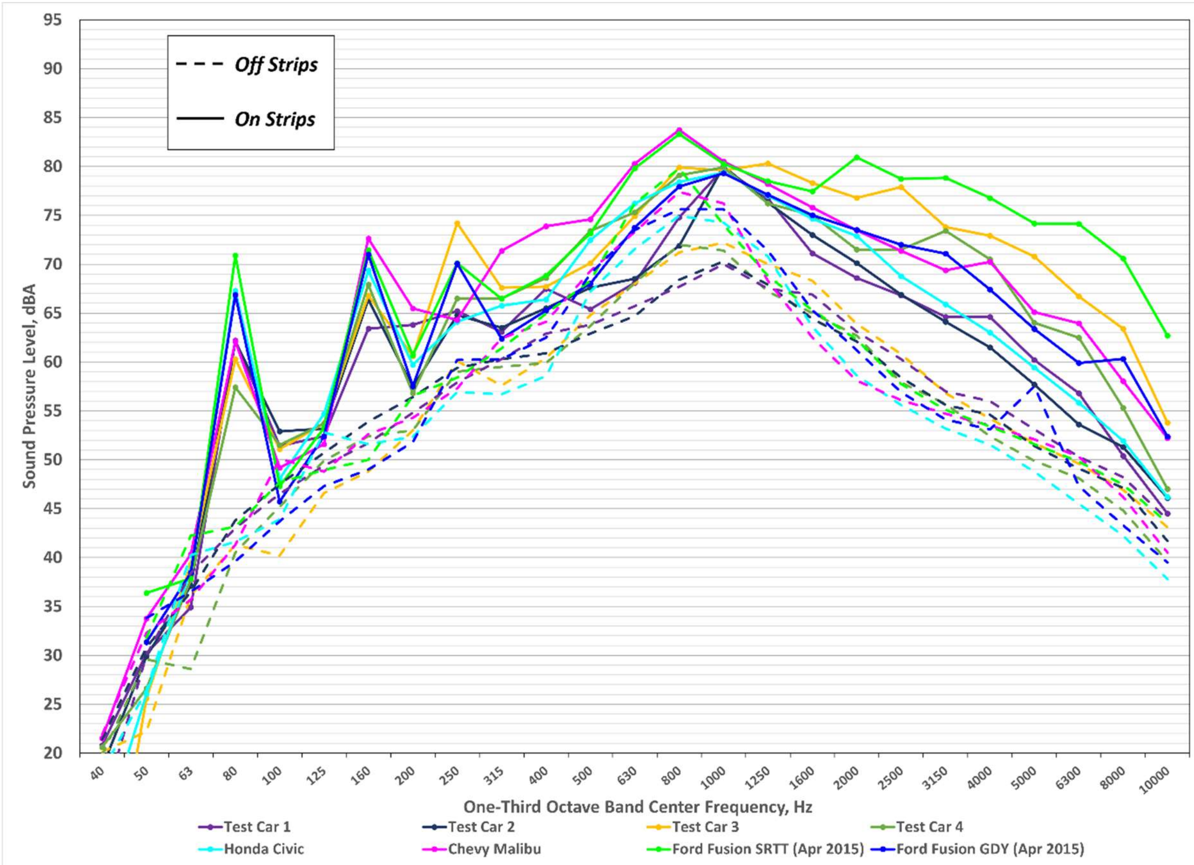
(a) mumble strips



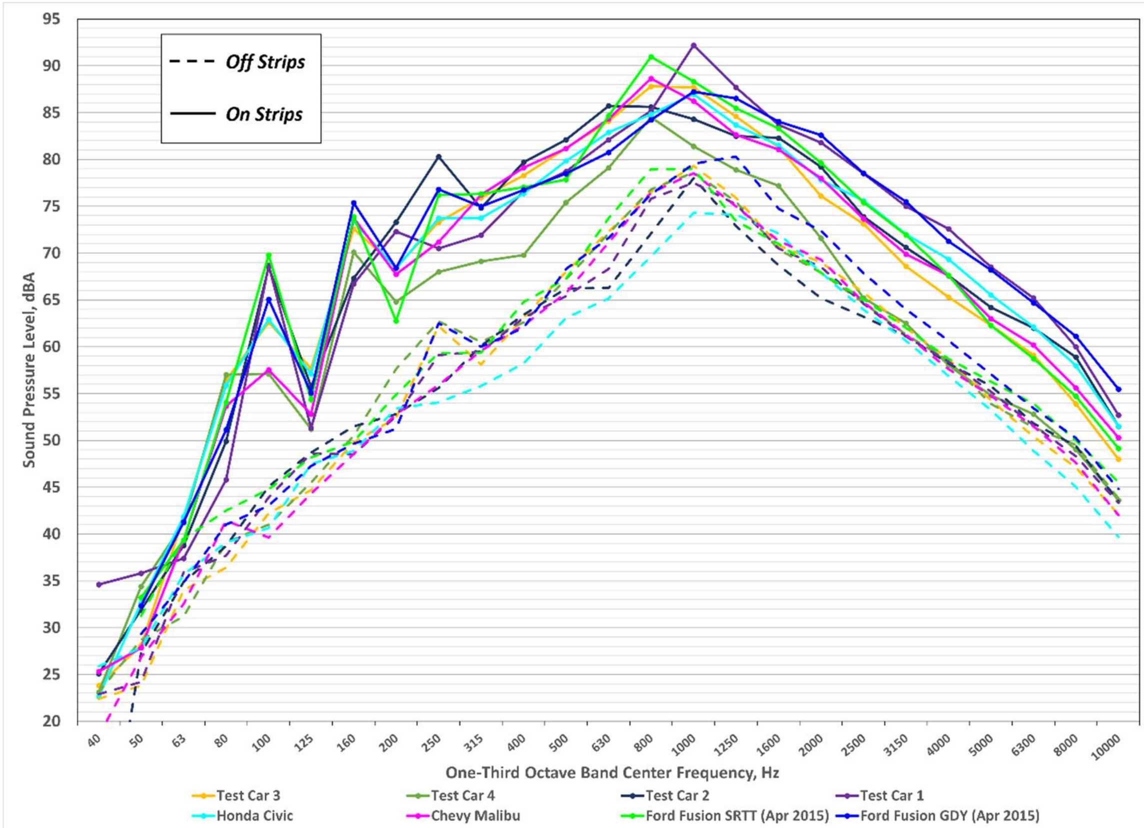
(b) conventional ground strips

Figure B-37: A-weighted one-third octave band spectra measured for all SUVs and minivan tested in 2018 and the 2012 Expedition on the (a) mumble strips and (b) conventional ground strips

Figure B-38 shows the pass-by one-third octave band spectra for the 2018 passenger cars, compared to the 2012 Honda Civic and Malibu and the 2015 Fusion with both test tires. Compared to the 2018 vehicles, the overall trends for the vehicles in the previous Caltrans studies were similar. While the 80 Hz peak measured on the mumble strips was more defined for each vehicle than the 100 Hz peak on the conventional ground strips, the on-strip levels show more variation from vehicle-to-vehicle at bands above 315 Hz on the mumble strips.



(a) mumble strips



(b) conventional ground strips

Figure B-38: A-weighted one-third octave band spectra measured for all passenger cars tested in 2018, the 2012 Honda Civic and Malibu, and the 2015 Fusions on the (a) mumble strips and (b) conventional ground strips

Interior Noise

Data Processing

Data processing for the interior noise measurements was somewhat different than the pass-by measurements. Traveling in the vehicle, the signals should be steady over the acquisition period of 8 seconds. As shown in Figure B-39, this is not always the case, particularly on the strips. During the time on the strips, the vehicle may tend to wander somewhat off the strips, as illustrated by Runs 8, 9, and 10 in Figure B-39. As a result, the run with the most consistent levels over a two-second time period, which were also representative of the higher levels was selected for further data processing. It was also sought to identify this period at or slightly after the four-second mark as this typically corresponded to the location of the pass-by microphone. Once this run and period were identified in one run and one interior microphone location, the other microphone locations were checked to verify that this condition was met at all four interior microphone locations. Once this was confirmed, the levels over the two-second period were averaged to produce the reported overall level. The spectra over this period were also averaged. For off strip levels, the levels were more consistent over time; however, they typically displayed some variation from one tenth-second sample to the next. For these data, one typical run was selected and averaged over the two-second period.

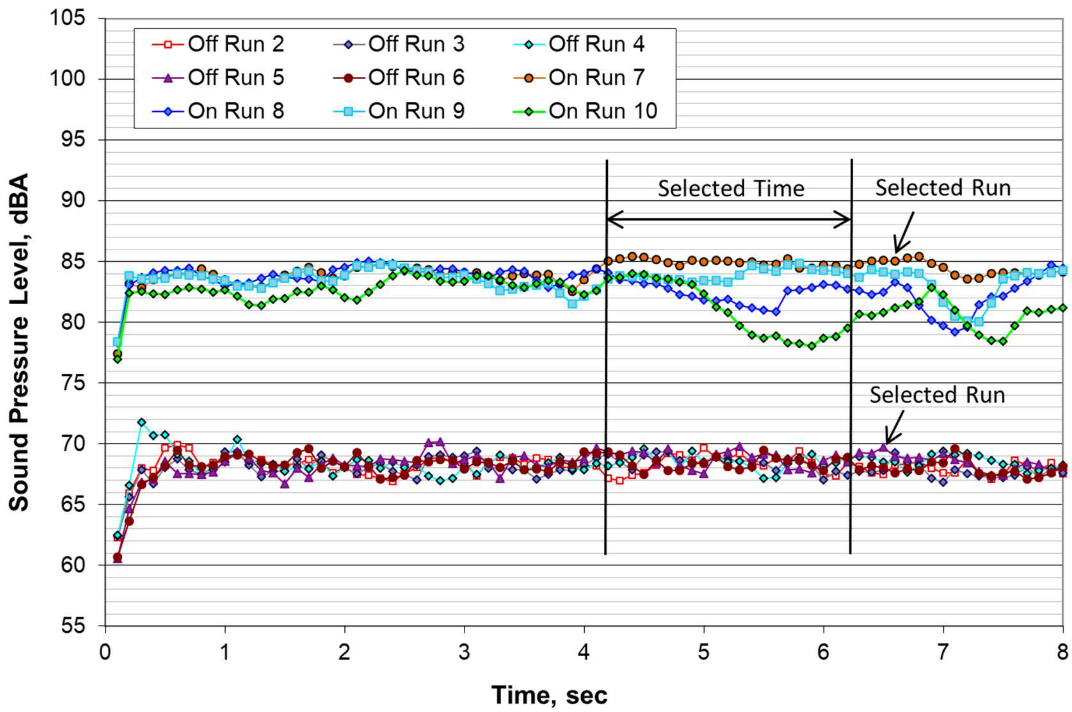


Figure B-39: Example of data selection for Test Car 3 on and off the mumble strips

Results

Interior noise measurements were made at six different locations: rear center (RC), rear outboard (RO), rear inboard (RI), center center (CC), and forward center (FC) positions in the front passenger seat, and at the driver's outboard ear (DE). As previously discussed, each of these microphones were hung vertically from the roof of the vehicle cabin at the same height. Figure B-40 shows the measured overall noise levels on the conventional ground strips and the mumble strips for all eight vehicles, while Figure B-41 shows the noise levels off the strips at both sites.

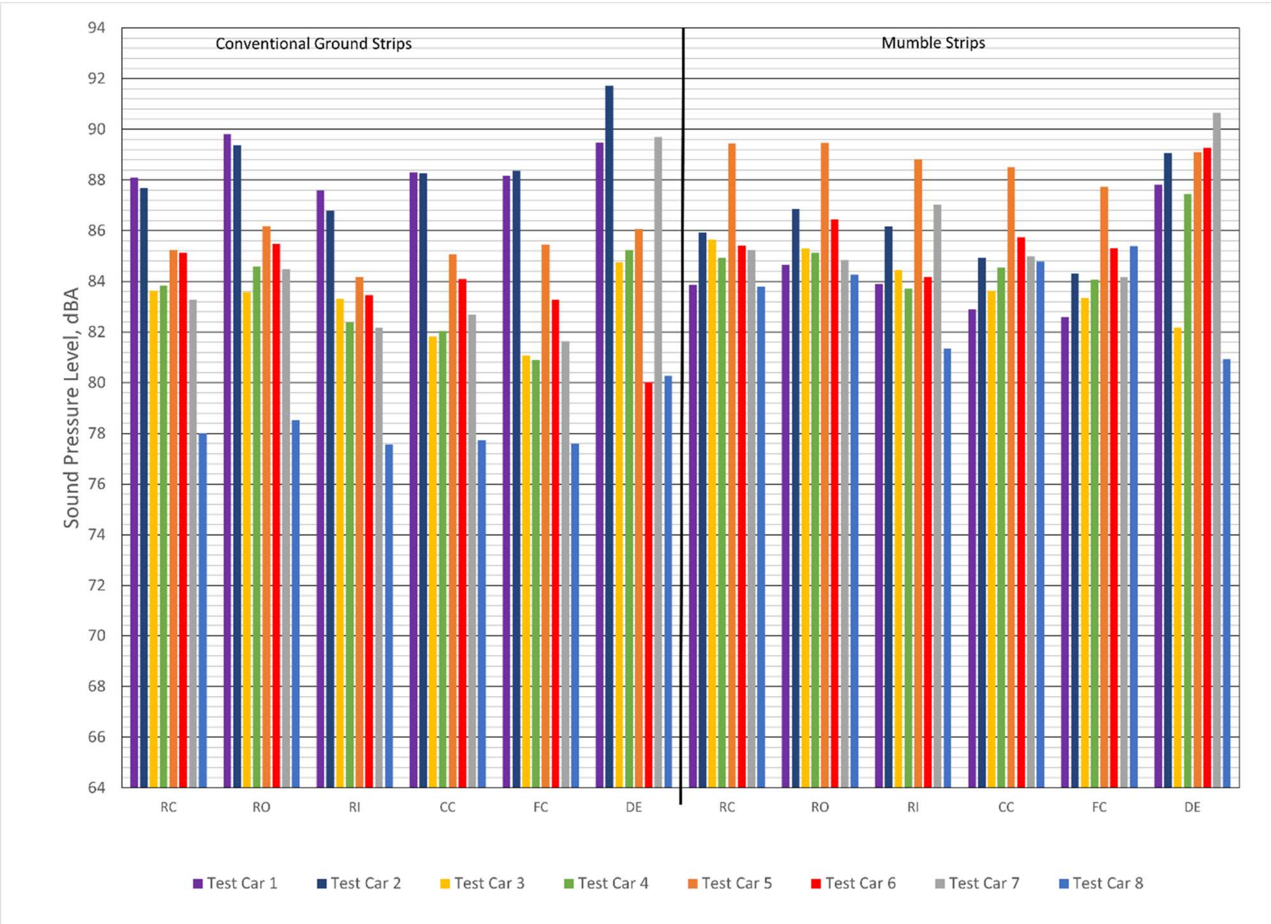


Figure B-40: Overall A-weighted interior sound pressure levels for all eight test vehicles on conventional ground strips and mumble strips

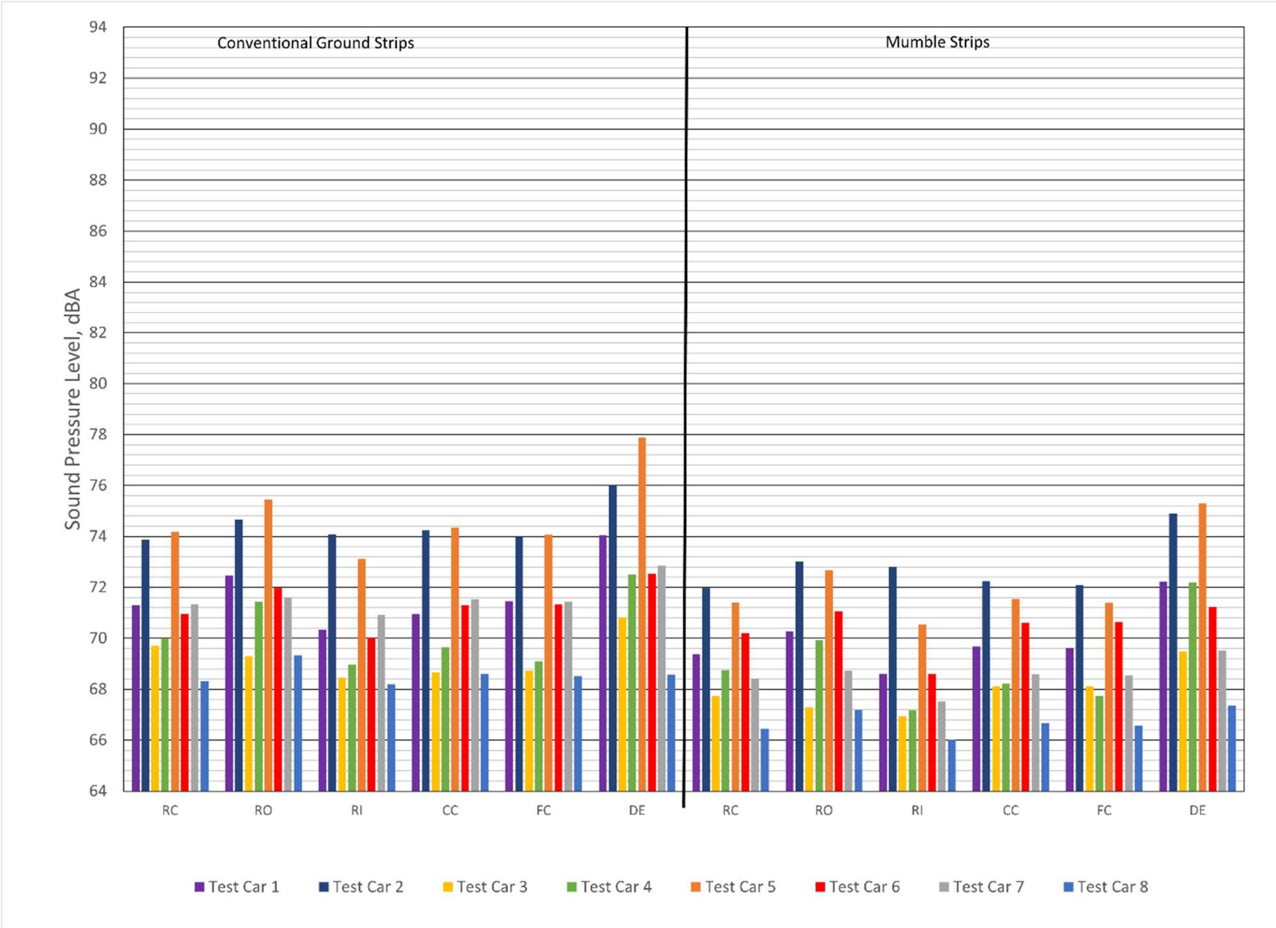


Figure B-41: Overall A-weighted interior sound pressure levels for all eight test vehicles off conventional ground strips and mumble strips

At each microphone except DE, Test Car 8 consistently had the lowest overall interior levels on the conventional ground strips, while Test Car 2 and Test Car 1 had the highest overall interior levels at this test site. At each of the microphone locations, Test Car 1 and Test Car 2 were 9.2 to 11.5 dBA higher than in Test Car 8. This likely is due to the varying luxury trim levels of the vehicles. Test Car 8 is more expensive and more luxurious than the low-end, base compact cars tested for this study. Similar to Test Car 8 but with levels 4.0 to 9.4 dBA higher than Test Car 8, Test Car 7 has relatively consistent levels for all passenger seat microphones on the conventional ground strips, with the DE position being an outlier. The DE position in Test Car 7 resulted in overall levels more than 5 dBA higher than all passenger seat microphones on the conventional ground strips. The crossover SUVs and sedans were fairly consistent on the conventional ground strips, except for the DE microphone in Test Car 6, which was lower than the other microphone positions. Overall, the standard deviation on the conventional ground strips for each microphone position ranged from 0.7 dBA in Test Car 5 to 3.0 dBA in Test Car 7.

On the mumble strips, Test Car 5 resulted in the highest levels at each of the passenger seat microphones, while maintaining relatively consistent levels at each of the microphones, including DE, that were higher than on the conventional ground strips by 2.3 to 4.6 dBA. Each microphone location in Test Car 8, Test Car 7, Test Car 6, Test Car 5, Test Car 4 (except DE), and Test Car 3 resulted in higher interior levels on the mumble strips than on the conventional ground strips. For both of the compact cars, however, the conventional ground strips resulted in higher levels.

The off strip overall levels in Figure B-41 show similar trends in levels for each vehicle and at each microphone. Test Car 5 and Test Car 2 consistently had the highest interior levels at each microphone, and at each test site, the DE microphone position resulted in the highest levels. Additionally, the overall interior levels at each microphone were higher at the conventional ground strips than at the mumble strips.

Figure B-42 shows the average interior noise levels on both test strips for following groupings: 1) large SUV and van, 2) crossover SUVs, 3) sedans, 4) compact cars, and 5) average of all test vehicles. At each microphone position, the large SUV and van, crossover SUVs, and sedans (except for the DE microphone position) groupings, as well as the average of all eight vehicles, in Figure B-42 are higher on the mumble strips than the conventional ground strips. The only grouping in which interior noise levels are higher on conventional ground strips than on mumble strips would be for the compact cars, and this was true for every interior microphone position.

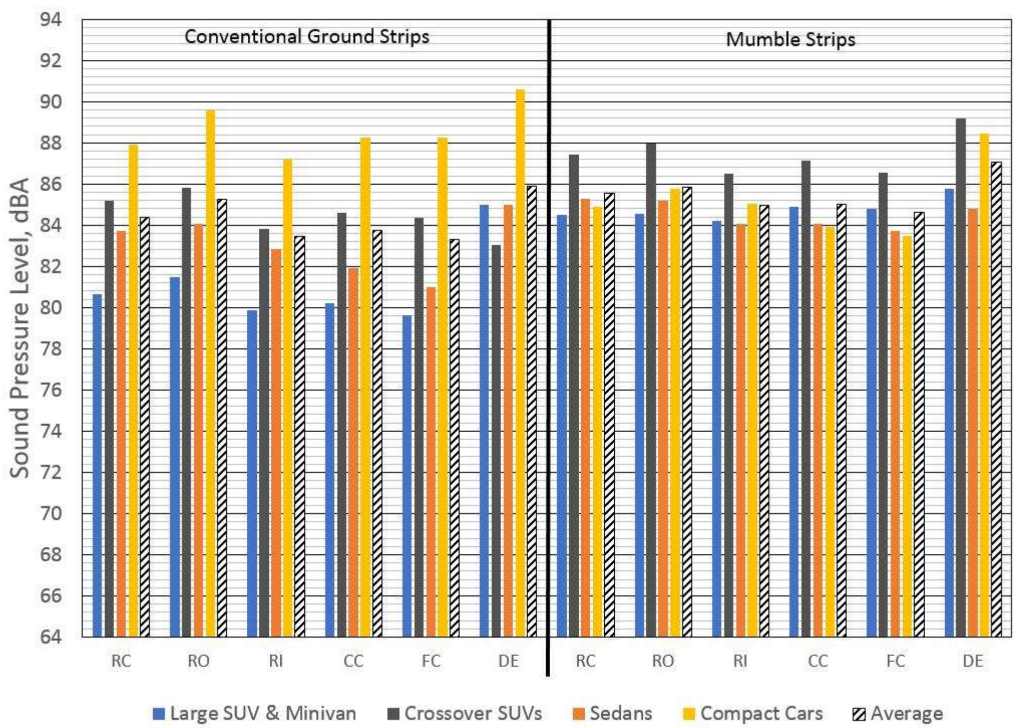


Figure B-42: Average overall A-weighted interior sound pressure levels for four groups, paired by vehicle type and size

By subtracting the off-strip data from the on-strip data, the on/off differences were calculated. These on/off differences are shown in Figure B-43 for each vehicle. Across all microphones in each vehicle, the overall interior levels measured on the mumble strips were 12.2 to 21.1 dBA above the off-strip measurements, while the levels on the conventional strips were 7.5 to 17.3 dBA above off strips. Previous literature has indicated that the on strips interior levels should be 12 to 14 dBA above off strips to be effective at alerting the driver. Based on these data, the mumble strips would be more consistent in achieving interior levels of 12 dBA or more above off strips. However, it should be noted that the on/off differences in both compact cars were higher on the conventional ground strips than on the mumble strips.

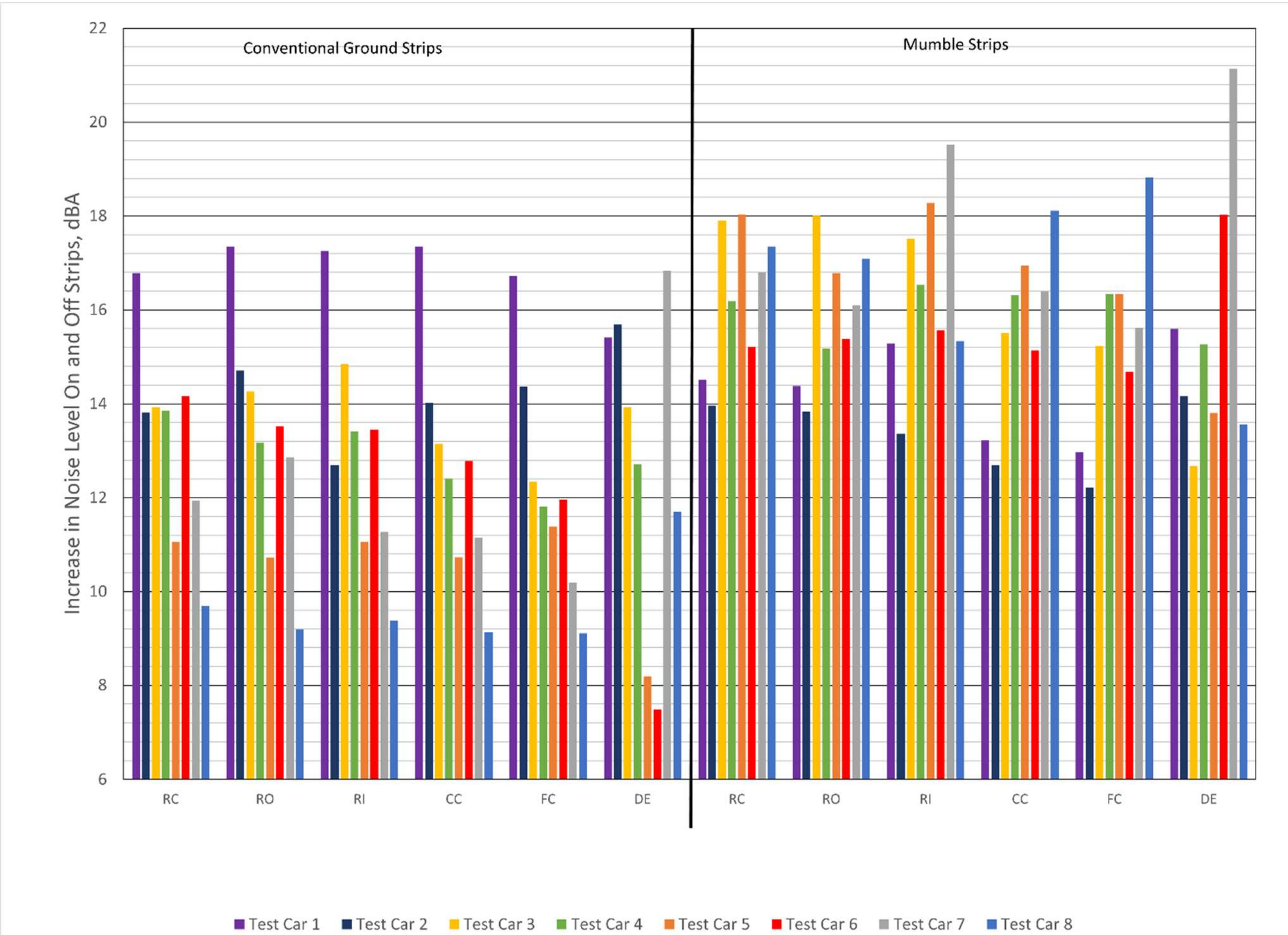


Figure B-43: Overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites for all test vehicles

Figure B-44 shows the average on/off differences for following groupings: 1) large SUV and van, 2) crossover SUVs, 3) sedans, 4) compact cars, and 5) average of all test vehicles. For the large SUV and van, crossover SUVs, sedans, and overall averages, all overall interior on/off differences were higher on the mumble strips, while on/off differences for the compact cars were higher on the conventional ground strips at each microphone.

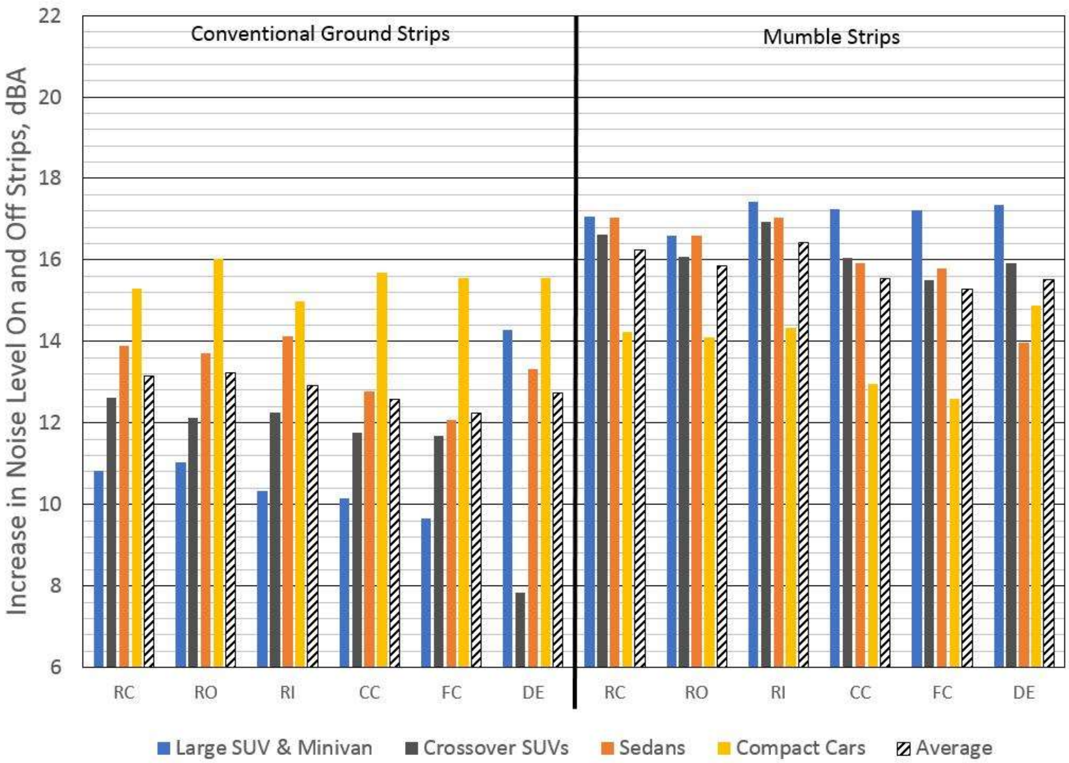


Figure B-44: Average overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites for four groups, paired by vehicle type and size

Figure B-45 shows the average on/off difference of all microphones measured in each vehicle. On average, the mumble strips generated interior noise levels 13 dBA or more above ambient off strips data, with on/off differences about 16 dBA for the large SUV and van, both crossover SUVs, and sedans. Both compact cars had on/off differences of 13 to 14 dBA on the mumble strips. The interior noise level results on the conventional ground strips were less consistent, with on/off differences averaging between 9 and 17 dBA. The overall average for all microphones and in each vehicle was about 16 dBA on mumble strips and about 13 dBA on conventional ground strips.

The vehicle averages at both sites are shown in Figure B-46 for each individual microphone. For the five microphones positioned at the passenger seat (i.e., rear center, rear outboard, rear inboard, center center, and front center), the standard deviation between the on/off differences for all vehicles was 1.4 to 2.1 dBA on the mumble strips and 2.2 to 2.5 dBA on the conventional ground strips. The driver's outboard ear position resulted in more variation, with standard deviations of 2.8 dBA on the mumble strips and 3.5 dBA on the conventional ground strips.

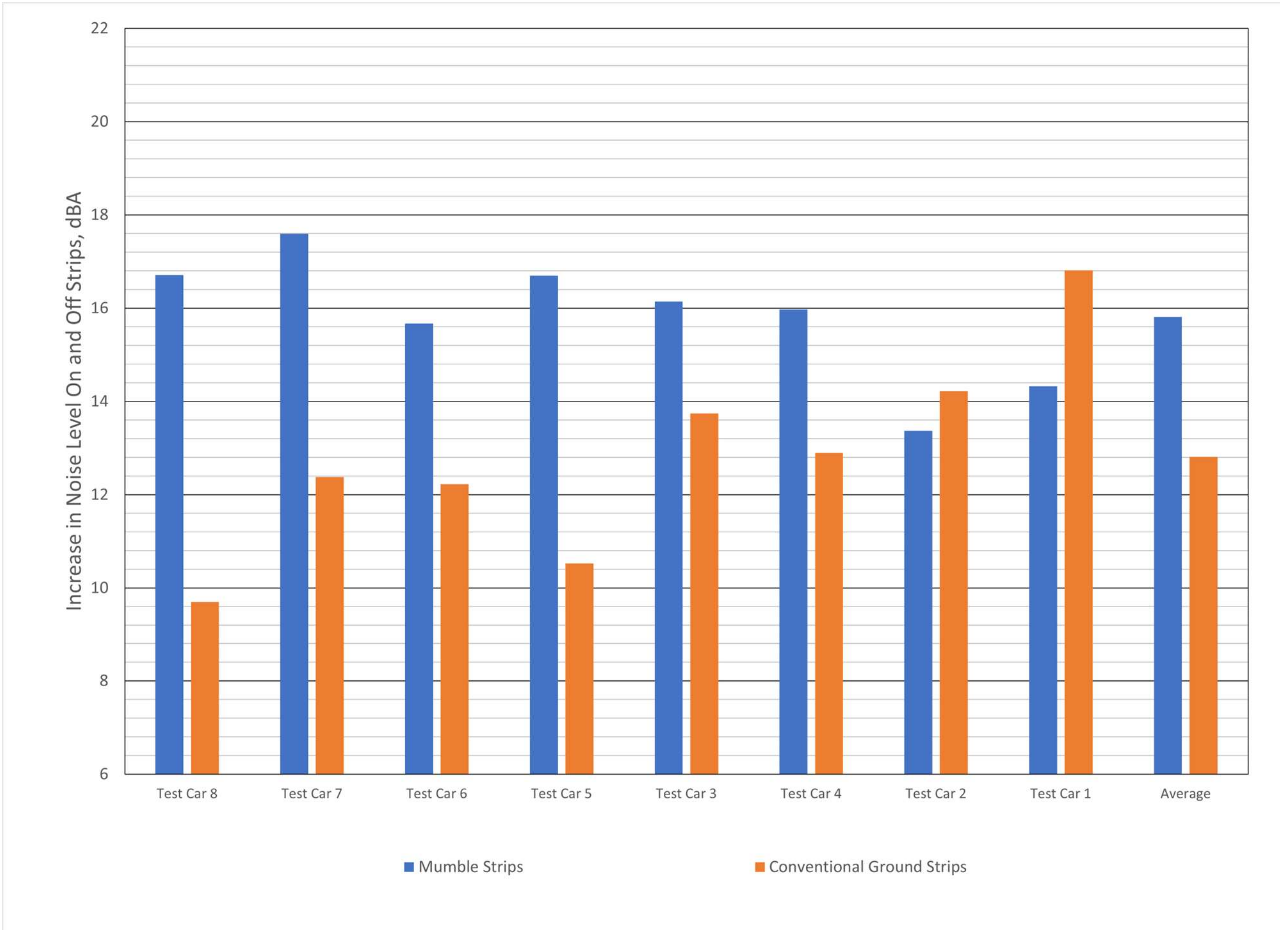
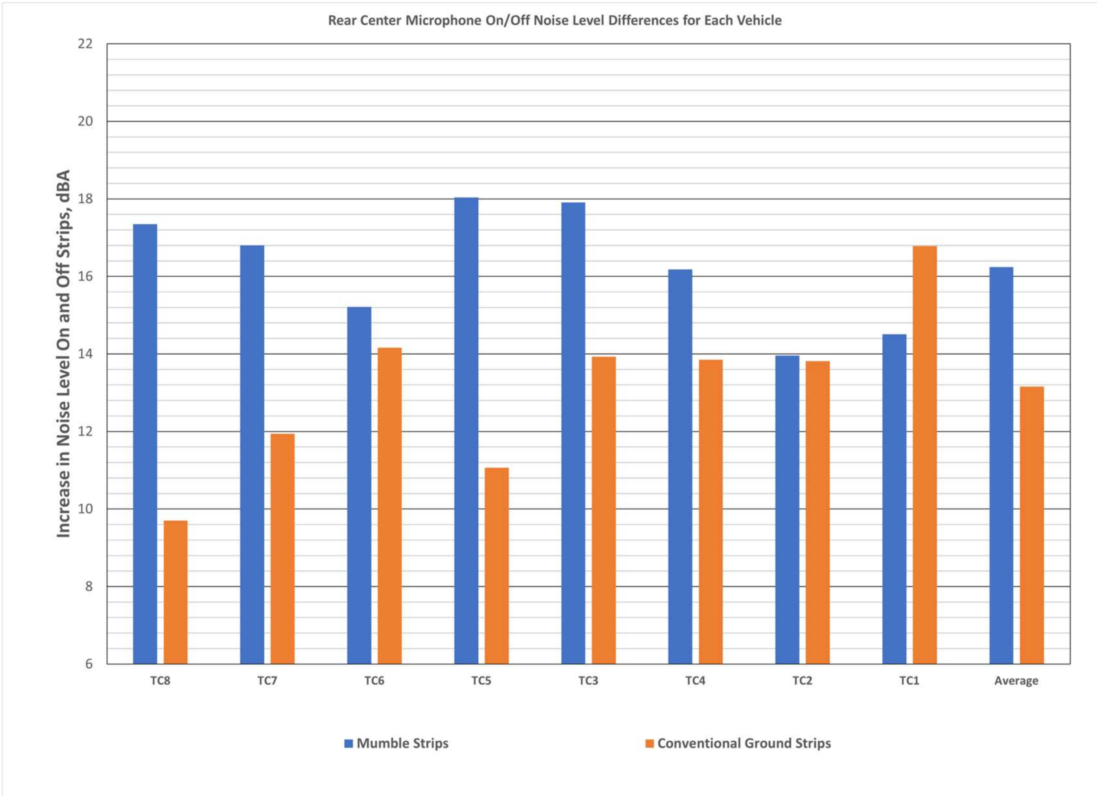
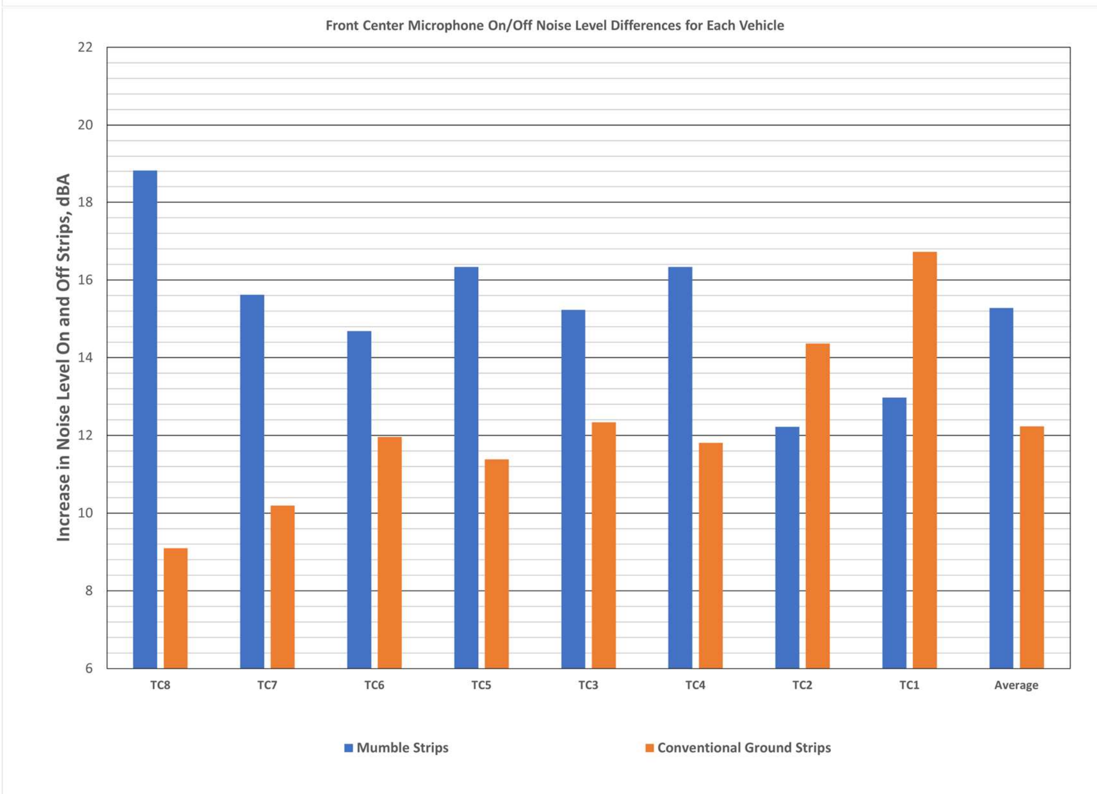
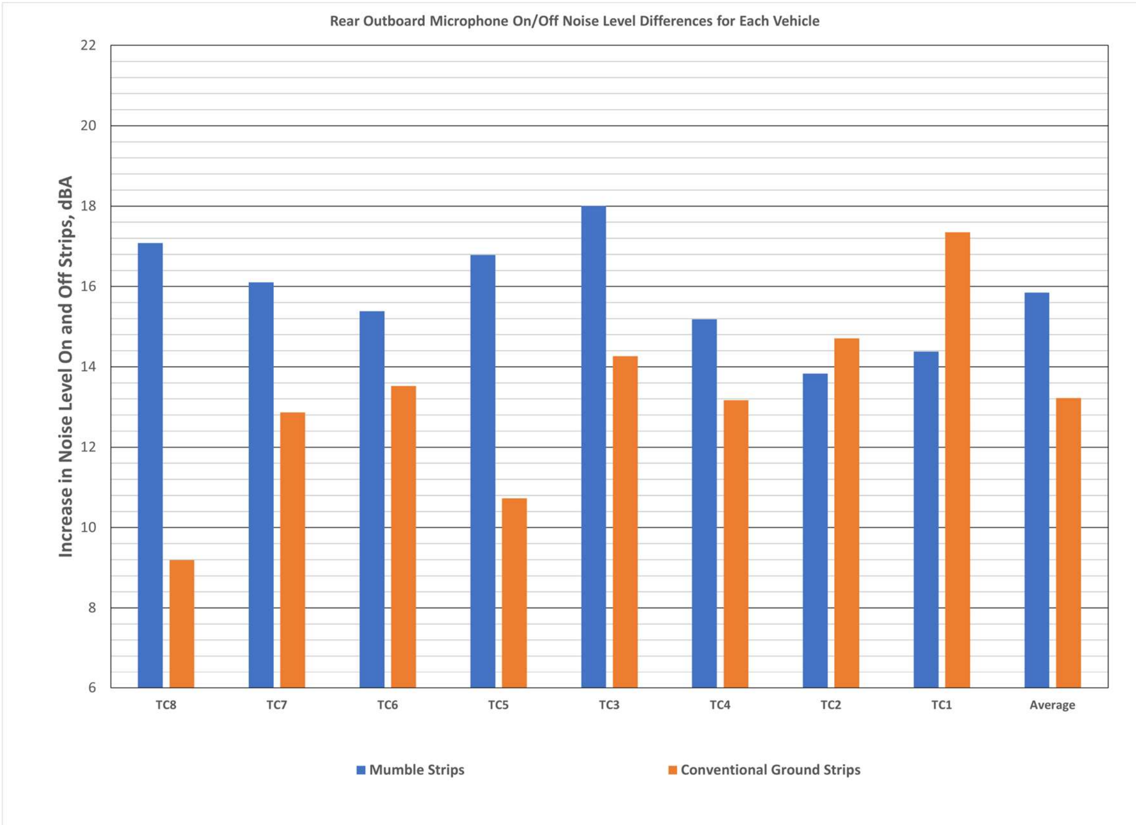
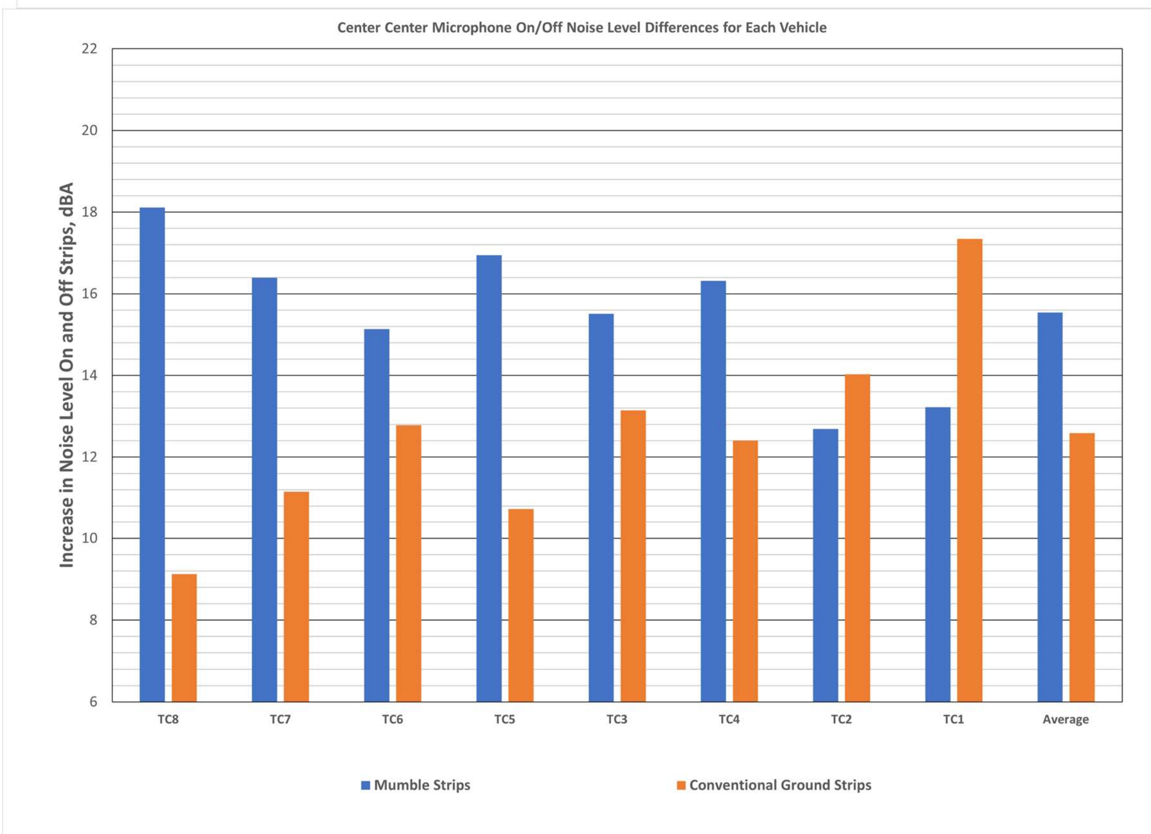


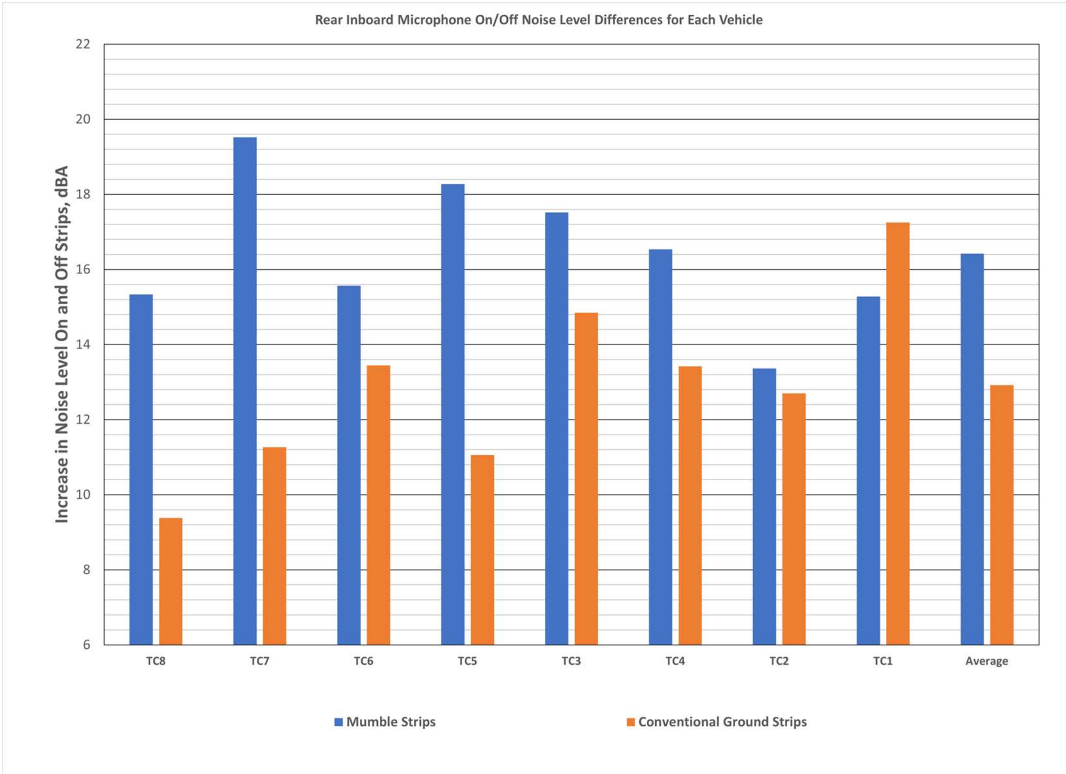
Figure B-45: Average overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites for the average of all interior microphones


Rear Center Microphone On/Off Noise Level Differences for Each Vehicle
Increase in Noise Level On and Off Strips, dBA
22
20
18
16
14
12
10
8
6
TC8
TC7
TC6
TC5
TC3
TC4
TC2
TC1
Average
Mumble Strips
Conventional Ground Strips


Front Center Microphone On/Off Noise Level Differences for Each Vehicle
Increase in Noise Level On and Off Strips, dBA
22
20
18
16
14
12
10
8
6
TC8
TC7
TC6
TC5
TC3
TC4
TC2
TC1
Average
Mumble Strips
Conventional Ground Strips


Rear Outboard Microphone On/Off Noise Level Differences for Each Vehicle
Increase in Noise Level On and Off Strips, dBA
22
20
18
16
14
12
10
8
6
TC8
TC7
TC6
TC5
TC3
TC4
TC2
TC1
Average
Mumble Strips
Conventional Ground Strips


Center Center Microphone On/Off Noise Level Differences for Each Vehicle
Increase in Noise Level On and Off Strips, dBA
22
20
18
16
14
12
10
8
6
TC8
TC7
TC6
TC5
TC3
TC4
TC2
TC1
Average
Mumble Strips
Conventional Ground Strips



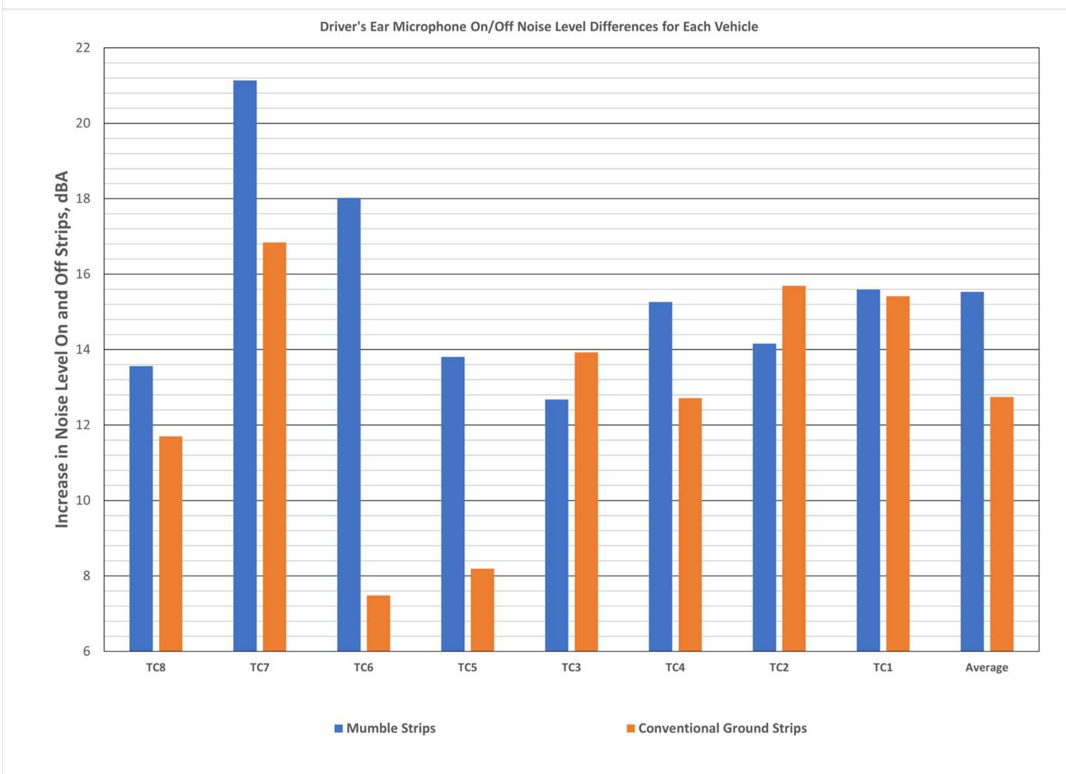
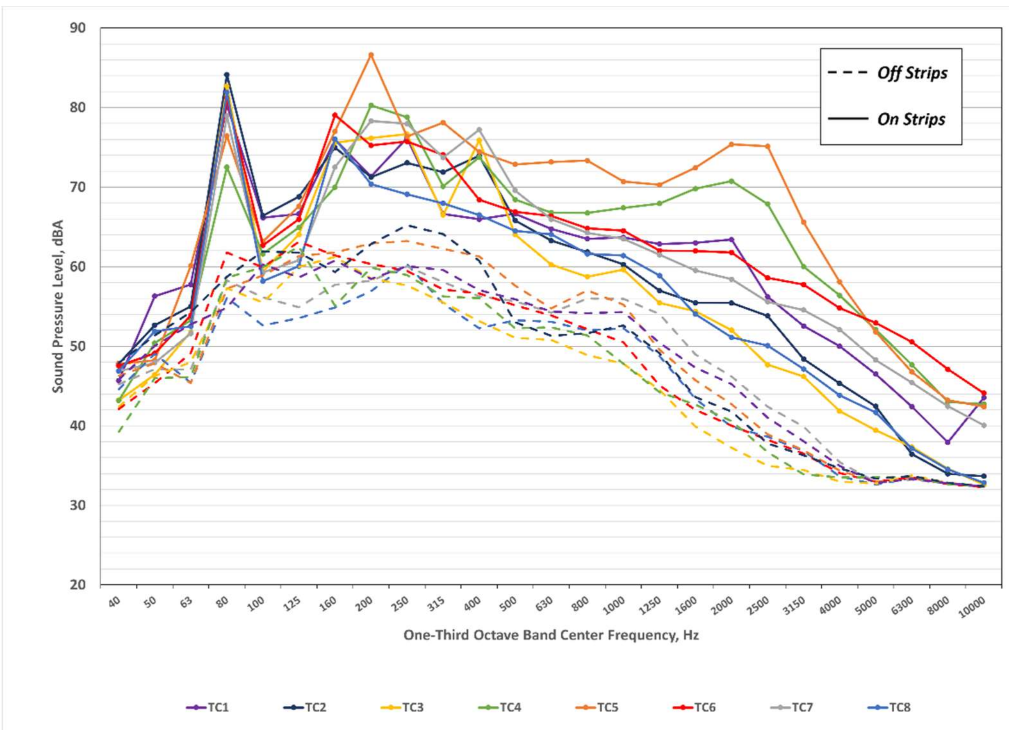
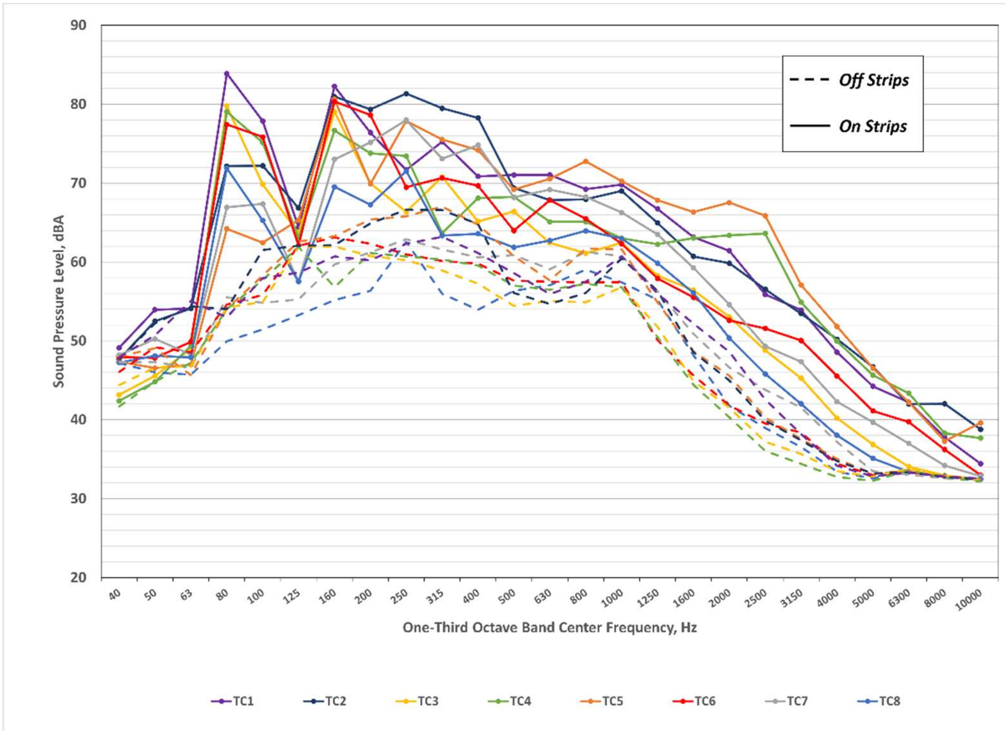


Figure B-46: Average overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites for each of the interior microphones

One-third octave band levels are shown in Figures B-47 through B-52 for each microphone position, on and off both rumble strips. In each figure, the data collected on the mumble strips is shown on the left, and the data collected on the conventional ground strips is shown on the right. For each microphone, there is an 80 Hz peak on the mumble strips measured in each vehicle, and Test Car 3 typically resulted in the lowest sound pressure level at this frequency for each microphone at the passenger seat position. Further, at each passenger seat microphone position, Test Car 5 appeared to have a secondary peak at about 200 to 250 Hz that was greater than the 80 Hz peak. On the conventional ground strips, the 80 Hz peak found on the mumble strips was split between 80 and 100 Hz. Each of the microphone positions show this, as well as a peak at 160 Hz. There was some variation at the upper frequencies where individual vehicles had some higher levels at specific microphone locations. Though, this occurred on both rumble strips. Also apparent at every microphone position was the obvious increase the on mumble strips levels were above off strips levels at frequency bands above about 125 Hz. In contrast, the increase above off strips at these upper frequency bands was not as apparent on the rumble strips.

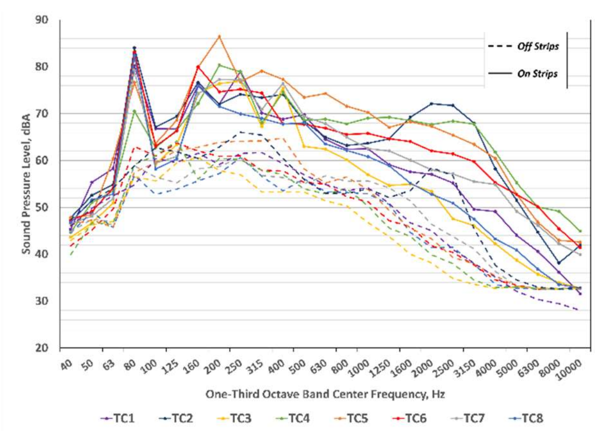


(a) mumble strips

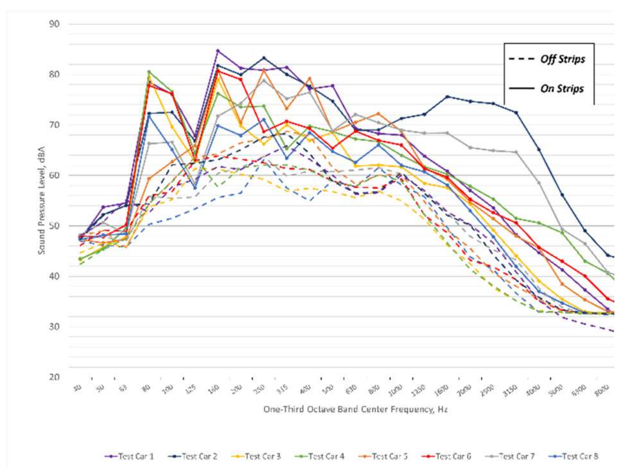


(b) conventional ground strips

Figure B-47: A-weighted one-third octave band spectra measured at the rear center microphone on the (a) mumble strips and (b) conventional ground strips

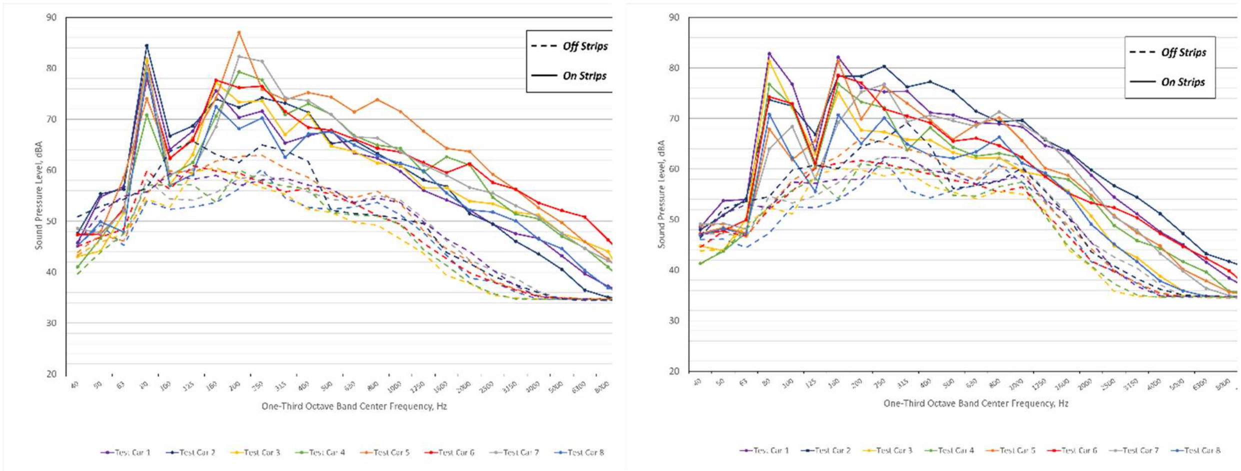


(a) mumble strips



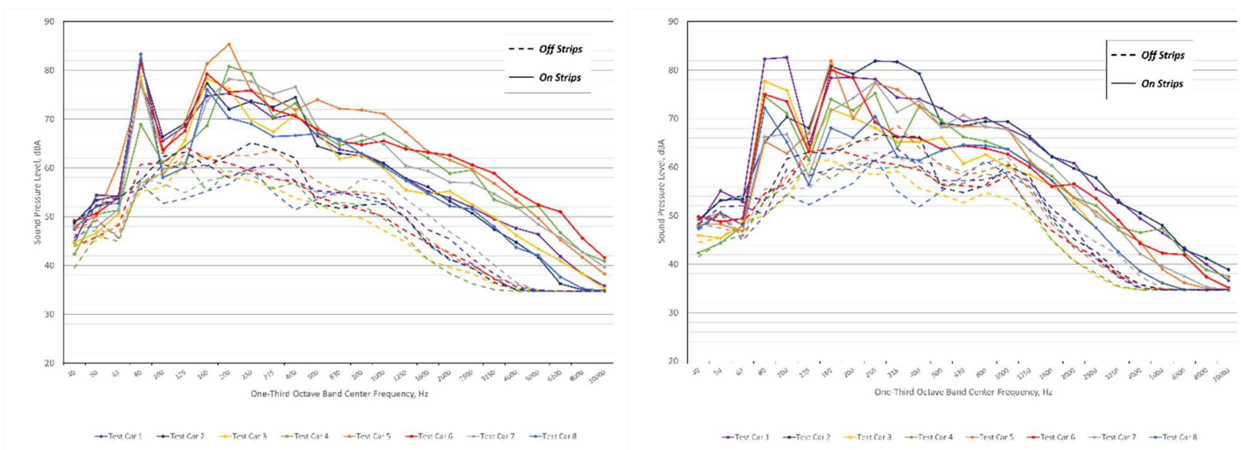
(b) conventional ground strips

Figure B-48: A-weighted one-third octave band spectra measured at the rear outboard microphone on the (a) mumble strips and (b) conventional ground strips



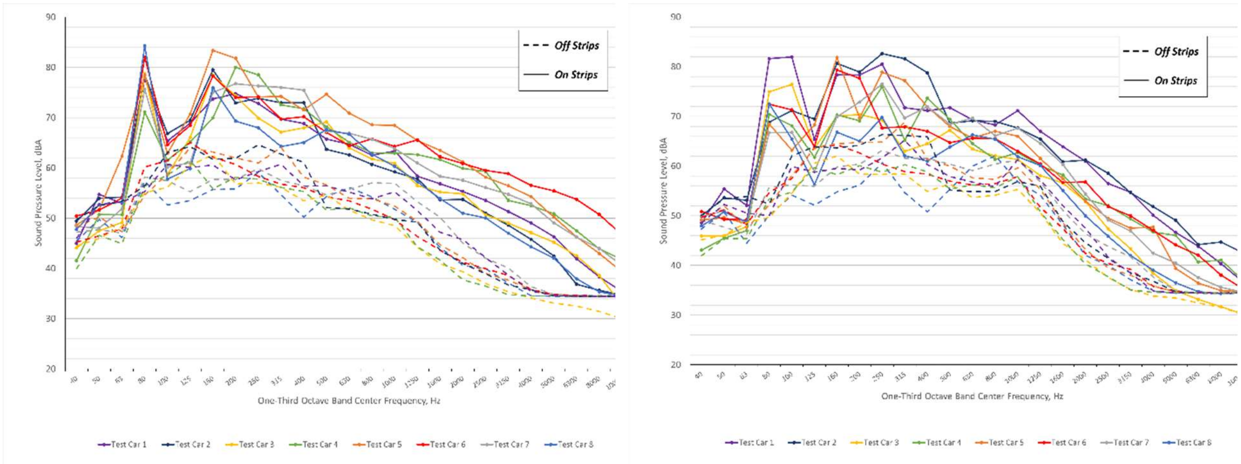
(a) mumble strips *(b) conventional ground strips*

Figure B-49: A-weighted one-third octave band spectra measured at the rear inboard microphone on the (a) mumble strips and (b) conventional ground strips



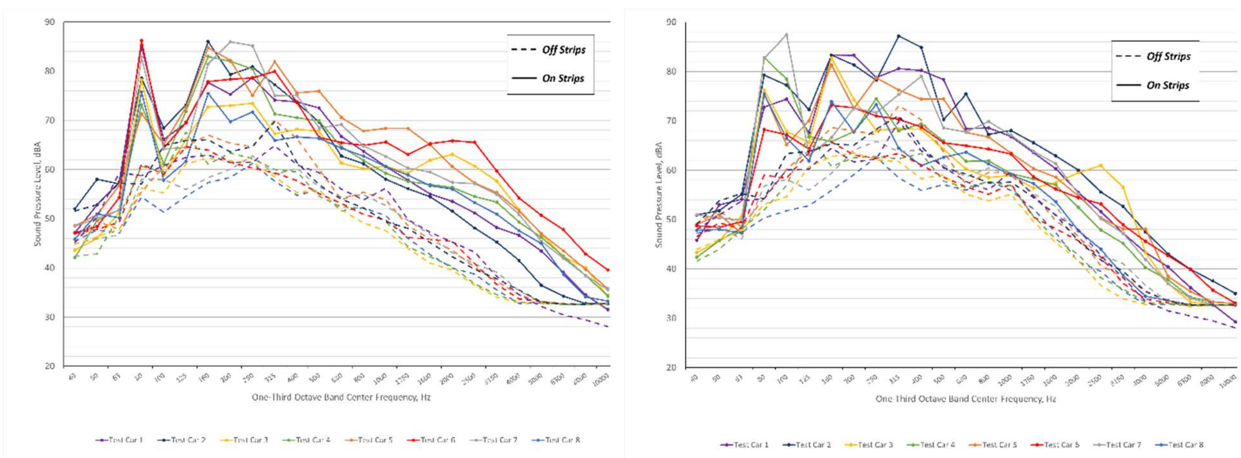
(a) mumble strips *(b) conventional ground strips*

Figure B-50: A-weighted one-third octave band spectra measured at the center center microphone on the (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

Figure B-51: A-weighted one-third octave band spectra measured at the front center microphone on the (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

Figure B-52: A-weighted one-third octave band spectra measured at the driver's ear microphone on the (a) mumble strips and (b) conventional ground strips

Speed Dependence

The following vehicles were used to make interior noise measurements during vehicle speeds of 45 mph at microphone positions of rear center, rear outboard, center center, and center forward: Test Car 8, Test Car 6, Test Car 4, Test Car 3, Test Car 2, and Test Car 1. Additionally, Test Car 7 was used to make 45 mph interior measurements on the conventional ground strips only. The overall interior noise levels measured during vehicle speeds of 45 mph are shown in Figures B-53 and B-54 for on strips and off strips, respectively.

Overall, noise levels on the mumble strips ranged from 73 to 86 dBA and on the conventional ground strips from 77 to 84 dBA. At 60 mph, overall noise levels ranged from 81 to 91 dBA on the mumble strips and from 78 to 92 dBA on the conventional ground strips. At the reduced speeds, the data taken on the conventional ground strips shows more consistency from vehicle-to-vehicle than the mumble strips. For Test Car 8 and Test Car 4, the results measured on the conventional ground strips were about 4 to 6 dBA higher than the results measured on the mumble strips. For Test Car 6, Test Car 2, and Test Car 1, levels were higher on the mumble strips than on the conventional ground strips by 5 to 7 dBA for Test Car 6 and Test Car 1 and by 1 to 2 for Test Car 2. Overall levels for Test Car 3 were within 1 dBA at each microphone. For each vehicle grouped together, as discussed above, the overall levels on the conventional ground strips for each pairing were similar for each microphone, except Test Car 2, which was about 4 to 6 dBA higher than Test Car 1. Test Car 8 and Test Car 6 were the only vehicles tested in their respective groupings that were tested at 45 mph on mumble strips. For the sedans, there was about 4 to 5.5 dBA variation in the overall levels on the mumble strips, while a difference of 2 dBA or less was measured for the compact cars. The off strips data was pretty consistent at each microphone. At each measurement position, the off strip conventional ground strip data was about 1 to 4 dBA higher than the off-strip mumble strip data.

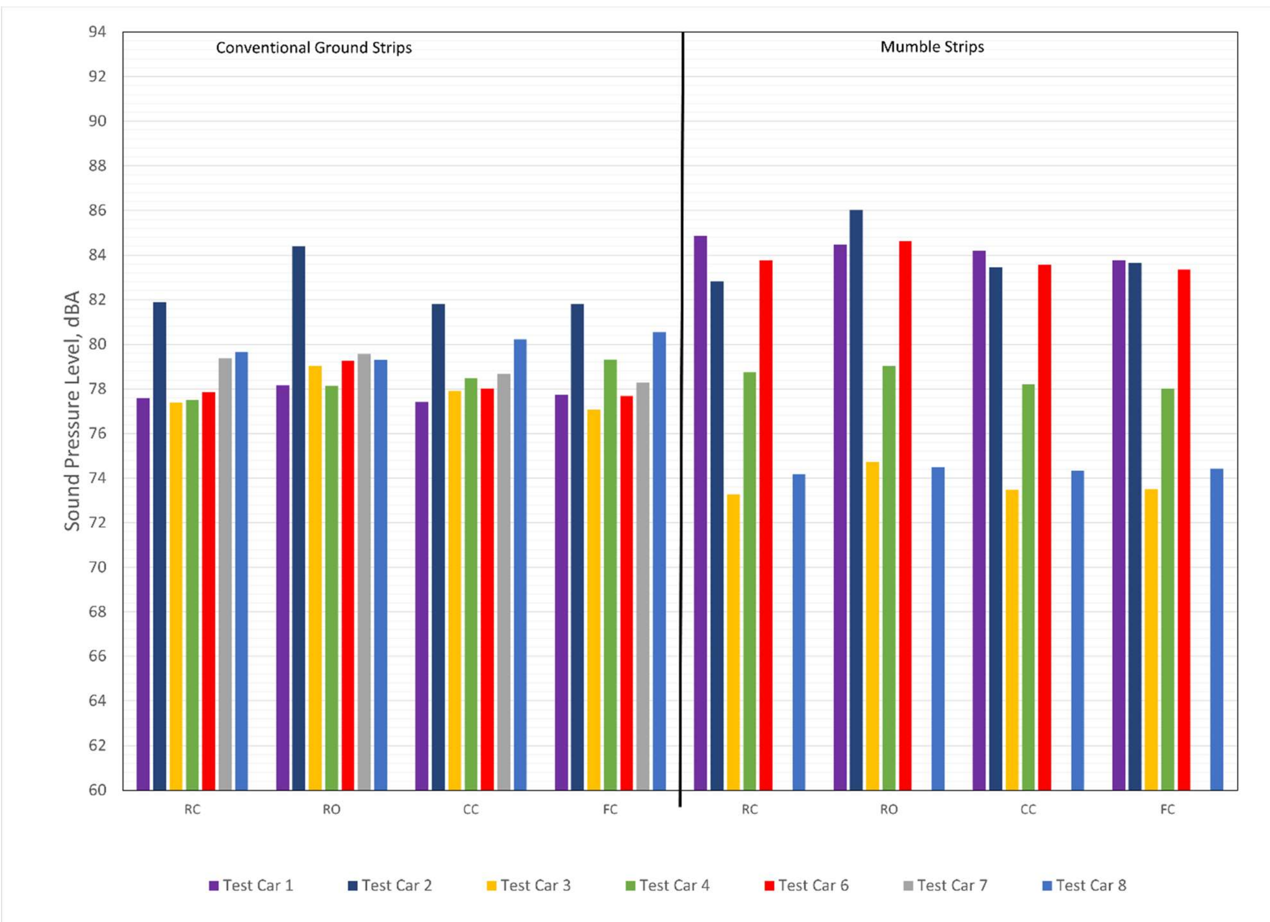


Figure B-53: Overall A-weighted interior sound pressure levels on conventional ground strips and mumble strips (45 mph)

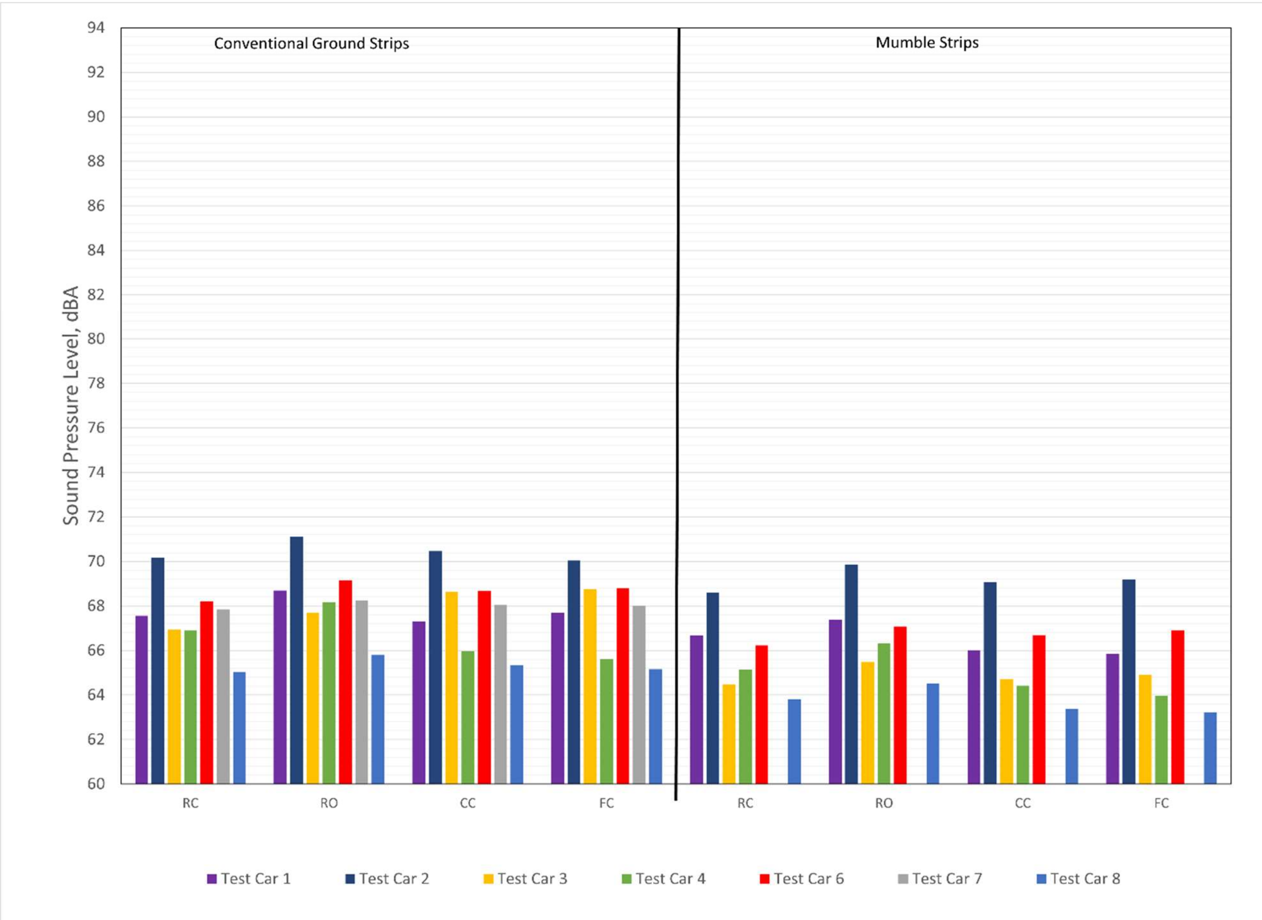


Figure B-54: Overall A-weighted interior sound pressure levels off conventional ground strips and mumble strips (45 mph)

Figure B-55 shows the average interior noise levels on both test strips for following groupings: 1) large SUV and van, 2) crossover SUVs, 3) sedans, 4) compact cars, and 5) average of all test vehicles. In contrast to the on strips results at 60 mph, the 45 mph data shows more consistency across all groups on the conventional ground strips. The overall levels for the large SUV and van group and the sedans are higher on the conventional ground strips, while the crossover SUVs and compact cars are higher on the mumble strips.

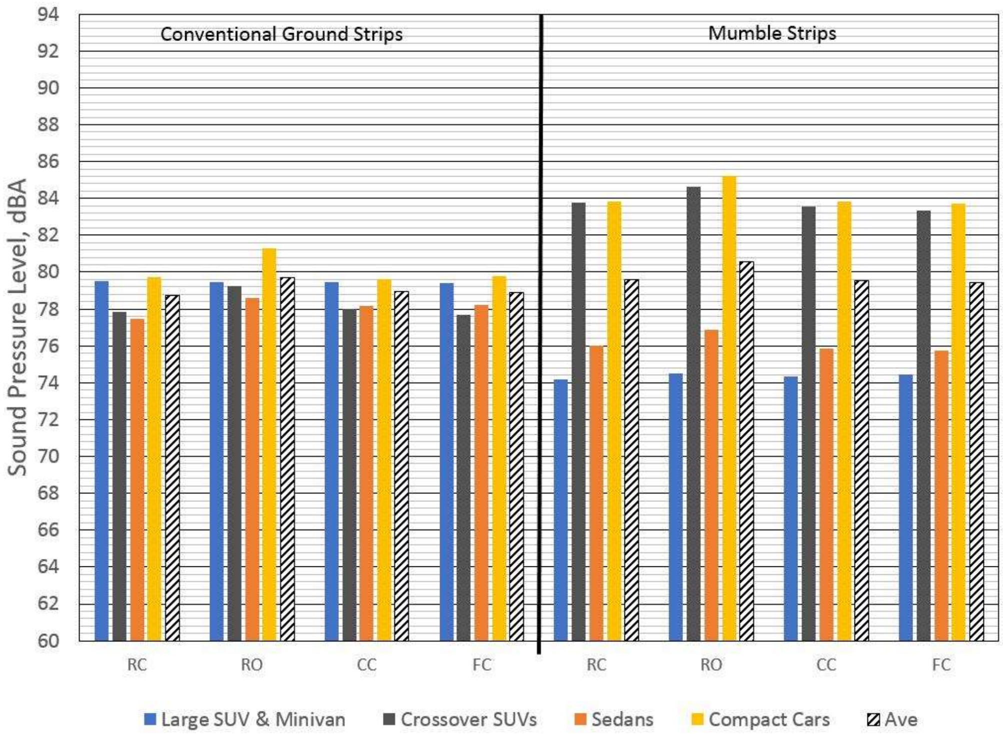


Figure B-55: Average overall A-weighted interior sound pressure levels for four groups, paired by vehicle type and size (45 mph)

Figure B-56 shows the noise level on/off differences at each test site when measurements were made at 45 mph. As stated above, the on/off differences are expected to be at least 12 dBA to effectively alert drivers of lane deviation. On the conventional ground strips, only one vehicle consistently met this requirement at each microphone location (Test Car 8), while Test Car 6, Test Car 3, Test Car 2, and Test Car 1 all met this requirement on the mumble strips. Between vehicles of similar size and capacity, the on/off differences varied considerably. For the large SUV and van vehicles, the on/off differences varied from 2 to 5 dBA, with Test Car 8 having greater differences. The variations between the on/off differences of the sedans ranged from 0.2 to 5.4 dBA on the conventional ground strips, and the variations for the compact cars ranged from 1.2 to 3.8 dBA. On the mumble strips, the variations between the two sedans ranged from 3.5 to 5.5 dBA, and between the two compact cars, the on/off differences varied by 0.9 to 4.0 dBA.

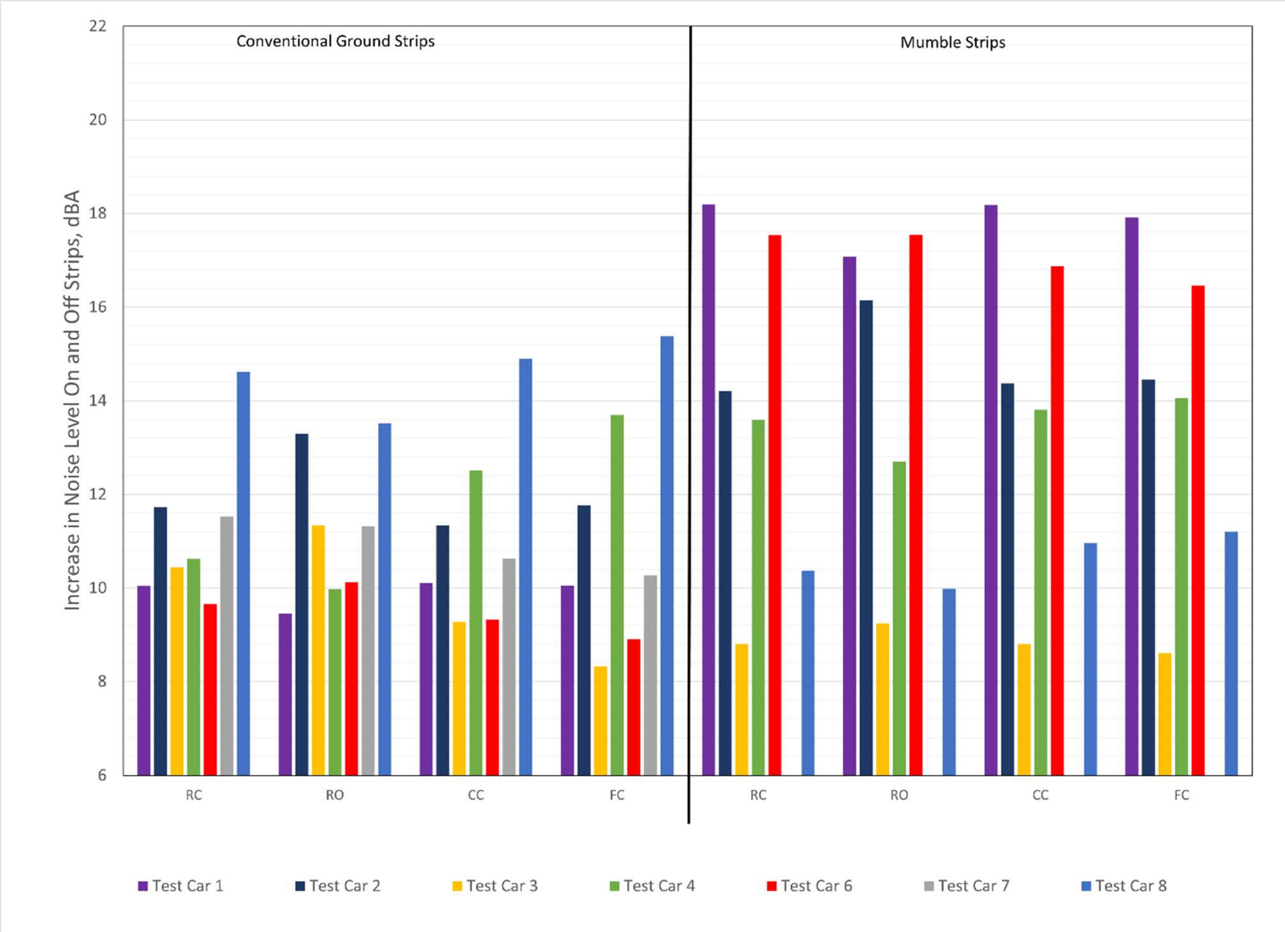


Figure B-56: Overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites (45 mph)

Figure B-57 shows the average on/off differences for each grouping previously discussed. On average, noise levels measured on the conventional ground rumble strips showed an increase over ambient of more than 12 dBA for the large SUV and van group, while all other groupings result in on/off differences ranging from 8.9 to 11.4 dBA. On the mumble strips, the increase over ambient ranged from 10.0 to 11.3 dBA for the large SUV and van group and for the sedans, while the crossover SUVs and compact cars had on/off differences ranging from 16.2 to 17.5 dBA. The overall on/off differences for all vehicles tested at 45 mph show levels on the conventional ground strips to be less than 12 dBA above ambient conditions (off strip), while levels on the mumble strips would be an average of 13.8 dBA above off strip data at each microphone.

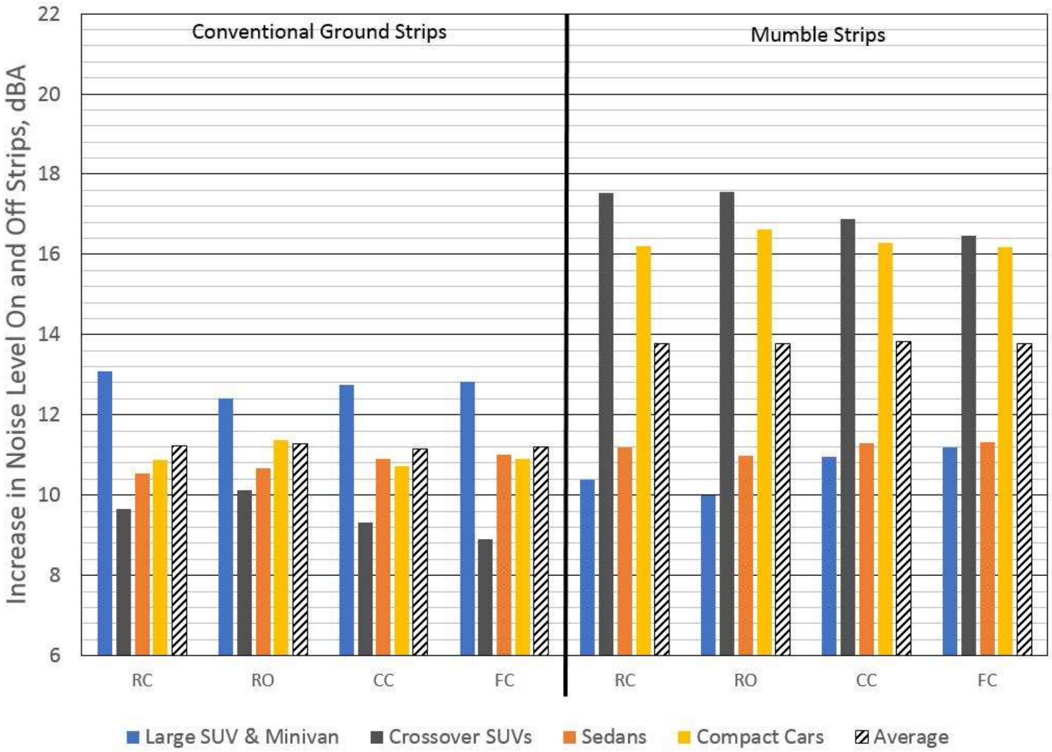


Figure B-57: Overall interior noise level differences between on and off strips at the conventional ground rumble strips and mumble strips sites for four groups, paired by vehicle type and size (45 mph)

Figure B-58 shows the average on/off difference of all microphones measured in each vehicle. On average, the mumble strips generated interior noise levels 9 to 18 dBA above ambient off strips data, with differences being highest for Test Car 6 and Test Car 1. On the conventional ground strips, average differences for all microphones ranged from about 9.5 to 14.5 dBA, with Test Car 8 having the highest average difference.

The vehicle averages at both sites are shown in Figure B-59 for each individual microphone. For each vehicle, the standard deviation for each microphone was 0.3 to 1.7 dBA on the conventional ground strips and 0.3 to 0.9 dBA on the mumble strips. Therefore, for these microphone locations, there is a less than 2 dBA variation between the on/off differences measured at each microphone when testing at 45 mph.

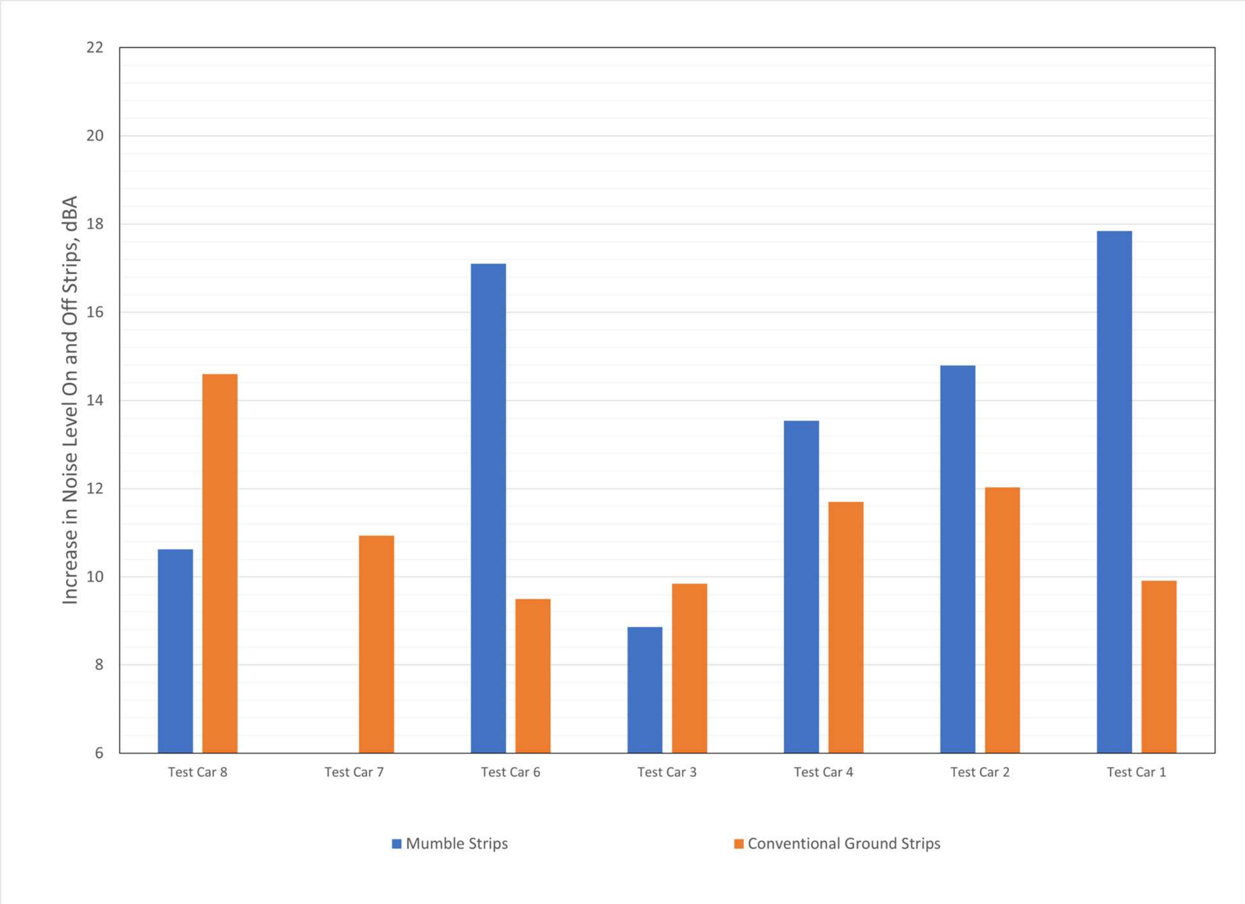


Figure B-58: Average overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites for the average of all interior microphones (45 mph)

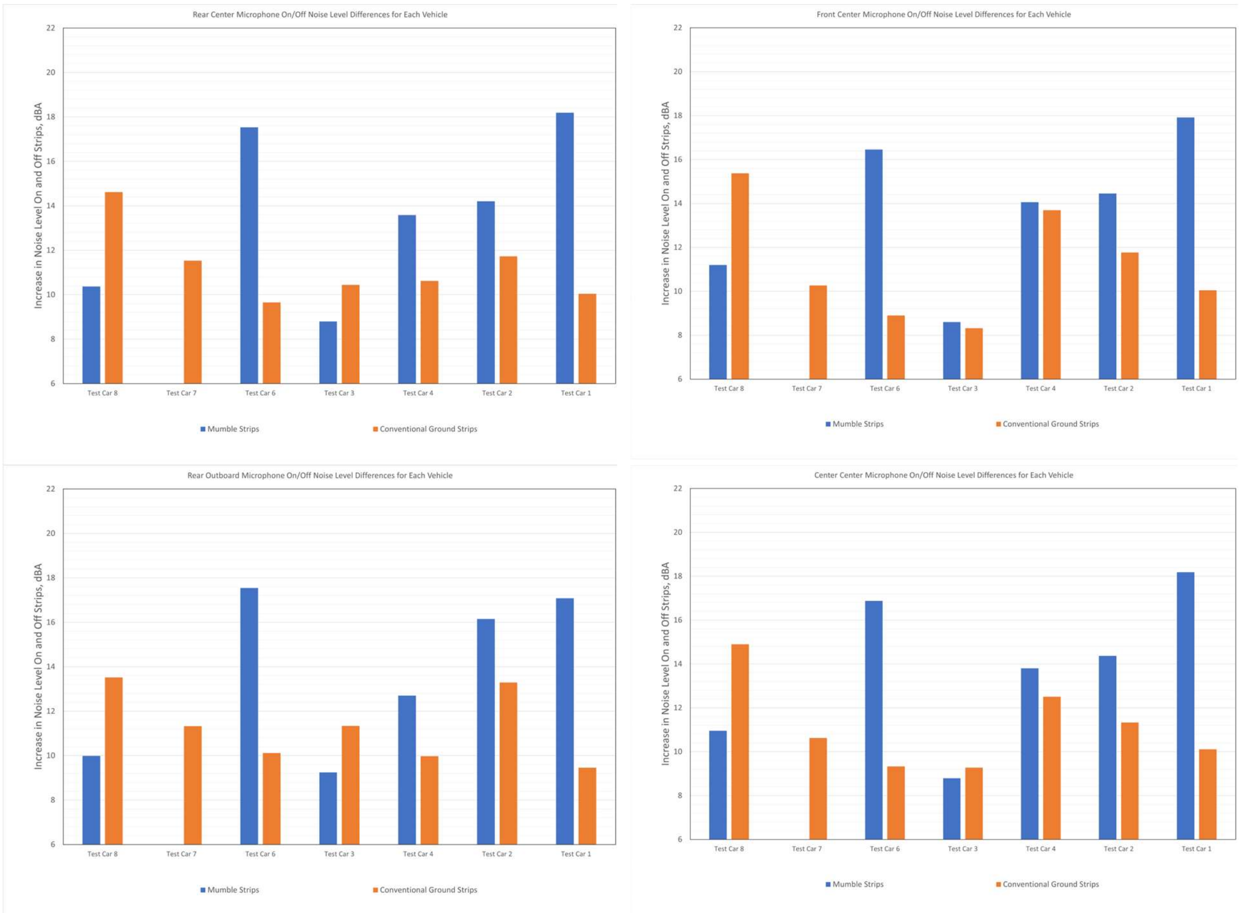
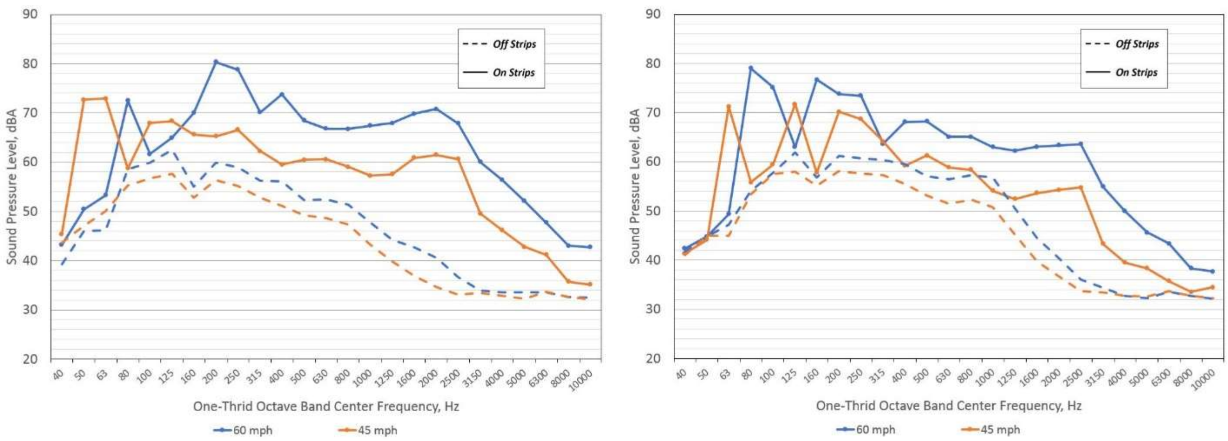


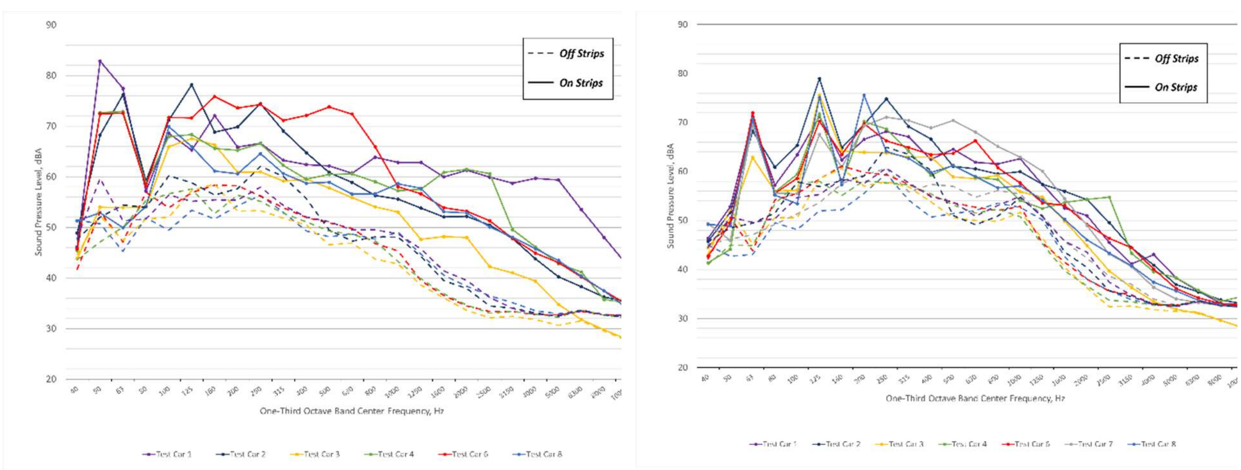
Figure B-59: Average overall interior noise level differences between on and off strips at the conventional ground strips and mumble strips sites for each of the interior microphones (45 mph)

Figure B-60 show the one-third octave band spectra for the rear center microphone position in Test Car 3 at 45 and 60 mph. The 80 Hz peak at 60 mph on the mumble strips shifted down to be a split peak at 50 and 63 Hz, while the 80 and 100 Hz split peaks on the conventional ground strips at 60 mph shifted down to be a peak at 63 Hz. At frequencies above 250 Hz on both sites, the levels at each frequency band were higher at speeds of 60 mph than at 45 mph. Figures B-61 through B-64 show all test vehicles at each of the four microphones tested at 45 mph. The peaks at 50 and 63 Hz are apparent at each microphone and in each test vehicle when testing occurred on the mumble strips. Test Car 6 also showed elevated levels in the 100 to 800 Hz range at each microphone on the mumble strips, while above 800 Hz, Test Car 1 consistently resulted higher levels than the other test vehicles. Test Car 2 showed unusual behavior at the rear outboard position in the 1,250 to 4,000 Hz range. At these higher frequency bands, noise levels were 68 to 79 dBA, which was about 11 to 27 dBA higher than in this range than the other microphone positions. The spectra collected at each microphone position on the conventional ground strips show consistent peaks at 63 and 125 Hz. The elevated levels in the 1,250 to 4,000 Hz range for the rear outboard microphone in Test Car 2 was also apparent on the conventional ground strips, with levels about 9 to 26 dBA higher than the other microphone positions.



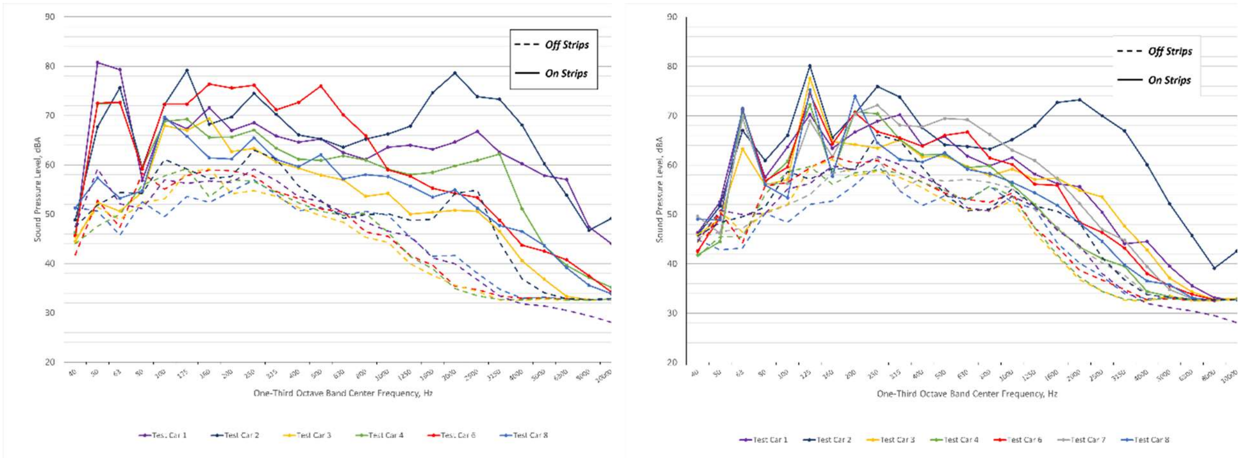
(a) mumble strips *(b) conventional ground strips*

Figure B-60: A-weighted one-third octave band spectra measured at the rear center microphone (45 and 60 mph) of Test Car 4 on the (a) mumble strips and (b) conventional ground strips



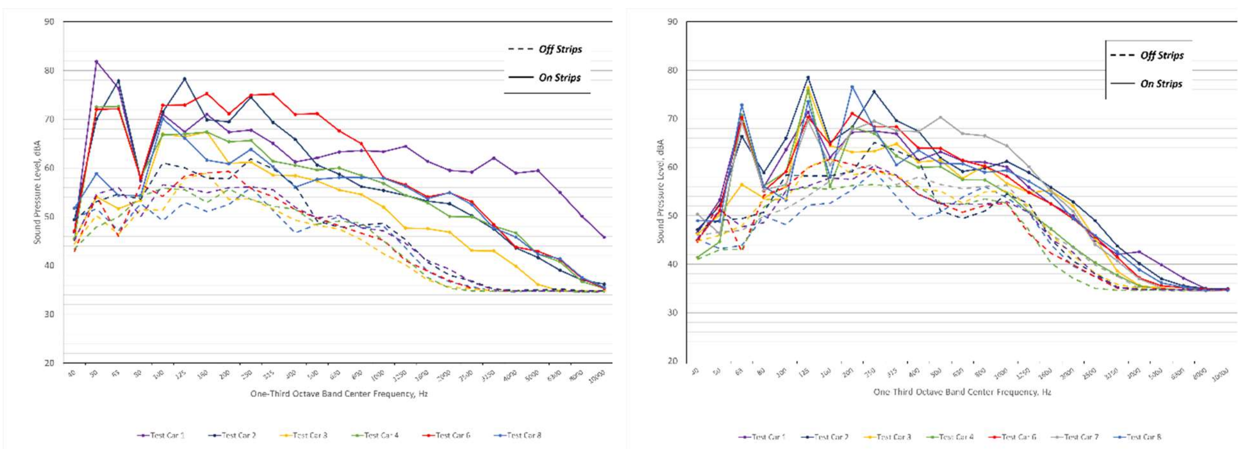
(a) mumble strips *(b) conventional ground strips*

Figure B-61: A-weighted one-third octave band spectra measured at the rear center microphone (45 mph) for all test vehicles on the (a) mumble strips and (b) conventional ground strips



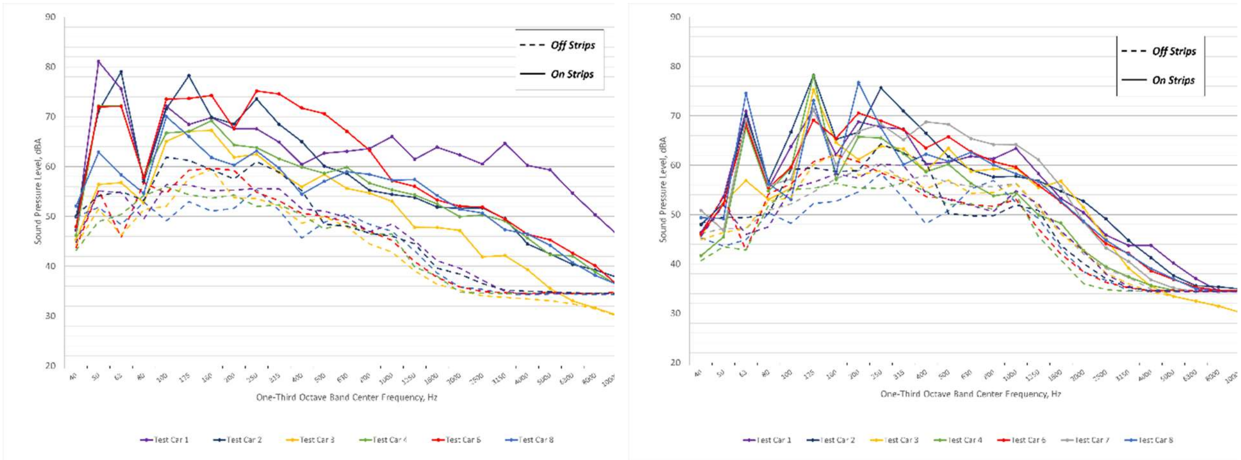
(a) mumble strips *(b) conventional ground strips*

Figure B-62: A-weighted one-third octave band spectra measured at the rear outboard microphone (45 mph) for all test vehicles on the (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

Figure B-63: A-weighted one-third octave band spectra measured at the center center microphone (45 mph) for all test vehicles on the (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

Figure B-64: A-weighted one-third octave band spectra measured at the front center microphone (45 mph) for all test vehicles on the (a) mumble strips and (b) conventional ground strips

Comparison to Previous Results

In the Caltrans studies completed in 2012 and 2015, a single microphone was positioned between the headrest and the seatback of the front passenger seat, facing forward. While the orientation and height of the Caltrans microphone may have been slightly different to the rear center microphone position used in this study in 2018, the results from the rear center microphone would most closely compare to the previous studies.

The overall interior noise levels for the previous Caltrans studies on the mumble strips and the conventional ground strips, compared to the 2018 overall levels are shown in Figures B-65 and B-66, respectively. On the mumble strips, the Expedition from 2012 resulted in the lowest overall levels, approximately 2.3 dBA lower than Test Car 8 in 2018 and 4 to 8 dBA lower than Test Car 6 and Test Car 5. The Honda Civic had overall levels on the mumble strips equivalent to the 2018 Test Car 4, which falls in the range of all 2018 passenger cars. The Malibu, on the other hand, resulted in the highest overall interior noise levels measured on the mumble strips in any year and in any vehicle. The overall levels in this vehicle were more than 4 dBA higher than all 2018 passenger cars. The 2015 Camry with the SRTT was about 1.8 dBA higher than the overall level for the 2018 Test Car 4 on mumble strips, and the 2015 Camry with the Goodyear was about 1.2 dBA lower than the 2018 Test Car 4.

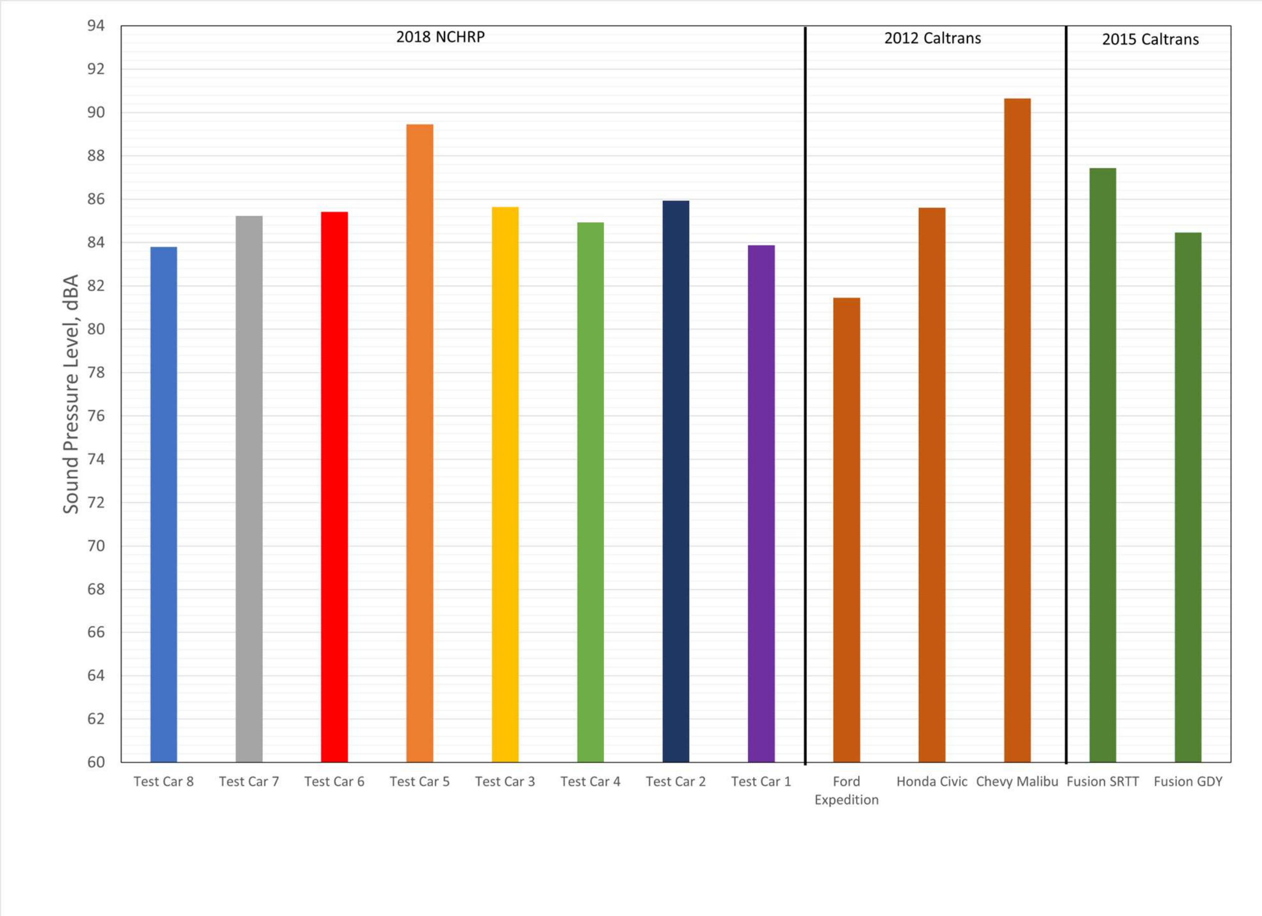


Figure B-65: Overall interior noise levels at the mumble strip site when compared to results of previous Caltrans studies

On the conventional ground strips, the Expedition again showed low overall levels, but the overall levels at this site were similar to Test Car 8 in 2018, with a difference of about 1 dBA. The Honda Civic had overall levels on the conventional ground strips higher than all other vehicles tested in 2012, 2015, and 2018; however, the overall levels measured in this vehicle are within 2 dBA of Test Car 2 and Test Car 1, which are similar sized vehicles. The Malibu also had higher overall interior noise levels, similar to Test Car 2 and Test Car 1 tested in 2018. Both 2015 Camry measurements were lower than the overall level in 2018, by approximately 1.6 to 3.6 dBA.

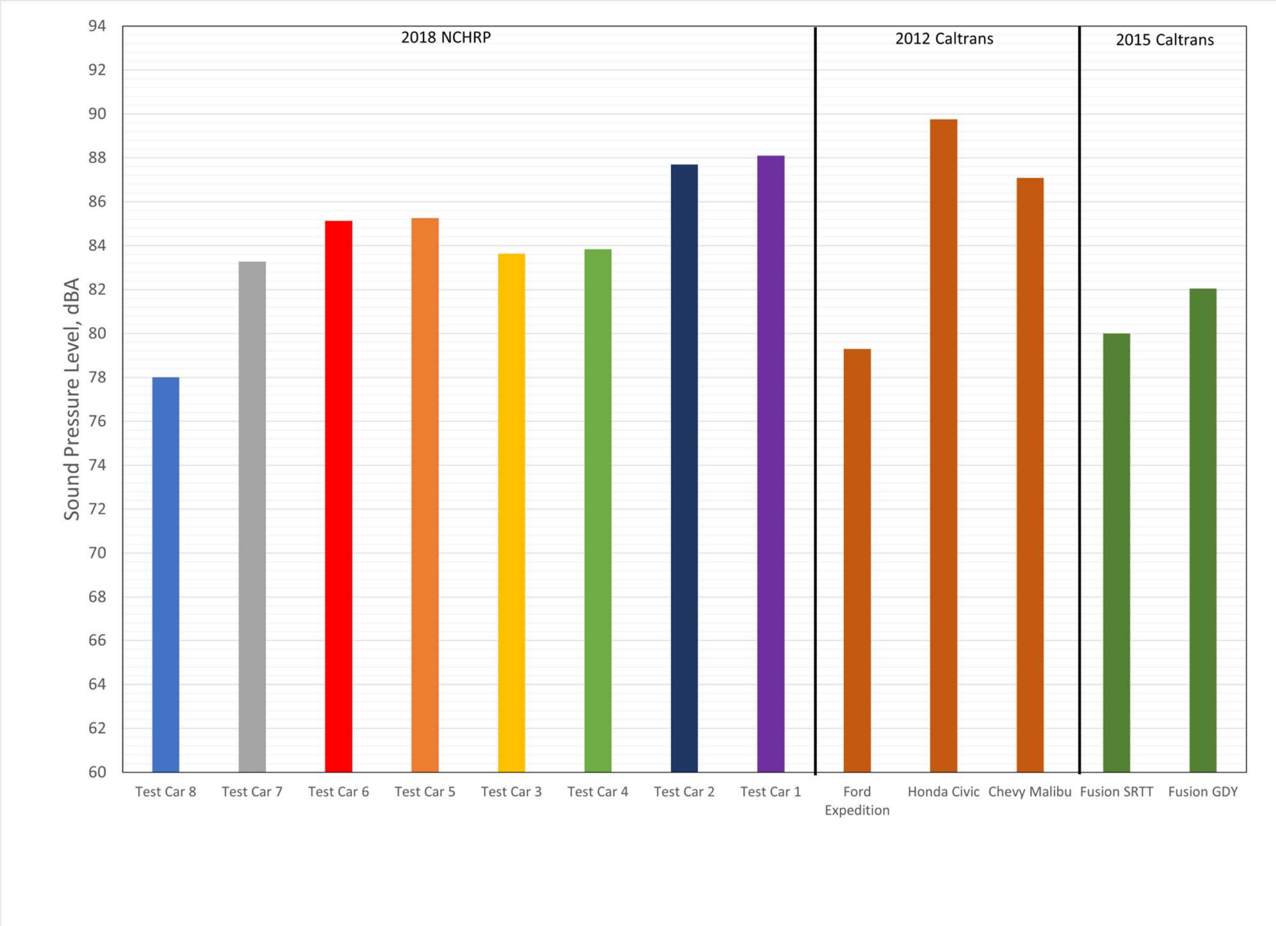


Figure B-66: Overall interior noise levels at the conventional ground strip site when compared to results of previous Caltrans studies

The overall noise level differences between on/off strips, measured on the mumble strips and conventional ground strips, are shown in Figures B-67 and B-68, respectively. Note, the 2018 differences shown in these figures were taken at the rear center microphone position. On the mumble strips, the Expedition had a lower on/off difference than all the SUVs tested in 2018 (i.e., Test Car 8, Test Car 6, and Test Car 5) by 1.5 to 4.3 dBA. In contrast, the Expedition had an on/off difference on the conventional ground strips that fell within the range of on/off differences measured in 2018. The Honda Civic and Malibu had on/off differences varying by about 6 dBA on the mumble strips, and each of these vehicles had differences lower than all passenger vehicles tested in 2018 (Honda Civic) and higher than all 2018 passenger vehicles (Malibu). On the conventional ground strips, the Honda Civic had on/off differences equivalent to the Test Car 1, with the Malibu less than 1 dBA lower. In 2015, the Camry was tested with two different tires: the SRTT and Aquatred. The 2015 Camry with the SRTT tire had on/off differences about 1.3 and 3.6 dBA lower than the 2018 Test Car 4 on the mumble and conventional ground strips, respectively, while the 2015 Camry with the Goodyear tire was 6.2 and 2.4 dBA lower than the 2018 measurements on the mumble and conventional ground strips, respectively. Compared to all the passenger vehicles tested in 2018 on the mumble strips, the on/off difference for the 2015 Camry with the SRTT fell within the range of passenger cars, while the Camry with the Goodyear tire had the lowest on/off differences of all vehicles shown in Figure 4.2.28. Both 2015

Camry tests on the conventional ground strips resulted in on/off differences lower than all passenger vehicles tested in 2018.

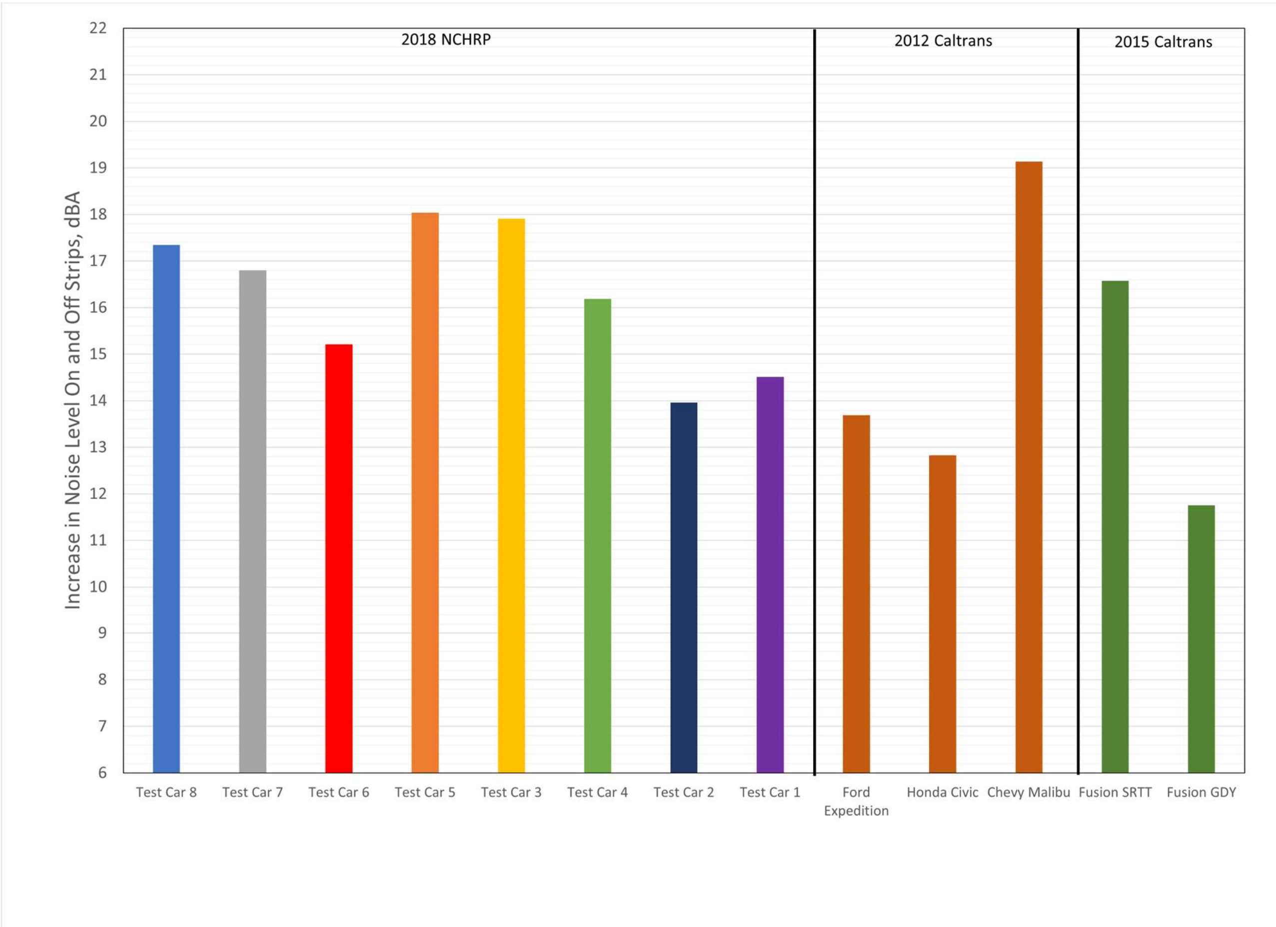


Figure B-67: Overall interior noise level differences between on and off strips at the mumble strip site when compared to results of previous Caltrans studies

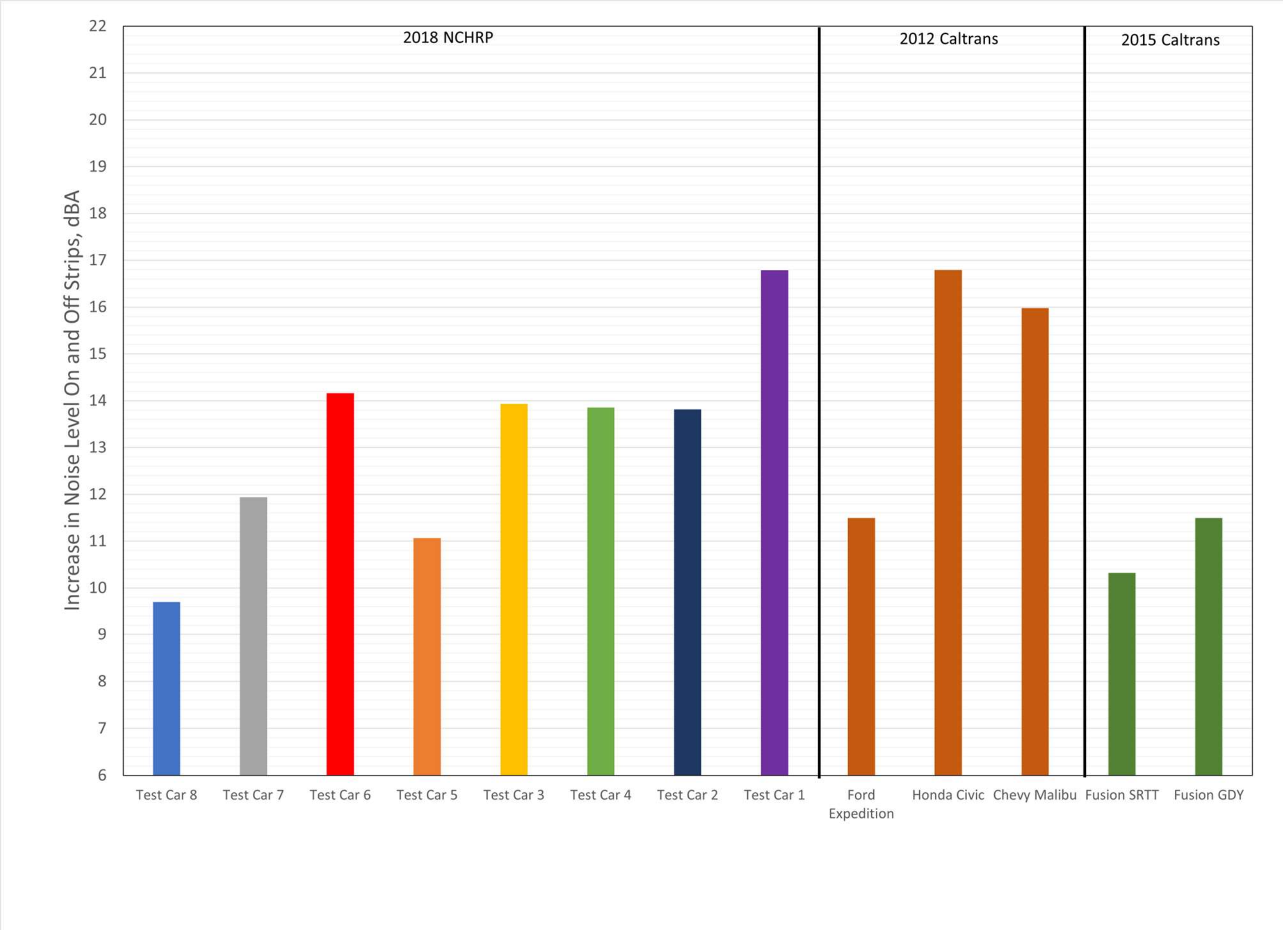
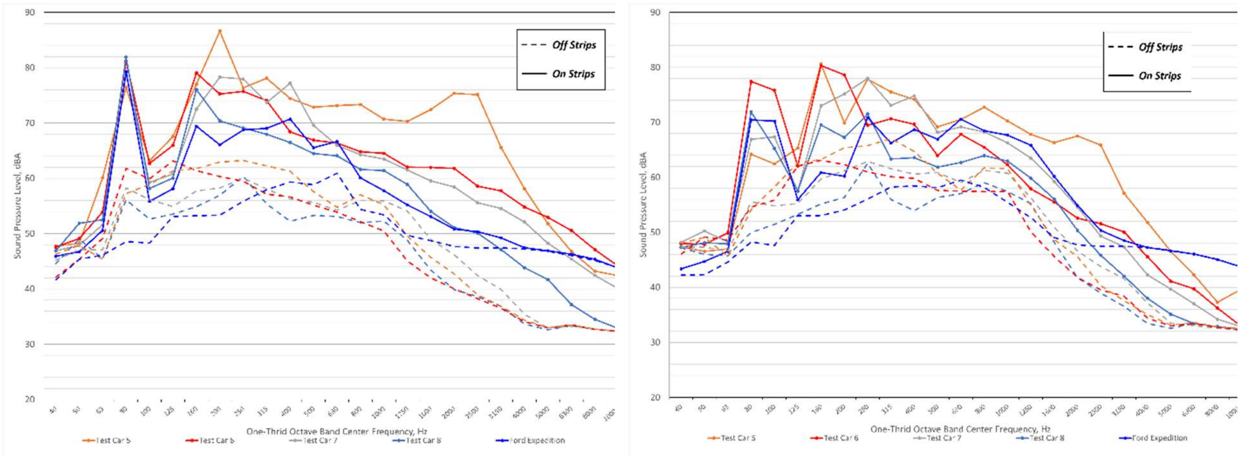


Figure B-68: Overall interior noise level differences between on and off strips at the conventional ground strip site when compared to results of previous Caltrans studies

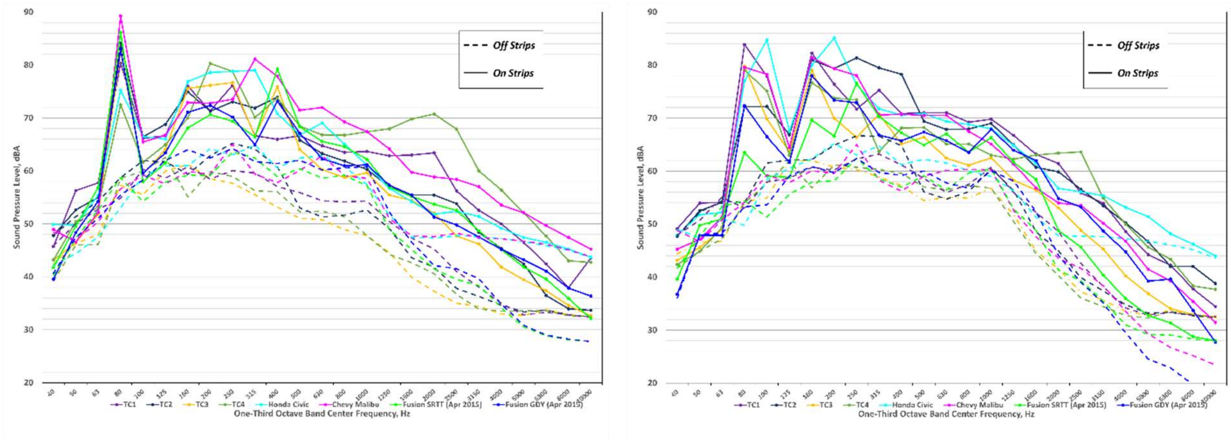
Figure B-69 shows the interior one-third octave band spectra for the 2018 SUVs and minivan, compared to the 2012 Expedition. The overall trend measured for the Expedition in 2012 is similar to the vehicles measured in 2018. The 80 Hz peak measured on the mumble strips had magnitudes ranging from 76.4 to 81.9 dBA, while the magnitudes of the peaks measured on the conventional strips ranged from 62.4 to 77.4 dBA. The peaks excited on the mumble strips were more consistent from vehicle-to-vehicle than the peaks excited on the rumble strips.



(a) mumble strips *(b) conventional ground strips*

Figure B-69: A-weighted one-third octave band spectra measured at the for all SUVs and minivan tested in 2018 and the 2012 Expedition on the (a) mumble strips and (b) conventional ground strips

Figure B-70 shows the interior one-third octave band spectra for the 2018 passenger cars, compared to the 2012 Honda Civic and Malibu and the 2015 Camry with both test tires. Compared to the 2018 vehicles, the overall trends for the vehicles in the previous Caltrans studies were similar. The 80 Hz peak measured on the mumble strips had magnitudes ranging from 72.5 to 89.2 dBA, while the magnitudes of the peaks measured on the conventional strips ranged from 59.1 to 84.7 dBA. The peak magnitudes varied more in the passenger cars than in the SUVs and minivan.



(a) mumble strips *(b) conventional ground strips*

Figure B-70: A-weighted one-third octave band spectra measured at the for all passenger cars tested in 2018, the 2012 Honda Civic and Malibu, and the 2015 Fusions on the (a) mumble strips and (b) conventional ground strips

Vehicle Vibration

Data Processing

The processing of the vehicle vibration data was done in a manner similar to that of the interior noise. The time histories of overall vibration levels were reviewed for each run, on and off the conventional ground strips and mumble strips. For on the strips, continuous two-second segments out of the eight-second histories were identified where the levels were the most stable and typical of the higher levels measured for configuration. The same two-second interval limits were applied to all vibration measurement locations for that run. An example of this is given in Figure B-71 for Test Car 4 on the mumble strips. It is noted that not all of the time histories have the same characteristics over the two seconds. Also, the amount of variation over time is slightly different for the measurement locations. An example of a run that was not selected is shown in Figure B-72. In this case, substantial variation is found between the measurement locations, as well as in the temporal variation in some of the locations. All 18 measurement locations could not be simultaneously captured with the 16-channel data acquisition system, leaving two locations being captured for a different run over the strips. Interestingly, the off-strips data also display variation both over time and from location-to-location, as shown in Figure B-73. Despite these variations in both the on and off strips runs, all of the data was processed into one-third octave band spectra for the selected two-second samples.

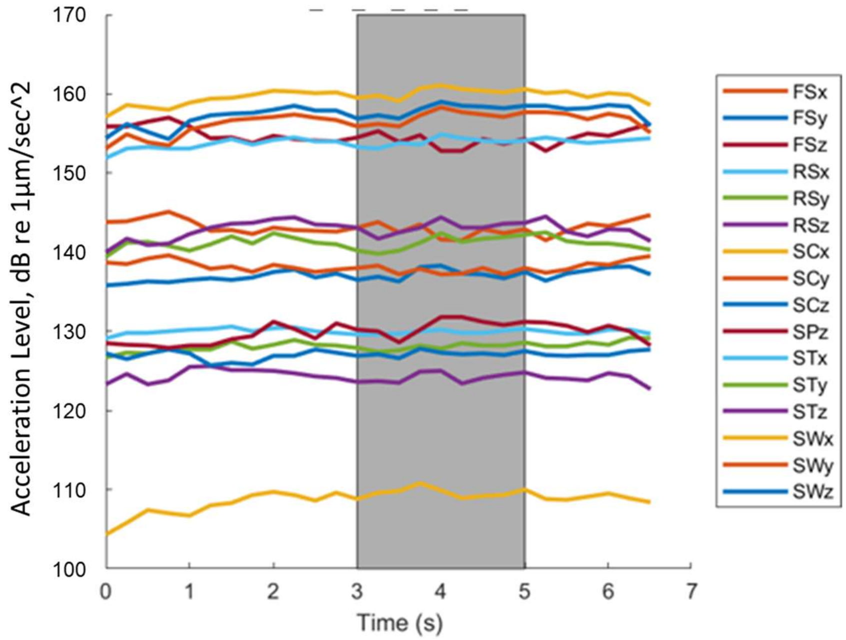


Figure B-71: Test Car 4 acceleration time histories for all locations for one run on the mumble strips showing 2-second time period selected for averaging (in gray)

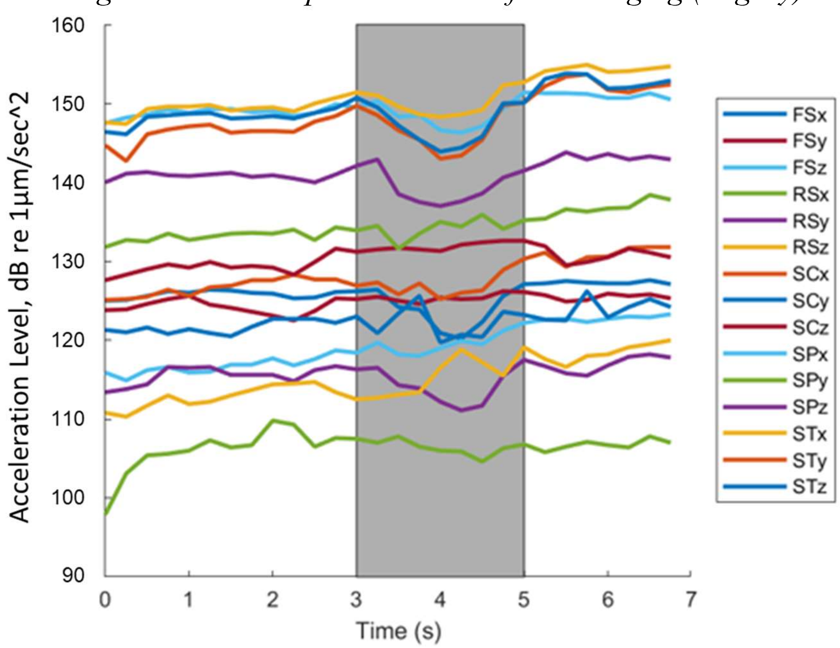


Figure B-72: Test Car 4 acceleration time histories for all locations for one run on the mumble strips showing 2-second time period not selected for averaging (in gray)

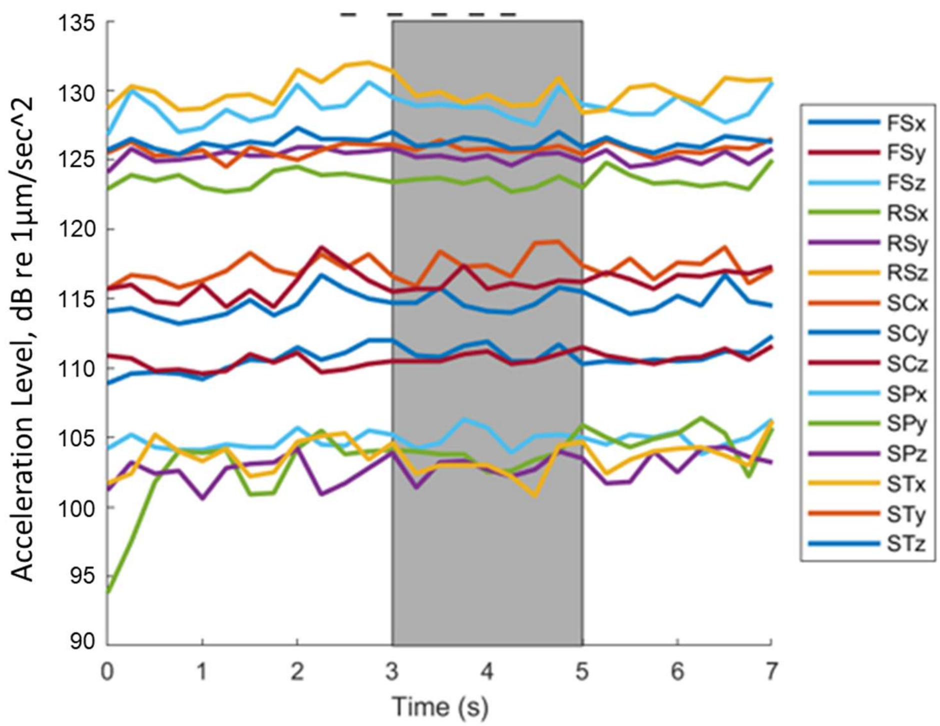


Figure B-73: Test Car 4 acceleration time histories for all locations for one run off the mumble strips showing 2-second time period selected for averaging (in gray)

Other criteria for selecting which runs to use was based on the evaluation of the spectra. Based on the repetition rates of the two rumble strip designs and past measurements, it was known that the mumble strips produce a distinct peak at 60 mph for the 80 Hz one-third octave band. For the ground strips, the repetition rate split into the 80 and 100 Hz bands. When speed varies from 60 mph, the results are apparent in the frequency content. An example of this is shown in Figure B-74 for Test Car 4 on the mumble strips for the seat track location in the vertical direction. These data indicate a pronounced peak at 80 Hz for four of the on-strip runs (1409, 1223, and 1228). For the other three (1405, 1413, and 1218), the 80 Hz peak is not as pronounced, indicating that a slightly slower speed was maintained. These data were not considered further. Of the three runs that were at 60 mph, 1409 produced a peak level at 80 Hz that was greater than or equal to the others. After identifying 1409 as the run to consider, the prominence of 80 Hz peak was verified for the other locations before being selected as the data to be used.

There were some other issues in the data that also had to be considered. For most conditions and vehicles, the highest levels corresponded to the strip passage frequencies and determined the resultant overall level. However, for some of the vehicles, the higher levels occurred at 2,000 Hz and above for the spindle locations. An example of this is shown in Figure B-75 for the rear spindle in the fore/aft direction on Test Car 5. This behavior was found for several of the vehicles and occurred only for the spindle measurements. The other measurement locations indicated a substantial reduction in level at higher frequencies. The elevated high frequency levels for the spindle locations produced greater on/off level differences for these measurements

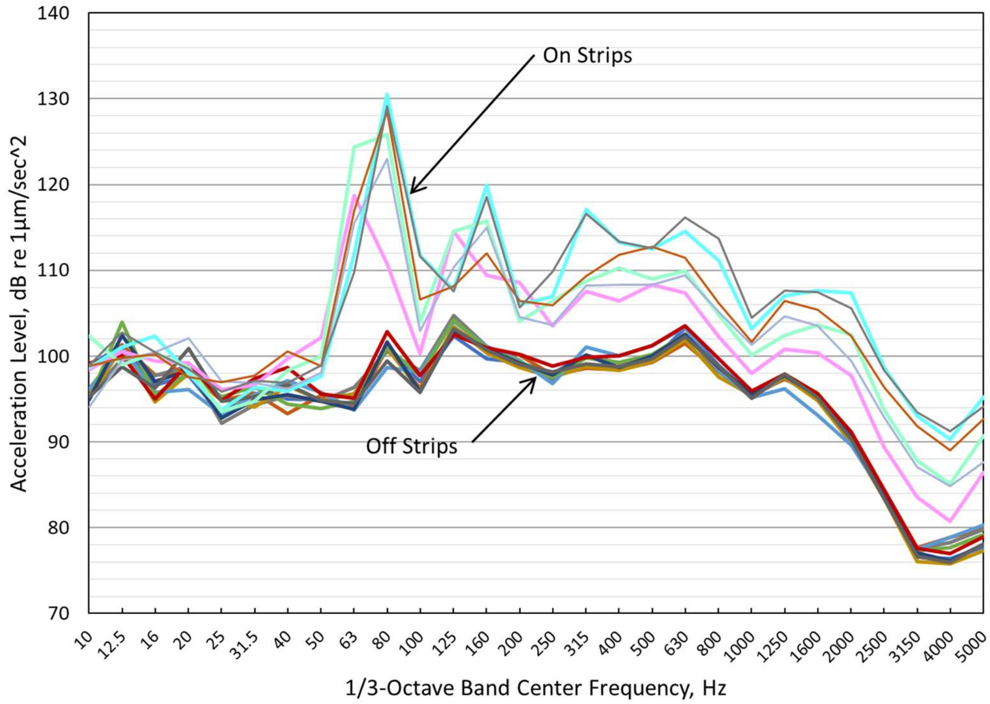


Figure B-74: Test Car 4 acceleration time histories for all runs for the seat track vertical direction on and off the mumble strips at 60 mph

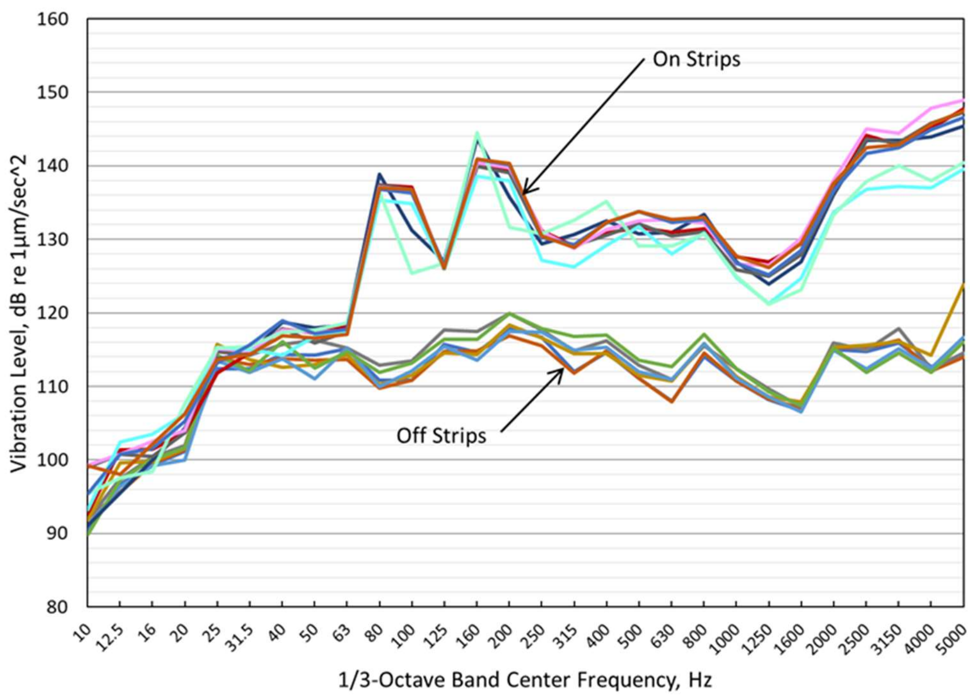


Figure B-75: Test Car 5 acceleration time histories for all runs for the rear spindle fore/aft direction on and off the conventional ground strips at 60 mph compared to the interior measurement locations. The cause of these elevated levels is not known but could be due to the absence of isolation between the rumble strip input and spindle, while the interior locations include suspension and body isolation. It could also be due to non-linearities in the suspension (such as component rattling) or shaking of the accelerometer cables while driving on the rumble strips. For most of vehicles, elevated acceleration levels at higher frequencies were not present in the data, as shown in Figure B-76 for Test Car 4 obtained on the steering column in the vertical direction. As indicated in this figure, at 40 Hz and below, there is no consistent difference between on/off the strips. This is the case for all vehicles, all measurement locations, and both test speeds. In the case shown in Figure B-76, these elevated levels will influence the overall on/off difference by lessening the actual effect of the strips. For calculating the overall levels and on/off differences, the levels below 40 Hz were eliminated in all cases.

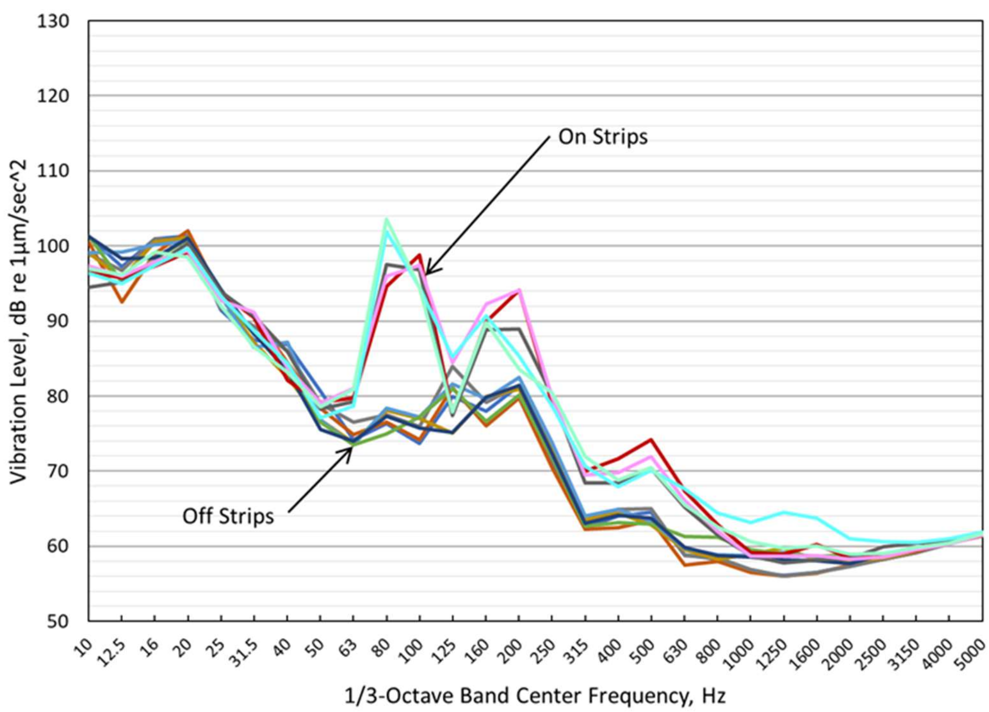


Figure B-76: Test Car 4 acceleration time histories for all runs for the steering column vertical direction on and off the conventional rumble strips at 60 mph

Results

The overall vibration levels were calculated on the summation of the one-third octave levels from 40 to 5,000 Hz for reasons discussed above. The resultant overall levels are shown in Figures B-77 and B-78 for the mumble and conventional strips, respectively, as measured at 60 mph and at all sensor locations. In general, the levels for the mumble strips are higher than the conventional strips. As expected from the above discussion, the levels for both the front and rear spindle are typically higher than the other measurement locations. For the other locations, trends between the mumble and conventional ground strips are quite similar. For the steering column (SC) location, the levels are fairly consistent in all three directions and tend to be slightly higher than the seat track (ST) location. The seat pad or pad (SP) levels show a decrease in level from the fore/aft direction to the lateral direction to the vertical direction, with these being the lowest of all locations. The seat track levels also have fairly consistent trends between directions; although, the levels for the vertical direction tend to be slightly lower for the conventional strips relative to the behavior on the mumble strips. For the steering wheel (SW), similar trends are also among the different directions for the mumble and conventional strips. In both sets of data, some individual levels stand out from the others at some locations. On the conventional strips, outstandingly high levels are indicated for the steering wheel in the fore/aft and lateral directions for Test Car 1. On the mumble strips, this only occurs in the lateral direction. For seat track locations, Test Car 7 has comparatively high levels in the lateral and vertical direction on the conventional strips, but not on the mumble strips. Across both types of strips, Test Car 1, Test Car 5, Test Car 2, and Test Car 7 tend to have levels that stand out as being higher than most.

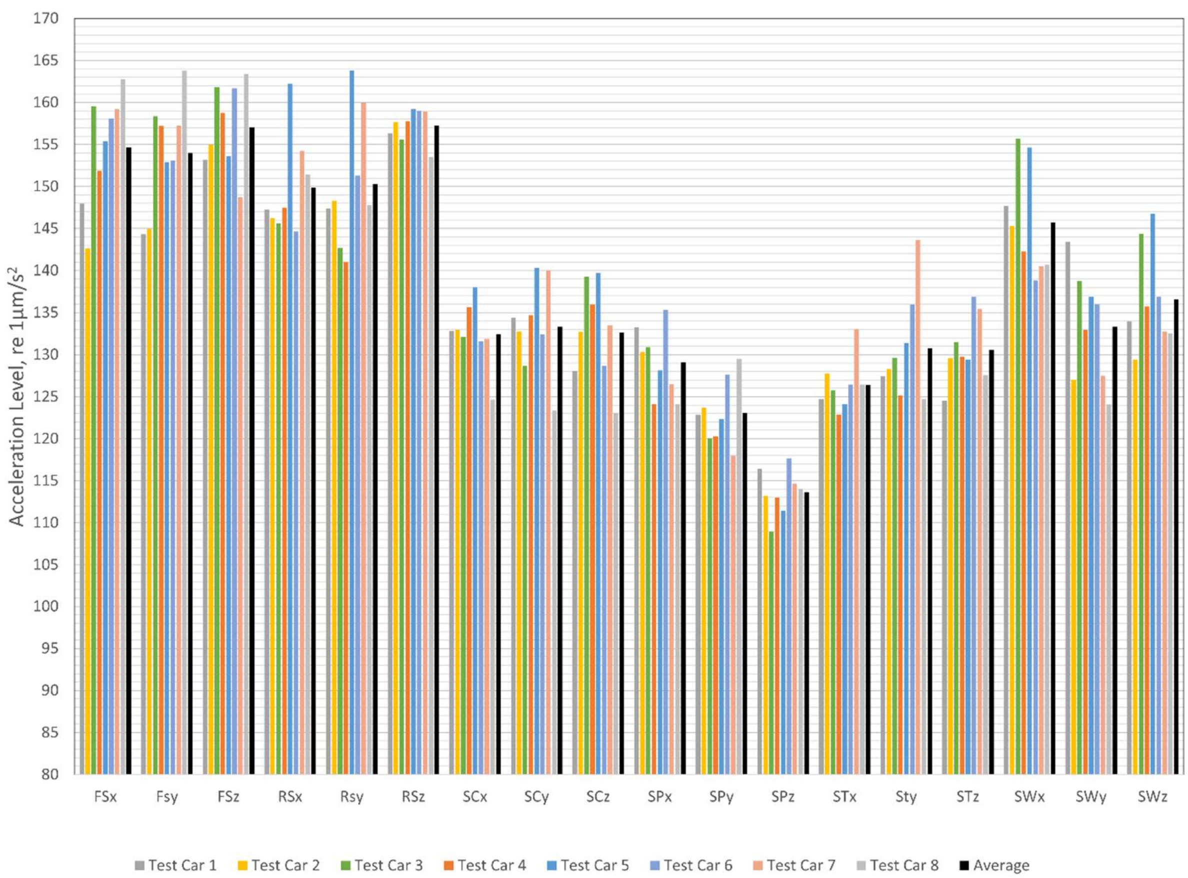


Figure B-77: Overall acceleration levels for all vehicles and measurement locations on the mumble strips

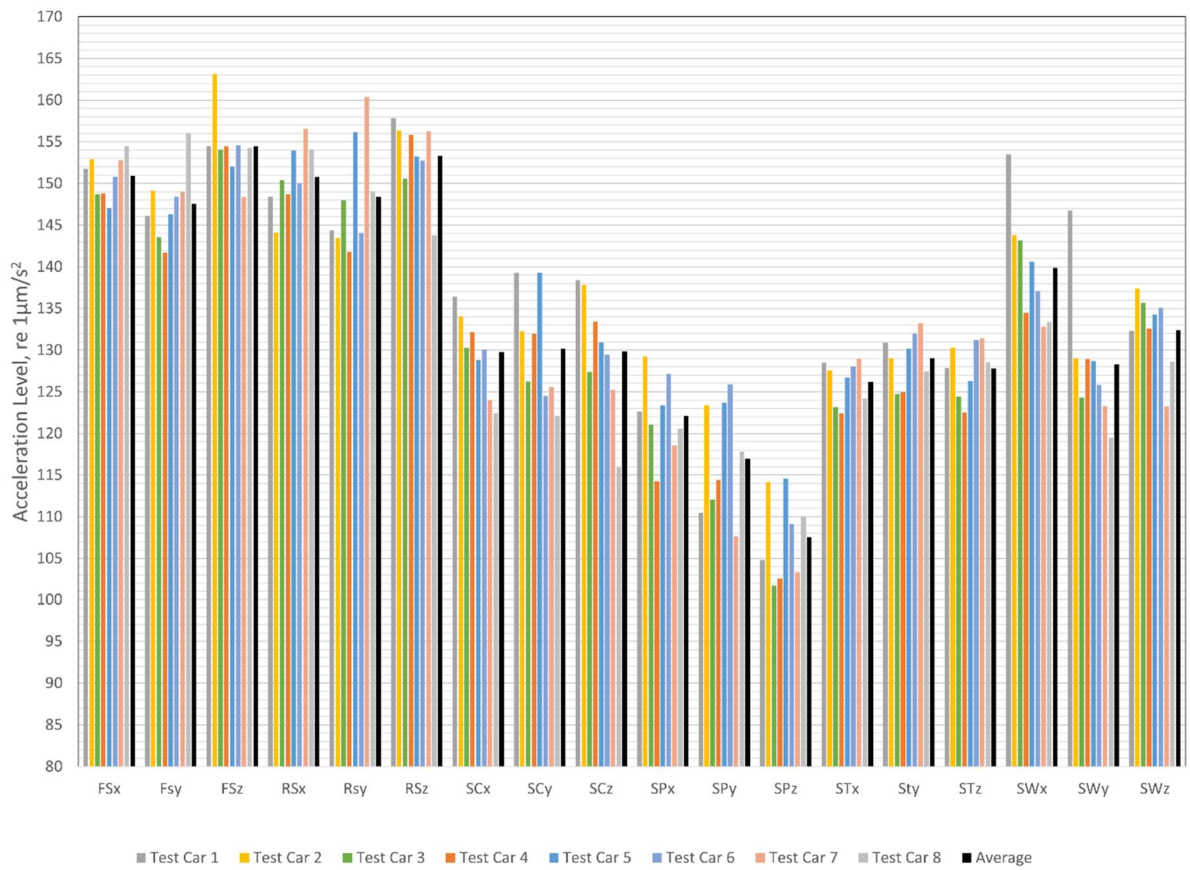


Figure B-78: Overall acceleration levels for all vehicles and measurement locations on the conventional rumble strips

In Figures B-79 and B-80, similar plots are presented for the levels off the strips at the mumble strip and conventional strip locations, respectively. Except for displaying lower levels, these plots look very similar in relative magnitude compared to the results on the strips. This implies that the shapes of the results are not dependent on the inputs but rather on the measurement location.

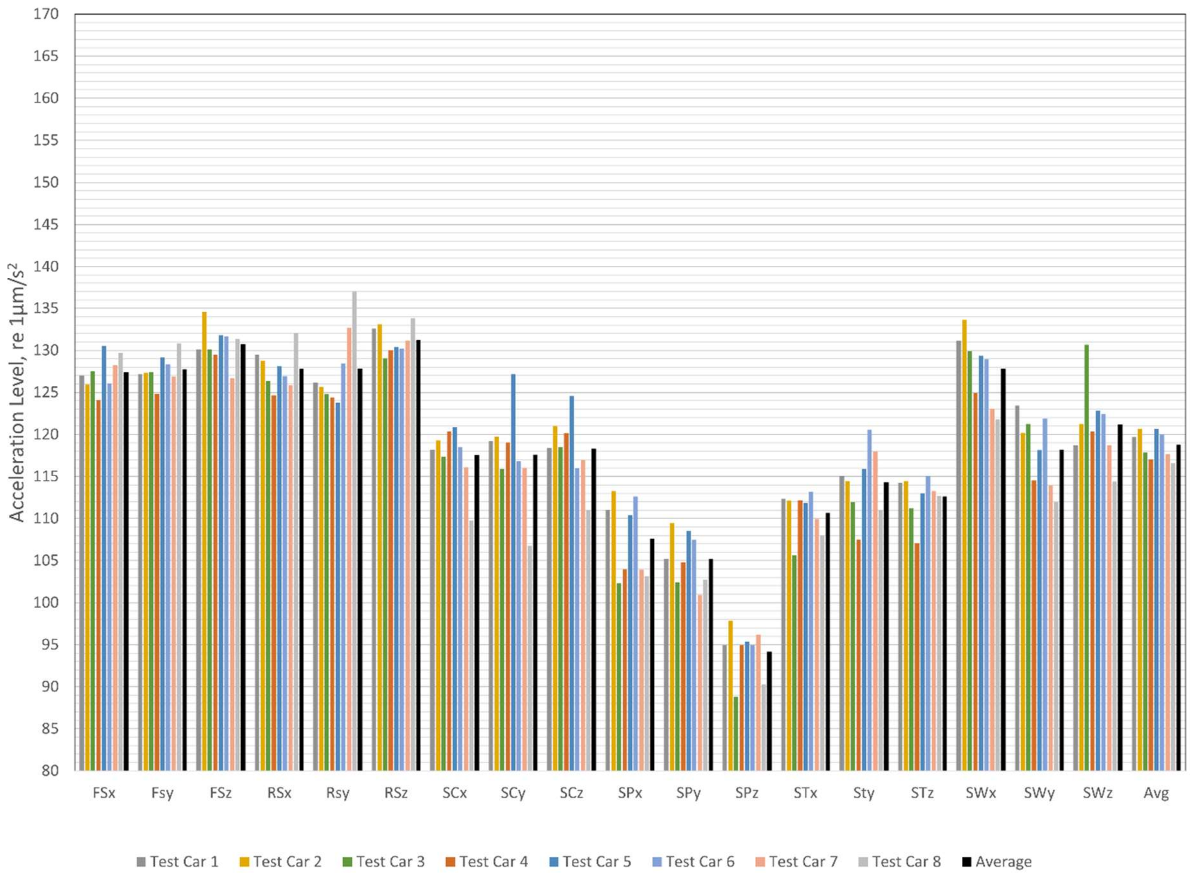


Figure B-79: Overall acceleration levels for all vehicles and measurement locations off the mumble strips

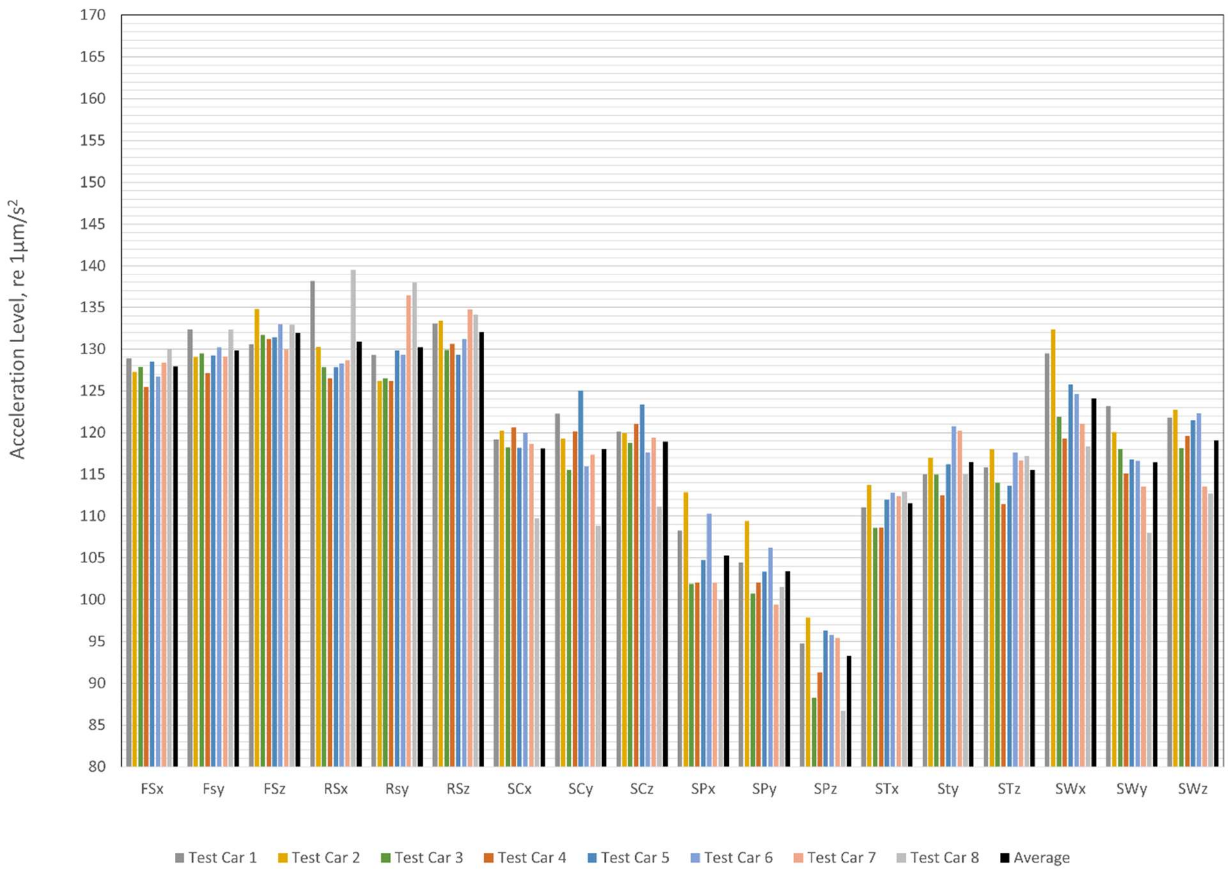


Figure B-80: Overall acceleration levels for all vehicles and measurement locations off the conventional ground strips

The results of Figures B-77 through B-80 were used to calculate the difference in acceleration levels on and off both rumble strips. These are shown in Figures B-81 and B-82 for the mumble and conventional strips, respectively. Comparison of these figures indicates that the on/off differences tend to be greater for mumble strips. The patterns noted in the overall levels are not so apparent in the increments. The increments for the spindles are greater than the other locations; however, the differences are less compared to those seen in the overall levels. Also, the difference between the increments for the other locations are not so pronounced as those of the overall levels. There is a good deal of variation between the increments for different locations, particularly for the mumble strips. These range from 9.0 to 40.0 dB, with an average of 19.5 dB, and three out of the 144 increments do not achieve a value of 10 dB. For the conventional strips, the increments range from 4.8 to 28.4 dB, with an average of 15.7 dB, and 14 out of 144 do not achieve 10 dB. For the mumble strips, Test Car 2 has the lowest average of the increments at 15.3 dB, while Test Car 7 has the highest at 22.1 dB. For the conventional strips, Test Car 7 has the lowest average at 14.6 dB, and Test Car 5 has the highest at 16.8 dB.

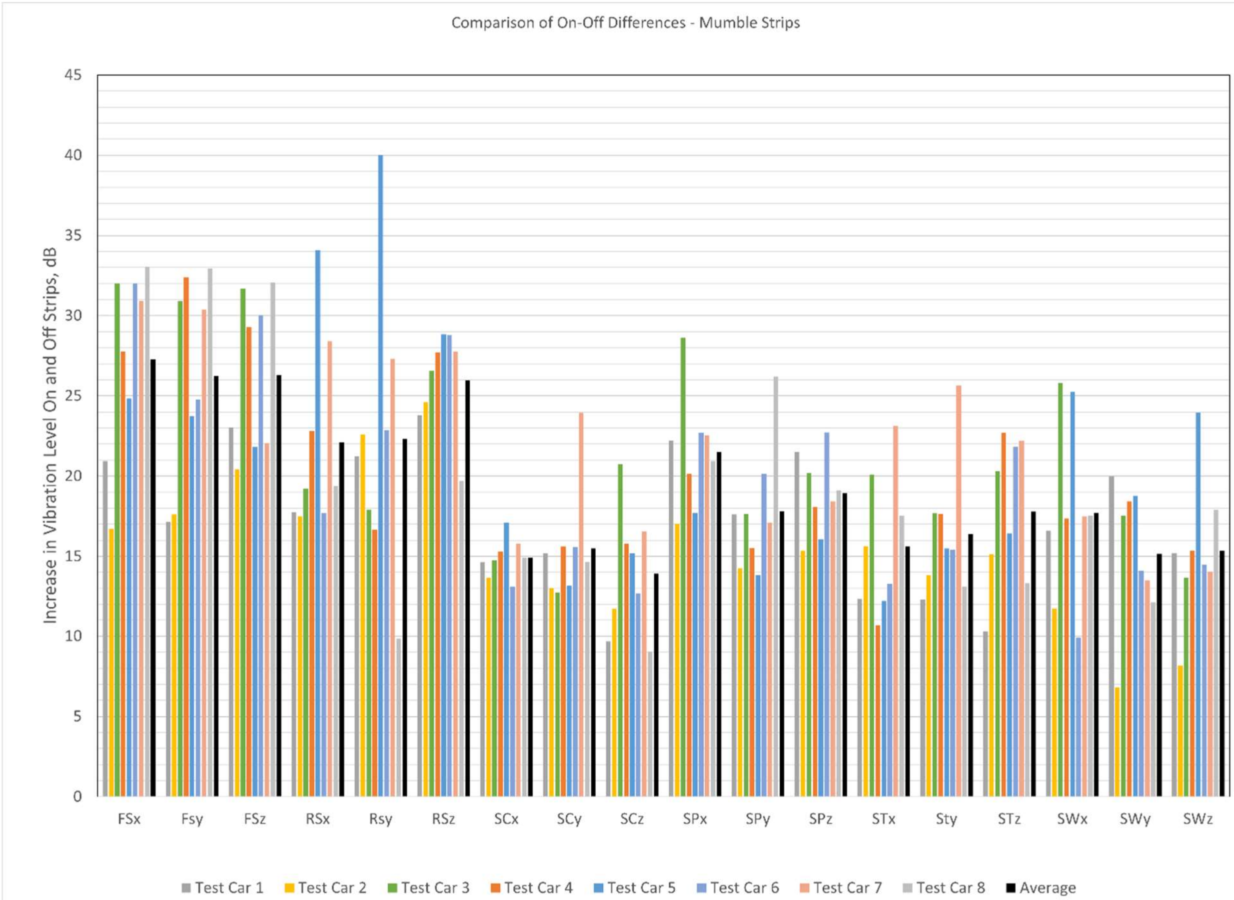


Figure B-81: Difference in level on and off the mumble strips for all vehicles and measurement locations

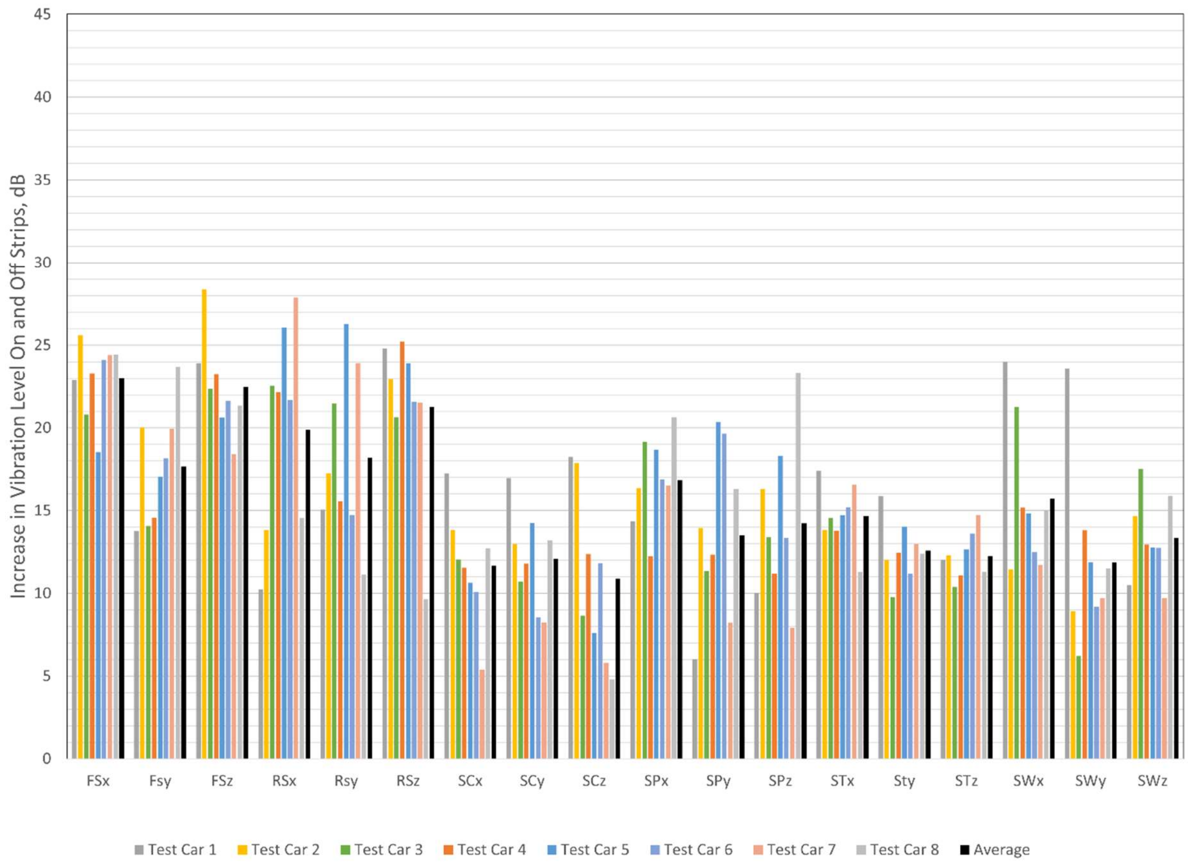


Figure B-82: Difference in level on and off the conventional ground strips for all vehicles and measurement locations

In order to simplify the comparison of the measurement locations, the acceleration levels for the three directions at each location were summed on an energy basis. The resultant levels are shown in Figures B-83 and B-84 for the mumble and conventional strips, respectively. Comparing the mumble and conventional strip levels, it is seen that the trends between vehicles vary from one strip to the other. That is, vehicles that produce the highest levels on one type of strip do not produce the highest on the other. Overall, these figures indicate that the rumble strip design is clearly a major factor in the resultant response, as is the vehicle design. For the off-strip levels shown in Figures B-85 and B-86, the relative levels of the vehicle are similar for each location, indicating very little interaction between the pavement and vehicle design. As for vehicle groups, there is very little variation in the group level between the two pavements, except for the steering wheel location where the levels are noticeably higher by about 5 dB.

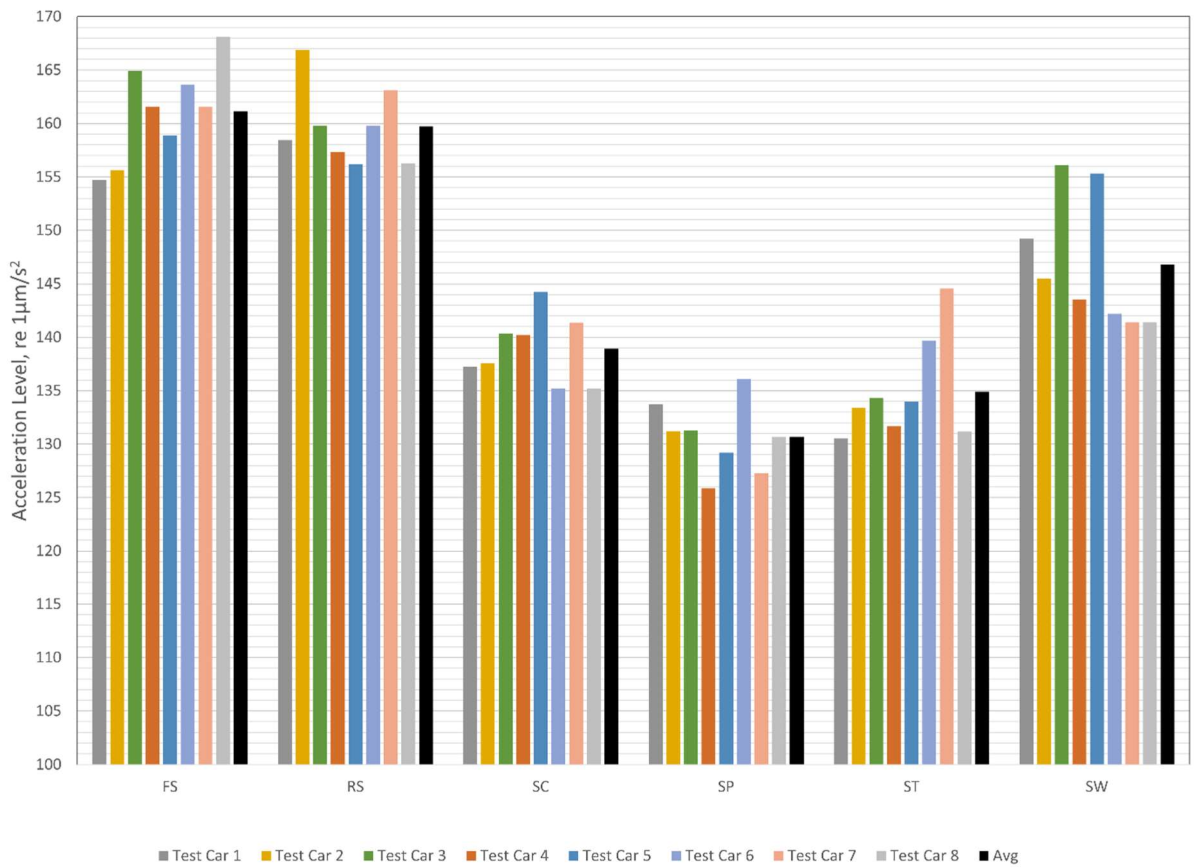


Figure B-83: Overall acceleration levels for all vehicles and summed for all three directions at each measurement location on the mumble strips

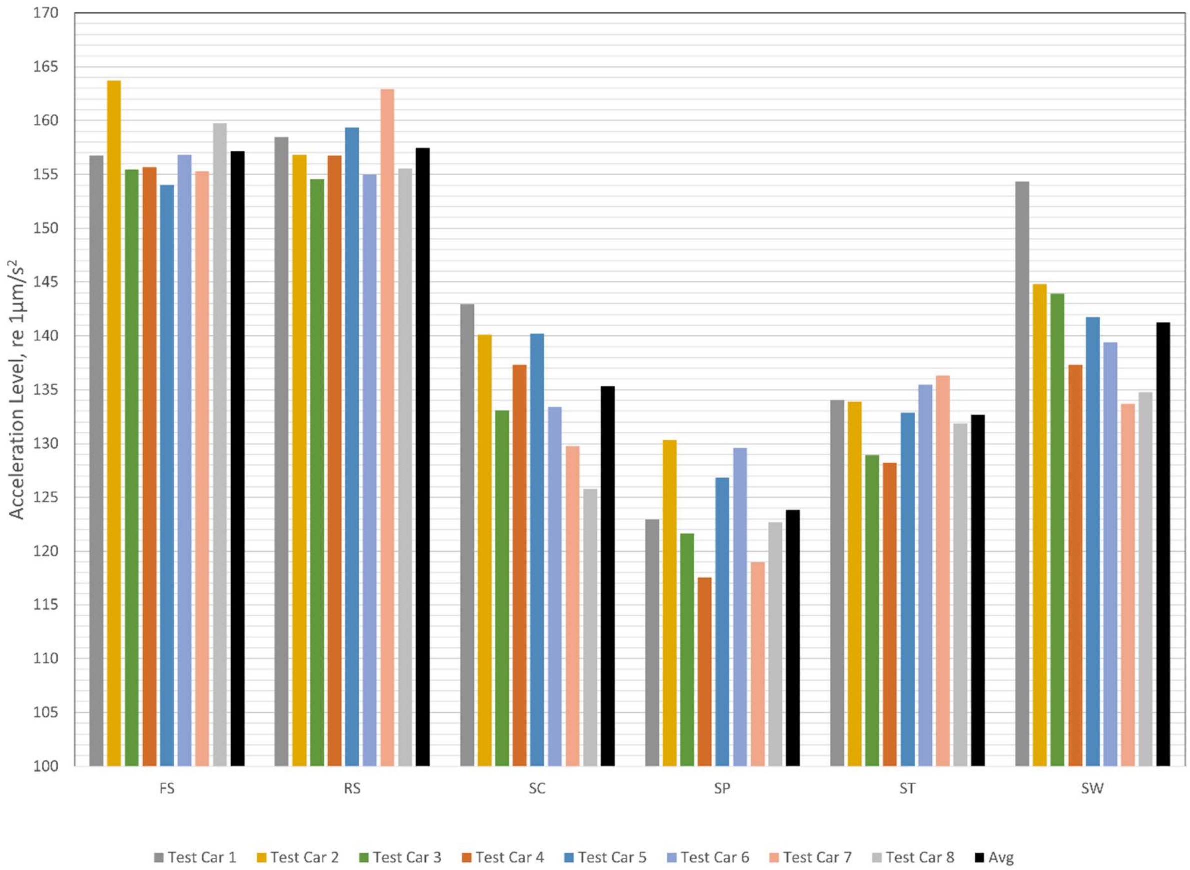


Figure B-84: Overall acceleration levels for all vehicles and summed for all three directions at each measurement location on the conventional ground strips

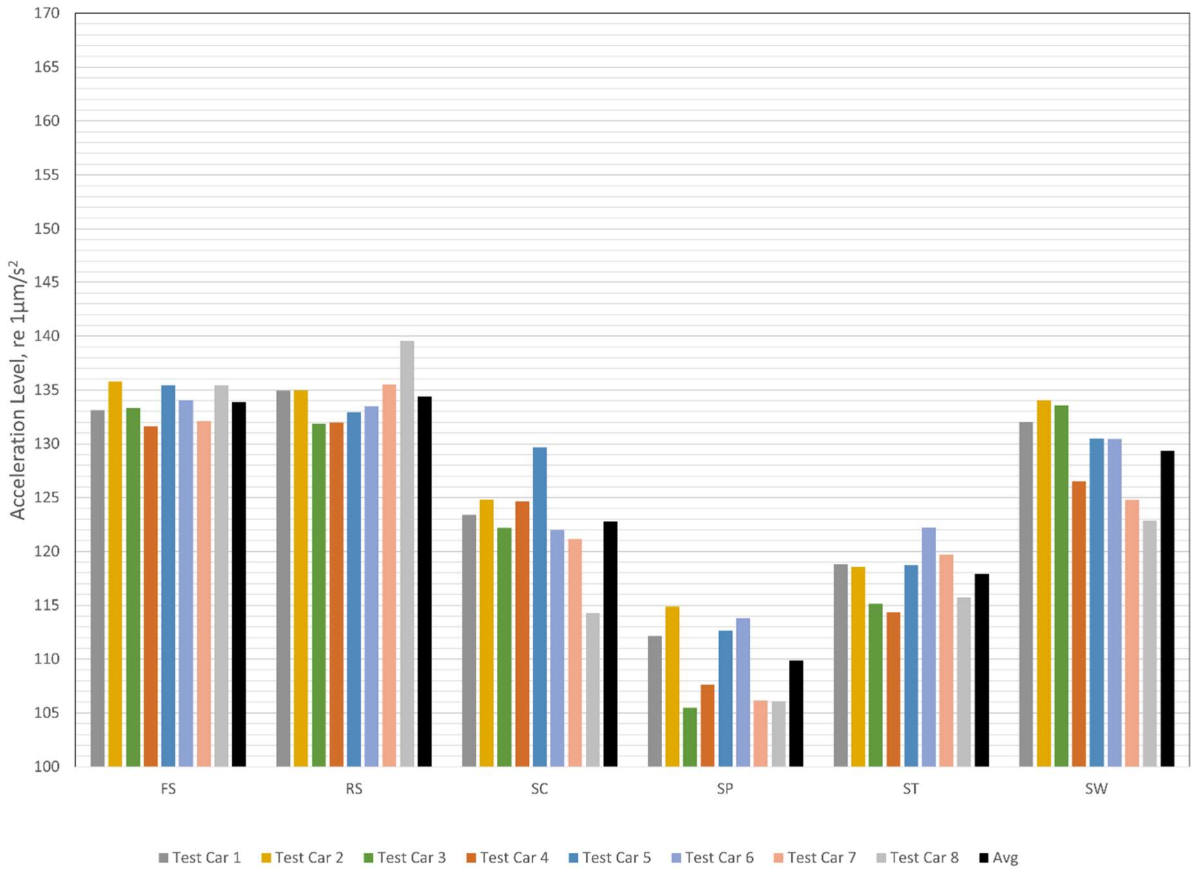


Figure B-85: Overall acceleration levels for all vehicles and summed for all three directions at each measurement location off the mumble strips

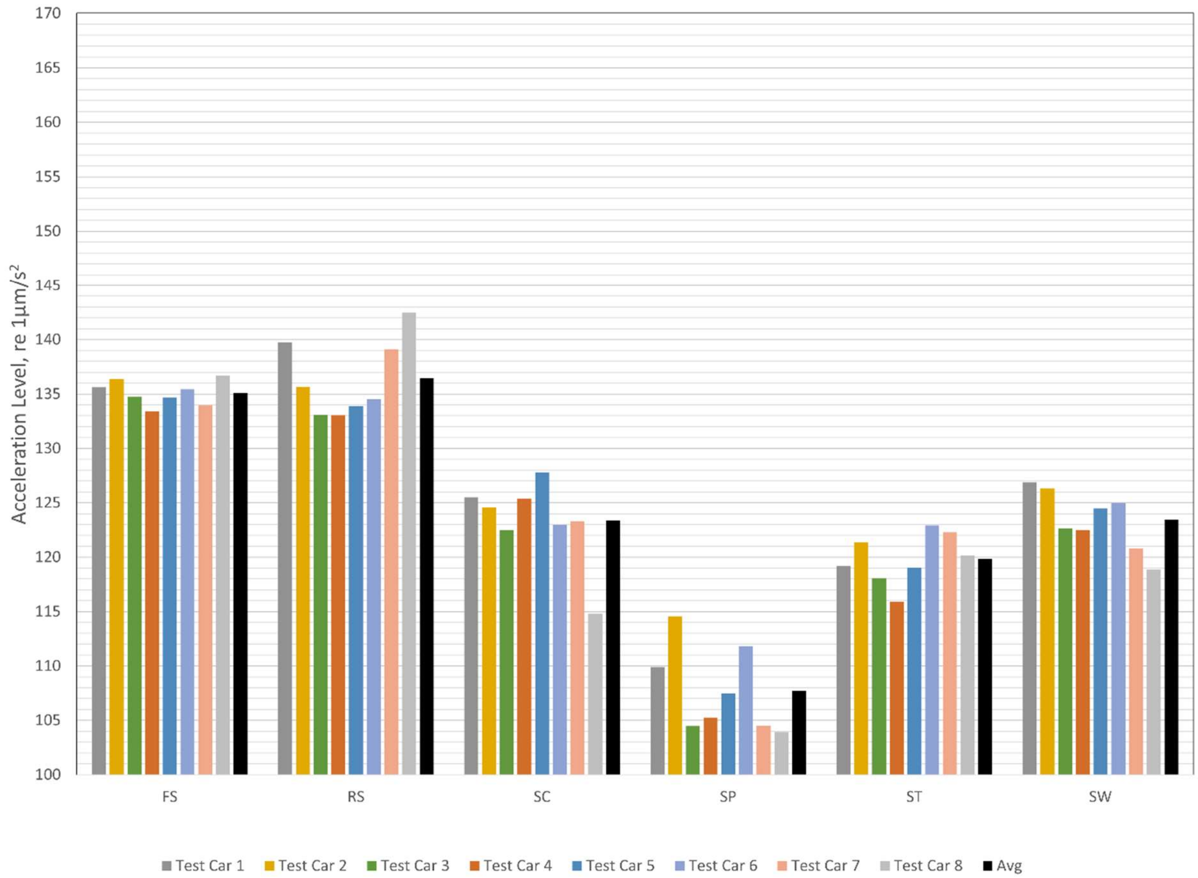


Figure B-86: Overall acceleration levels for all vehicles and summed for all three directions at each measurement location off the conventional ground strips

The on/off increments of the summed levels are shown in Figures B-87 and B-88 for the mumble and conventional strips, respectively. With the exception of the steering wheel results in Test Car 1, the increments for the different locations on the conventional strips are within 5 dB or less across the vehicle designs. For Test Car 1 at the steering wheel location, the difference is about 11 dB. On the mumble strips, the Test Car 1 increment is almost equal to the average. In general, for the mumble strips, the difference between the average and individual vehicles is greater (5 or more dB) for all measurement locations, and there is more vehicle-to-vehicle variation than on the conventional strips.

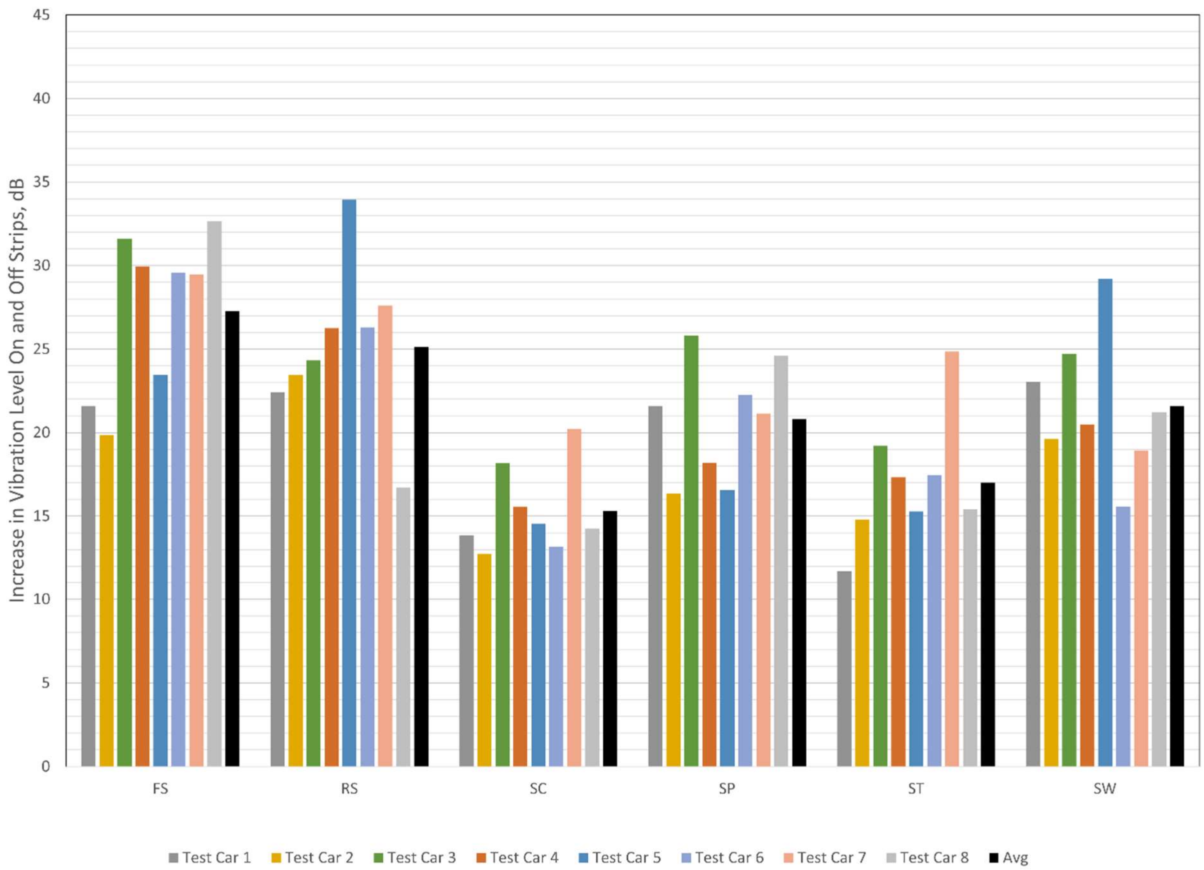


Figure B-87: Difference in level summed for all three directions on and off the mumble strips for all vehicles at each measurement location

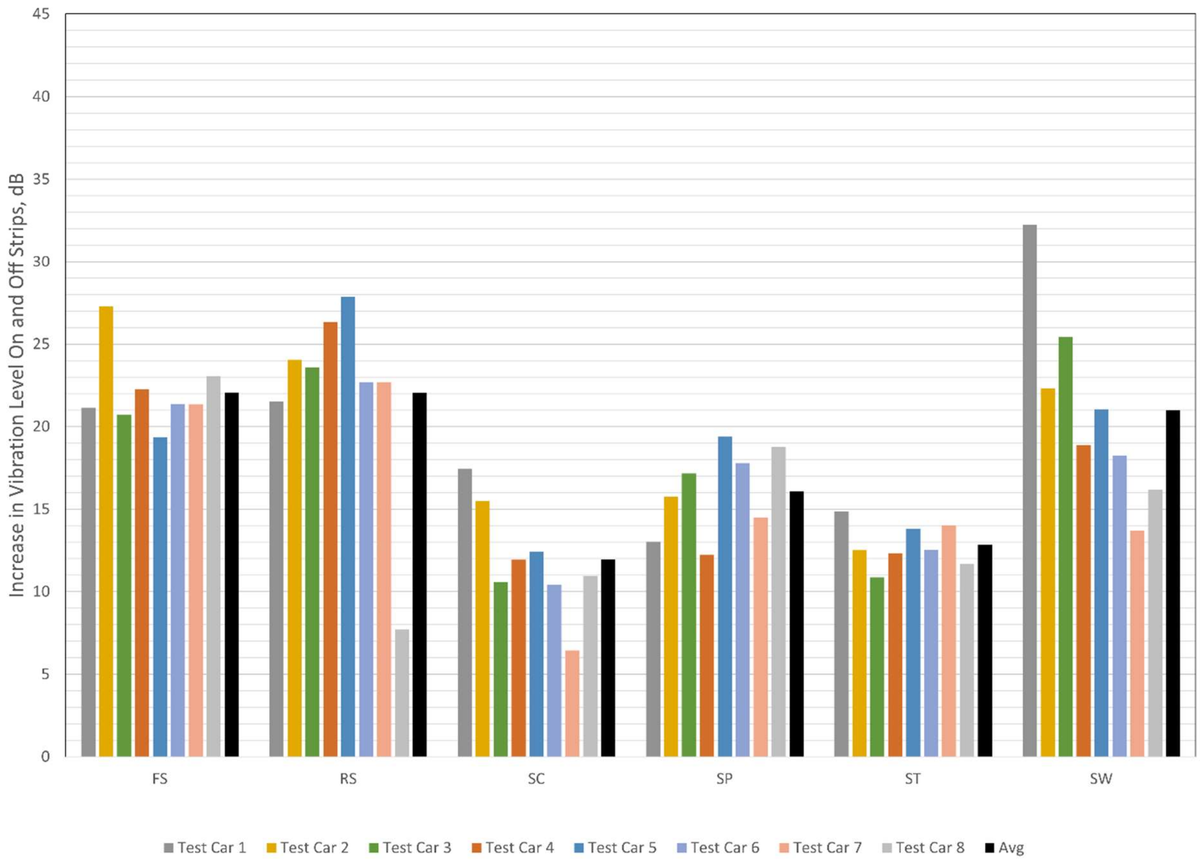


Figure B-88: Difference in level summed for all three directions on and off the conventional ground strips for all vehicles at each measurement locations

The average increments for all measurement locations and for each vehicle are compared in Figure B-89 for the mumble and conventional strips. For six of the eight test vehicles, the on/off increments for the mumble strips are about 4 dB, or more, greater than the conventional ground strips. For the two subcompact cars (Test Car 2 and Test Car 1), the increments are much closer, and the increment for the conventional strip is greater than the mumble strips for Test Car 2. These two vehicles are 500 to 1,000 pounds (lbs) lighter than any of the other vehicles and have the shortest wheelbase (see Table B-1). Due to the higher increment levels for the spindle locations, the averages of increments were also considered without these locations, as shown in Figure B-90. The trends are similar to those of Figure B-89; however, the averages of the increments are lower without the spindle data.

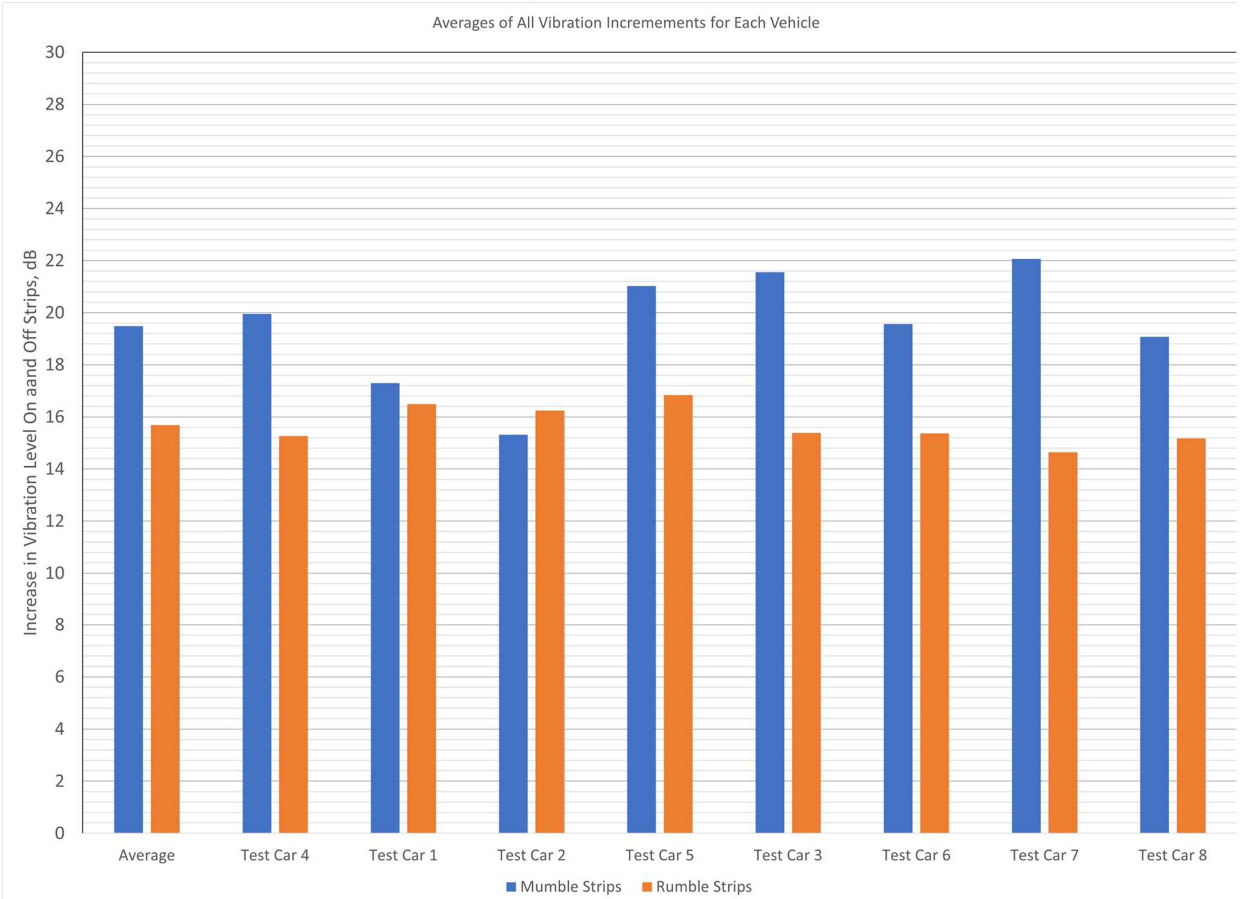


Figure B-89: Difference in level summed for all three directions on and off the mumble and conventional ground strips for all vehicles and averaged for all measurement locations

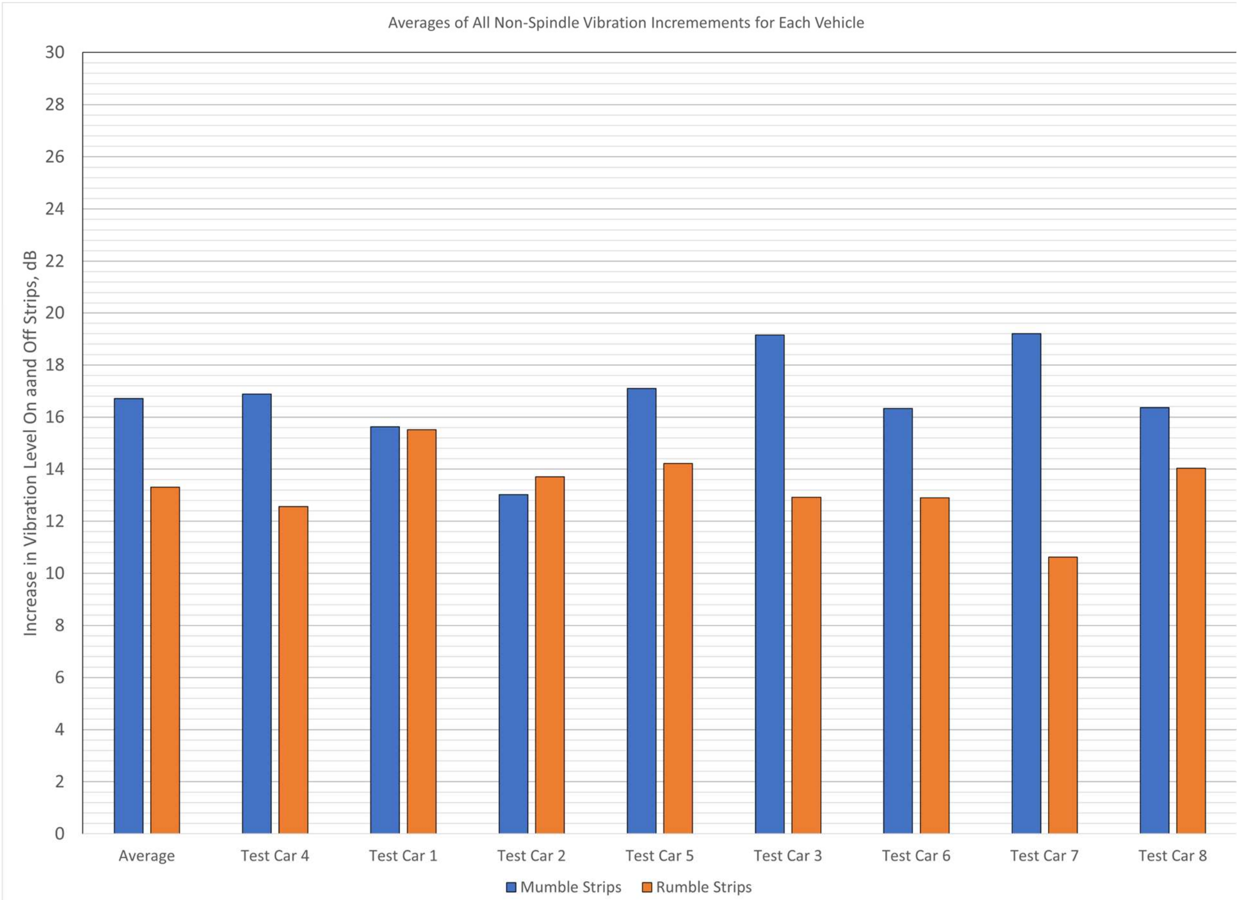


Figure B-90: Difference in level summed for all three directions on and off the mumble and conventional ground strips for all vehicles and averaged for all measurement locations excluding the front and rear spindles

In Figure B-91, the increments for individual measurement locations and directions are presented for those points related to operator inputs from the steering wheel assembly. These are represented by the steering wheel and steering column acceleration increments. For these individual increments, there is considerable variation between the measurement location and directions. Using the results of the summation of the directions at each location from Figures B-87 and B-88, the increments related to operator inputs from the steering wheel are shown in Figure B-92. These increments display some resemblance to the average of all the non-spindle locations shown in Figure B-90; however, there are also significant differences in the relationship between the mumble and conventional strips. For the summation of the steering column directions, as shown in Figure B-93, the results are generally lower in magnitude than the steering wheel location. For Test Car 1 and Test Car 2, the increments for steering wheel are directionally not consistent with the steering column. Compared to the average of increments (Figure B-90), the values for the steering wheel (Figure B-92) are greater in magnitude while those of steering column (Figure B-93) are more comparable.

Figure B-91: Difference in level on and off the mumble and conventional ground strips for all vehicles in each direction at locations related to steering wheel and column, SWx, SWy, SWz, SCx, SCy, and SCz

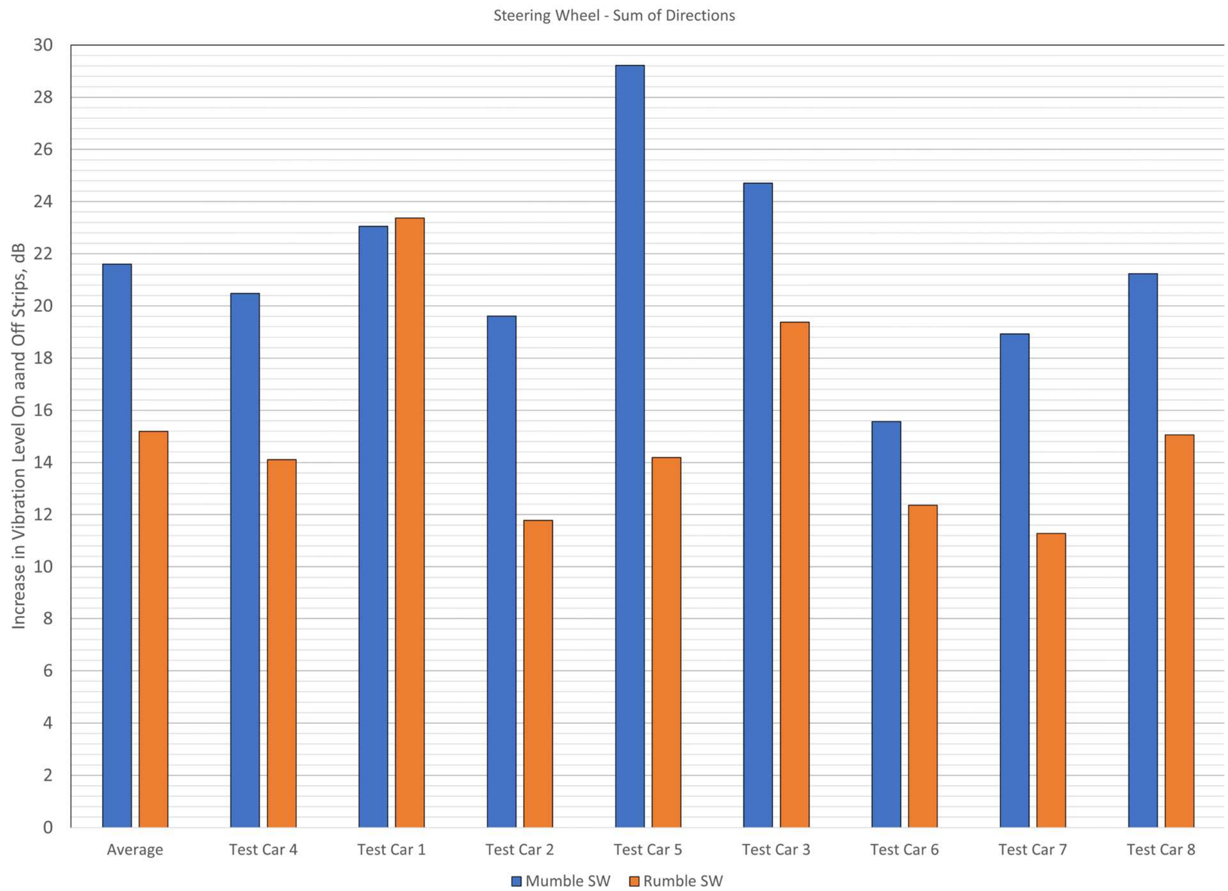


Figure B-92: Difference in level summed for each direction at the steering wheel location on and off the mumble and conventional ground strips for each vehicle

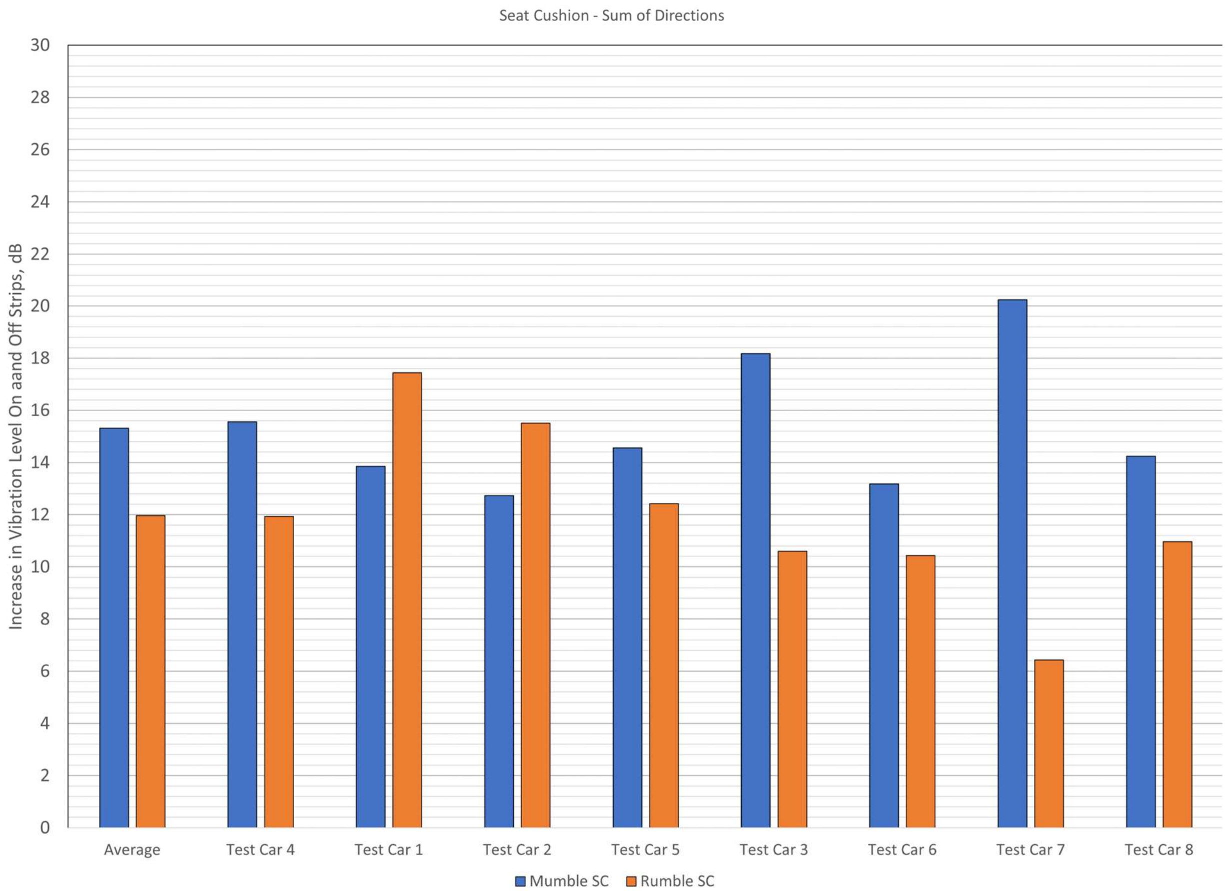


Figure B-93: Difference in level summed for each direction at the steering column location on and off the mumble and conventional ground strips for each vehicle

The increments for the locations and directions related to the seated operator are shown Figure B-94, as represented by the seat pad and the seat track data. Similar to the inputs relative to the steering wheel, these display considerable variation between the measurement locations and directions. Of all the locations shown in Figure B-94, the seat pad in the fore/aft direction provide best representation of the trends of Figure B-90. The summations for the seat pad and seat track locations are shown in Figures B-95 and B-96, respectively. Both locations provide a good representation of the results of Figure B-90, except for Test Car 1 and Test Car 2, where the mumble and conventional strip increment differences are about 2 to 3 dB different than the total increment average.

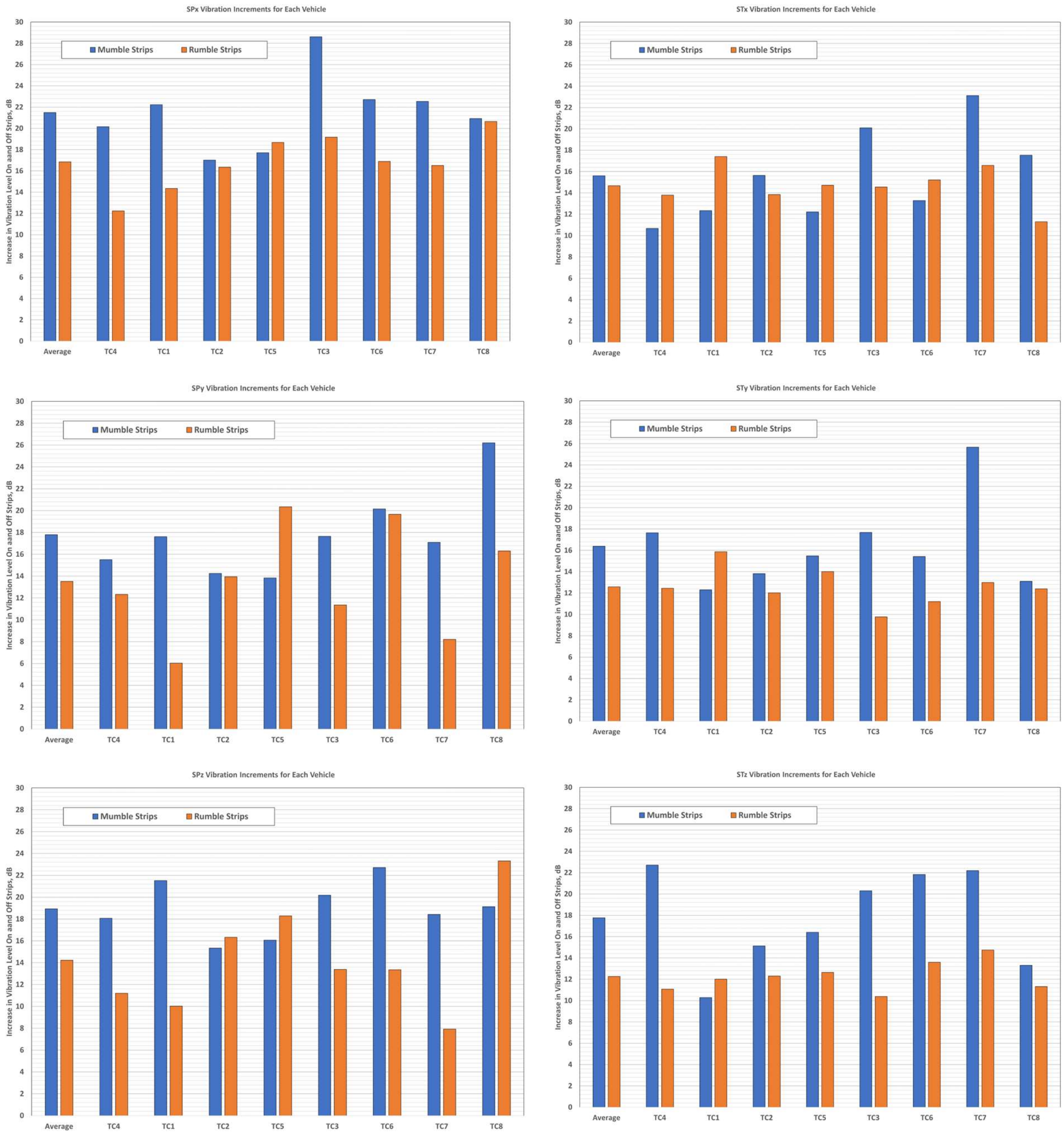


Figure B-94: Difference in level on and off the mumble and conventional ground strips for all vehicles in each direction at locations related to seated operator input, STx, STy, STz, SPx, SPy, and SPz

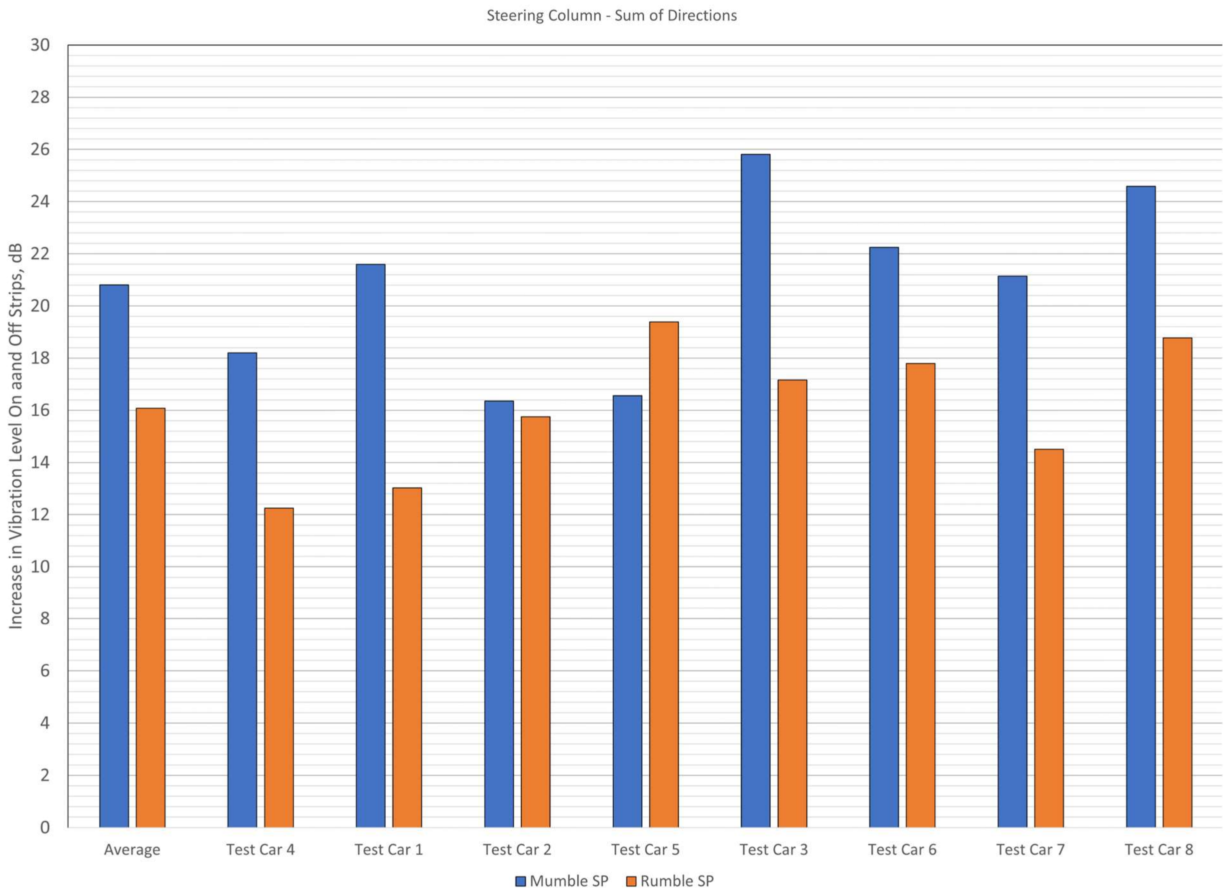


Figure B-95: Difference in level summed for each direction at the seat pad location on and off the mumble and conventional ground strips for each vehicle

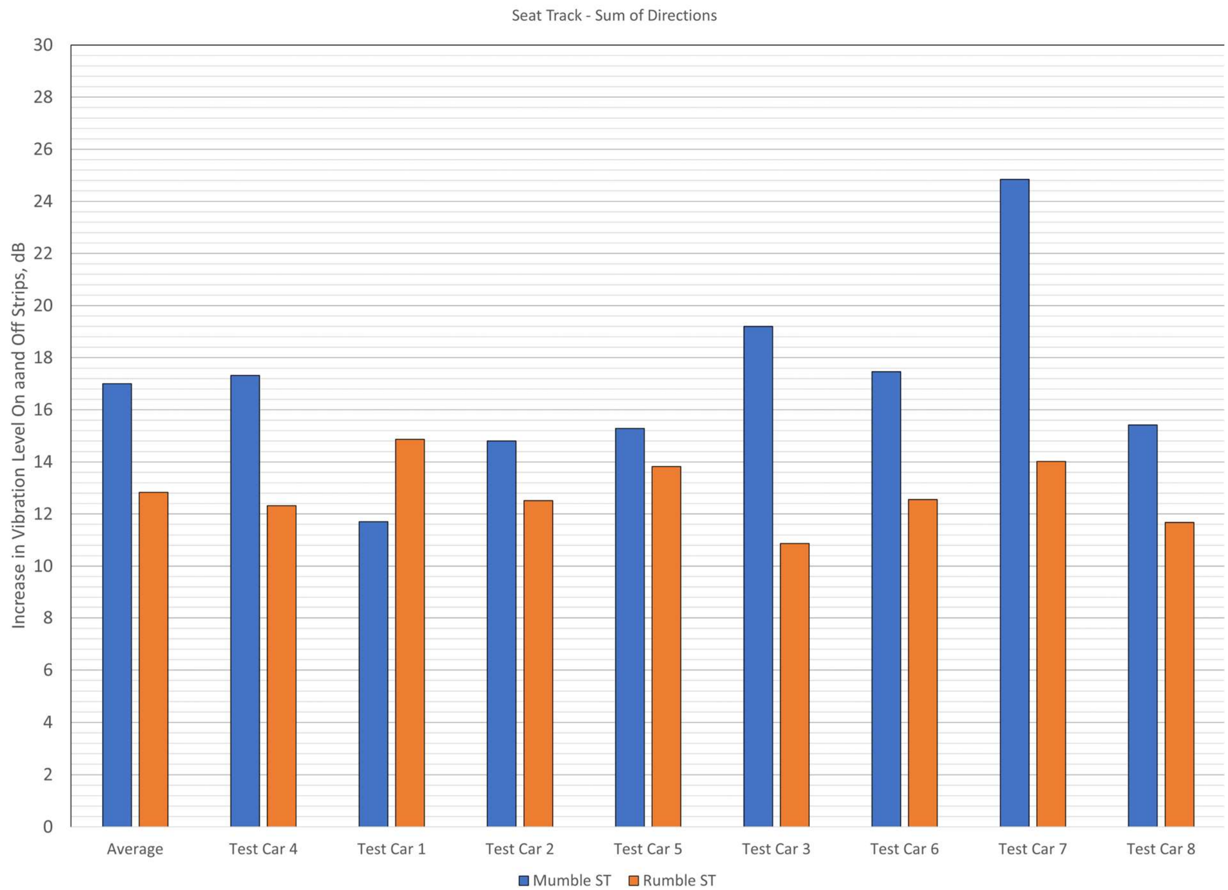
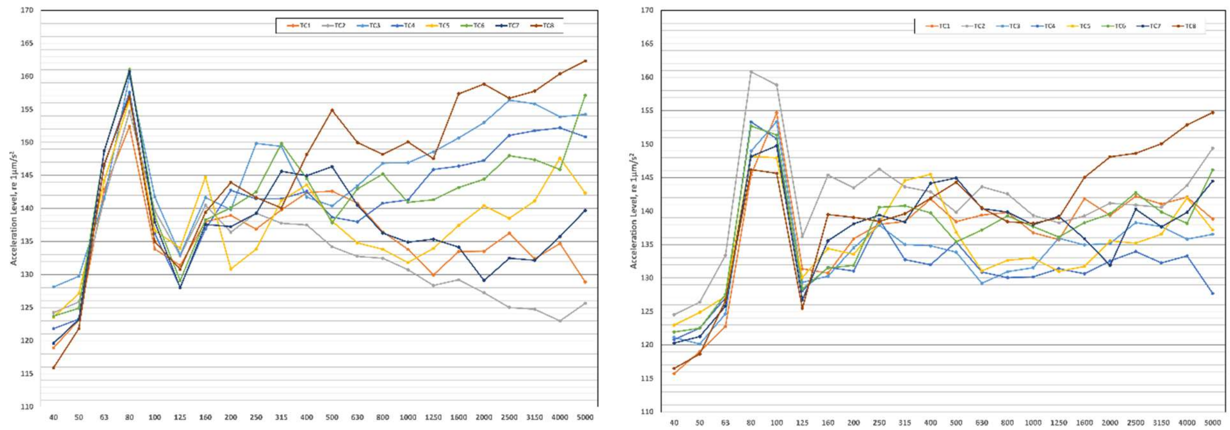


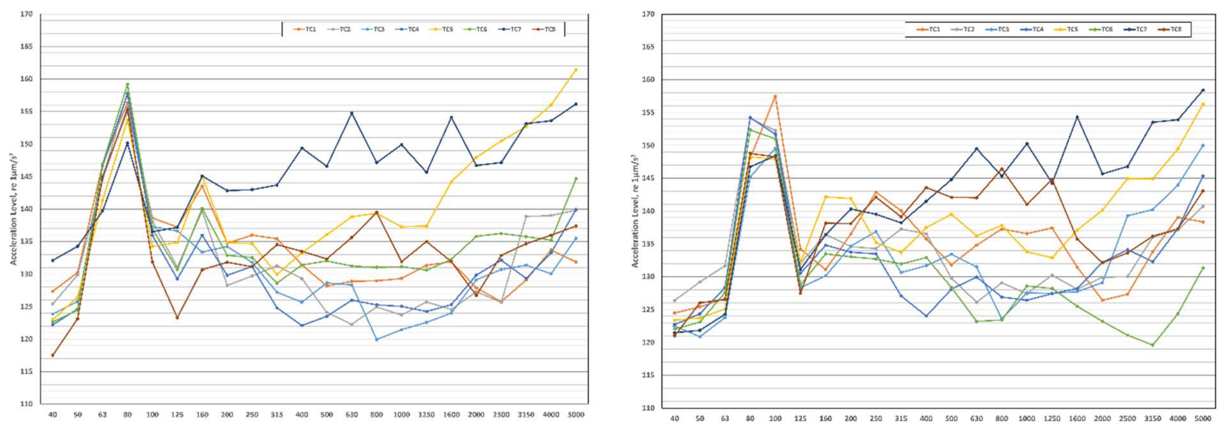
Figure B-96: Difference in level summed for each direction at the seat track location on and off the mumble and conventional ground strips for each vehicle

Spectra for the eight test vehicles on the mumble and conventional strips are shown in Figure B-97 for the front spindle where each spectrum is the summation of three directions. These spectra demonstrate the expected behavior with peaks at 80 Hz for the mumble strips and a split between 80 and 100 Hz for the conventional strips based on the repetition rate of strip features at 60 mph. For up to the 200 Hz one-third octave band, the levels for the mumble strips are 8 dB different from each other provided a defined peak at 80 Hz. At 200 Hz and above, the levels for the different vehicles diverge from each other by as much as 37 dB at 5,000 Hz, as noted above. On the conventional strips, this divergence begins at 125 Hz and is typically 10 to 15 dB up to 1,250 Hz and then diverges up to about 27 dB. Also, on the conventional strips, there is a larger range in the levels at the repetition rate frequencies than there is for the mumble strips. The spectra for the rear spindle are shown in Figure B-98. These are generally similar to the front spindle data without as much variation in the levels at the passage frequencies on the conventional strips.



(a) mumble strips *(b) conventional ground strips*

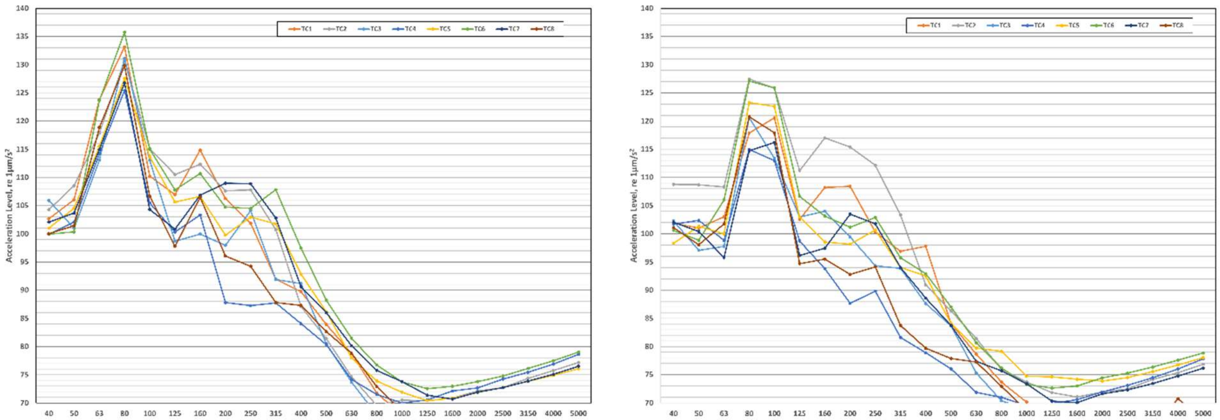
Figure B-97: One-third octave band spectra for the front spindle locations on (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

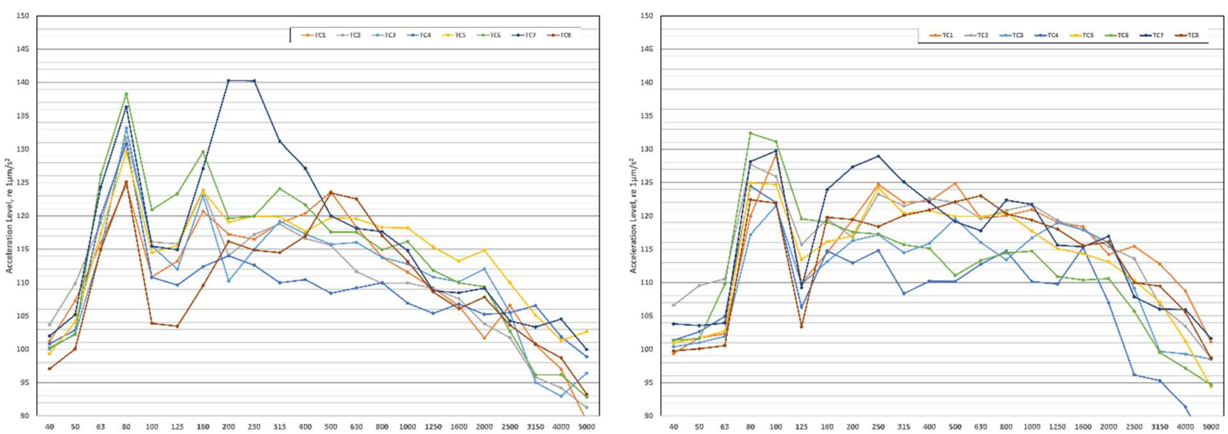
Figure B-98: One-third octave band spectra for the rear spindle locations on (a) mumble strips and (b) conventional ground strips

Spectra for the seat pad location are shown in Figure B-99. For this location, the variation in level at the repetition rate frequency is smaller than other locations: less than 10 dB for the mumble strips and 12 dB for the conventional strips. The levels fall very rapidly with frequency compared the other locations, indicating that the seat provides additional vibration isolation. This is particularly apparent in comparison to the seat track location spectra shown in Figure B-100. At the repetition rate frequencies on both strips, the difference between vehicles is greater than it is for the seat pad location: about 13 dB for the mumble strips and 15 dB for the conventional strips. The spectrum of Test Car 7 between 200 and 400 Hz is also of interest. On the mumble strips, Test Car 7 produces levels that are 20 to 30 dB greater than any of the other vehicle. Higher levels are also noted on the conventional strips, but the differences are not so pronounced. This behavior may be related to the structure of the vehicle as it is the only van included in the eight vehicles. The seat pad location also displays broad, elevated levels in this same frequency range. At the repetition rate frequencies, Test Car 7 produces higher levels than the other vehicles except for Test Car 6.



(a) mumble strips *(b) conventional ground strips*

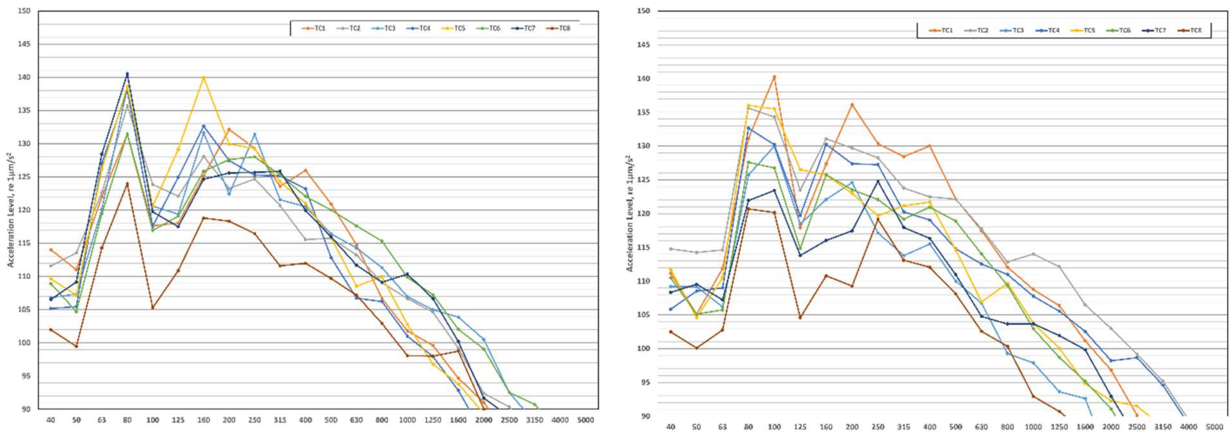
Figure B-99: One-third octave band spectra for the seat pad locations on (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

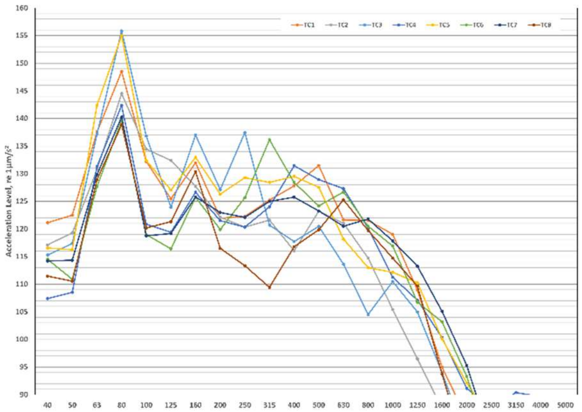
Figure B-100: One-third octave band spectra for the seat track locations (a) mumble strips and (b) conventional ground strips

Spectra for the steering column location are shown in Figure B-101. For this location, greater differences between the vehicles are apparent at the repetition frequencies. On the mumble strips, the difference at 80 Hz is more than 15 dB, with the levels for Test Car 8 being consistently lower at 80 Hz and at higher frequencies up to 630 Hz. This is likely due to the additional isolation from road inputs typical of full-frame vehicles as the body has additional isolators between the frame and body that are not present on the other unibody designs. On the conventional strips, there is also a large range in the levels, with the greatest difference of about 20 dB at 100 Hz. The levels for Test Car 8 are again lower than or equal to the other vehicles. For the steering wheel location shown in Figure B-102, the variation at the strip repetition rate is also large and similar the steering column location, with a range of 16 dB on the mumble strips and 26 dB on the conventional strips. In the higher frequencies, above 125 Hz, there is more variation in the levels on the steering wheel than on the steering column. This could be due to the response the modal behavior of the steering wheels themselves. For both steering system locations, the spectrum levels drop off more rapidly than the seat track location beginning at about 800 Hz indicating some additional isolation from the suspension inputs.

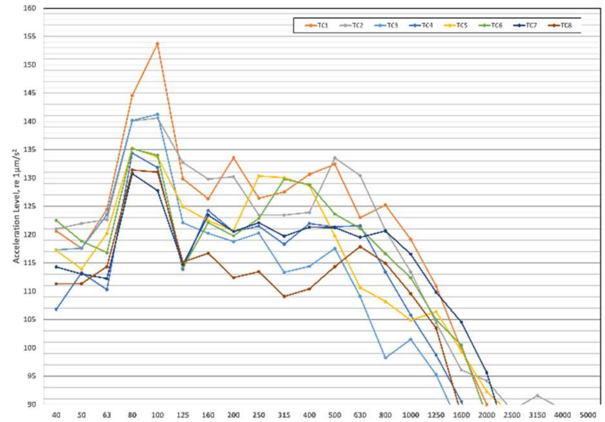


(a) mumble strips *(b) conventional ground strips*

Figure B-101: One-third octave band spectra for the steering column locations on (a) mumble strips and (b) conventional ground strips



(a) mumble strips



(b) conventional ground strips

Figure B-102: One-third octave band spectra for the steering wheel locations on (a) mumble strips and (b) conventional ground strips

Speed Dependence

The overall levels at 45 mph are shown in Figures B-103 and B-104 for the mumble and conventional strips, respectively. In comparison to the levels at 60 mph, the overall appearance of the results in terms of the relative levels for the various locations are similar, although the magnitudes of the levels are lower at 45 mph. For the slower speed, however, the outstandingly higher levels tend to occur in Test Car 8 and Test Car 5 and not Test Car 1 and Test Car 2. It should be noted that Test Car 7 was not measured at 45 mph and no steering wheel data was collected.

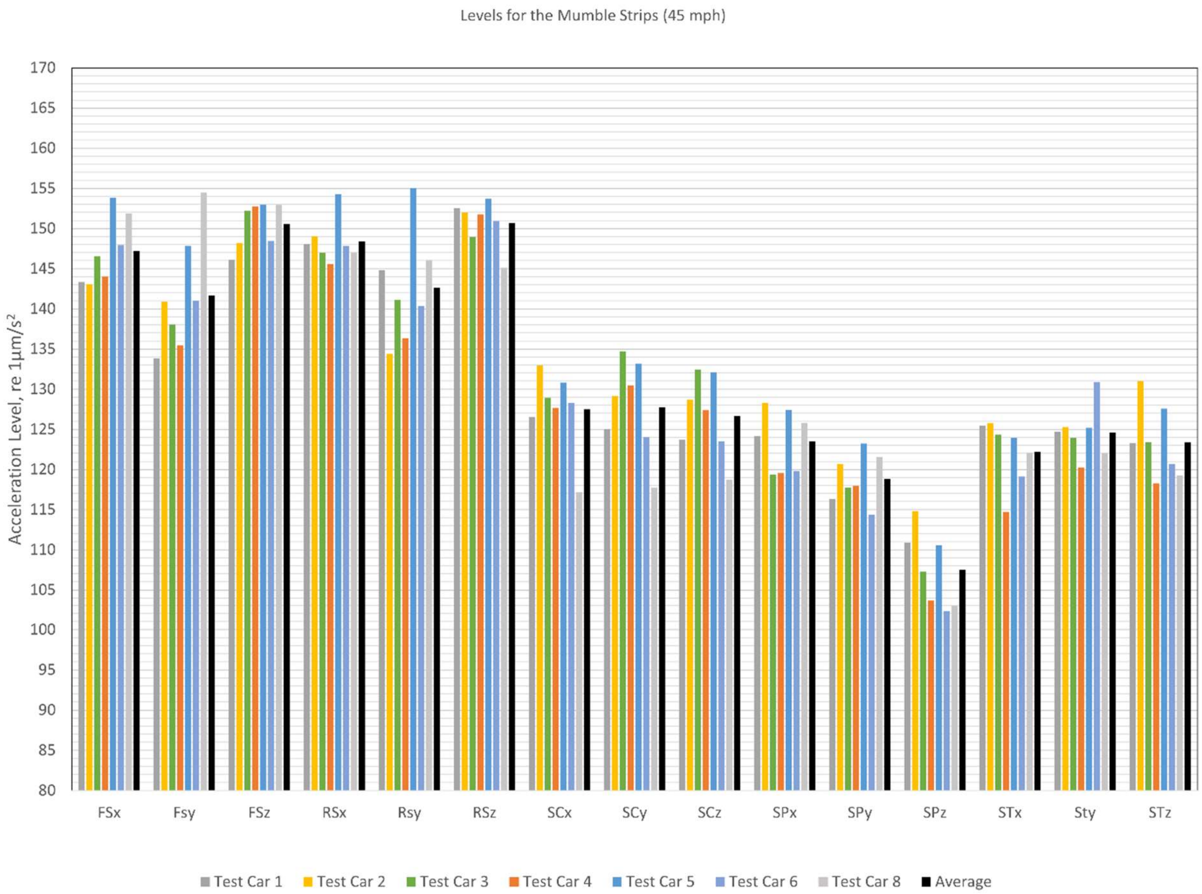


Figure B-103: Overall acceleration levels for all vehicles and measurement locations on the mumble strips at 45 mph

The summations of the acceleration levels for each directional vector, which yields a less complex plot of the results, are shown in Figures B-105 and B-106 for the mumble and conventional strips, respectively, at 45 mph for comparison to the results at 60 mph. For 45 mph, the difference between the vehicles at any one location tend to be slightly less than the corresponding data at 60 mph. The rank ordering of the vehicles from each location do vary somewhat with speed, e.g., at 45 mph on the mumble strips, the levels for Test Car 2 at the rear spindle are the highest of that group at 60 mph, while at 45 mph, Test Car 5 produces the highest level. Similar differences occur in comparing the conventional strip results in Figures B-106 to the 60 mph data.

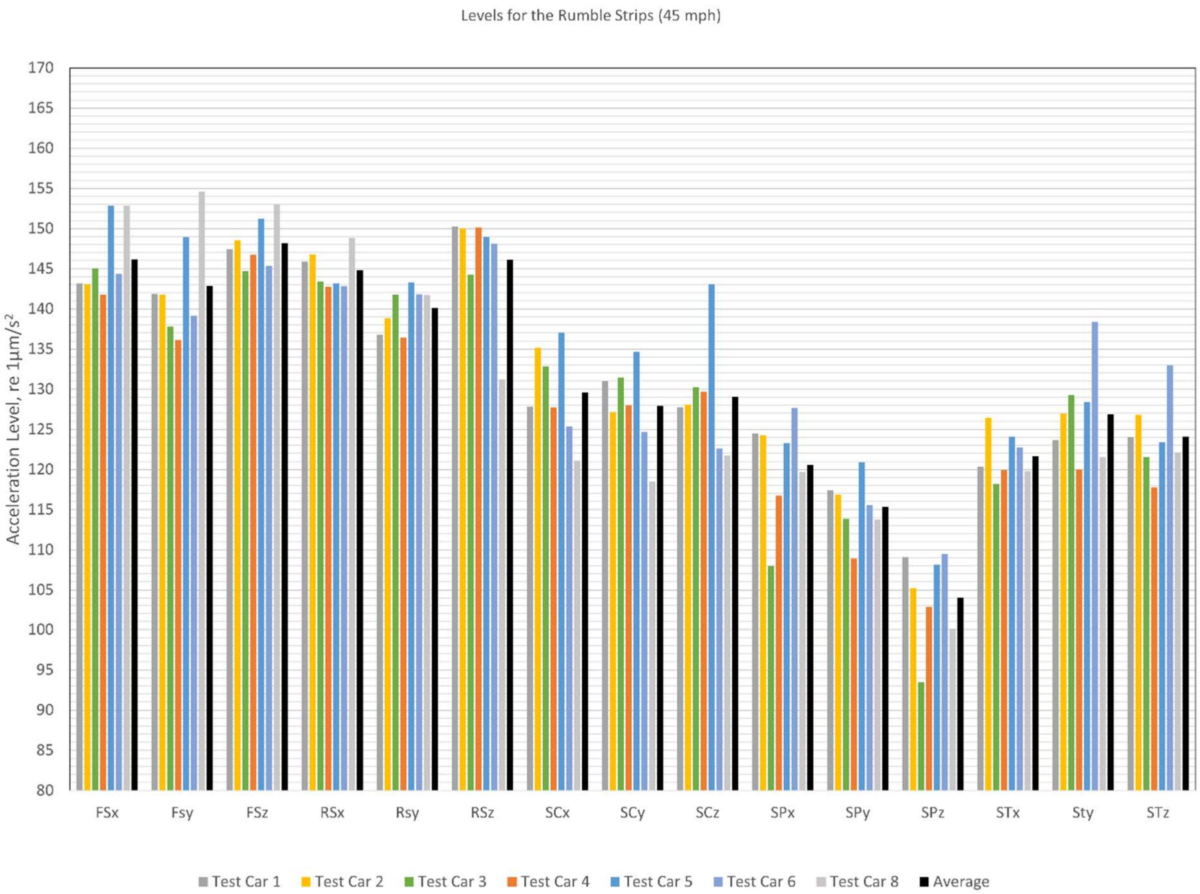


Figure B-104: Overall acceleration levels for all vehicles and measurement locations on the conventional ground strips at 45 mph

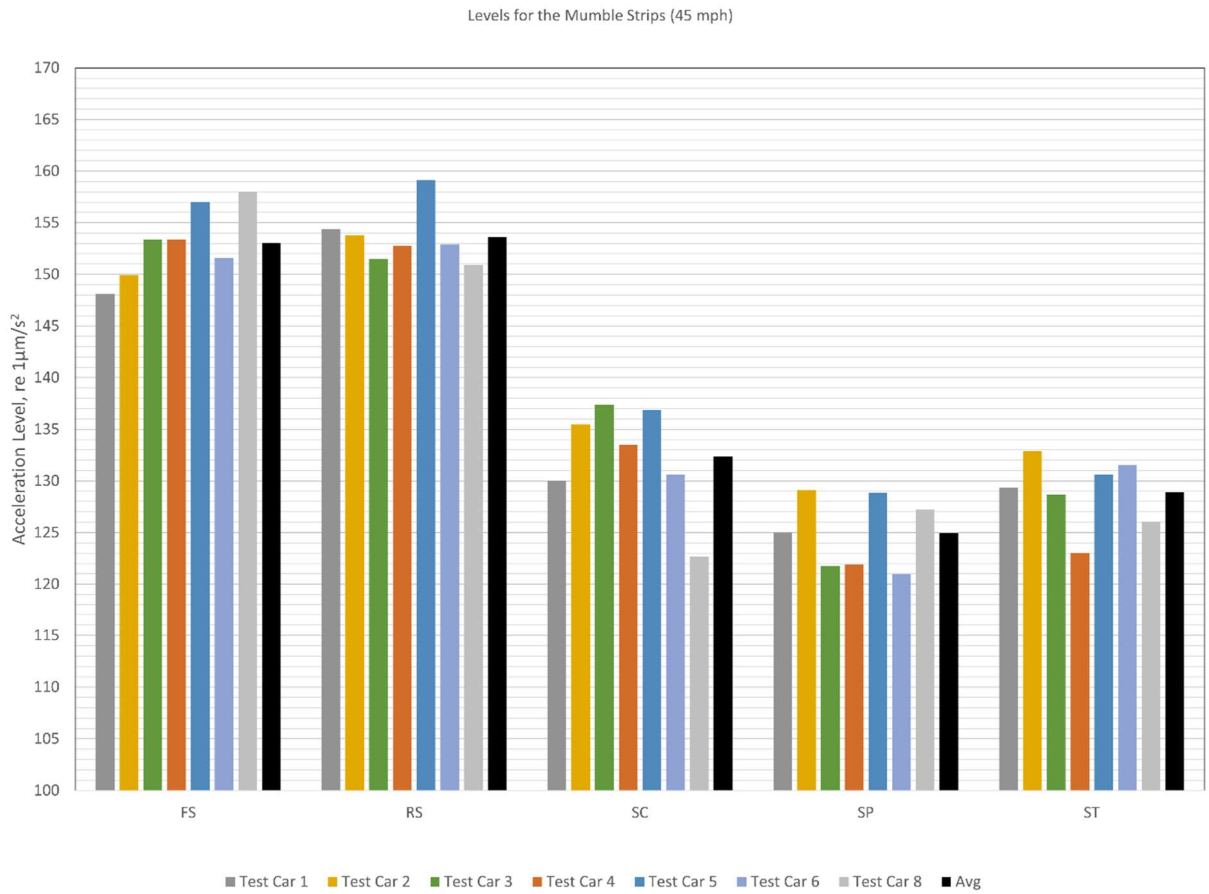


Figure B-105: Overall acceleration levels for all vehicles and summed for all three directions at each measurement location on the mumble strips

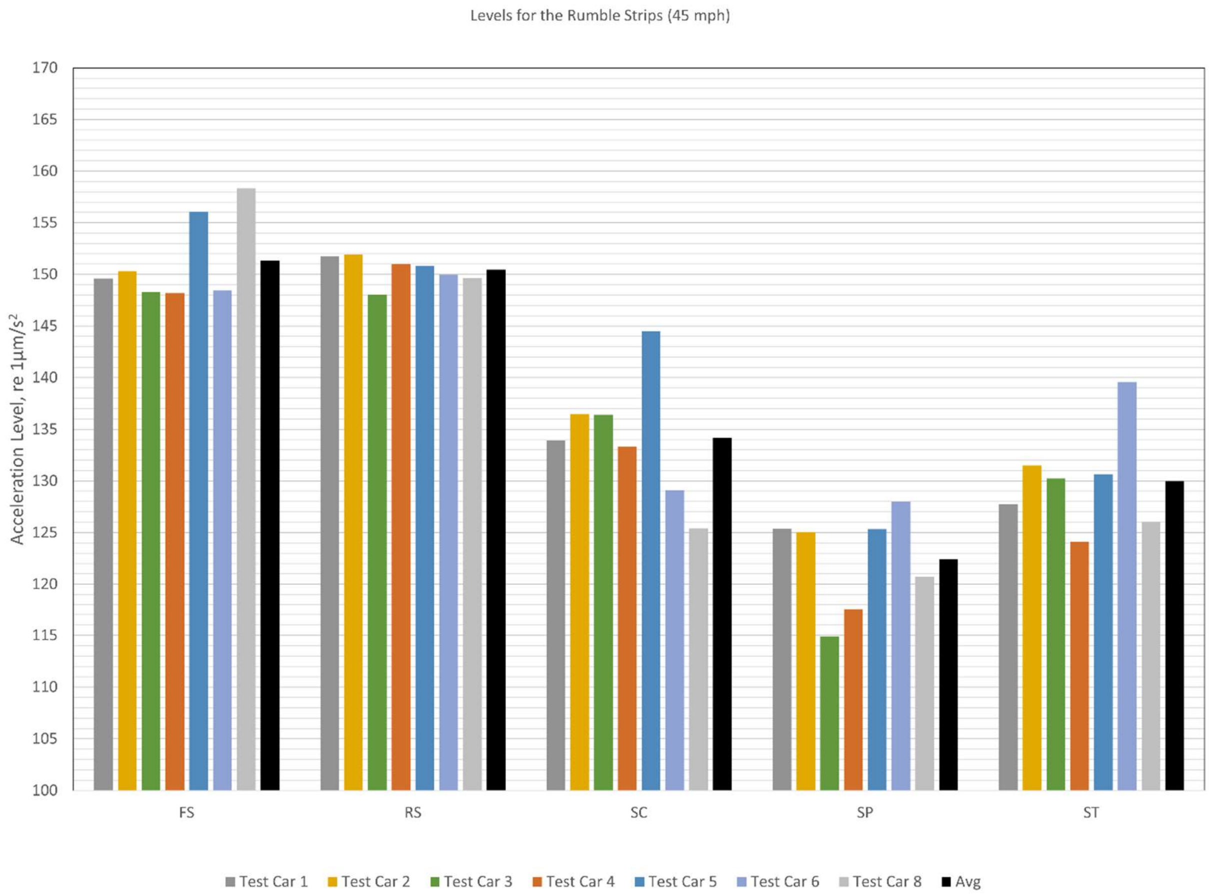


Figure B-106: Overall acceleration levels for all vehicles and summed for all three directions at each measurement location on the conventional ground strips

The increments for the 45 mph on and off the strips are shown in Figure B-107 and B-108 for the mumble and conventional strips, respectively. In comparison to the 60 mph results, the increments at 45 mph are generally less than those at 60 mph; however, the characteristics are similar in comparison of the rank ordering of the measurement locations. Also, the variation in the increments at any one location is somewhat less at 45 mph than those at 60 mph.

Increments for the summed levels on and off the strips at 45 mph are shown in Figures B-109 and B-110 for the mumble and conventional strips, respectively. For the mumble strips, the increments are lower at 45 mph than 60 mph by typically 4 to 6 dB on average for all locations except the seat track where the difference is only about 1 dB. This presentation of the results also indicates the variation from vehicle-to-vehicle is less at 45 mph. For the conventional strips shown in Figure B-110, the 45 mph increments are also lower than those for 60 mph, however, ranging -1 to 4 dB. It should be noted that the increments for the non-spindle locations have low values; that is, some are less than 10 dB.

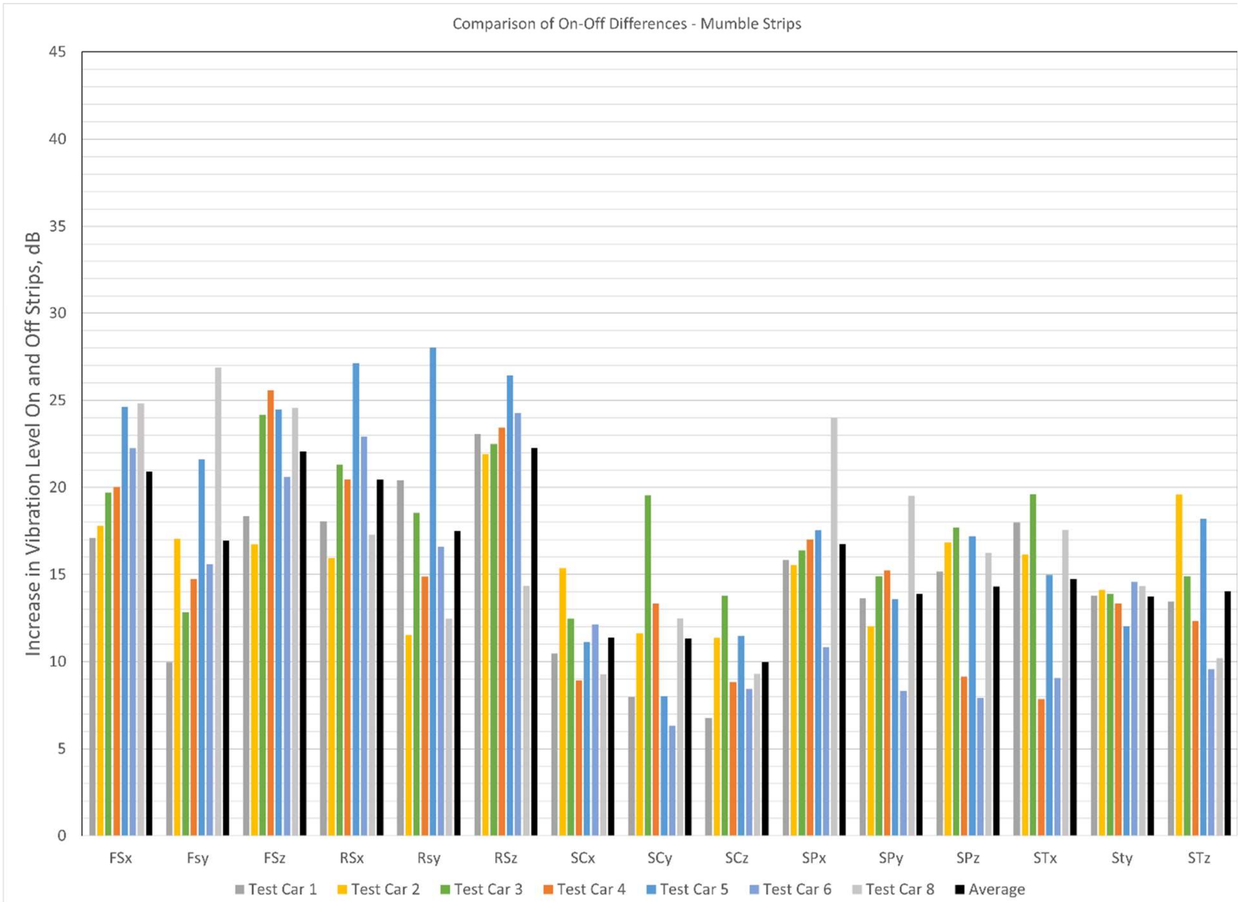


Figure B-107: Difference in level on and off the mumble strips for all vehicles and measurement locations at 45 mph

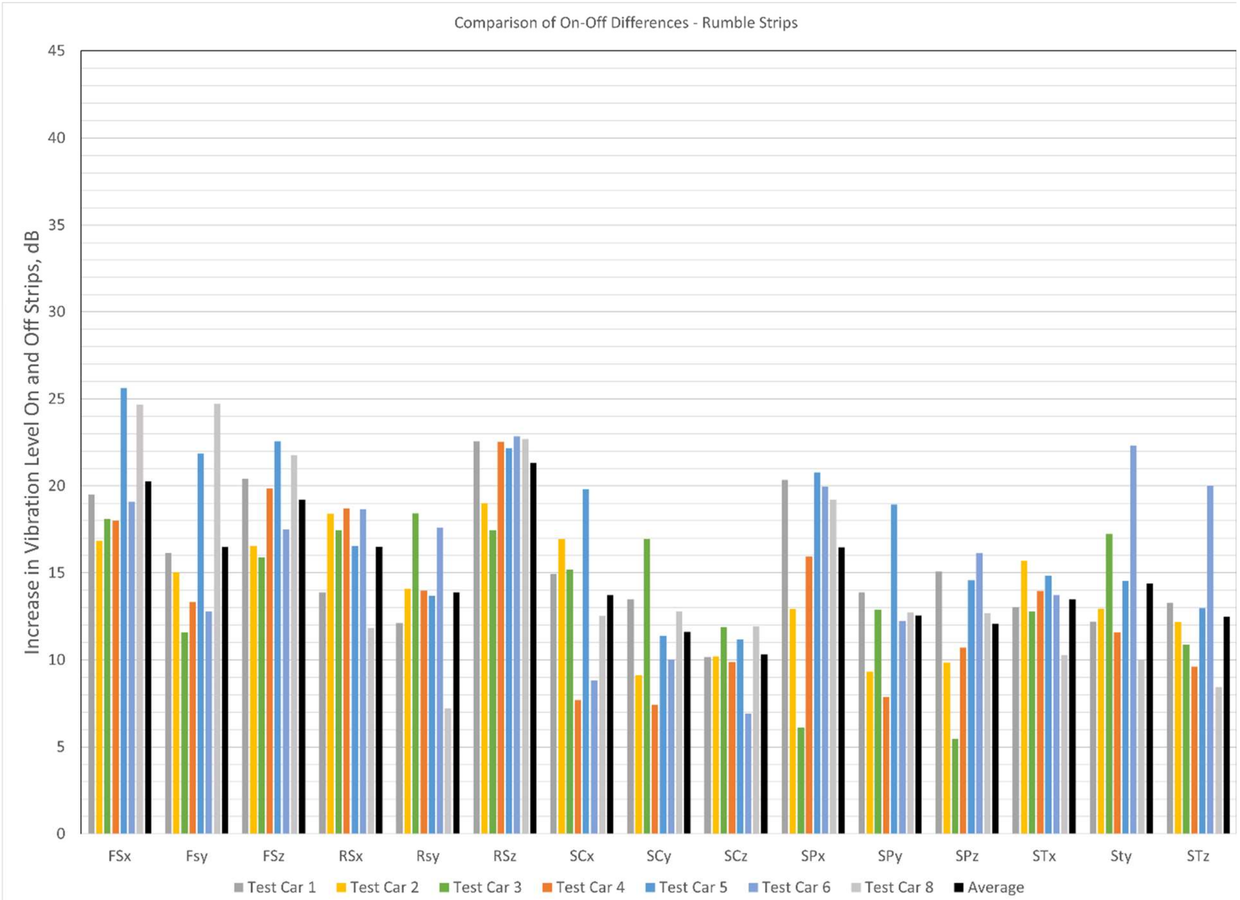


Figure B-108: Difference in level on and off the conventional ground strips for all vehicles and measurement locations at 45 mph

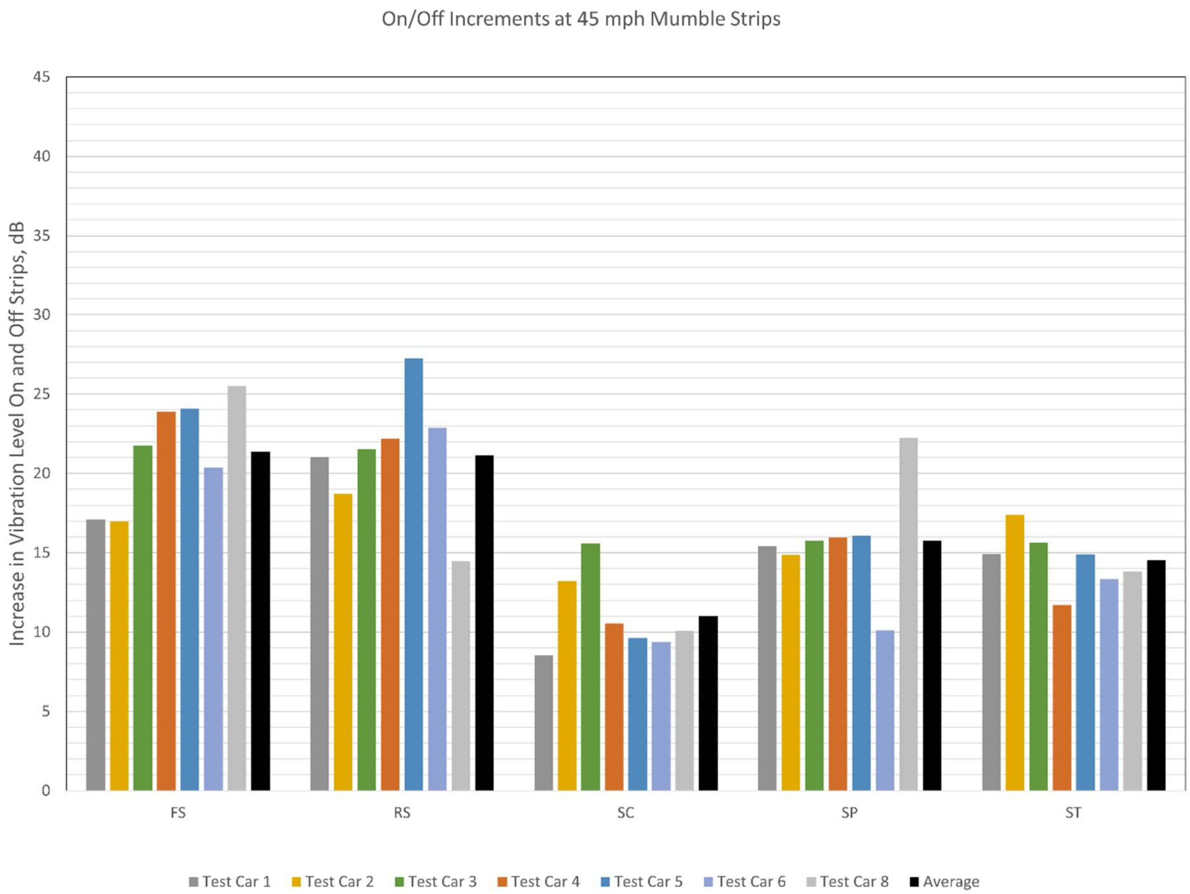


Figure B-109: Difference in level summed for all three directions on and off the mumble strips for all vehicles at each measurement location at 45 mph

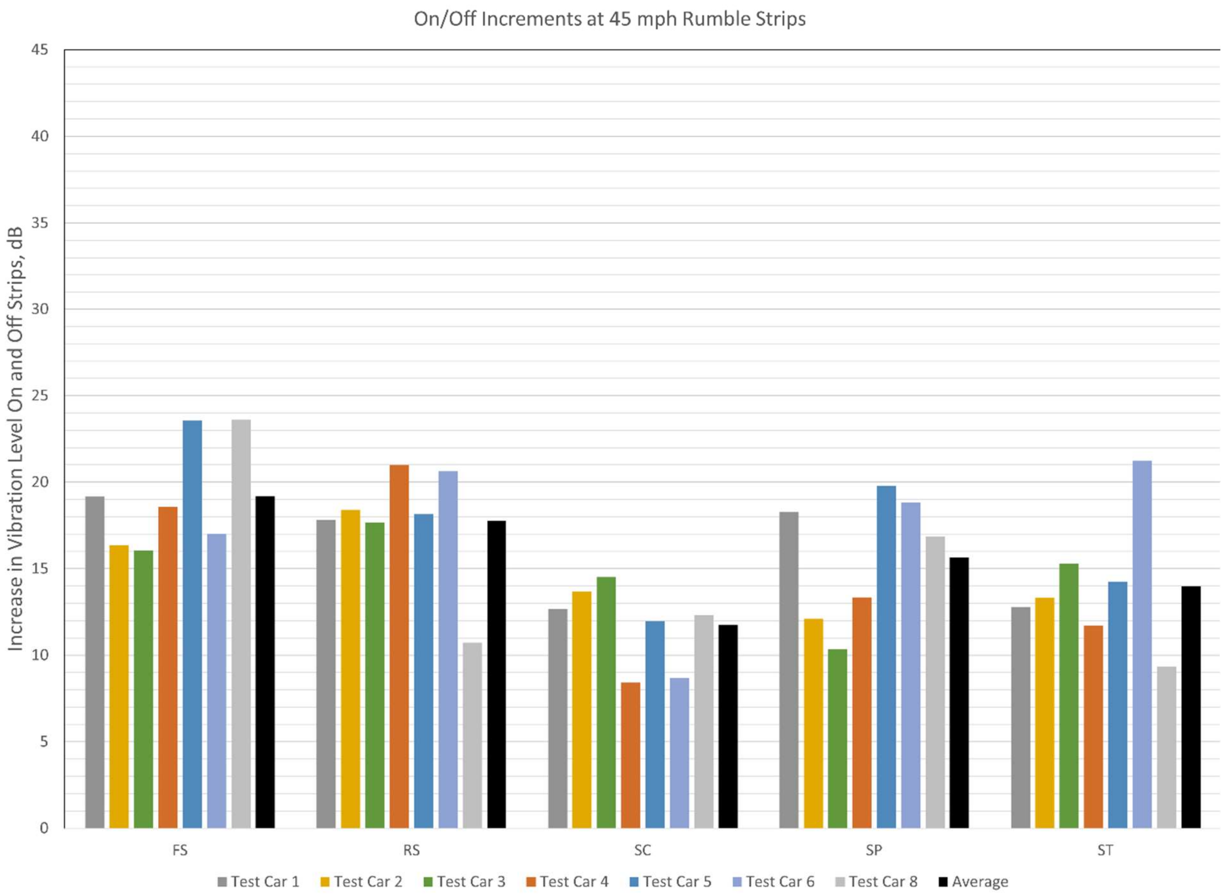


Figure B-110: Difference in level summed for all three directions on and off the conventional ground strips for all vehicles at each measurement location at 45 mph

On and off spectra for mumble strips are shown in Figure B-111 for 60 and 45 mph, as summed for the directions of the seat track acceleration for Test Car 4. These data illustrate the shift in repetition rate frequency between the speeds. At 60 mph, the repetition rate generates a peak in the 80 Hz band (only), while at 45 mph, the repetition rate is split between the 50 and 63 Hz bands. The first harmonic of the repetition rate is apparent in the 160 Hz band at 60 mph, while at 45 mph, it is split between 100 and 125 Hz band. Beginning at 250 Hz, the spectra are more broadband for both speeds; however, the level difference in these frequency bands between 60 and 45 mph is large, as much as 10 to 13 dB. A similar spectral comparison for the conventional strips is shown in Figure B-112. For these strips, the repetition at 60 mph is 88 Hz, which falls between the 80 and 100 Hz one-third octave bands. However, at 45 mph, the rate is 66 Hz, which falls completely in the 63 Hz one-third octave band, producing the peak at 63 Hz. The harmonic at 45 mph then falls in the 125 Hz one-third octave band. Above 315 Hz, the conventional strips produce higher vibration levels at 60 mph; however, they are only 5 dB or less and not as much as the mumble strips.

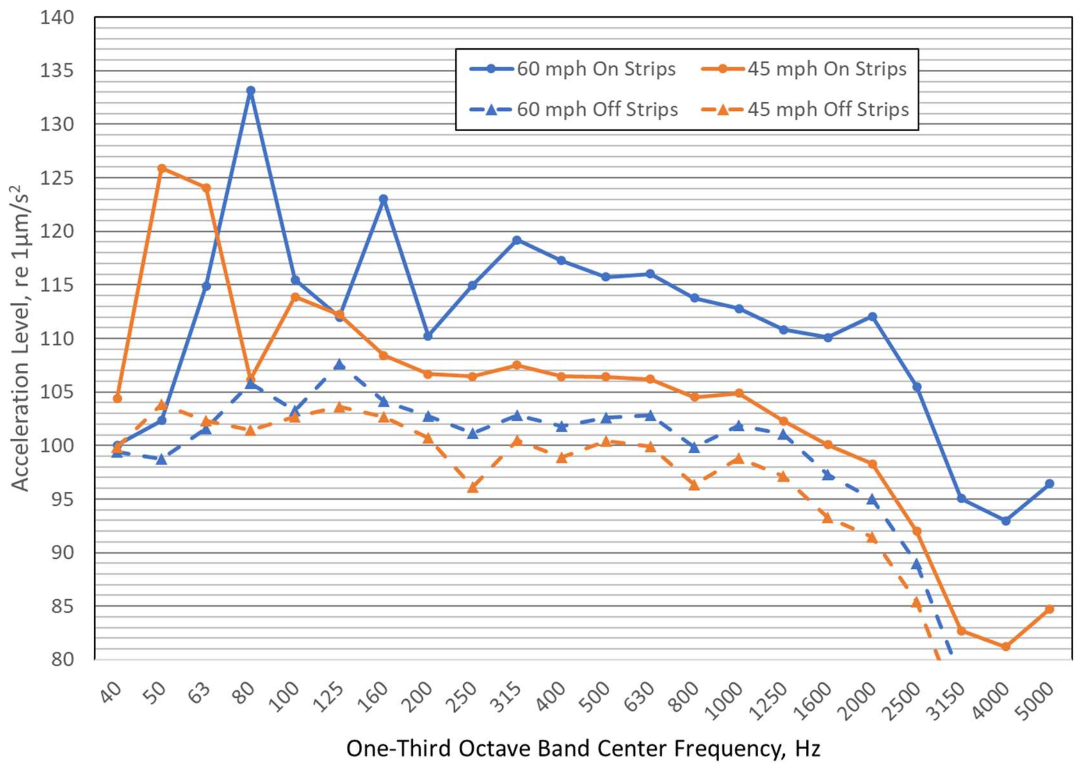


Figure B-111: One-third octave band spectra for the summed seat track locations on mumble strips at 45 and 60 mph for Test Car 4

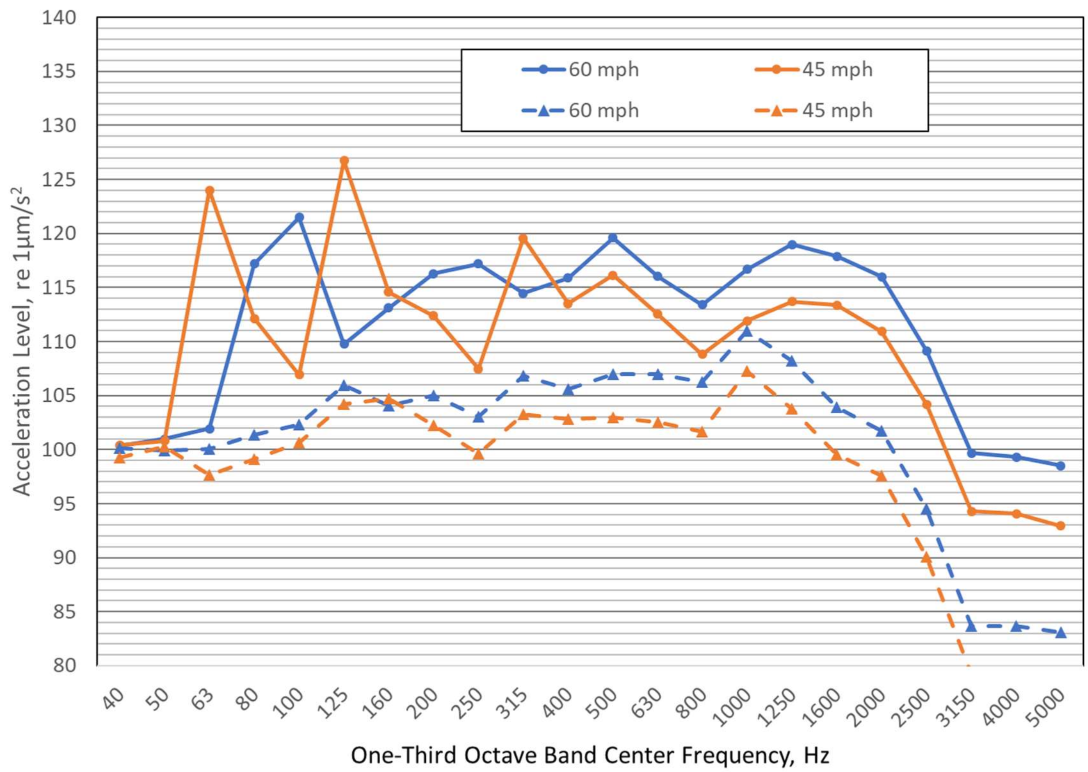
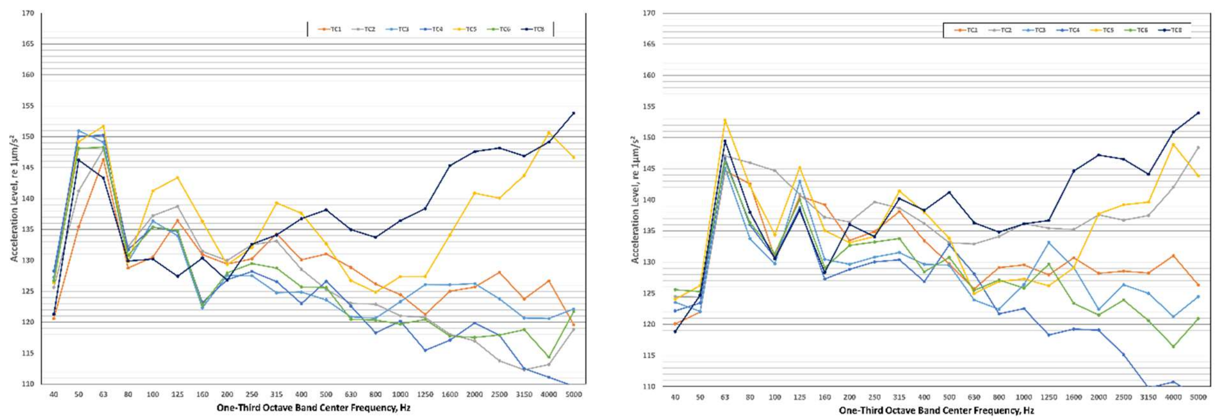


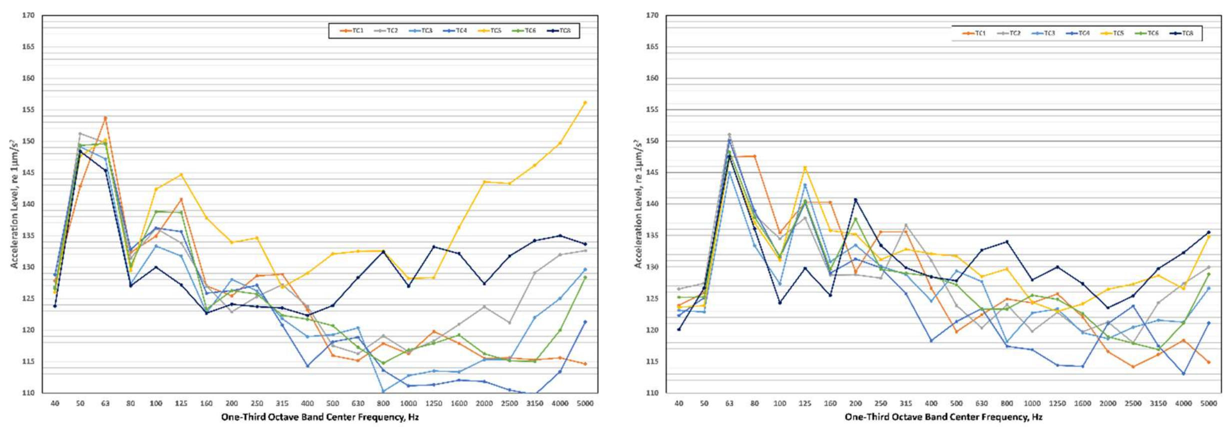
Figure B-112: One-third octave band spectra for the summed seat track locations on conventional ground strips at 45 and 60 mph for Test Car 4

Acceleration spectra for the front spindle location are shown in Figure B-113, as measured on the mumble and conventional strips at 45 mph. Except for the frequency shift, the results are somewhat similar to those at 60 mph. For the mumble strip data, there is also a divergence of some of spectra above 315 to 400 Hz with two vehicles, Test Car 8 and Test Car 5, producing much higher levels than the others. This is also displayed on the conventional ground strips, with Test Car 2 joining the other two at the higher frequencies. In Figure B-114 for the rear spindle on the conventional ground strips, the levels at the repetition rate frequency and first harmonic are consistent with each other, except for Test Car 2 which does not display the isolated peak associated with the rate.



(a) mumble strips *(b) conventional ground strips*

Figure B-113: One-third octave band spectra for the front spindle locations on (a) mumble strips and (b) conventional ground strips at 45 mph

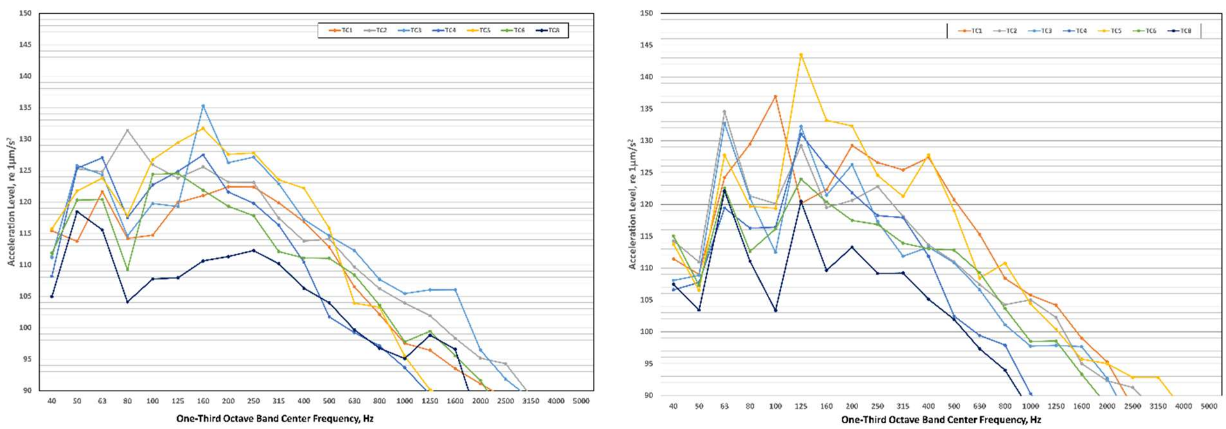


(a) mumble strips *(b) conventional ground strips*

Figure B-114: One-third octave band spectra for the rear spindle locations on (a) mumble strips and (b) conventional ground strips at 45 mph

On the mumble strips, the repetition rate frequencies are apparent; however, there is more variation in level in these one-third octave bands. Similar to the mumble strip data at the front spindle, some high frequency divergence is apparent in the higher frequencies again for Test Car 8 and Test Car 5.

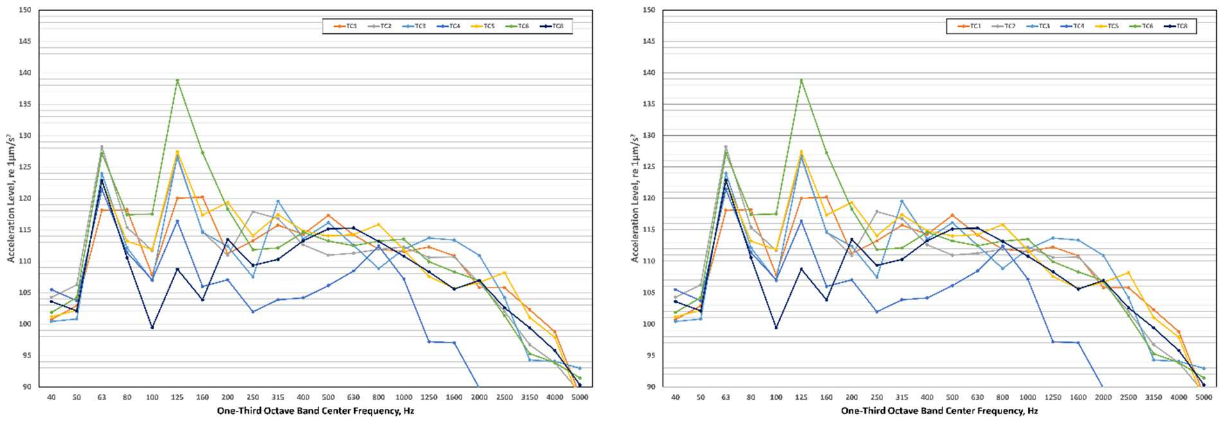
For the steering column location results shown in Figure B-115, aside from the shift in frequency content due to the speed difference, the results are somewhat similar to the 60 mph results. Test Car 8 produces lower levels compared to the other vehicles throughout most of the frequency range for both speeds. Also, the levels tend to reduce for all vehicles at the higher frequencies beginning around 400 Hz. However, there are some differences. On the



(a) mumble strips *(b) conventional ground strips*

Figure B-115: One-third octave band spectra for the steering column locations on (a) mumble strips and (b) conventional ground strips at 45 mph

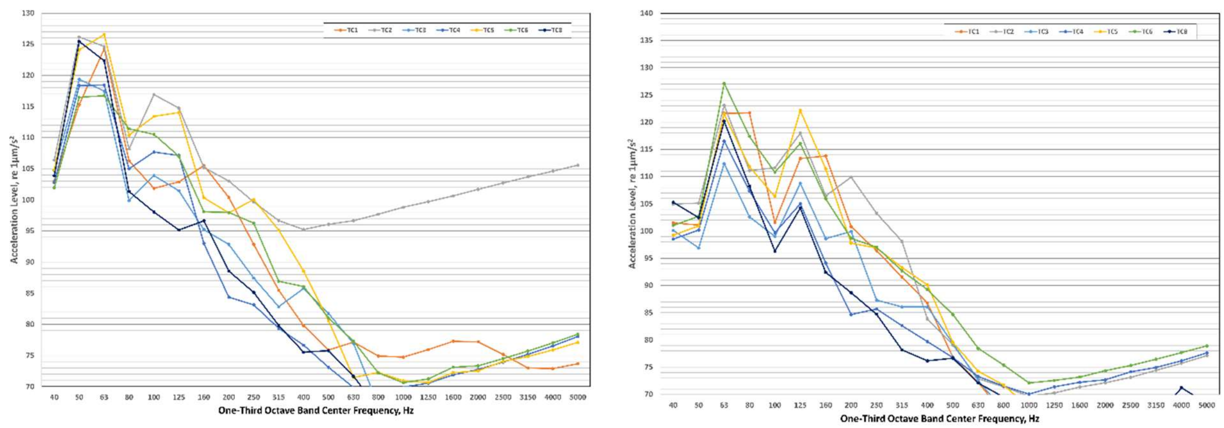
mumble strips, Test Car 2 produces a peak at 80 Hz where the levels at this frequency for all the other vehicles dip down. However, Test Car 2 has similar behavior to the other vehicles, with comparable levels at the mumble strip repetition rate frequencies of 50 and 63 Hz. This may indicate some resonant in the vehicle at 80 Hz that is not excited at 60 mph or on the conventional strips at 45 mph. For Test Car 4 on the mumble strips, there is also a peak in the spectra that occurs at 160 Hz, which is not related to the mumble strip repetition rate and may also be a resonant effect. On the conventional strips, there is not the consistent isolation of the peak at the 63 Hz repetition rate and of its harmonic at 160 Hz. Test Car 1 spectrum peaks at a frequency of 100 Hz and displays a level more than 15 dB lower at 125 Hz, which is the harmonic frequency of the repetition rate and is indicated in the spectra of all of the other vehicles. At 125 Hz, Test Car 5 produces levels 10 to 23 dB higher than the other vehicles, and the highest of the vehicle occurs at 160 and 200 Hz. For the seat track data shown in Figure B-116, the characteristics of the repetition rates and their harmonics are more apparent on both types of strips. The levels for Test Car 6 at harmonic frequencies, however, are quite pronounced, producing levels about 10 dB higher than the other vehicles on the conventional strips and levels about 12 dB higher than the other vehicles, with the exception of Test Car 5. These behaviors are not seen in the 60 mph results.



(a) mumble strips *(b) conventional ground strips*

Figure B-116: One-third octave band spectra for the seat track locations on (a) mumble strips and (b) conventional ground strips at 45 mph

Spectra for the seat pad locations are shown in Figure B-117. Allowing for the frequency shift due to the slower speed, there are several other differences in the 45 mph data and the 60 mph data. On the mumble strips, Test Car 6 produces the lowest levels at the repetition rate frequencies divided between 50 and 63 Hz at 45 mph, while for 60 mph, it has the highest level at the 80 Hz repetition rate frequency. On the conventional strips, Test Car 6 has the highest level at the repetition rate for both strip types. This suggests that this vehicle has some resonant behavior in the 80 to 100 Hz range, in comparison to other vehicles. At 100 Hz and above, the range in level for 45 mph is similar to that of 60 mph on both types of strips. As noted for the 60 mph results, the levels fall-off more rapidly with frequency than the other measurement locations. On the mumble strips at 45 mph, there appears to be some background noise issue for Test Car 2 above about 250 Hz, which parallels the noise floor indicated for several of the other vehicles starting at 1,000 Hz. Assuming this is a noise floor issue for Test Car 2, the results for this vehicle should not be considered above 250 Hz.



(a) mumble strips *(b) conventional ground strips*

Figure B-117: One-third octave band spectra for the seat pad locations on (a) mumble strips and (b) conventional ground strips at 45 mph

Comparison to Previous Results

As noted in above, the measurements made in the Caltrans research of 2012 and 2015 at these same mumble and conventional strip sites provide the most relevant comparison to the current results. In the 2012/15 measurements, acceleration was measured at a seat track location similar to that used in the current measurements, although only the vertical component of the acceleration was acquired. Measurements were also made at a steering column location similar to the current measurements but also only in the vertical direction. The 2012/15 data included four test vehicles: a Honda Civic, a Malibu, an Expedition, and a 4-yard dump truck tested in 2012 and a Camry with two different sets of tires in tested in 2015. A comparison of the overall acceleration levels, as measured on the mumble and conventional rumble strips, is provided in Figure B-118 for the seat track location for the 2018 and 2012/15 testing. On both types of strips, the levels for the 2012/15 testing tend to be lower. For the Camrys, the two different tire sets in 2015 produced levels about 6 to 7 dB lower on both types of strips for this location. The other 2012 vehicles, excluding the 4-yard dump truck, produced levels comparable to the 2018 levels. For the steering column results shown in Figure B-119, the trends are similar, with the 2018 levels being generally higher. For Test Car 4, the levels for 2018 are about the same compared to the 2015 results.

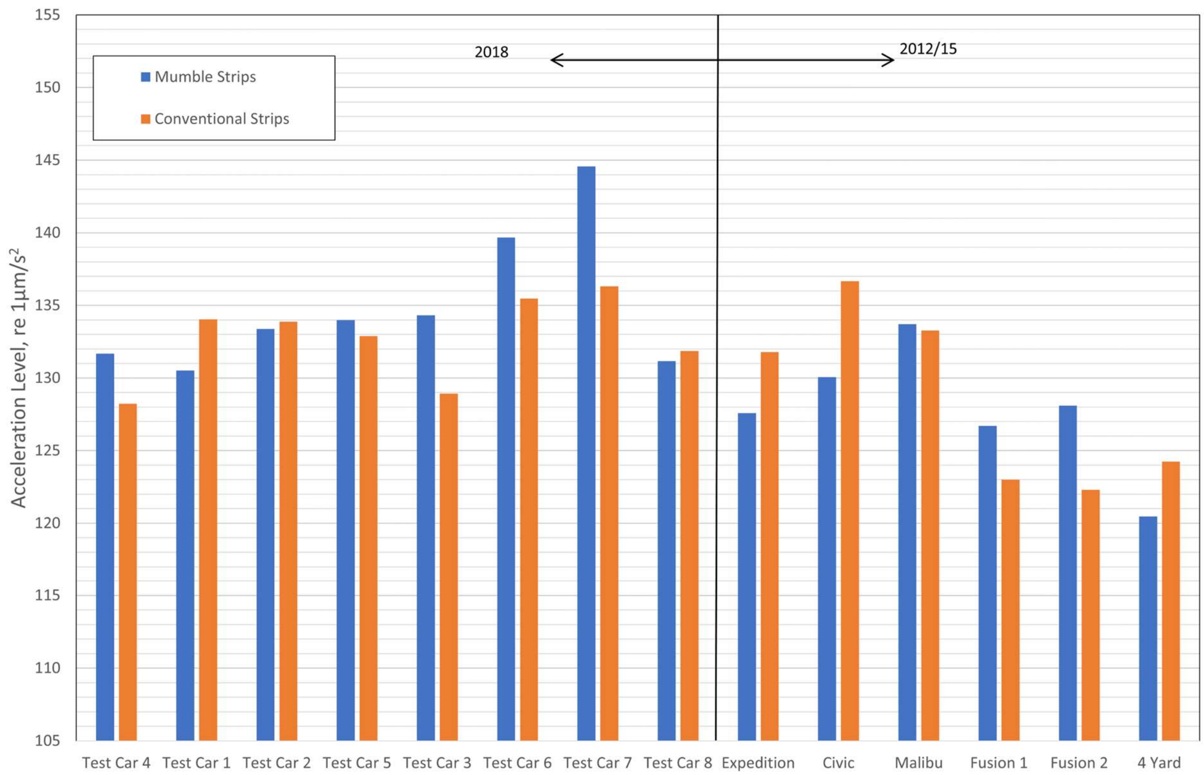


Figure B-118: Overall acceleration levels for seat track location for vehicles tested in the current study and those from the Caltrans study (2012/15)

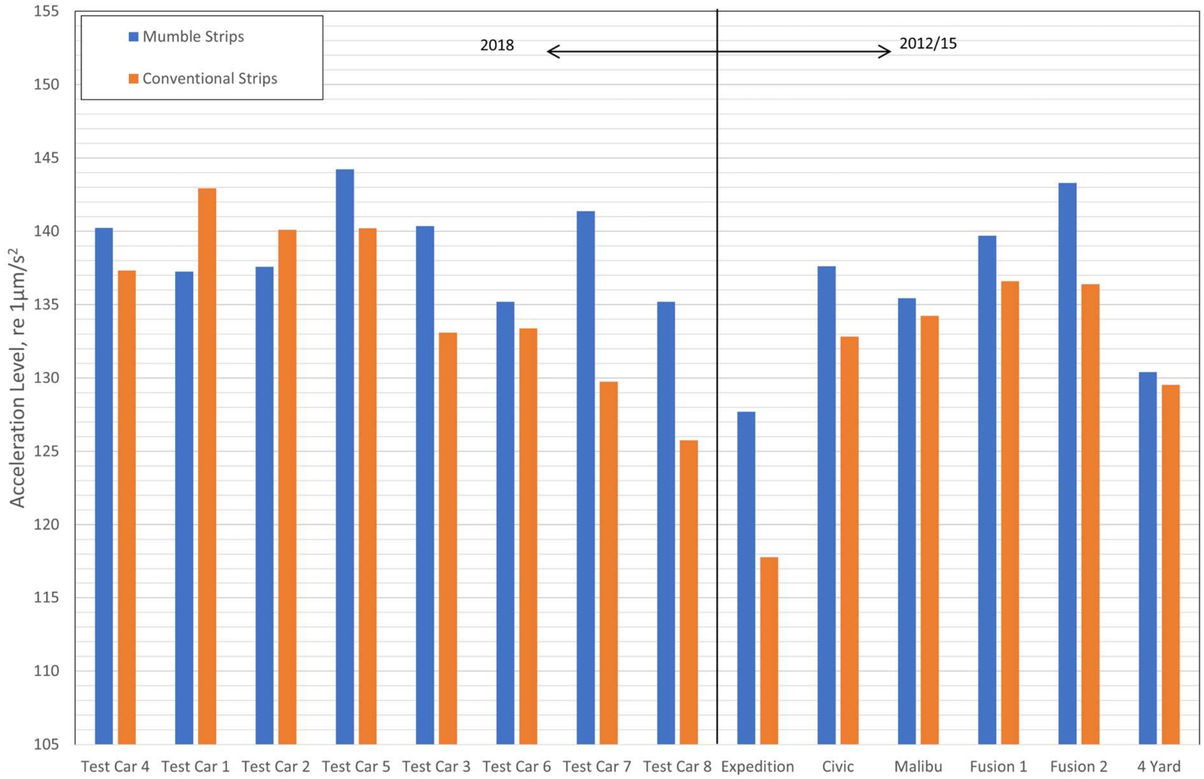


Figure B-119: Overall acceleration levels for steering column location for vehicles tested in the current study and those from the Caltrans study (2012/15)

The on/off increments for the seat track location are shown in Figure B-120 for 2018 and 2012/15 measurements. With a few exceptions, the increments for all of the data fall into a range of about 10 to 15 dB or greater. As noted in the 2012/15 report, the increments for the 4-yard dump truck are low on both types of strips, even though it was noticeable in the truck cab when it was on the strips. Test Car 7 has an unusually high increment on the mumble strips. As noted in regard to Figure B-100, this may be due to the structure of the vehicle and a susceptibly to the frequencies generated by the harmonic of the repetition rate. The levels on the mumble strips for Test Car 4 from 2018 are also higher than those of 2015 by 4 to 6 dB, although on the conventional strips the difference is not as pronounced. The steering column results are compared in Figure B-121. For this position, the 2012/15 increments appear similar to those of 2018. Considering the data from both locations, the conclusion that the mumble strips provide more operator input remains valid except for the smaller Test Car 1 and Test Car 2.

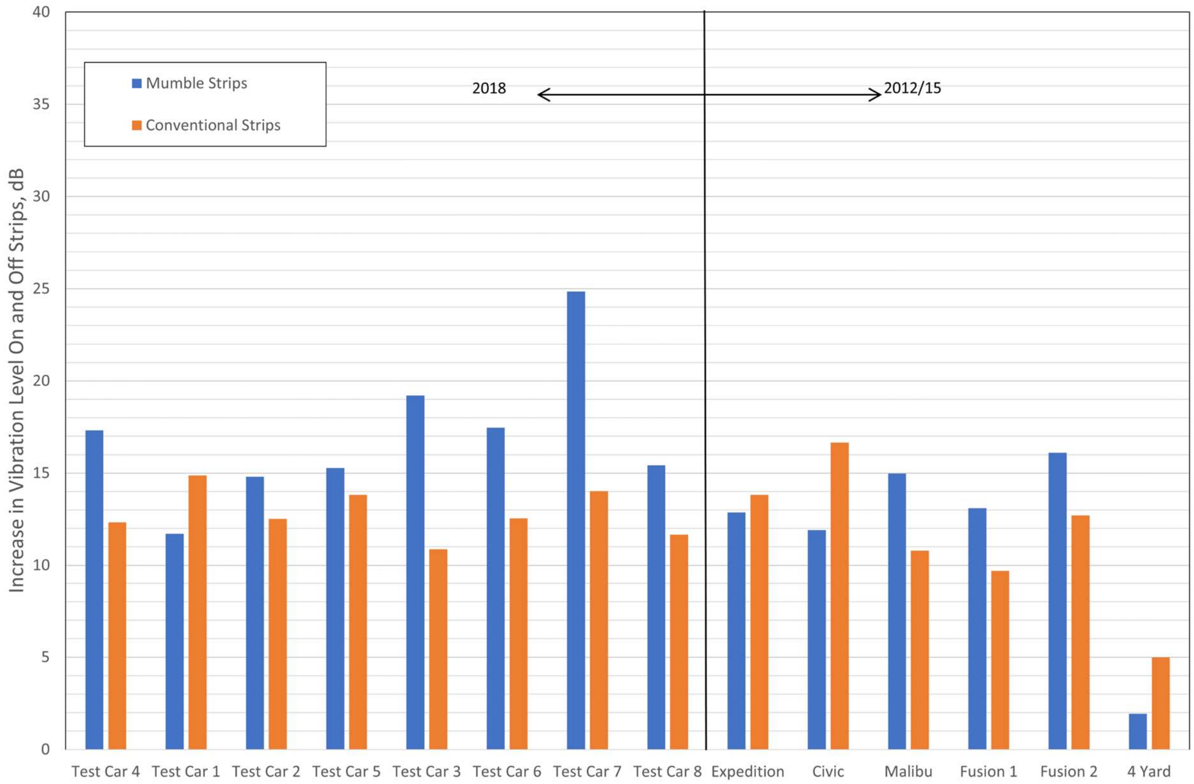


Figure B-120: On/off increments for seat track location for vehicles tested in the current study and those from the Caltrans study (2012/15)

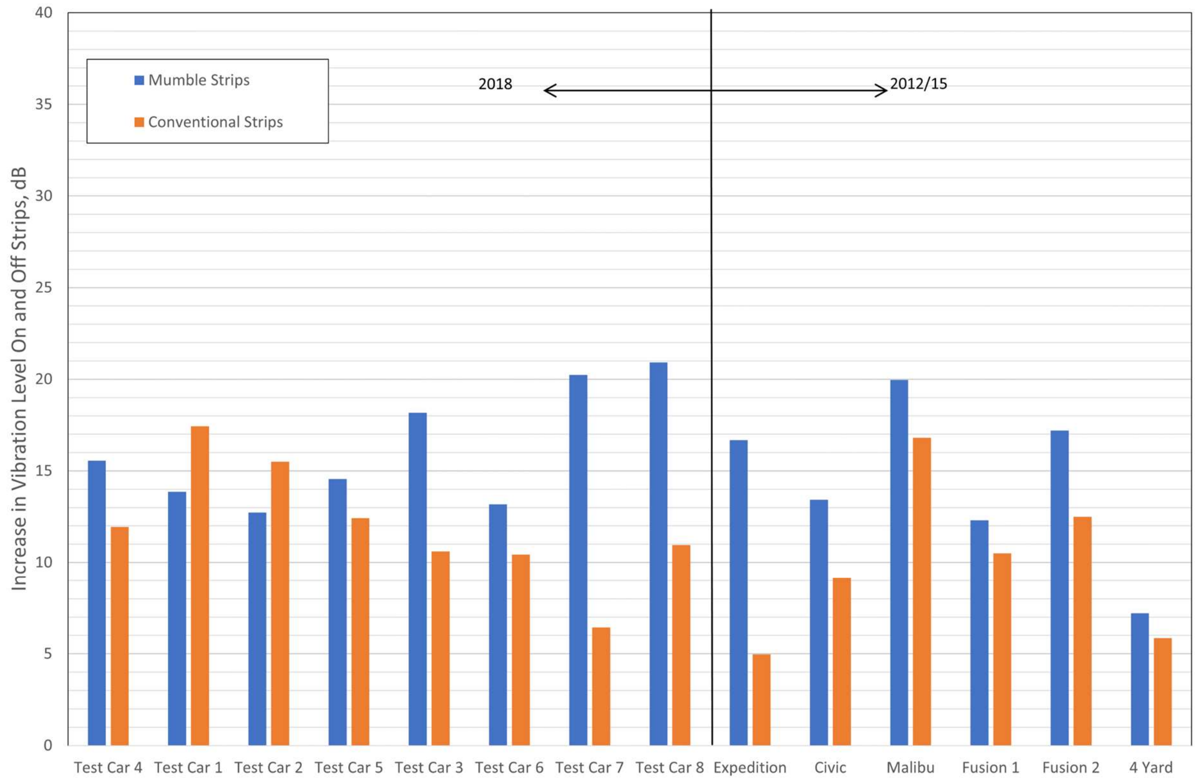
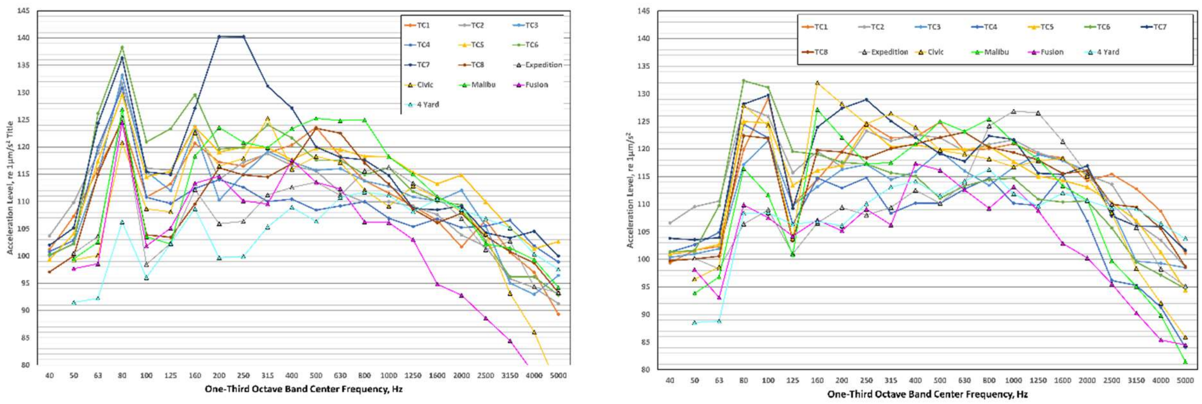


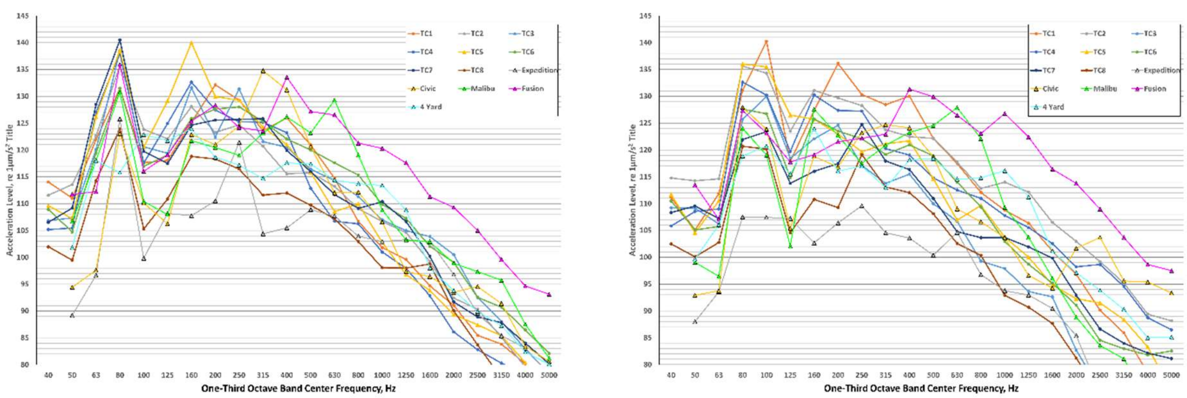
Figure B-121: On/off increments for steering column location for vehicles tested in the current study and those from the Caltrans study (2012/15)

The seat track spectra from the current measurements and the 2012/15 study are shown in Figure B-122 for the mumble strips and the conventional rumble strips. For the mumble strips, the results fall within about a 15 dB band, with the exception of Test Car 7 in 2018 and the 4-yard dump truck in 2012. All the data show some peak at the 80 Hz repetition rate. Generally, for the light vehicles, the two data sets overlap in level throughout the range of frequencies and display the same tendencies of level versus frequency. For the seat track location on the conventional ground strips, the results of 2012/15 measurements are again similar to the 2018 results, with the 2012/15 values spanning those of 2018. All vehicles display higher levels at the 100 and 125 Hz bands containing the repetition rate; however, the levels for Expedition, Test Car 4, and 4-yard dump truck are considerably (10 to 20 dB) lower. However, the levels for the Civic in 2012 are close to the higher levels measured in 2018. The spectra for the steering column locations from the 2012/15 and 2018 for the mumble and conventional strips are shown in Figure B-123. At repetition rate frequencies, the levels are similar on both strips, although the levels for the Expedition on the conventional strips are about 7 dB lower than the other vehicles, and the 4-yard dump truck does not indicated a peak for the mumble strips at the 80 Hz repetition rate. At frequencies above 250 Hz, the levels for both types of strips display similar tendencies, although there is considerable scatter in the results. Test Car 8 and Expedition are both lower than the other vehicle in the range from 160 to 500 Hz likely due the isolation provided by the full-frame designs.



(a) mumble strips *(b) conventional ground strips*

Figure B-122: One-third octave band spectra for the seat track locations on (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

Figure B-123: One-third octave band spectra for the steering column locations on (a) mumble strips and (b) conventional ground strips

Comparison of Pass-by, Interior Noise, and Vehicle Vibration

In the previous three subsections, comparisons are made between vehicles for their performance on the rumble strips for each measurement type. In this subsection, comparison is made of the measurement types to determine their interrelationships. One approach is to plot the overall levels from two types of measurements against each other in an X-Y plot. This is done for the overall A-weighted sound pressure levels for the pass-by and interior noise using the rear center microphone on the two types of strips, as shown with linear regressions in Figure B-124. Based on the low values of the coefficients of determination (R^2) for each type of strip and the visual scatter in the data, there is no discernable relationship between the data points. The slight upward trend of the conventional ground strips may be due to the higher levels at higher frequencies that occur on these strips. In Figure B-125, the similar plots are shown for interior vibration levels at the seat pad, steering column, seat track, and steering wheel locations compared to the interior noise sound pressure level for the mumble strips. Again, there is appreciable scatter in the plots and values of R^2. Interestingly, the steering column and interior noise regression displays the highest R^2 value, despite the fact that it would not be expected for the steering column to be a sound radiating element. However, the individual data points range about 1 to 7 dB from the regression line. The regressions on the conventional strips, as shown in Figure B-126, display low R^2 values except for the steering wheel again, which yields an R^2 of 0.80. For these strips, the steering wheel also has a higher R^2 value of 0.56 and, like the steering wheel, this would not be expected.

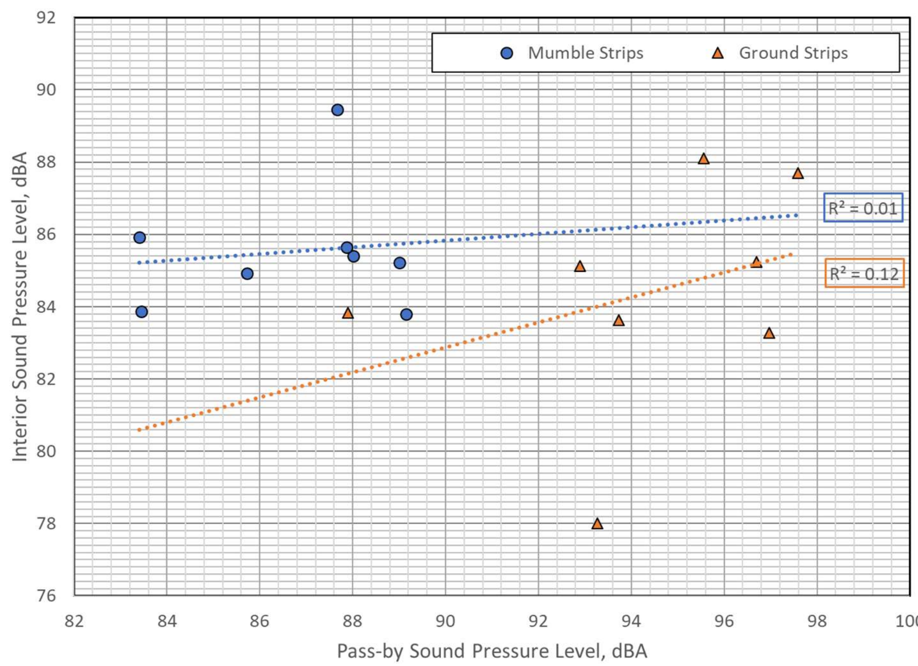


Figure B-124: Interior sound pressure levels vs pass-by noise levels for mumble and conventional ground strips for all test vehicles

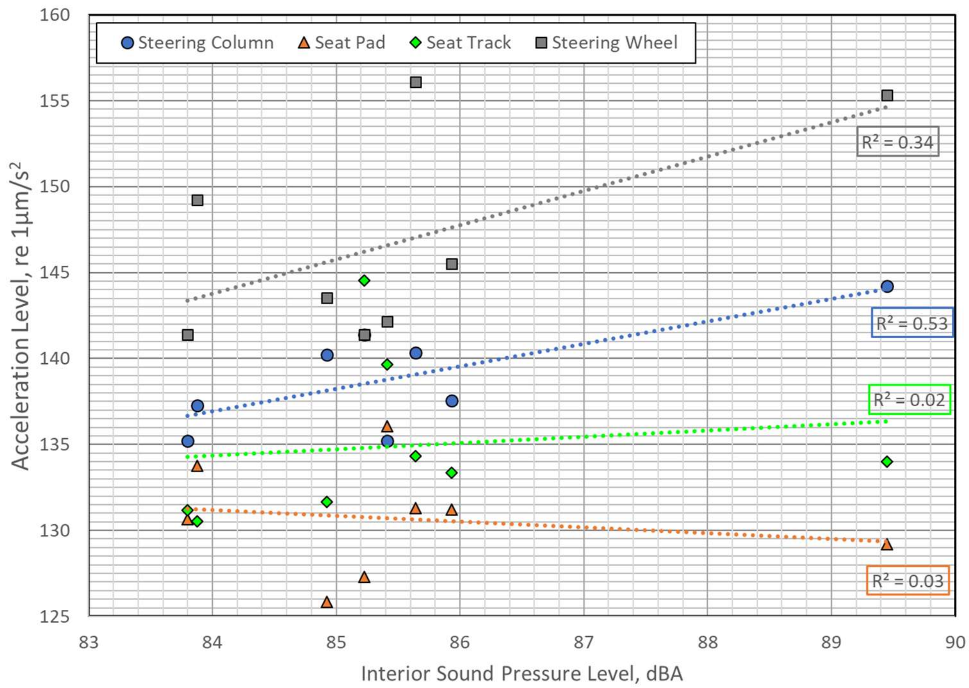


Figure B-125: Overall acceleration levels vs interior sound pressure level for seat pad, steering column, seat track, and steering wheel locations on mumble strips for all vehicles

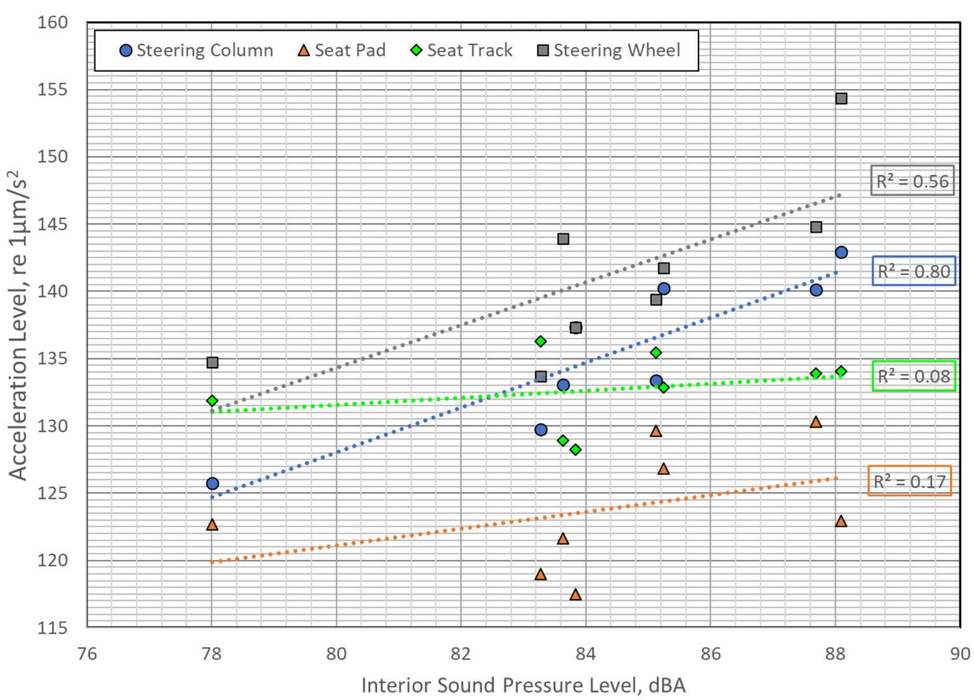


Figure B-126: Overall acceleration levels vs interior sound pressure level for seat pad, steering column, seat track, and steering wheel locations on conventional ground strips for all vehicles

The increments for the data can also be examined in a similar manner. In Figure B-127, the increments for on/off the mumble and conventional strips are shown. For these data, the mumble strips still show no correlation between the pass-by and interior noise results. For the conventional strips, there is an upward trend with increased increment values; although, the R^2 value is low. This again may be influenced by the higher levels in the frequencies above about 250 Hz for the pass-by data, which have more influence on the overall A-weighted levels. The interior noise increments are compared to the interior vibration increments in Figure B-128 for the mumble strips. These results do show an upward trend with increasing increment values; however, the scatter about the regression lines is substantial. The steering column and steering wheel yield the higher R^2 values; however, these are still quite low. On the conventional strips shown in Figure B-129, the steering wheel and seat pad both show upward trends, with the steering wheel having the highest R^2 value of 0.56. The seat track and steering column show flat and declining relationships, respectively, between the interior noise and vibration data.

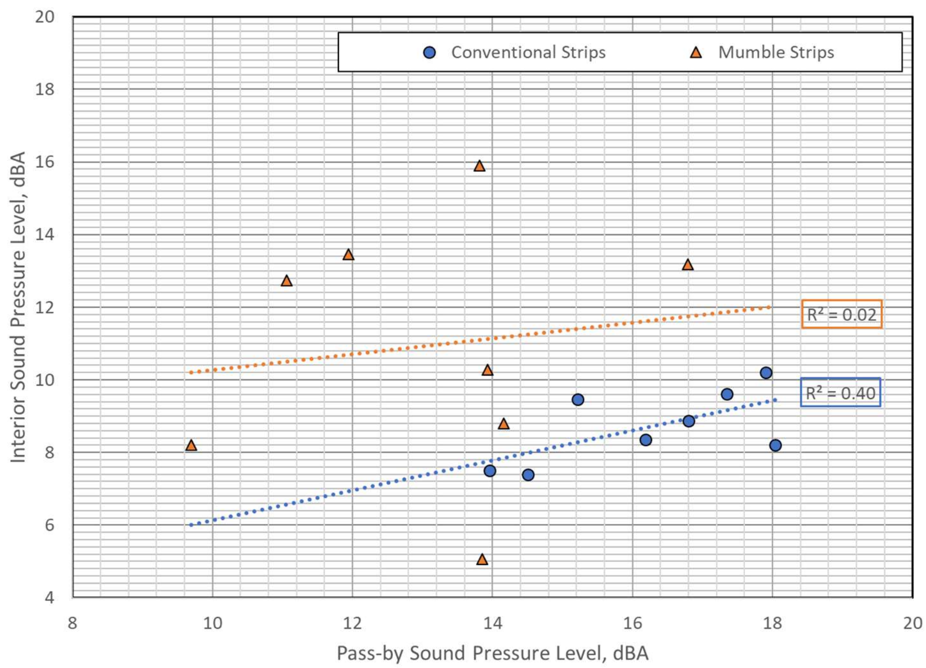


Figure B-127: Interior sound pressure level vs pass-by noise on/off increments for mumble and conventional ground strips for all test vehicles

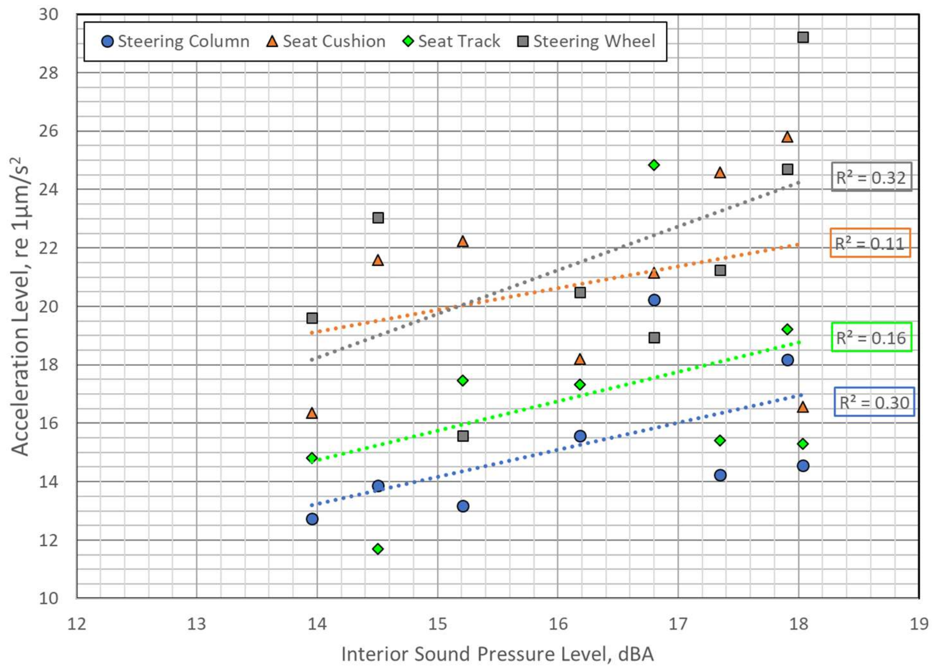


Figure B-128: Interior vibration level vs interior sound pressure level on/off increments for mumble strips for all test vehicles

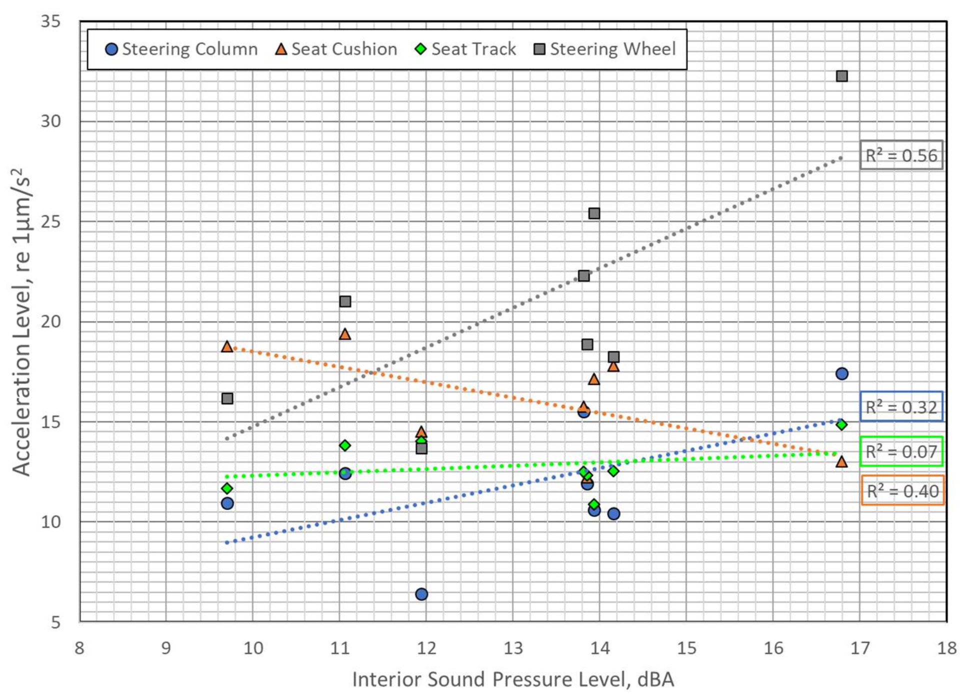
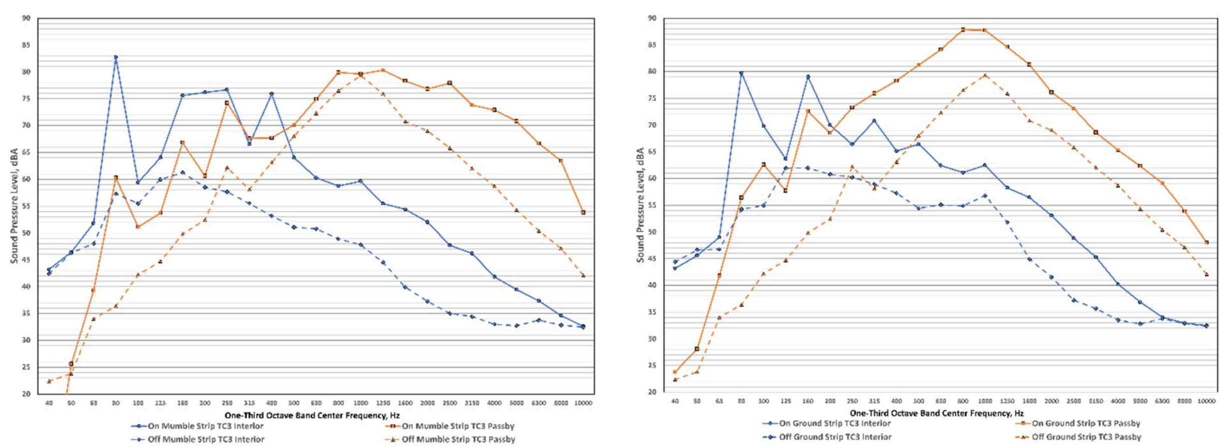


Figure B-129: Interior vibration level vs interior sound pressure level on/off increments for conventional ground strips for all test vehicles

To gain more insight on the relationships between the pass-by and interior noise results, the spectra of levels on and off the two types of rumble strips were compared for several vehicles. Plots for Test Car 4 are shown in Figure B-130. For both types of strips, the noise levels on the inside of the car are higher than the pass-by noise in the lower frequencies, while the opposite is true in the higher frequencies. In the low frequencies, the larger differences occur at the rumble strips' repetition rates and their first harmonic. The transition from interior noise being louder to pass-by being louder occurs at different frequencies: 500 Hz on the mumble strips and 250 Hz on the conventional strips. Off the strips, a similar transition occurs in the range of 250 to 315 Hz. Collectively, these trends indicate the transition from structure-borne noise being the dominate contributor to interior where airborne noise is the dominant contributor. Structure-borne noise is generated by the contact between the tire and the road surface, which is transmitted as vibrational energy from the tires through the suspension and body structure to the interior body panels that vibrate and radiate noise. Airborne noise is that radiated on the outside of the vehicle by the tire/road contact and transmitted into the vehicle interior through the body panels acoustically. The energy in structure-borne path also receives some attenuation provided by isolators between the body and the suspension components. In vibration measurements, this is apparent by levels of the spindles being typically 15 to 20 dB higher than the interior vibration measurement locations. The amount of reduction provided by the suspension components and other isolators will also vary from vehicle to vehicle, changing the contribution of the structure-borne noise.

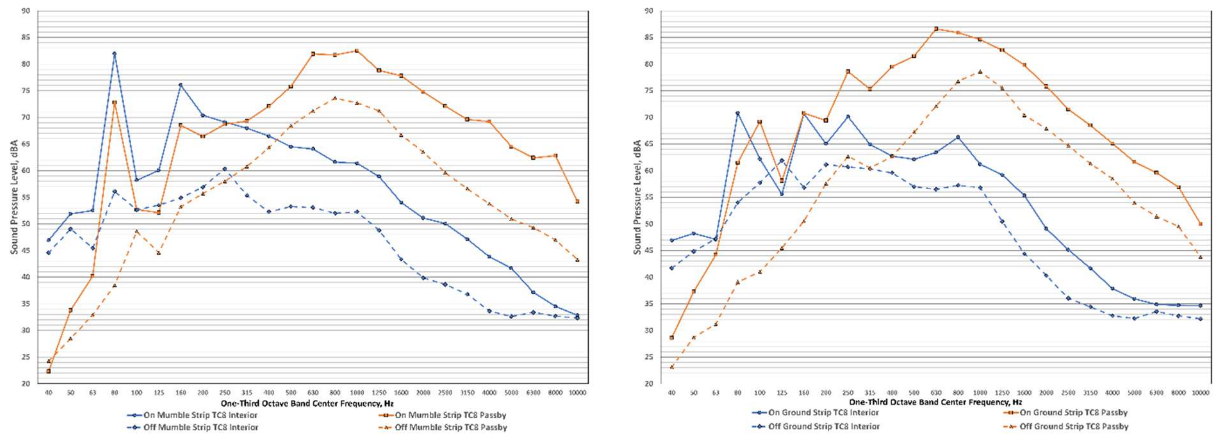


(a) mumble strips *(b) conventional ground strips*

Figure B-130: Test Car 4 on/off pass-by and interior noise spectra for (a) mumble strips and (b) conventional ground strips

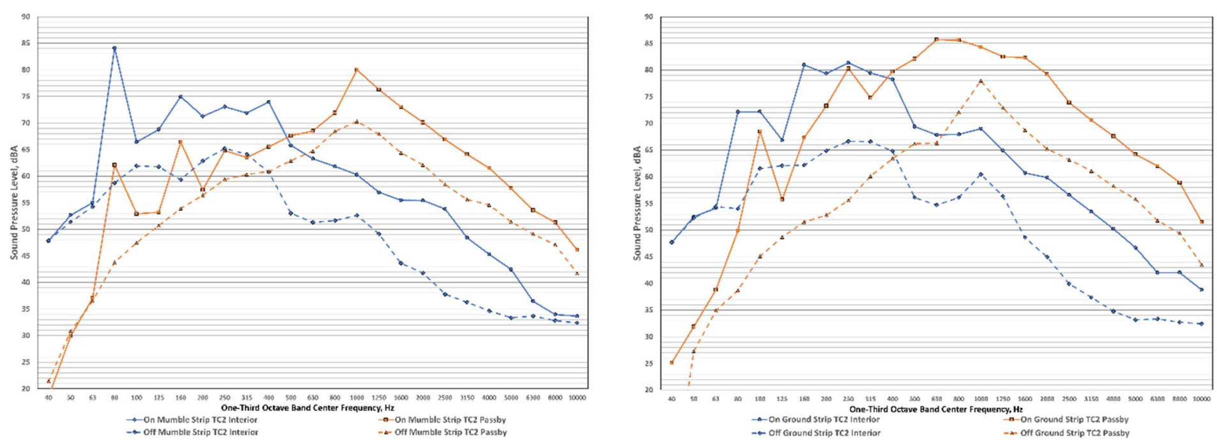
The influence of body isolation is apparent in the comparison of the pass-by and interior noise spectra for Test Car 8 shown in Figure B-131 on both types of strips. Unlike the other test vehicles, Test Car 8 has a full frame between the suspension and the body. This provides an additional level of interior isolation. For Test Car 8, the transition between higher interior noise and exterior pass-by noise occurs at lower frequencies than the unibody (no intermediate frame) Test Car 4. With the additional isolation, the difference between vibration levels at the rumble strip repetition rates and the pass-by noise is more than 10 dB less than Test Car 4. For Test Car

8, considering the difference in spectra level between the pass-by and interior noise, the overall level will be determined largely by the airborne component. For Test Car 4, this is likely for the conventional strips also; however, on the mumble strips it is less apparent. For Test Car 2 shown in Figure B-132, the structure-borne noise plays an even larger role in determining the overall level on the rumble strips.



(a) mumble strips *(b) conventional ground strips*

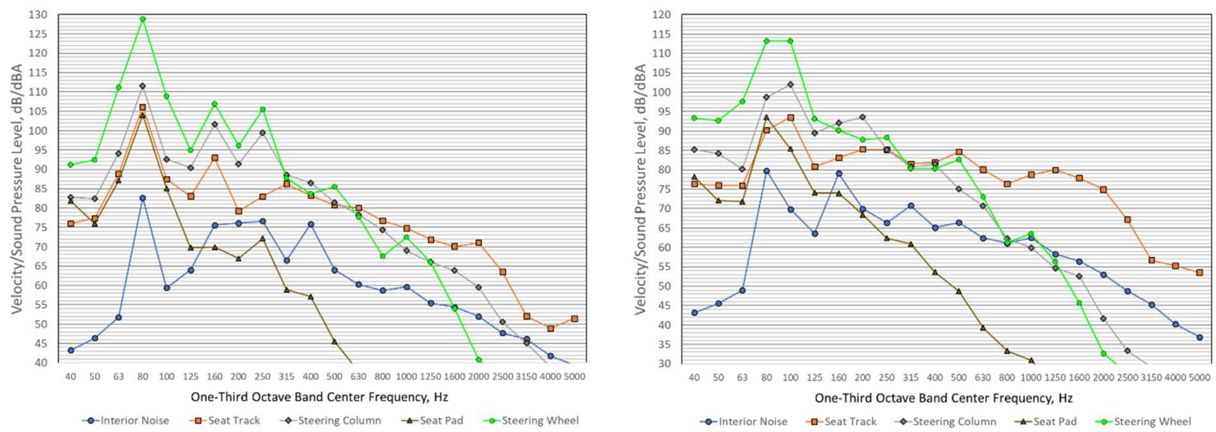
Figure B-131: Test Car 8 on/off pass-by and interior noise spectra for (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

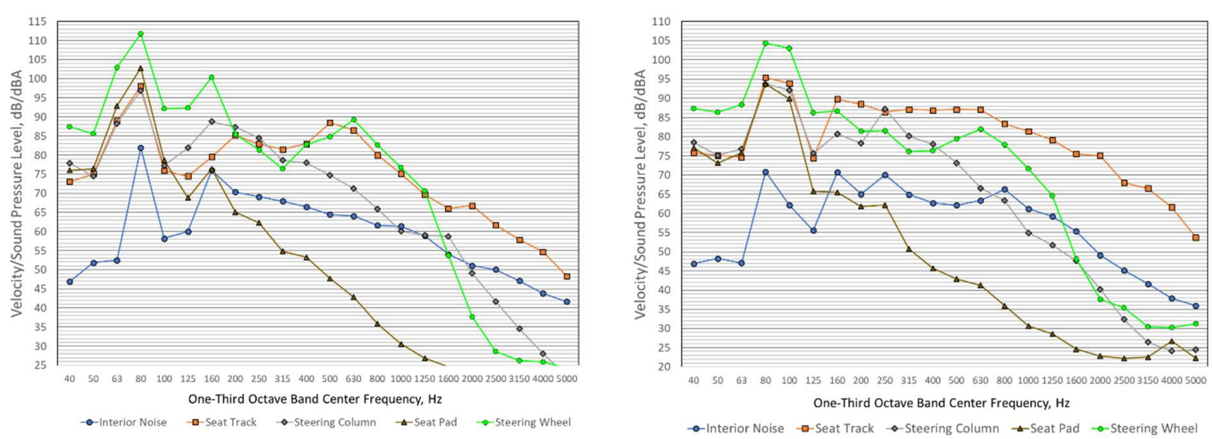
Figure B-132: Test Car 2 on/off pass-by and interior noise spectra for (a) mumble strips and (b) conventional ground strips

The vibration spectra for the seat track, seat pad, steering column, and steering wheel were also compared to the interior noise spectra for Test Car 4 on the mumble and conventional strips, as shown in Figure B-133. In these comparisons, the vibration is presented as velocity levels, as the sound radiated by interior surfaces is directly related to velocity of panels, such as the roof, fixed glass surfaces, floor, and other body panels. However, since the motion of the radiating surfaces themselves were not measured directly, the ability of these panels to radiate sound is only inferred from the measurements, which indicates vibration energy in the body structure. On the mumble strips, the one-third octave band containing the repetition rate shows quite distinctly at 80 Hz. At the harmonic frequency (160 Hz), the noise levels rise, but a peak is not as apparent as it is for seat track, seat pad, and steering wheel. On the conventional strips, the repetition rate frequency for the vibration is split between the 80 and 100 one-third octave bands; however, the interior noise spectrum indicates a peak at 80 Hz only. This is also apparent at the harmonic of the repetition rate where the noise data only shows a peak at 160 Hz. For this vehicle, effect may be due to the rear center placement of the microphone, as the forward location does indicate a split in the peak similar to the vibration data. Some similar observations apply to the corresponding plot in Figure B-134 for Test Car 8. On the mumble strips, the interior noise has a peak at 80 Hz and is similar to the vibration data. There is a defined peak at the 160 Hz harmonic; however, it is not well defined, as the adjacent higher band is only about 5 dB lower. On the conventional strips, the interior noise repetition rate is only apparent in the 80 Hz band and not in the 100 Hz, as it is for the vibration data.



(a) mumble strips *(b) conventional ground strips*

Figure B-133: Test Car 4 vibration and interior noise spectra for (a) mumble strips and (b) conventional ground strips



(a) mumble strips *(b) conventional ground strips*

Figure B-134: Test Car 8 vibration and interior noise spectra for (a) mumble strips and (b) conventional ground strips

Ground Vibration

Data Processing

In post-processing, the ground vibration data were reduced to 1-second RMS averages with one-third octave band frequency data from 10 to 500 Hz. The maximum vibration level during each valid pass-by event was extracted. Validity was determined based of field notes for the event and event examination. When there was definite contamination from other vibration sources (other vehicles too close to wayside sensor line), those events were eliminated. Events that indicated possible contamination and all "good" events were examined on a spectral basis. Outliers were removed, and vibration levels for the remaining events were linearly averaged for each one-third octave band for each of the four conditions (on/off mumble strip and on/off conventional ground strip) at each speed.

Results

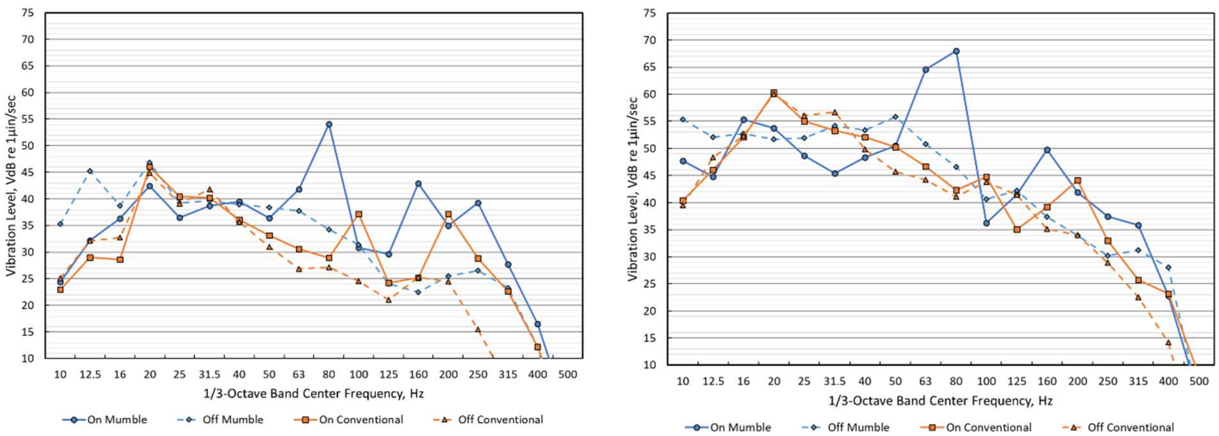
Results for wayside ground-borne vibration are shown in Table B-4. The table summarizes the overall vibration levels from 10 to 500 Hz for six different vehicles driving on the two types of rumble strips (Caltrans mumble strip and Caltrans cylindrical conventional ground strip) compared to off the strips (highway pavements adjacent to the strips). Results are shown as vibration velocity levels referenced to 1 μin/sec. The units chosen for this analysis allow comparison to published ground-borne vibration level criteria found in the Federal Transit

Table B-4: Overall ground-borne vibration levels from 10 to 500 Hz and differences between driving on and off the two types of strips.

Vehicle	Speed (mph)	On Mumble (VdB)	On/Off Mumble Strip Difference (VdB)	On Conventional Ground Strip (VdB)	On/Off Conventional Ground Strip Difference (VdB)
Test Car 6	45	70.1	23.3	49.4	3.9
Caltrans Truck	45	NA	NA	NA	NA
Test Car 8	45	NA	NA	NA	NA
Minivan	45	NA	NA	NA	NA
Test Car 5	45	70.7	18.7	51.6	6.3
Test Car 3	45	59.6	9.8	49.1	-0.9
Test Car 6	60	55.6	2.5	50.0	1.5
Caltrans Truck	60	70.1	7.0	64.1	0.3
Test Car 8	60	68.5	20.8	54.3	3.4
Minivan	60	56.1	4.2	46.8	-3.7
Test Car 5	60	60.4	-3.5	51.4	0.9
Test Car 3	60	58.5	11.1	51.0	-0.7

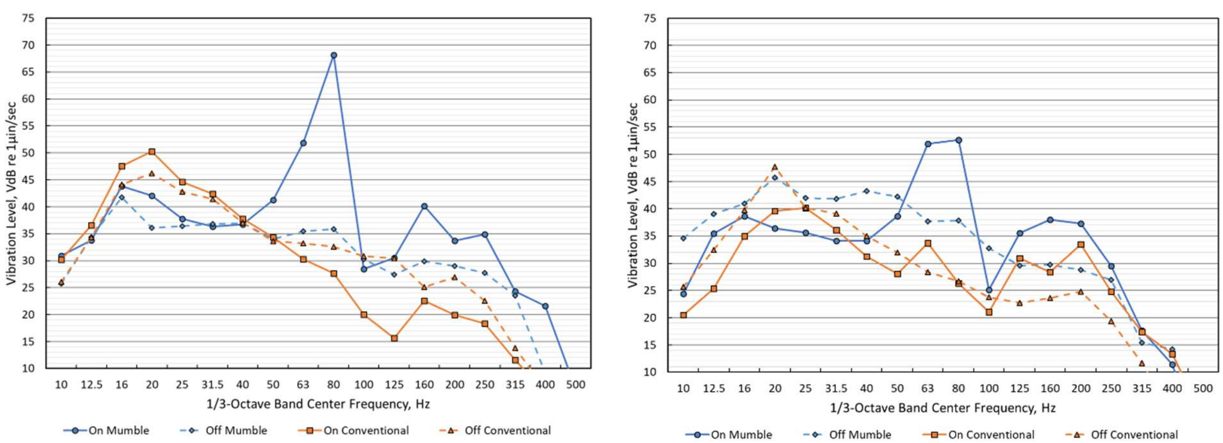
Adstration (FTA) guidance.[4] For 60 mph, these levels indicate that the mumble strips generate higher wayside ground-borne vibration than the conventional ground cylindrical strips for all vehicles. For Test Car 6 and Test Car 5, the levels on the mumble strips at 45 mph are 15 and 10 dB higher than those at 60 mph.

In Figures B-135 to B-137, the one-third octave band spectra for the six vehicles that were measured at 60 mph are presented. In each figure, the levels for vehicles on and off the mumble strips and on and off the conventional ground strips are shown. For the mumble strips, the highest level for each vehicle is in the 80 Hz band, with levels ranging from 53 to 68 VdB and



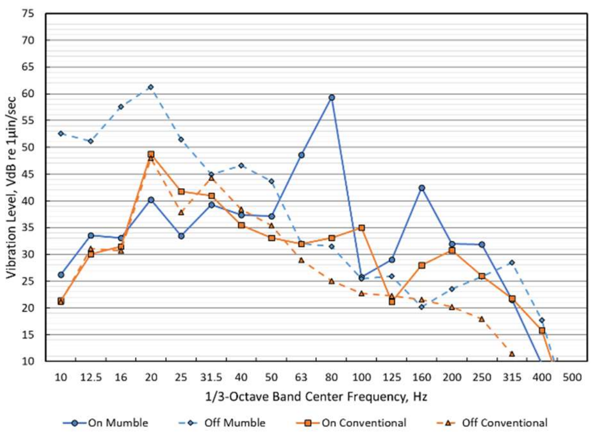
(a) Test Car 6 *(b) Caltrans dump truck*

Figure B-135: One-third octave band spectra for the (a) Test Car 6 and (b) Caltrans dump truck on and off the mumble and conventional ground strips at 60 mph

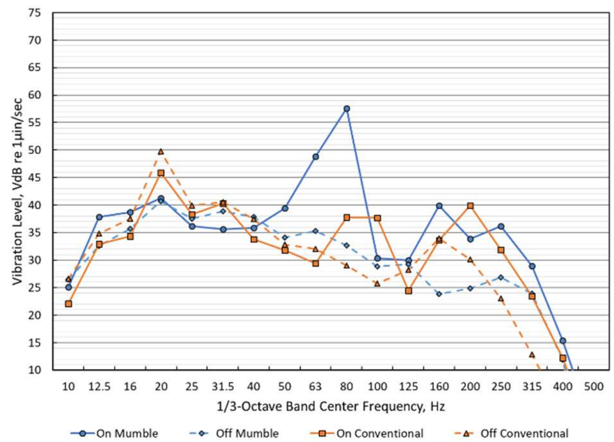


(a) Test Car 8 *(b) Test Car 7*

Figure B-136: One-third octave band spectra for the (a) Test Car 8 and (b) Test Car 7 on and off the mumble and conventional ground strips at 60 mph



(a) Test Car 5



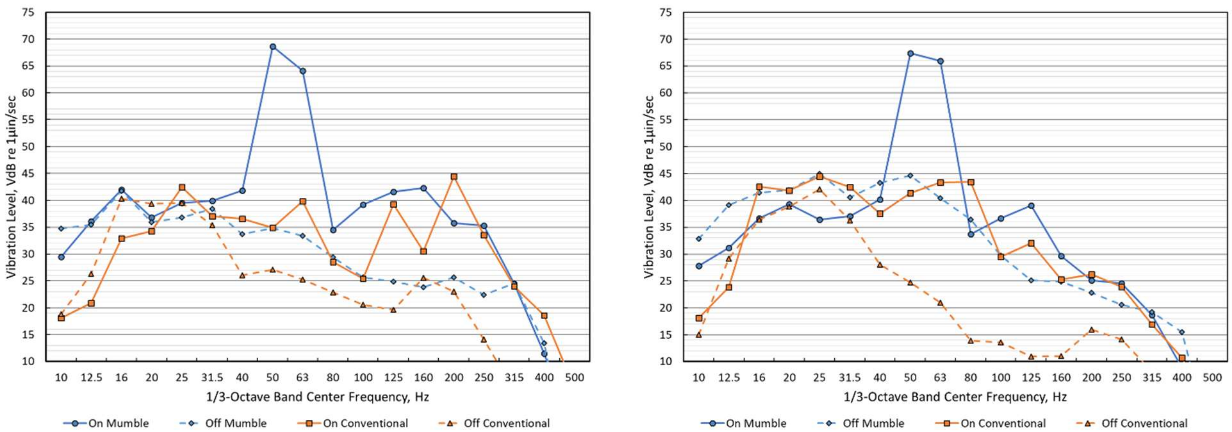
(b) Test Car 3

Figure B-137: One-third octave band spectra for the (a) Test Car 5 and (b) Test Car 3 on and off the mumble and conventional ground strips at 60 mph

differences compared to off the strips of 15 to 32 dB with the lowest values occurring for Test Car 7 and highest for Test Car 8. As noted previously, peak at 80 Hz corresponds to the repetition rate of mumble strips at this speed. Unlike the vehicle vibration spectra, the 80 Hz peak is not as well defined as there is some spill-over to the 63 Hz band. On the conventional ground strips, only four of the vehicles show evidence of the repetition rate frequency, which is split between the 80 and 100 Hz bands. For Test Car 8 and Test Car 7, the levels do not show any indication of the repetition rate at these frequencies. Except for the Test Car 8, all of the vehicles show higher levels on the conventional ground strips than off the strips at frequencies of about 160 Hz and above. This is also seen in the mumble strip cases, except for the Test Car 5 above 250 Hz.

Speed Dependence

As noted in Table B-4, data at 45 mph was available for three of the vehicles. The one-third octave band spectra for Test Car 6, Test Car 5, and Test Car 3 are shown in Figures B-138 and B-139. For Test Car 6 and Test Car 5 on the mumble strips, elevated levels between 64 and 69 VdB occur in the 50 and 63 Hz bands, consistent with the vehicle vibration results



(a) Test Car 6 *(b) Test Car 5*

Figure B-138: One-third octave band spectra for (a) Test Car 6 and (b) Test Car 5 on and off the mumble and conventional ground strips at 45 mph

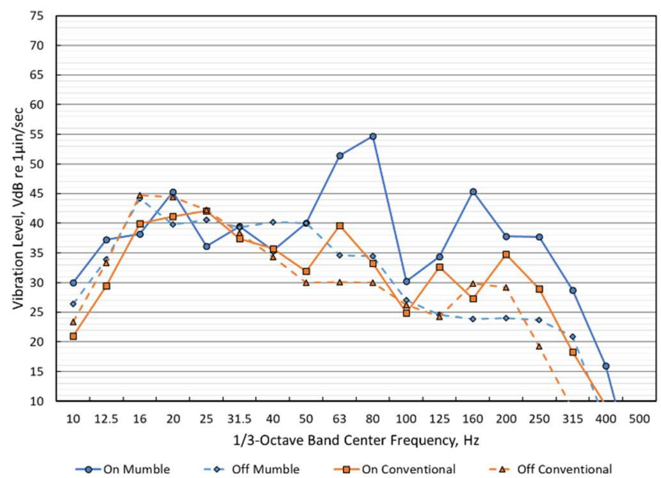


Figure B-139: One-third octave band spectra for Test Car 3 on and off the mumble and conventional ground strips at 45 mph

and corresponding to the repetition rate of the strips. These are 10 to 15 dB (Test Car 6) and 7 to 8 dB (Test Car 5) higher than the highest levels at 60 mph for these two vehicles. For the Test Car 3, there are bands with higher levels, but in slightly higher frequency bands of 63 and 80 Hz unlike the vehicle vibration results for this vehicle. Also, compared to the peak level at 60 mph, the 45 mph levels are lower by 4 to 7 dB. For all three vehicles, higher levels than those off the strips occur at frequencies above 80 Hz, with maximum differences of 14 to 22 dB. For the conventional ground strips, the repetition rate should produce a peak at 63 Hz; however, there is only slight evidence of this for Test Car 6 and Test Car 3, where the difference between on/off level is 14 and 9 dB, respectively. As a result, the spectrum levels at frequencies of 50 and 63 Hz are comparable or less than those at higher frequencies.

As noted above and shown in Table B-4, two out of the three vehicles measured at 45 mph produced higher overall and spectrum levels than those measured at 60 mph, unlike what was observed in the vehicle vibration data. One contributing factor to this result is that the vehicle vibration data was reported in acceleration level, while the ground-borne vibration is in velocity level. The conversion from acceleration to velocity lowers the levels in the higher frequencies and raises the level in the lower frequencies. This effects the spectrum level, as is illustrated for Test Car 6 in Figures B-140 and B-141 for 60 and 45 mph, respectively. This has two effects on the reported levels. For acceleration (vehicle vibration), peaks at higher frequencies will be lowered when reported in velocity. Further, for overall level, when reported in acceleration, the higher frequencies will contribute more to the overall level if they are reported in velocity. This is indicated in Figure B-140 for Test Car 6, where frequencies from 160 to 250 Hz are contributing substantially to the overall level at 60 mph when reported as acceleration. At 45 mph (Figure B-141), these higher frequencies contribute little to the overall vibration level. The shift of the dominant frequencies between 60 and 45 mph can also be influenced by the propagation through the soil. Example propagation curves, in terms of transfer mobility (velocity response/input force), as provided by the FTA guidance [4] are reproduced in Figure B-142. For this example, the maximum response occurs at about 40 to 50 Hz and falls off with both increasing

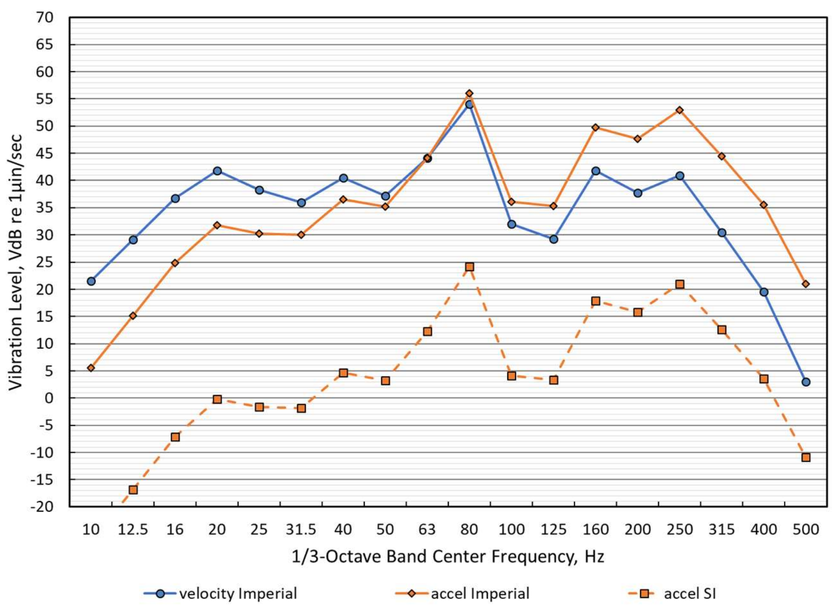


Figure B-140: Vibration Levels with Varying Units (velocity re 1 μin/s, acceleration re 1 μin/s², acceleration re 1 μm/s²) for Test Car 6 Single Events at 60 mph

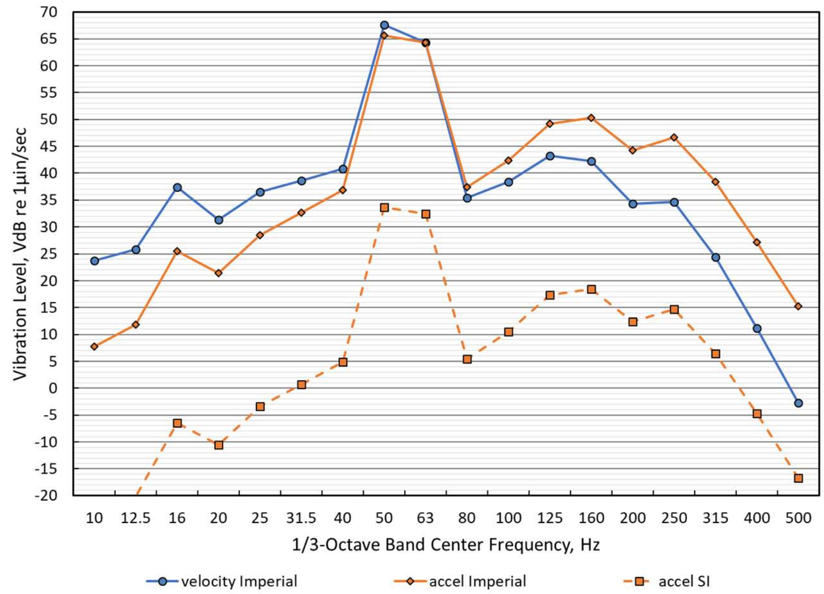


Figure B-141: Vibration Levels with Varying Units (velocity re 1 µin/s, acceleration re 1 µin/s², acceleration re 1 µm/s²) for Test Car 6 Single Events at 45 mph

and decreasing frequency. If the test sites behaved similar to this example, that could at least partially explain higher levels for the mumble strips in the shift from an 80 Hz input at 60 mph to 63 and 50 Hz at 45 mph. Regardless of the cause, the 45 mph results indicate that levels of 70 VdB are possible at distances of 25 ft from the strips.

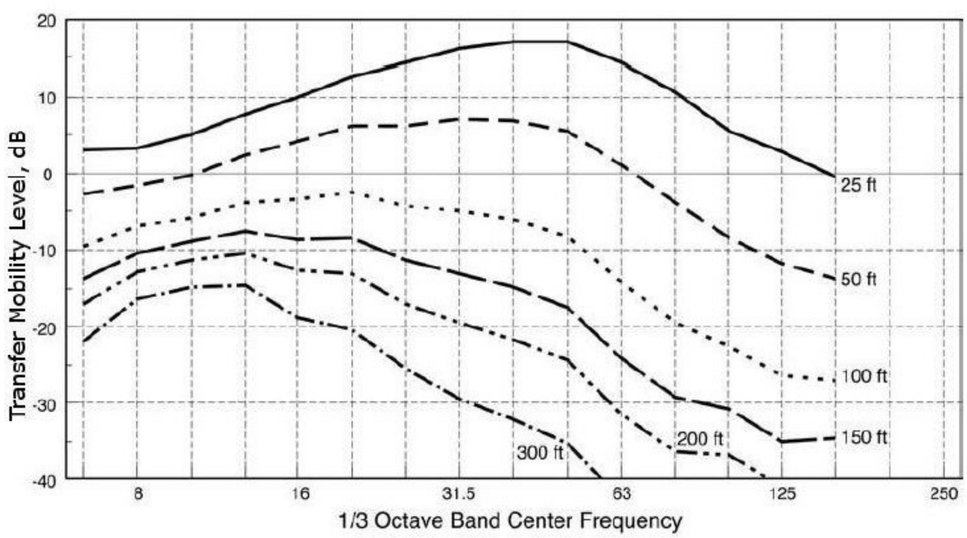


Figure B-142: Example of point-source mobility transfer mobility from FTA Guidance[2]

<u>*Comparison to FTA Guidance*</u>

The FTA Transit Noise and Vibration Impact Assessment Manual[4] provides guidance on relating ground-borne vibration levels to potential impacts on building uses and human sensitivity to vibration. It identifies 75 VdB as the approximate dividing level between barely perceptible and distinctly perceptible levels. For impact on buildings and their occupants, it considers the building uses and frequency of events. The events are in three categories: 1) Frequent Events – more than 70 events per day, 2) Occasional Events – 30 to 70 per day, and 3) Infrequent Events – fewer than 30 per day. With these definitions and the three categories of building use, the impact criteria are defined in Table B-5, as taken from the FTA Guidance. Special buildings such as concert halls, television and recording studios, and theaters are not included in the table may require additional consideration and criteria.

Table B-5: FTA Indoor Ground-Borne Vibration (GBV) Impact Criteria for General Vibration Assessment

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)		
	Frequent Events	Occasional Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB *	65 VdB *	65 VdB *
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB

* This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. For equipment that is more sensitive, a Detailed Vibration Analysis must be performed.

With vibration levels of nearly 71 VdB at 45 mph, ground-borne vibration generated by vehicles traveling on rumble strips should not create impacts to anything other than Category 1 buildings or special buildings. However, vibration could approach the limit for Frequent Events for the Category 2 buildings, depending on the expected number of rumble strip strikes per day. If rumble strips, and particularly sinusoidal designs, were used at distances less than 25 ft from a land use, the potential ground-borne vibration levels generated may be a concern if the expected number strikes approaches 70 per day or 3 per hour. For application near Category 1 buildings, ground-borne vibration could be a concern depending on the rumble strip design, distance to the building, and ground type. Using the curve in the FTA Guidance, reproduced here as Figure B-143 for rubber-tired vehicle, or Equation 6-3 in the FTA guidance, a level of 71 VdB at 25 ft could result in vibration levels of 63 VdB at 50 ft, which would be approaching the Category 1 limit of 65 VdB. In general, if the expected rumble strip strikes exceed 3 per hour, or if Category 1 buildings are less than 50 ft from the rumble strips, ground-borne vibrations may be a consideration in the placement of the rumble strips.

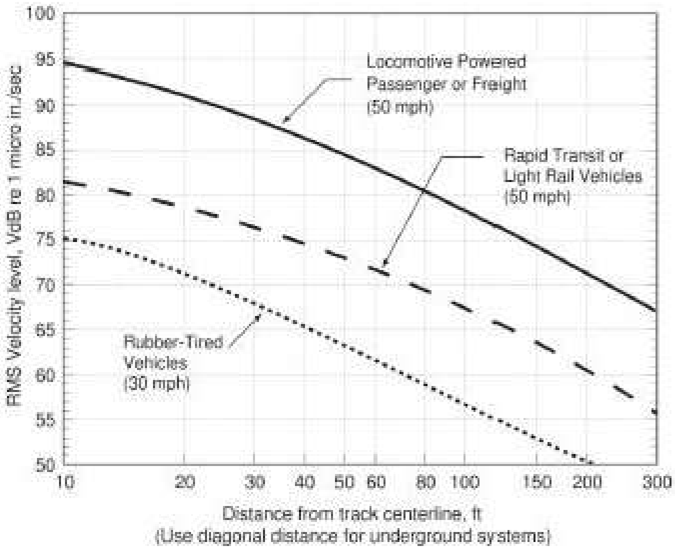


Figure B-143: Generalized ground surface vibration curves from FTA Guidance[2]

SUMMARY AND CONCLUSIONS

The purpose of this measurement program was to collect and process data to determine the best measures to assess rumble strip performance with regards to mizing exterior noise and providing sufficient audio and tactile input to the vehicle operator of roadway departures. From previous research, it is known that the magnitude of pass-by noise levels and the inputs to the operator differ across various vehicle types on any given rumble strip design. Ultimately, the intent is to determine which are most essential to measures in a recommended procedure that can be completed or supervised by SDOT's. To this end, pass-by noise, interior noise, vehicle vibration, and ground-borne vibration measurements were completed with eight vehicles on and off sinusoidal and conventional cylindrical ground rumble strips at 60 and 45 mph in October of 2018 at test sites used in early Caltrans research. The test vehicles ranged from small compact cars to a large sport utility vehicle. A medium-duty dump truck, measured previously in the Caltrans project, was also measured for ground-borne vibration. Pass-by noise was measured using conventional means with a single microphone positioned 25 feet from the centerline of vehicle travel lane. Interior noise was measured at six positions inside each vehicle. Vehicle vibration was measured tri-axially at six locations. The purpose of the multiple locations for interior noise and vibration was to understand how their selection influenced the evaluation of rumble design in terms of performance. In addition, ground-borne vibration at 25 feet from the centerline of vehicle travel lane was acquired for seven vehicles to determine if this is an issue of concern.

For pass-by noise, only the existing AASHTO procedures were used. In previous research, it was determined that significant variations in noise level occur even when it is attempted to consistently maintain the vehicle on the rumble strip. This was also found in the current testing. The intent of a standard procedure is to mize measurement variation between different organizations, and it was clear that transient events would introduction even more variability. In the current study, the range in pass-by levels on the conventional strips was 10 dB, while in the Caltrans study consisting of five vehicles and configurations, it was 5 dB. This difference was attributable to one test vehicle in the current study, the Test Car 3, which produced levels about 6 dB lower than any other. On the mumble strips, the range in the current study was 5 dB and was 4 dB in the Caltrans study. These differences were concluded to not be related to the test method, but rather the wider range in performance with the larger number of vehicles in the current study.

For interior noise, some differences in overall level on/off increments were found for different microphone positions across the different test vehicles. Relative to the average of the increments for all positions, the driver's ear position stood out as having some of largest deviations from the average. In regard to the spectra, several positions had unusually high levels in the frequency bands above 1,250 Hz. This was particularly apparent in the rear outboard position on both the mumble and conventional strips. For the rear center position, this was only pronounced for the mumble strips. Some variation was also noted in spectra around the frequencies of the mumble and conventional rumble strip repetition rates and their harmonics. These data will be studied further for developing a recommended microphone position. Comparing 60 and 45 mph on/off increments, those at 45 mph were typically lower than 60 mph. However, there were exceptions: Test Car 8 had the lowest increments of any vehicle at 60 mph on the conventional strips, but the highest at 45 mph; the increments for Test Car 1 were about 4 dB higher on the mumble strips at 45 mph than at 60 mph; and Test Car 6 increments on the mumble strips were 2 dB higher at 45 mph than at 60 mph, except for the driver's ear position.

For vehicle vibration, the front and rear spindle locations provided the highest levels and largest on/off increments. However, it was difficult to install the accelerometers, and there were issues with cable routing within the confines of the wheel wells. Of the other locations, the seat pad location provided the lowest levels, particularly in the vertical direction; however, the increments were typically equal to or greater than those of the seat track, steering column, and steering wheel. In regard to the fore/aft, lateral, and vertical directions, there was not a dominant direction. Further, the multiple directions actually made comparisons between locations more difficult, as rank ordering of levels and increments for different vehicles and strip design changed for each direction. By energy summing the levels for the three directions for each location and vehicle, the results became more useful in sorting out the differences in locations and from vehicle-to-vehicle. With the summation, the increments for the seat pad and seat track were similar in defining which strip design provided consistent operator input. However, the rank ordering of vehicle did show variation for locations. Both of the steering column and wheel achieved increments greater than 10 dB for all but one of the vehicles on the conventional strips. For the steering system, there were some significant differences between the steering wheel and column, particularly for Test Car 5, Test Car 2, and Test Car 1. Of the interior vibration locations, the steering wheel had the widest range increment values and typically more variation from vehicle-to-vehicle. These variations suggest some difference in the steering wheel as a component and its response to vibration input. It should also be noted that steering wheel measurements are not commonly used by vehicle manufacturers, due to variation between operators in terms of hand location and grip and variation in designed modal response of the steering wheels. Similar to the interior noise results, the on/off increments were lower at 45 mph than at 60 mph for the vibration data.

Comparing pass-by noise, interior noise, and vehicle vibration levels, there was very little correlation between the measures. An upward trend between increasing interior noise and vehicle vibration was noted for seat pad and steering wheel levels, but not for the increments. Comparing pass-by and interior noise spectra, it was demonstrated that there is a transition in the source of interior noise from structure-borne noise contribution to airborne noise in the range from about 250 to 500 Hz, depending on the design of the vehicle. Because of this transition, overall levels and increments do not indicate consistent relationships between pass-by and interior noise due to different portions of the spectra controlling the overall level depending on vehicle and rumble strip design. Comparing interior noise and vehicle vibration spectra, a correspondence between the two types of measurements can be seen up to about 250 Hz. However, the locations where vibration was measured were not points that efficiently radiate sound into the interior. The vibration measurements do provide an indication of the structure-borne sound energy in the body that will feed into the body panels that radiate sound efficiently. In this respect, using points that have their own resonate responses should be avoided because these will be dominated by those local resonances and not necessarily the vibration generating the interior noise.

The measurements of ground-borne vibration during a vehicle pass-by on the rumble strips indicated that sufficient vibration could be generated to be of concern for uses and occupants of buildings under certain circumstances. Generally, if a building is located within about 25 feet of a rumble strip, vibration levels could be generated that exceed FTA impact criteria. For buildings with vibration-sensitive uses, this distance may extend out to as far as 50 feet. For residential uses, ground-borne vibrations are likely not an issue if the number of rumble strip strikes per day is less than 70.

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