**NCHRP Project 15-68(01)**

**EFFECTIVE LOW-NOISE RUMBLE STRIPS**

# APPENDIX D: WASHINGTON STATE SINUSOIDAL STRIPS TESTING

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
of
The National Academies of Sciences, Engineering, and Medicine

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## APPENDIX D

## WASHINGTON STATE SINUSOIDAL STRIPS TESTING

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## INTRODUCTION

This appendix contains the NCHRP Rumble Strip Project Washington sinusoidal strips testing, completed in 2021 and 2022.

## MEASUREMENT PROGRAM

The purpose of Task 3 of the project was to develop an optimal rumble strip design capable of consistently and effectively alerting the driver of lane departure while reducing noise propagated to receptors along the wayside of the roadways as much as possible. Previous work and the results of the Phase I literature review indicated that sinusoidal profiles could provide equal or better performance than conventional strips in producing interior noise and vibration to alert the vehicle operator of lane departures. Further, the sinusoidal designs provide lower pass-by noise levels, which should result in fewer noise complaints from nearby residents. A number of research projects have evaluated different wavelengths of sinusoidal rumble strips, and these have been installed at a number of locations in the country. Phases I and II provided interior noise and vibration and exterior pass-by results at previously tested sites in California, Indiana, and Michigan using the procedures developed in Phase I of the NCHRP 15-68 project. For Task 3, the Research Team was able to work with the Washington State Department of Transportation (WSDOT) in identifying a candidate test location. WSDOT was planning on installing shoulder rumble strips along 10 miles of State Route 105 (SR 105), which is a 55-mph, rural two-lane highway between Aberdeen and Westport, Washington, as shown in Figure D-1. WSDOT also agreed to use Surface Preparation Technologies, LLC for installation of rumble strips for both

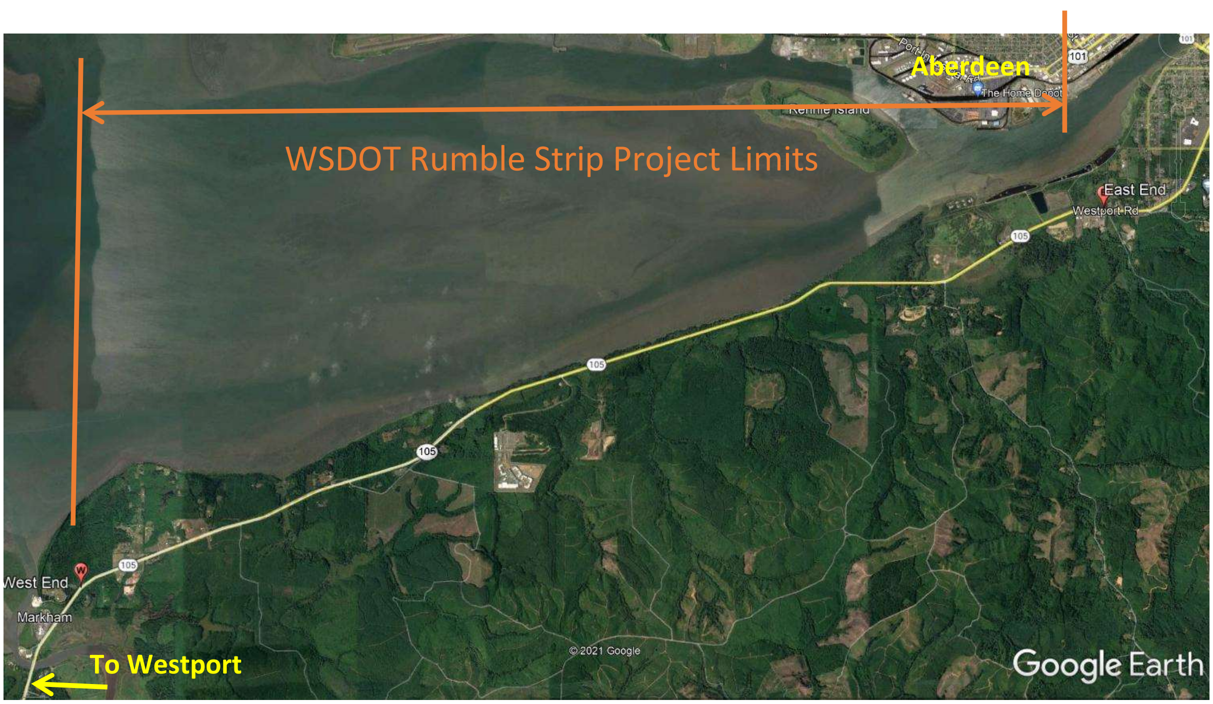



*Figure D-1: Aerial view of SR 105 near Aberdeen, WA*

WSDOT standard strips and the experimental sinusoidal strips specified by the Research Team.

This contractor had a computer controlled milling head so different sinusoidal designs could be installed with little set-up time. Photographs of the milling head and an installation of one of the sinusoidal strip designs are shown in Figure D-2.

*Figure D-2: Milling head and milling operation*

**Description of Rumble Strips**

Twenty varying sinusoidal strips were designed and installed along SR 105. The wavelengths of the sinusoidal strips range from 12 to 24 inches, which includes the same designs as the Indiana test sites. Table D-1 summarizes the nominal site dimensions of the 20 sinusoidal sites. In addition to the sinusoidal wavelength, the parameters of peak-to-peak amplitude, and recess of the rumble strip below the pavement surface were included in the matrix. The location of the 20 sinusoidal rumble strip sites on SR 105 are indicated in Figure D-3. There are nine sites in the westbound direction (right to left), designated by WB, and 11 in the eastbound direction (left to right), labeled as EB. The test site for WSDOT strips was between EB2 and EB3 and closer to EB2. These consisted of cylindrical milling of the pavement at a regular interval with an unground portion in between, as shown in Figure D-4. The ground portions are typically 5 inches long in the direction of travel, with a depth of ⅜ inches and radius of curvature of 12 inches. Spacing of the cylindrical depressions is 12 inches, and they extend in length 48 feet, after which there is a 12-foot gap, without depressions for bicycle access.

The profiles for all 20 of the sinusoidal rumble strips are provided at the end of this appendix, along with the WSDOT rumble strips. The specified and measured dimensions of the 20 sinusoidal strips are given in Table D-2 and compare generally well. For the wavelength, only three were measured to be one-half inch shorter than the specified. Some of this may be due to measurement uncertainty, as aggregate size resulted in some roughness in the surfaces similar to that found in the Midwest testing, which was noted in the Task 1 Interim Report. The measured peak-to-peak amplitudes followed the specified dimensions to within $^{1}/_{16}$ of an inch or less. The recess of the installations did not totally vanish on any of the strips but were typically within $^{1}/_{16}$ of an inch or less of the specified depth.

*Table D-1: Washington Sinusoidal Test Strip Designs*

| Test Site ID | Wavelength, in. | 60 mph Repetition Rate(s), Hz (⅓ OB) | Peak-to-Peak, in. | Recess, in. |
|---|---|---|---|---|
| WB1 | 14 | 75.4 (80) | 3/8 | 1/8 |
| WB2 | 16 | 66.0 (63) | 3/8 | 1/8 |
| WB3 | 18 | 58.7 (63) | 3/8 | 1/8 |
| WB4 | 16 | 66.0 (63) | 5/16 | 0 |
| WB5 | 15 | 70.4 (63, 80) | 5/16 | 0 |
| WB6 | 16 | 66.0 (63) | 1/2 | 0 |
| WB7 | 12 | 88.0 (80, 100) | 3/8 | 1/8 |
| WB8 | 14 | 75.4 (80) | 7/16 | 0 |
| WB9 | 14 | 75.4 (80) | 1/2 | 1/8 |
| EB1 | 14 | 75.4 (80) | 5/16 | 0 |
| EB2 | 14 | 75.4 (80) | 3/8 | 0 |
| EB3 | 14 | 75.4 (80) | 1/2 | 0 |
| EB4 | 16 | 66.0 (63) | 3/8 | 0 |
| EB5 | 14 | 75.4 (80) | 7/16 | 1/8 |
| EB6 | 24 | 44.0 (40, 50) | 3/8 | 1/8 |
| EB7 | 14 | 75.4 (80) | 5/16 | 1/8 |
| EB8 | 17 | 62.1 (63) | 3/8 | 1/8 |
| EB9 | 13 | 81.2 (80) | 3/8 | 1/8 |
| EB10 | 15 | 70.4 (63, 80) | 1/2 | 0 |
| EB11 | 15 | 70.4 (63, 80) | 3/8 | 1/8 |

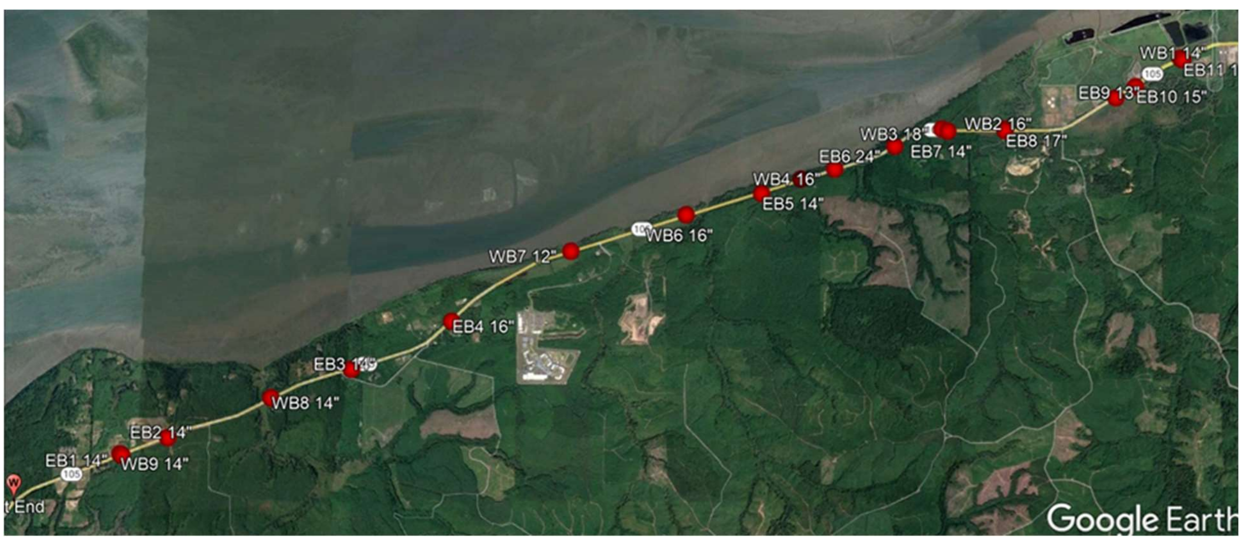



*Figure D-3: Location of the 20 sites for sinusoidal rumble strips*

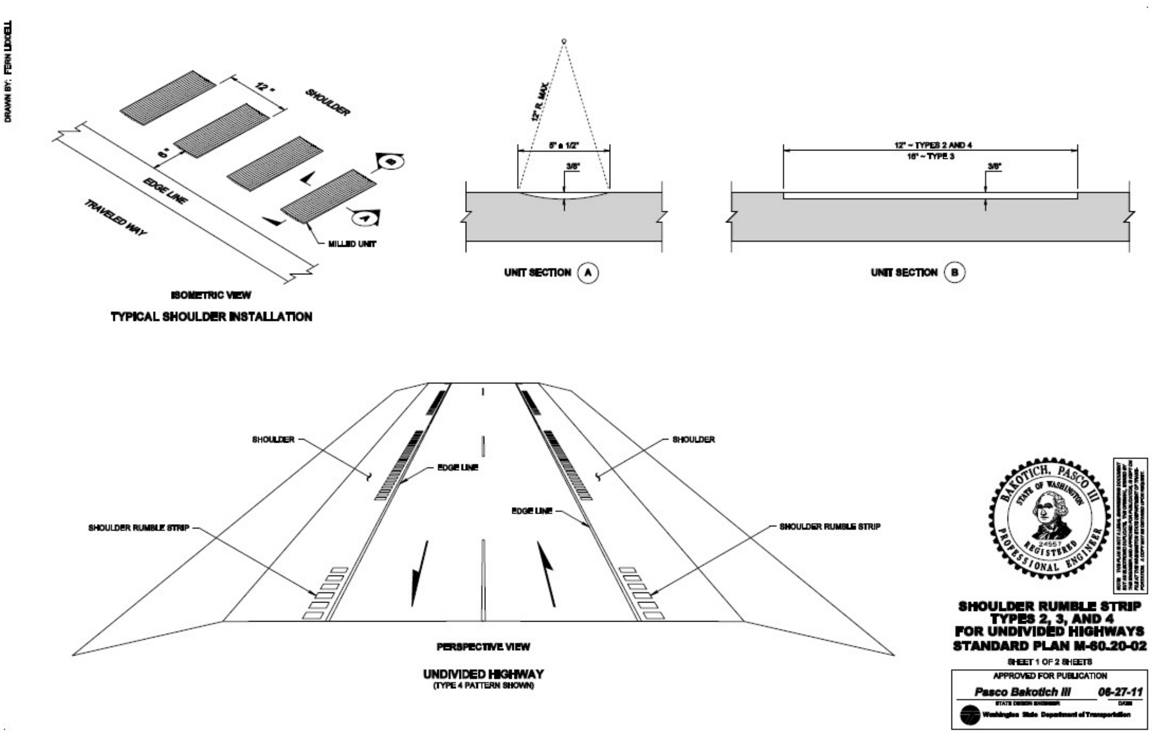



*Figure D-4: Plan for WSDOT rumble strips for two lane, undivided highways*

*Table D-2: Specified and as installed dimensions of the sinusoidal rumble strips*

| Site | Wavelength, in. | | Amplitude, in. | | Recess, in. | |
|---|---|---|---|---|---|---|
| | Specified | Actual | Specified | Actual | Specified | Actual |
| WB1 | 14 | 14 | 3/8 | 3/8 | 1/8 | 0-3/16 |
| WB2 | 16 | 16 | 3/8 | 3/8 | 0-1/8 | 1/8 |
| WB3 | 18 | 18 | 3/8 | 3/8 | 1/8 | 1/8-3/16 |
| WB4 | 16 | 16 | 5/16 | 5/16 | 0 | 0-1/16 |
| WB5 | 15 | 15 | 5/16 | 5/16 | 0 | 0-1/16 |
| WB6 | 16 | 16 | 1/2 | 7/16 | 0 | 0-1/16 |
| WB7 | 12 | 12 | 3/8 | 3/8-7/16 | 1/8 | 1/8 |
| WB8 | 14 | 14 | 7/16 | 7/16 | 0 | 1/8 |
| WB9 | 14 | 14 | 1/2 | 1/2 | 1/8 | 1/8 |
| EB1 | 14 | 14 | 5/16 | 1/4-5/16 | 0 | 0-1/16 |
| EB2 | 14 | 14 | 3/8 | 5/16 | 0 | 0-1/8 |
| EB3 | 14 | 14 | 1/2 | 7/16-1/2 | 0 | 0-3/8 |
| EB4 | 16 | 15½ | 3/8 | 3/8 | 0 | 1/16-1/8 |
| EB5 | 14 | 13½ | 7/16 | 7/16 | 1/8 | 3/16-1/8 |
| EB6 | 24 | 24 | 3/8 | 3/8 | 1/8 | 1/8 |
| EB7 | 14 | 13½ | 5/16 | 5/16 | 1/8 | 1/8 |
| EB8 | 17 | 17 | 3/8 | 3/8 | 1/8 | 0-1/8 |

| Site | Wavelength, in. | | Amplitude, in. | | Recess, in. | |
|---|---|---|---|---|---|---|
| | Specified | Actual | Specified | Actual | Specified | Actual |
| EB9 | 13 | 13 | 3/8 | 1/4-3/8 | 1/8 | 1/8-3/16 |
| EB10 | 15 | 15 | 1/2 | 7/16-1/2 | 0 | 0-1/16 |
| EB11 | 15 | 15 | 3/8 | 3/8 | 1/8 | 1/8 |

**Test Vehicles**

Following the recommended test procedure developed in Phase I, four vehicles were included in each type of measurement. These represented one each from a small compact car, mid- to full-size sedan, mid-size SUV, and large, full frame pickup truck or SUV categories. To complete the Task 9 testing, two sets of vehicles were used. For the interior noise and vibration testing completed in October 2021, the test vehicles included: a Nissan Versa, a Toyota Camry, a Chevrolet Equinox, and a Ford Expedition, as shown in Figure D-5. For the pass-by testing completed in January 2022, due to vehicle availability, the Chevrolet Equinox was replaced by a Ford Escape mid-size SUV, and the Ford Expedition was replaced with a full-size Chevrolet Yukon SUV. These two replacement vehicles are shown in Figure D-6.


*Figure D-5: Test vehicles used for the interior noise and vibration measurements*



*Figure D-6: Test vehicles mid-size and large-size SUVs used for the pass-by measurements*

With the exception of the Expedition and Yukon, all other test vehicles were front wheel drive vehicles. The Expedition and Yukon are 4-wheel drive capable, but tested in rear axle, 2-wheel drive. Table D-3 summarizes the vehicles' tire information and wheelbase, and Table D-4 summarizes the wheelbase divided by the wavelengths for each of the designs included in Task 3.

*Table D-3: Test vehicles with tire sizes and wheelbase dimensions*

| Test Car | Tire Size | Tire Dia. (in.) | Wheelbase (in.) |
|---|---|---|---|
| Test Car D-1 | 185/65R15 | 24 | 102 |
| Test Car D-2 | 215/55R17 | 26 | 112 |
| Test Car D-3 | 225/65R17 | 28 | 107 |
| Test Car D-4 | 275/65R18 | 32 | 145 |
| Test Car D-5 | 235/55R17 | 26 | 106 |
| Test Car D-6 | 265/70R17 | 31 | 140.5 |

*Table D-4: Wheelbases divided by wavelength calculations*

| Test Car | WB/λ 12 in. | WB/λ 13 in. | WB/λ 14 in. | WB/λ 15 in. | WB/λ 16 in. | WB/λ 17 in. | WB/λ 18 in. | WB/λ 24 in. |
|---|---|---|---|---|---|---|---|---|
| Test Car D-1 | 8.5 | 7.8 | 7.3 | 6.8 | 6.4 | 6.0 | 5.7 | 4.3 |
| Test Car D-2 | 9.3 | 8.6 | 8.0 | 7.5 | 7.0 | 6.6 | 6.2 | 4.7 |
| Test Car D-3 | 8.9 | 8.2 | 7.6 | 7.1 | 6.7 | 6.3 | 5.9 | 4.5 |
| Test Car D-4 | 10.3 | 9.5 | 8.8 | 8.2 | 7.7 | 7.2 | 6.8 | 5.1 |
| Test Car D-5 | 8.8 | 8.2 | 7.6 | 7.1 | 6.6 | 6.2 | 5.9 | 4.4 |
| Test Car D-6 | 10.2 | 9.4 | 8.7 | 8.1 | 7.6 | 7.2 | 6.8 | 5.1 |

The wheelbase divided by the sinusoidal wavelength (WB/λ) defines the phase relationship of inputs to the vehicles. For ratios near to 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 driven down. These relationships may have implications for the vibration response of the different vehicles.

For acoustical response, the geometry of the interior space of the vehicle is significant, as it relates to interior cavity modes and measurements at fixed locations in the cabin. This is particularly important for lower frequencies, where standing waves (cavity modes) create spatial maximum and minimum sound pressure levels at anti-node and node points. The interior dimensions for the six test vehicles are reported in Table D-5. The corresponding interior cavity first and second modes are given in Table D-6 for the fore/aft, lateral, and vertical directions.

*Table D-5: Test vehicle interior dimensions*

| **Test Car** | **Windshield/Backlite (Inches)** | **Door-to-Door (Inches)** | **Floor to Roof (Inches)** |
|---|---|---|---|
| Test Car D-1 | 115 | 54 | 47.5 |
| Test Car D-2 | 113 | 61 | 46 |
| Test Car D-3 | 130 | 60 | 49 |
| Test Car D-4 | 101 | 71 | 48 |
| Test Car D-5 | 125 | 60 | 48 |
| Test Car D-6 | 96.5 | 71 | 48 |

*Table D-6: 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 D-1 | 59 | 118 | 125 | 251 | 143 | 285 |
| Test Car D-2 | 60 | 120 | 111 | 221 | 147 | 294 |
| Test Car D-3 | 52 | 104 | 113 | 226 | 138 | 276 |
| Test Car D-4 | 67 | 134 | 95 | 191 | 141 | 282 |
| Test Car D-5 | 54 | 108 | 113 | 226 | 141 | 282 |
| Test Car D-6 | 70 | 140 | 95 | 190 | 141 | 281 |

**Exterior Noise Measurements**

*On-Board Sound Intensity*

On-board sound intensity (OBSI) measurements were made at each of the SR105 sites. These measurements were conducted according to the AASHTO Standard Method of Test T 360[1] at standardized vehicle speed of 60 mph. A Toyota Camry equipped with a Standard Reference Test Tire (SRTT) was the test vehicle used for the OBSI on April 22, 2021, between 3:00 p.m. and 6:00 p.m. Three runs were made at each site and had standard deviations of 0.2 dB or less. Measurements were also made on the shoulder pavement outboard of the rumble strips at sites WB4 and WB6 where conditions were such that the measurements could be made safely.

Pass-by Noise Measurements

The shoulder rumble strip pass-by noise measurements were performed following the AASHTO TP-98 procedure,[2] modified for measurements of specific vehicles in a manner consistent with the previous testing conducted in this project. To expedite testing, measurements were made at two rumble strip sites simultaneously, with two test vehicles operating independently. Larson Davis 831 sound level meters (SLMs) were used at each site to acquire the sound level time histories. The measurement microphones were supported on extendable poles, and a microphone cable was used to accommodate different terrain, so microphones were positioned at heights of 5 feet above the pavement surface, as illustrated in Figure D-7. For pass-by runs off the rumble strips, the microphone was positioned 25 feet from the center of the 12-foot width lane of test

*Site WB2 – microphone 5'1" above ground* *Site WB5 – microphone 7'8" above ground*

*Figure D-7: Examples of microphone placements to be 5ft above pavement surface*

vehicle travel. For on-rumble strip measurements, the microphone was re-positioned 3 feet further away from the center of the lane of travel to account for the displacement of the passenger side tires being closer to the microphone when the vehicles were on the rumble strips. The SLMs captured the one-third octave band pass-by noise levels using ⅛-second exponential averaging ("fast" response), sampled every 0.1 seconds for the duration of the event pass-by.

*Interior Noise Measurements*

Following the recommended procedure from the conclusion of Phase I of the 15-68 project, interior noise was measured at the primary position, "center center," and at the secondary position, "front center." Both positions were 29 inches above the seat cushion. The center center (CC) microphone was hung from the roof at the middle of the limits of the fore/aft seat adjustment and centered on the headrest. The front center (FC) was hung from the roof at the foremost seat adjustment position and centered on the headrest.

*Interior Vibration Measurements*

Also following the recommended procedure from the conclusion of Phase I of the project, triaxial acceleration was measured at the primary seat track (ST) location and at the secondary steering column (SC) position. All acceleration and interior noise data were acquired using National Instruments analog-to-digital converters and LabView software. These consisted of $L_{eq}$ values acquired every 0.1 second for a total duration of 10 seconds. The levels from the three directions were summed to produce the reported acceleration levels.

## EXTERIOR NOISE MEASUREMENT RESULTS

### On-Board Sound Intensity

SR 105 in Washington is a two-lane highway with a chip seal overlay. An older DGAC pavement is located along the shoulder, on which the rumble strips were installed. The pre- and post-grind pavements are shown in Figure D-8. Visual comparison of the images gives some indication of the surface roughness of the dense grade shoulder and the chip seal surface.

*Figure D-8: Pavement surfaces prior to and after sinusoidal strip installation*

OBSI measurements were conducted on chip seal surface at each of the 20 sinusoidal test sites, and two runs were completed on the older DGAC shoulder. Each measurement was a continuous five-second average, in accordance with the AASHTO Standard Method of Test T 360.[1] Figure D-9 summarizes the overall OBSI results at each test site and the shoulder DGAC pavement.

The chip seal pavement at each of the 20 sites resulted in overall OBSI levels ranging from 105.9 to 107.1 dB (average of 106.6 dB) for all the sites. The older DGAC pavement along the shoulder resulted in an average OBSI level of 103.9 dB.

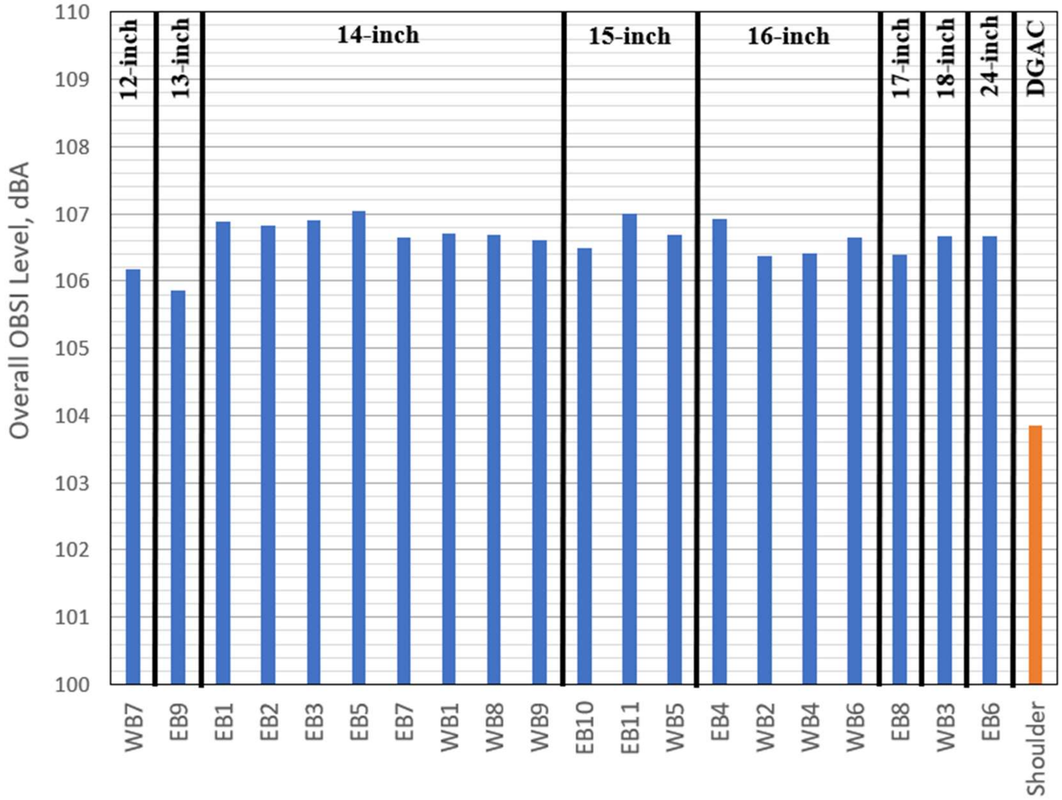



*Figure D-9: Temperature-corrected average OBSI levels measured along SR 105 at the chip seal sinusoidal test sites and along the shoulder DGAC pavement*

The average spectrum measured at each sinusoidal test site and along the shoulder are shown in Figure D-10. At one-third octave bands below 1,000 Hz, average OBSI levels for the chip seal pavement was 5.1 to 7.8 dB higher than the older DGAC. Additionally, at bands of 1,250 and 1,600 Hz, the chip seal OBSI levels are 2 to 2.9 dB higher than the older DGAC. Based on the general spectral trends shown in Figure D-10, the higher levels for the chip seal sites are dominated by the levels below 1,000 Hz.

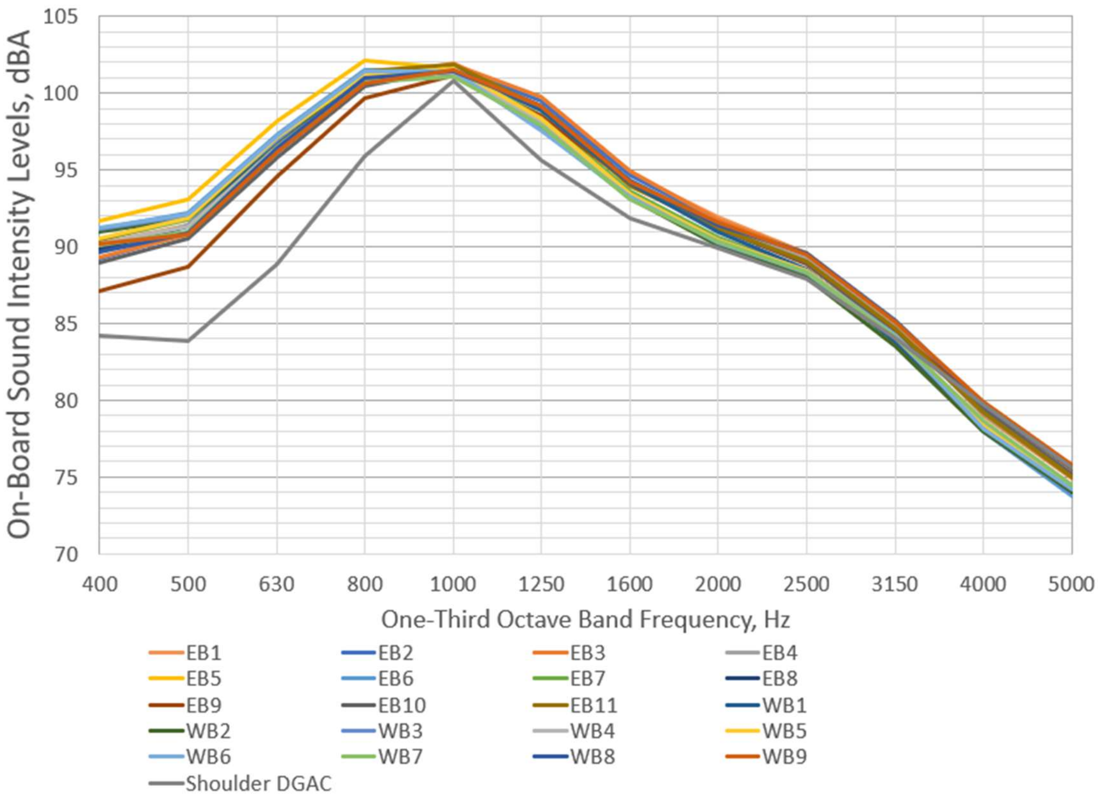



*Figure D-10: Average one-third octave band spectra measured at each sinusoidal test site and along the shoulder of SR 105 in Washington*

The chip seal and older DGAC levels measured along SR 105 in Washington were compared to the OBSI levels measured in Indiana, Michigan, and California. Figure D-11 shows the overall levels for each site. The chip seal pavement in Indiana generated OBSI levels ranging from 106.5 to 107.2 dB (average of 106.8 dB). On average, the chip seal OBSI in Washington was within 0.2 dB of the chip seal pavement in Indiana. The aged DGAC pavement in California was 107.1 dB, which is at the upper range of both Indiana and Washington chip seal sites. The older DGAC pavement in Indiana and Michigan ranged from 103.6 to 103.7 dB, which is within 0.3 dB of the older DGAC pavement in Washington. The fairly new DGAC pavement at the California sinusoidal site resulted in the lowest overall level of 101.7 dB, which was about 2 dB lower than the older DGAC pavements and about 5 dB lower than the chip seal and aged DGAC pavements. The indicated higher OBSI levels for those pavements, of about 106 dB and higher, indicate that the difference in overall A-weighted levels on and off rumble strips will be reduced due to the pavement and not necessarily due to the strip design.

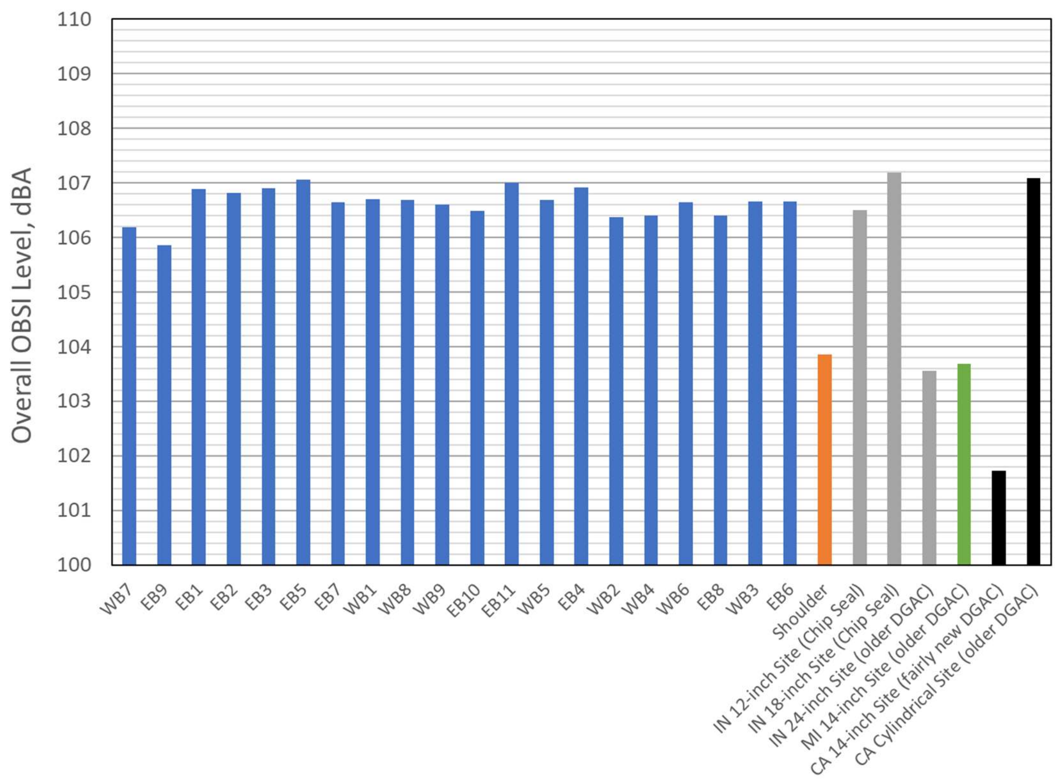



*Figure D-11: Average overall OBSI levels along SR 105 in Washington compared to the Indiana, Michigan, and California test sites*

**60 mph Pass-by**

Pass-by measurements were made at 25 feet from the centerline of the nearest travel lane during off-strips test runs. During on-strips test runs, pass-by measurements were made 25 feet from the centerline of the test vehicle when the passenger-side tires are positioned on the strips. At least three on-strips test runs were made for each vehicle at each sinusoidal test site and at a site representative of the conventional WSDOT rumble strips. This section discusses the pass-by measurements and results.

To process the pass-by data, the overall noise level for 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 sinusoidal strips. As noted in regard to Figures D-9 and D-11, the OBSI levels on the shoulders of SR 105 were 2 to 3 dB lower than those of the mainline chip seal surface. As a result, the pass-by levels for the off-strip pass-by events (on the chip seal) were at times just as noisy or noisier than the on-strips, in terms of overall A-weighted level, as illustrated by Figure D-12. In this case, the tone at 80 Hz is audible during the pass-by; however, the elevated levels off the strips, which is due to chip seal, is dominated by the energy in the bands above 200 Hz, summing to make the overall A-weighted level higher.

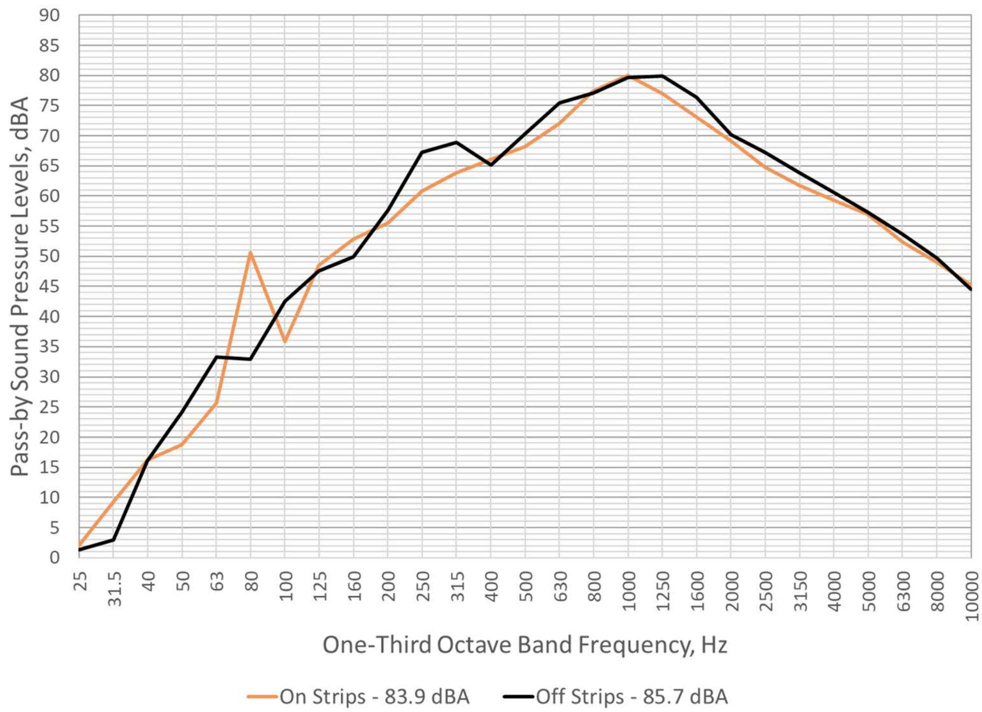



*Figure D-12: Toyota Camry pass-by spectra on and off 13-in sinusoidal strips – Site EB9*

Examples of overall levels off and on rumble strips for Test Car D-6 and Test Car D-1 for the complete set of strip designs are shown in Figures D-13 and D-14, respectively. Similar plots for Test Car D-5 and the Test Car D-2 can be found at the end of this appendix.

As shown in Figures D-13 and D-14, the overall levels on the sinusoidal strips were within a few dB of or lower than the band-passed levels off the strips. This effect was encountered for all twenty sinusoidal designs and all four test vehicles. For the WSDOT standard rumble strips, this was not the case, as pass-by levels on the strips were 5.6 to 8.3 dB higher than the off strips.

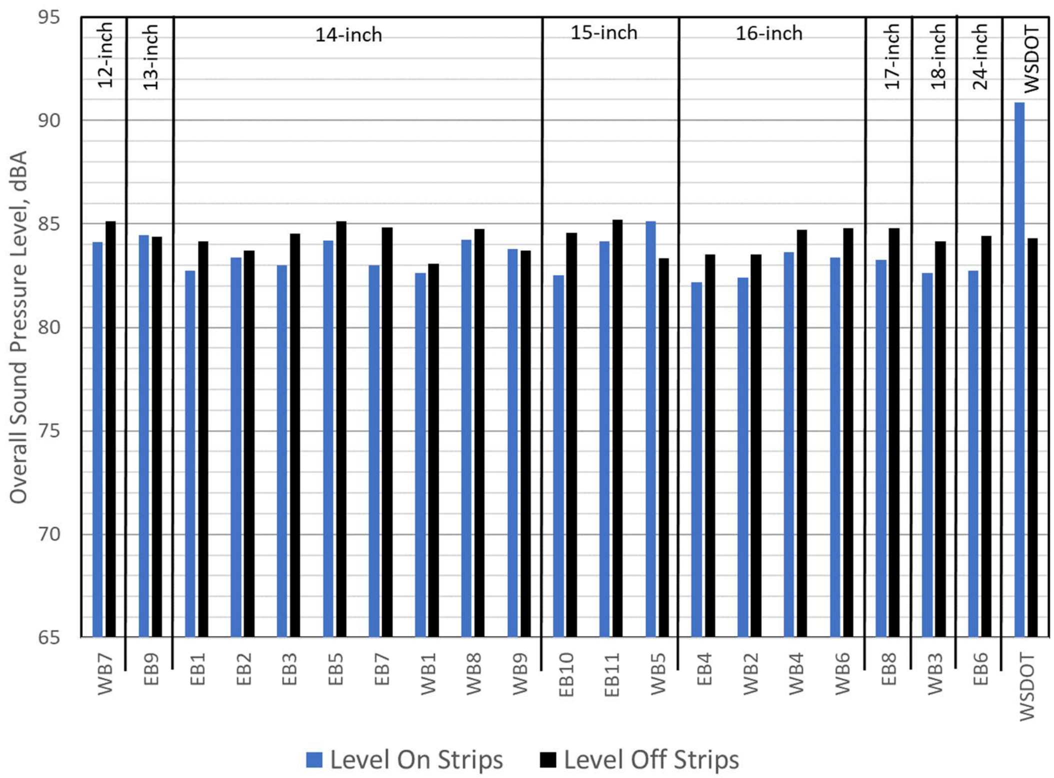



*Figure D-13: Overall A-weighted pass-by levels on and off strips for Test Car D-6*

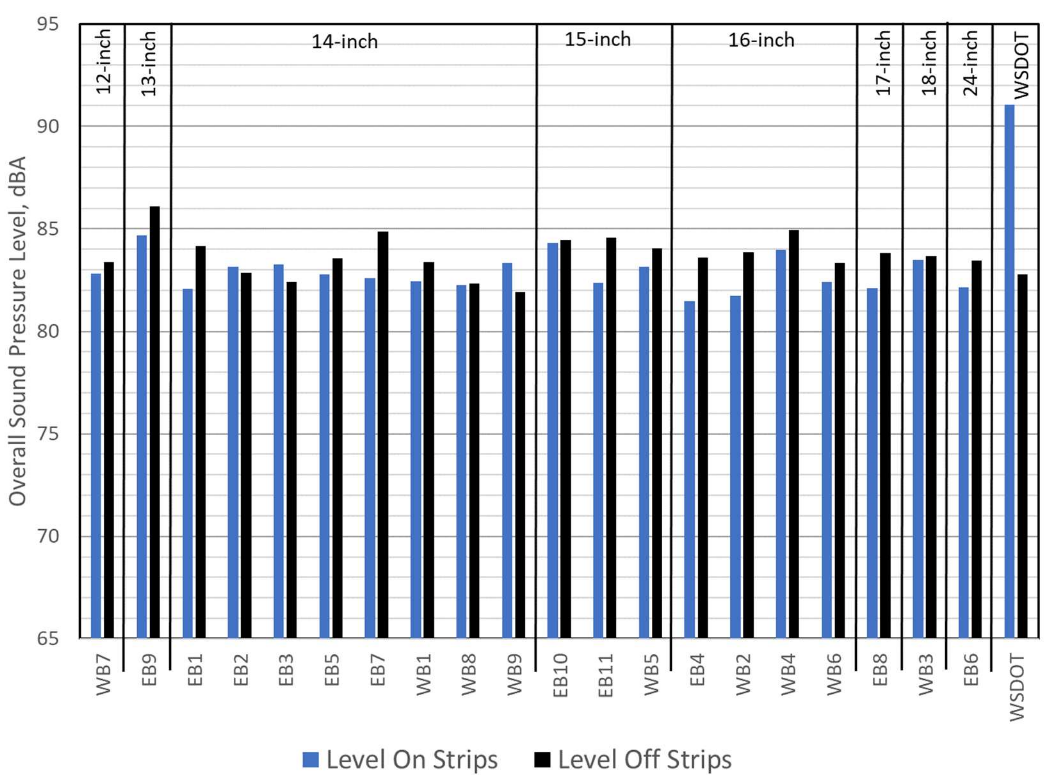



*Figure D-14: Overall A-weighted pass-by levels on and off strips for Test Car D-1*

Although the overall level differences of Figure D-13 and D-14 at the sinusoidal sites display virtually no on/off difference, subjectively, there were clear differences with tonal sounds on the strips that were audible. For this reason, the overall levels on and off strips were recalculated by summing the energy from 31.5 to 200 Hz in the maximum overall spectra, which would eliminate the upper frequency levels dominated by the pavement and retain that portion of the spectra more strongly influenced by the sinusoidal repetition rates ranging from 40 to 100 Hz (see Table D-1). The band-passed levels determined by the summation of the energy from 31.5 to 200 Hz are shown in Figures D-15 through D-18 for each of the four test vehicles. For each vehicle except Test Car D-2, the WSDOT standard rumble strips had the highest band-passed levels, which ranged from 71.7 to 74.8 dBA for the Yukon, Escape, and Versa. The highest level on the sinusoidal strips was 70.0 dBA. The 17-, 18-, and 24-inch strips resulted in band-passed levels of about 62 dBA or below, which were the lowest levels of all the sites. Of the sinusoidal test sites, EB1, EB2, WB8, and WB9 (all 14-inch wavelengths) resulted in the highest on-strips levels across all the vehicles. High levels at WB7 (12-inch wavelength) were also measured for the Yukon and the Escape in the large SUV and mid-size SUV categories, respectively.

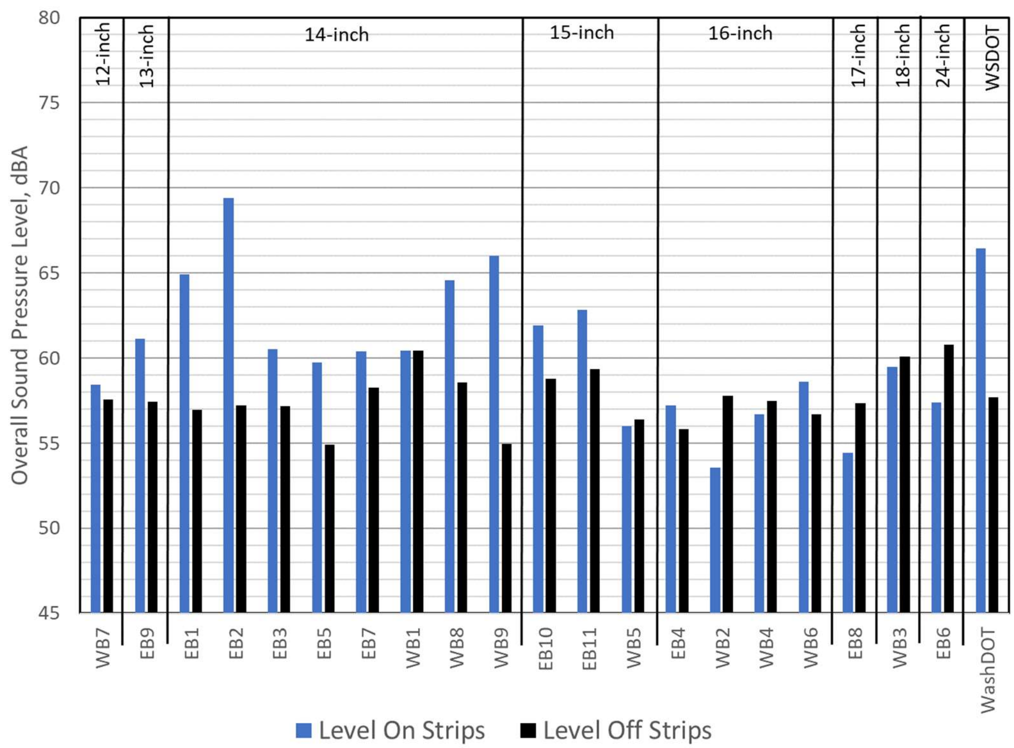



*Figure D-15: Band-passed A-weighted pass-by levels 31.5 to 200 Hz for Test Car D-2*

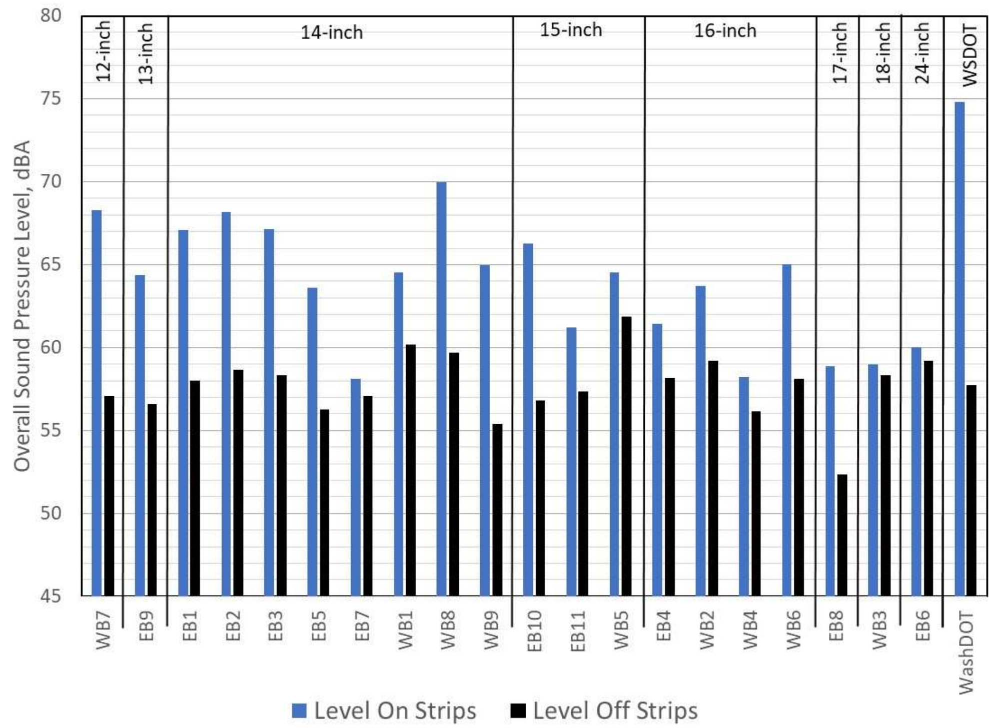



*Figure D-16: Band-passed A-weighted pass-by levels for 31.5 to 200 Hz Test Car D-5*

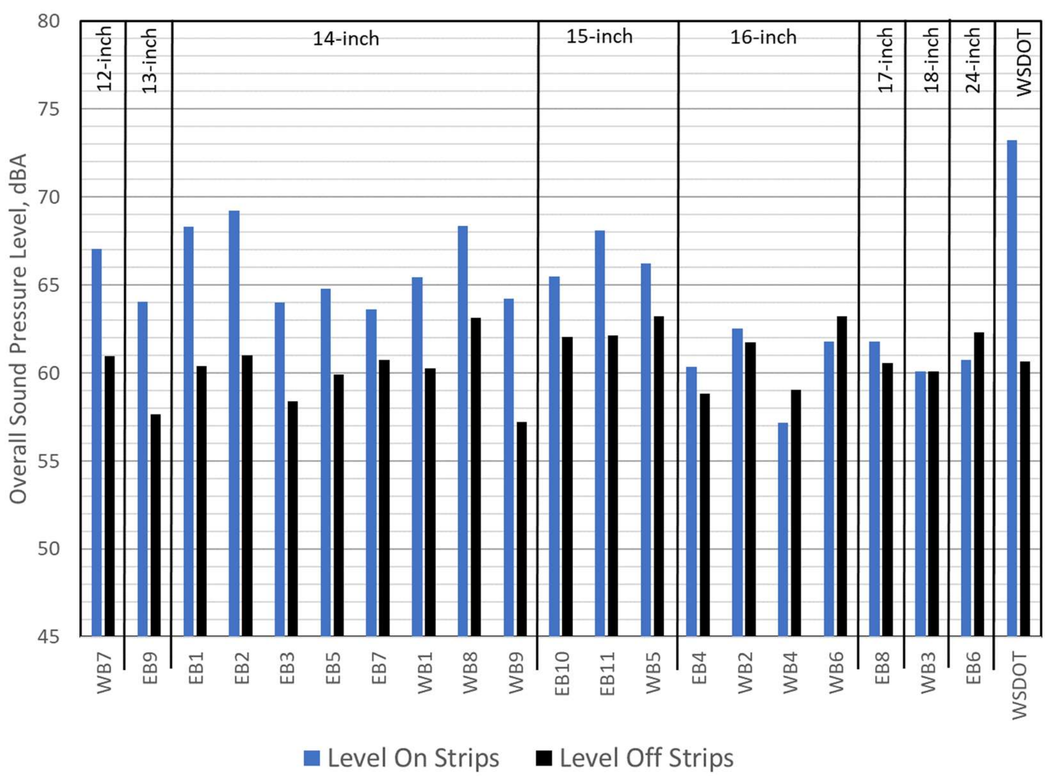



*Figure D-17: Band-passed A-weighted pass-by levels for 31.5 to 200 Hz Test Car D-6*

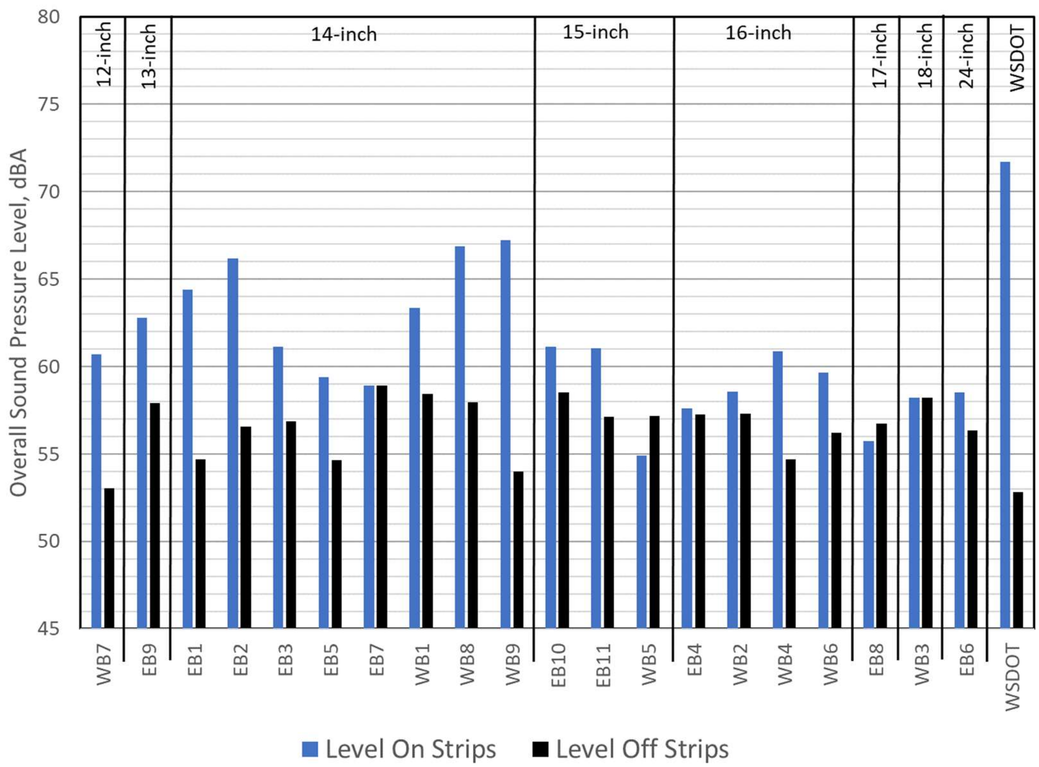



*Figure D-18: Band-passed A-weighted pass-by levels for 31.5 to 200 Hz Test Car D-1*

The time histories for the repetition rate frequencies at each site were also reviewed. A sound pressure level (SPL) spectra and overall SPL were measured every 0.1 seconds for a total time of five to 10 seconds per run. At each site, the on-strips driving frequency for each wavelength was known, and in addition to plotting the time histories for the overall SPLs, the time histories at the driving frequencies were also plotted. In Figure D-19, time histories for the overall A-weighted level and the levels for the 63, 80, and 100 Hz ⅓ octave band levels are plotted for Test Car D-2 on site EB1 (14-inch wavelength). For this wavelength, the repetition rate is 75.4 Hz, falling within the 80 Hz band. It is seen that the maximum level in that band rises above the adjacent bands in Figure D-19. It is also apparent that there is a time delay between the maximum band-passed levels and that in the 80 Hz band of 0.6 seconds, corresponding to about 53 feet of vehicle travel from the spot where the maximum band-passed occurs. This phenomenon was found for all the sites and all the vehicles. For the wavelengths of 12, 15, and 24 inches, the repetition rate falls between two one-third octave bands at 60 mph. In these cases, time histories for both split frequency bands were plotted. An example of this is shown in Figure D-20 for the Test Car D-2 at EB6 (24-inch wavelength). The repetition rate is 44 Hz, which falls in between the 40 and 50 Hz bands. From the example time histories shown in Figure D-20, the peak SPLs in the 40 and 50 Hz time histories show average time delays of 1.2 and 0.8 seconds, respectively, from the peak SPLs in the overall time histories. Standard deviations of 0.1 seconds were calculated for each delay at all three runs. Each test vehicle at each of the sinusoidal test sites had similar time delays; though, the delays varied. Table D-7 summarizes the average time delays for each site and for each vehicle at 60 mph.

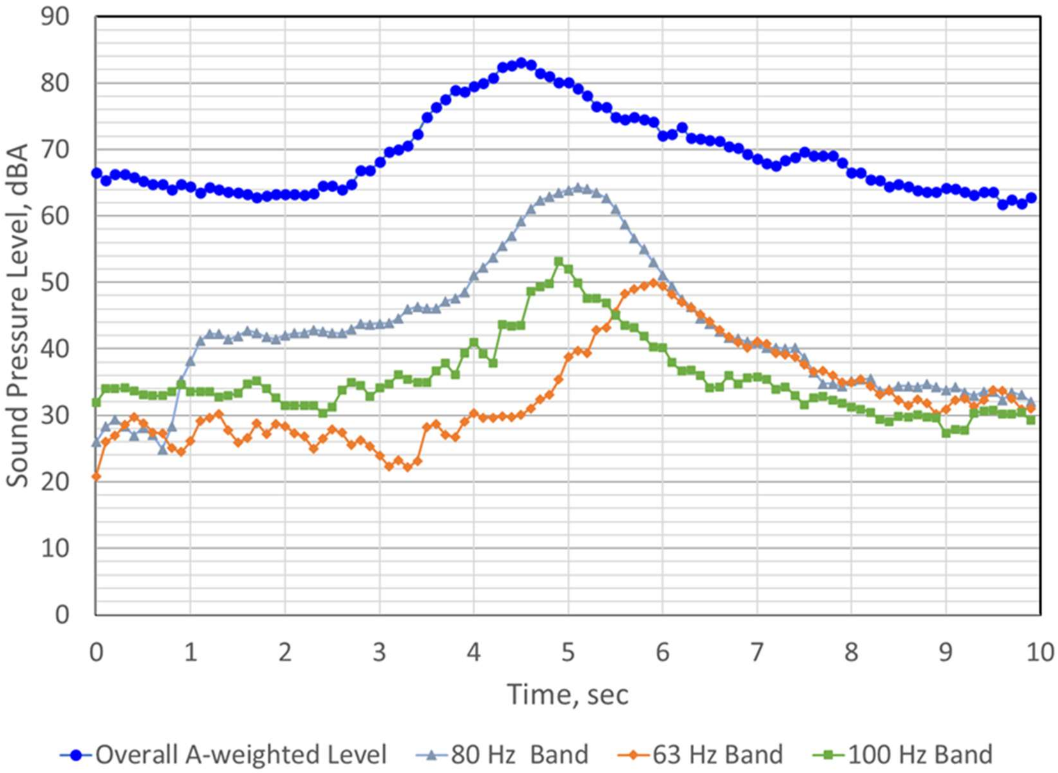
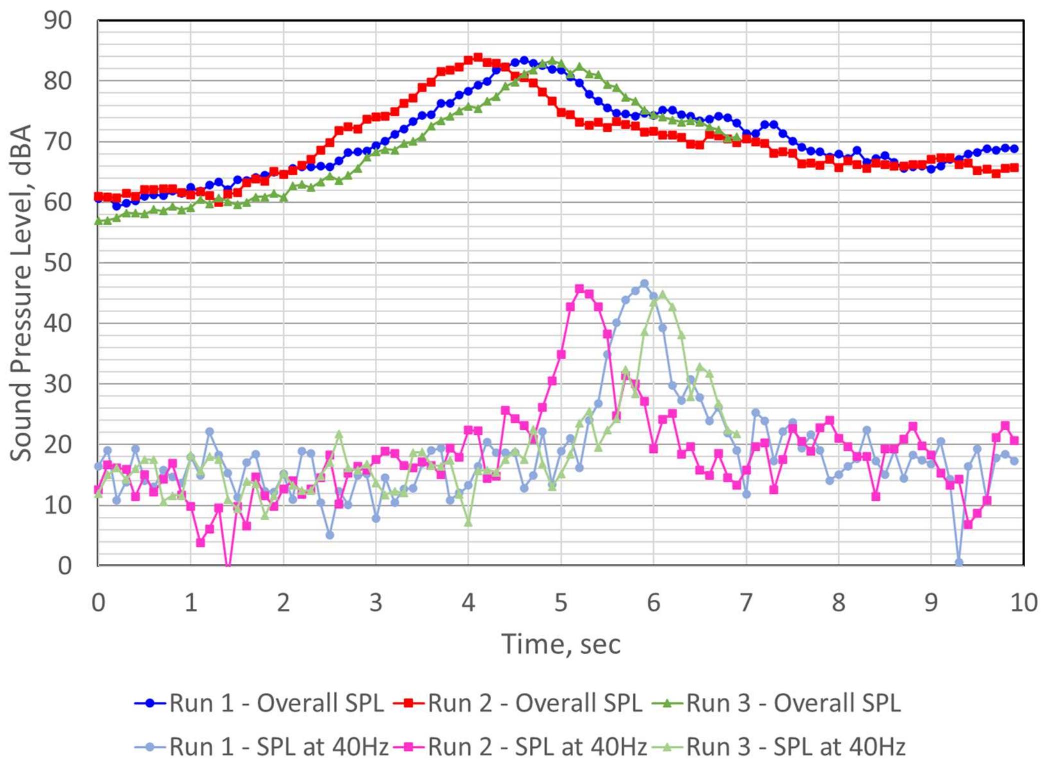



*Figure D-19: Overall and ⅓ octave band level time histories for Test Car D-2 at 60 mph at site EB1 with 14-inch wavelength*



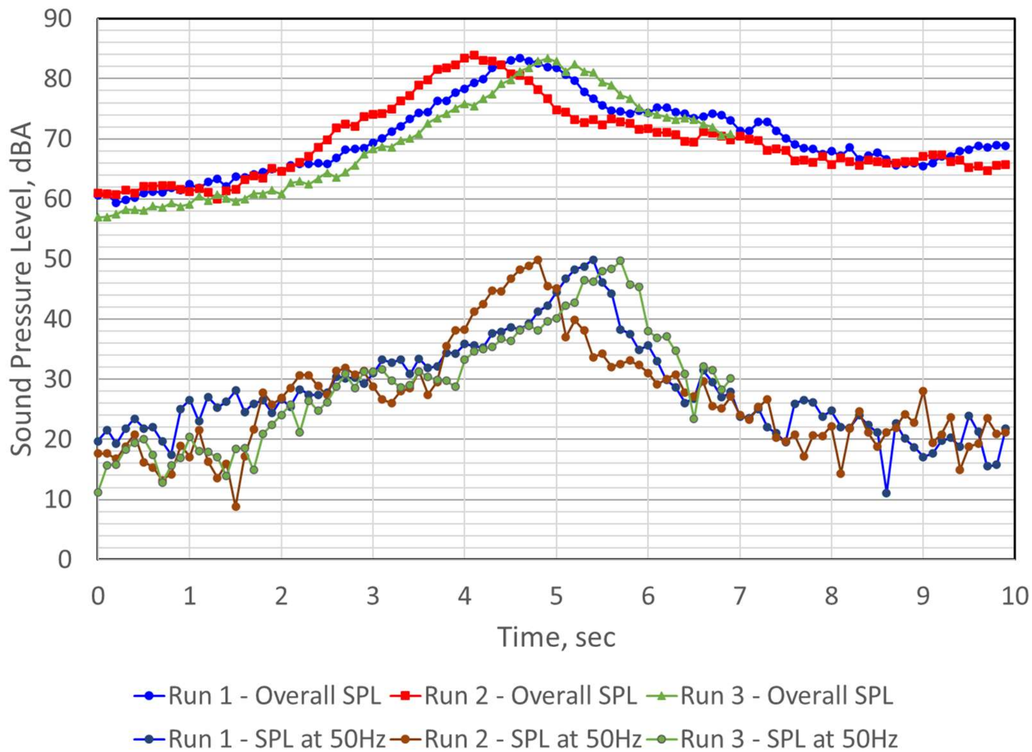




*Figure D-20: Overall and 40 Hz and 50Hz ⅓ octave band level time histories for Test Car D-2 at 60 mph at site EB1 with 24-inch wavelength*

*Table D-7: Time Delays between the maximum band-passed level and maximum level for the one-third octave band level containing the rumble strip sinusoidal frequency*

| Site | Wavelength (inches) | Test Car D-6 | Test Car D-2 | Test Car D-5 | Test Car D-1 | Average |
|---|---|---|---|---|---|---|
| EB1 | 14 | 0.5 | 0.6 | 0.5 | 0.5 | **0.5** |
| EB2 | 14 | 0.6 | 0.8 | 0.5 | 0.6 | **0.6** |
| EB3 | 14 | 0.6 | 0.6 | 0.5 | 0.6 | **0.6** |
| EB4 | 16 | 1.0 | 1.0 | 0.7 | 0.9 | **0.9** |
| EB5 | 14 | 0.8 | 0.7 | 0.6 | 0.7 | **0.7** |
| EB6 | 24 | 1.3<br>0.9 | 1.2<br>0.8 | 1.2<br>0.6 | 1.3<br>0.5 | **1.3**<br>**0.7** |
| EB7 | 14 | 0.7 | 0.3 | 0.6 | 0.9 | **0.6** |
| EB8 | 17 | 0.6 | 0.8 | 0.5 | 0.5 | **0.6** |
| EB9 | 13 | 0.6 | 0.7 | 0.9 | 0.5 | **0.7** |
| EB10 | 15 | 1.0<br>0.0 | 0.9<br>0.6 | 0.8<br>0.5 | 1.1<br>0.8 | **1.0**<br>**0.5** |
| EB11 | 15 | 1.0<br>0.4 | 0.9<br>0.6 | 1.0<br>0.8 | 0.8<br>0.5 | **0.9**<br>**0.6** |
| WB1 | 14 | 0.7 | 0.8 | 0.6 | 0.4 | **0.6** |
| WB2 | 16 | 1.0 | 1.0 | 0.7 | 0.8 | **0.9** |
| WB3 | 18 | 0.8 | 0.9 | 0.7 | 0.8 | **0.8** |
| WB4 | 16 | 0.8 | 0.9 | 0.7 | 0.7 | **0.8** |
| WB5 | 15 | 1.0<br>0.4 | 1.0<br>0.7 | 0.9<br>1.1 | 0.9<br>0.6 | **1.0**<br>**0.7** |
| WB6 | 16 | 1.1 | 1.0 | 0.7 | 0.7 | **0.9** |
| WB7 | 12 | 0.9<br>0.3 | 1.0<br>0.5 | 0.8<br>0.2 | 1.0<br>0.4 | **0.9**<br>**0.4** |
| WB8 | 14 | 0.6 | 0.5 | 0.5 | 0.3 | **0.5** |
| WB9 | 14 | 0.6 | 0.3 | 0.5 | 0.3 | **0.4** |
| | **Average** | **0.7** | **0.8** | **0.7** | **0.7** | **0.7** |

For the sinusoidal sites with a single rumble strip frequency, the peak levels occurred 0.3 to 1.1 seconds after the peak of the overall level for all vehicles. For the sinusoidal sites with split rumble strip frequencies, peak levels for the first frequency were delayed 0.8 to 1.3 seconds after the overall, and the peak levels for the second frequency were delayed 0.0 to 1.1 seconds after the band-passed level. For Test Car D-6, D-5, and D-1, the average delay for the sinusoidal rumble strip peaks was 0.7 seconds, and for Test Car D-2 was 0.8 seconds.

Results from data collected in California in Phase I and in Indiana and Michigan in Phase II reveal that all the sinusoidal strips had delays between the maximum A-weighted level and the frequency band corresponding to the repetition rate. This interesting phenomenon is important for assessing the pass-by noise performance of rumble strips, and particularly, sinusoidal strips. Typically, practitioners just look at the frequency content at the time of maximum overall A-weighted level; however, by doing so, tonal sounds from sinusoidal rumble strips would be overlooked. In this analysis, the maximum A-weighted level and the maximum level at the frequency band corresponding to the repetition rate(s) are each site and in each vehicle were used to assess the various sinusoidal designs, as demonstrated in the following sections.

The spectra for Test Car D-2 on the 13-inch wavelength strips of site EB9 from Figure D-12 is also shown in Figure D-21 with the inclusion of spectra at the time of the 80 Hz peak, which occurred 0.7 seconds (Table D-7) after the overall A-weighted peak. At the delayed time, the peak at 80 Hz is 12.7 dB higher than that of the peak of the maximum overall spectra and 30.3 dB higher than the off-strip level in that band. In ANSI S12.9, the presence of a prominent tone is identified if the level in the ⅓ octave band containing the tone is 15 dB greater than the (arithmetic) average of the levels in the two adjacent bands.[3] In this case, the adjacent bands average to 41.0 dB, and the 80 Hz tone is 63.3 dB, indicating a prominent tone. The result is that the tone is clearly audible. Similar tonal prominence is indicated for all the strips except for the non-sinusoidal WSDOT strips. The complete set of 60 mph spectra for all four vehicles at all 21 sites for the time of maximum A-weighted level on and off the strips, along with the spectra at the time of the maximum level at the repetition rate, are provided at the end of this appendix.

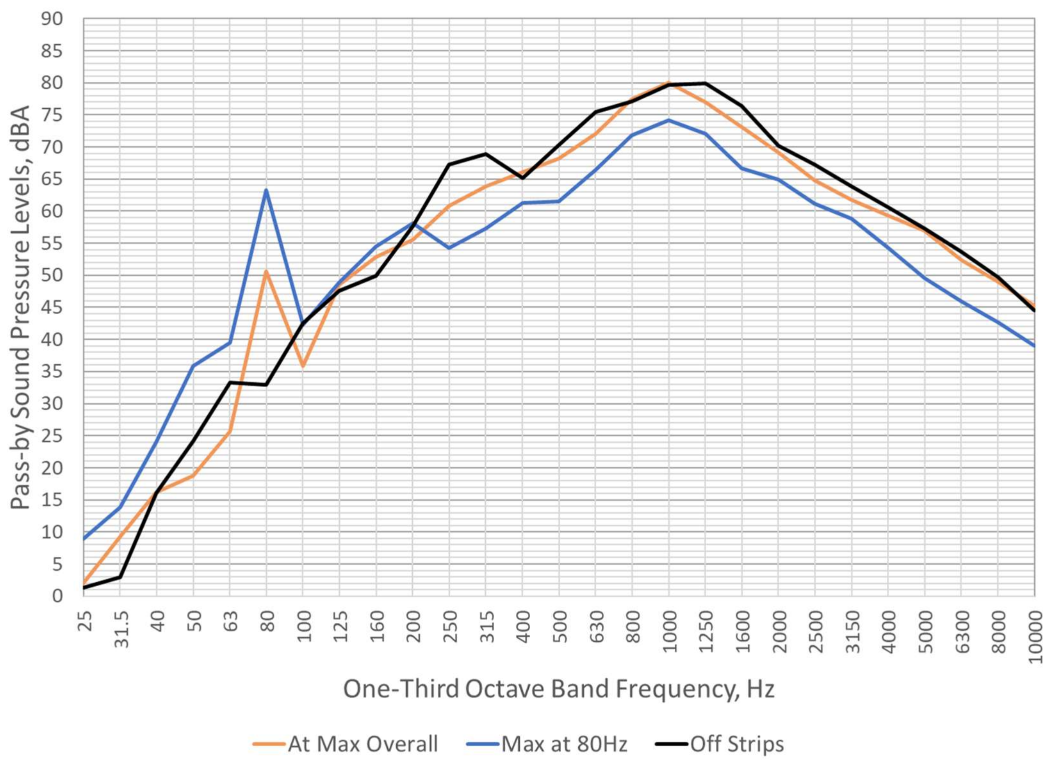



*Figure D-21: Comparison of spectra for Test Car D-2 on 13-inch sinusoidal strips at EB9 for off strips, on strips at maximum band-passed A-weighted level, and maximum 80 Hz band level*

The on/off increments were calculated by subtracting the band-passed 31.5 to 200 Hz off-strip levels from the corresponding on-strip levels at each site. These are shown for all vehicles in Figure D-22. Across all test vehicles, the band-passed on/off differences varied. The lowest increments were measured at WB3 (18-inch wavelength), EB6 (24-inch wavelength), EB7 (14-inch wavelength), and EB4 (16-inch wavelength). Test Car D-6, D-5, and D-1 resulted in increments over 12 dB on the conventional WSDOT strips, with Test Car D-2 having increments of about 9 dB. On/off increments at EB1, EB2, and WB9 (all 14-inch wavelengths) ranged from about 7 to 13 dB across all of the vehicles, and these were the most consistent of the sites.

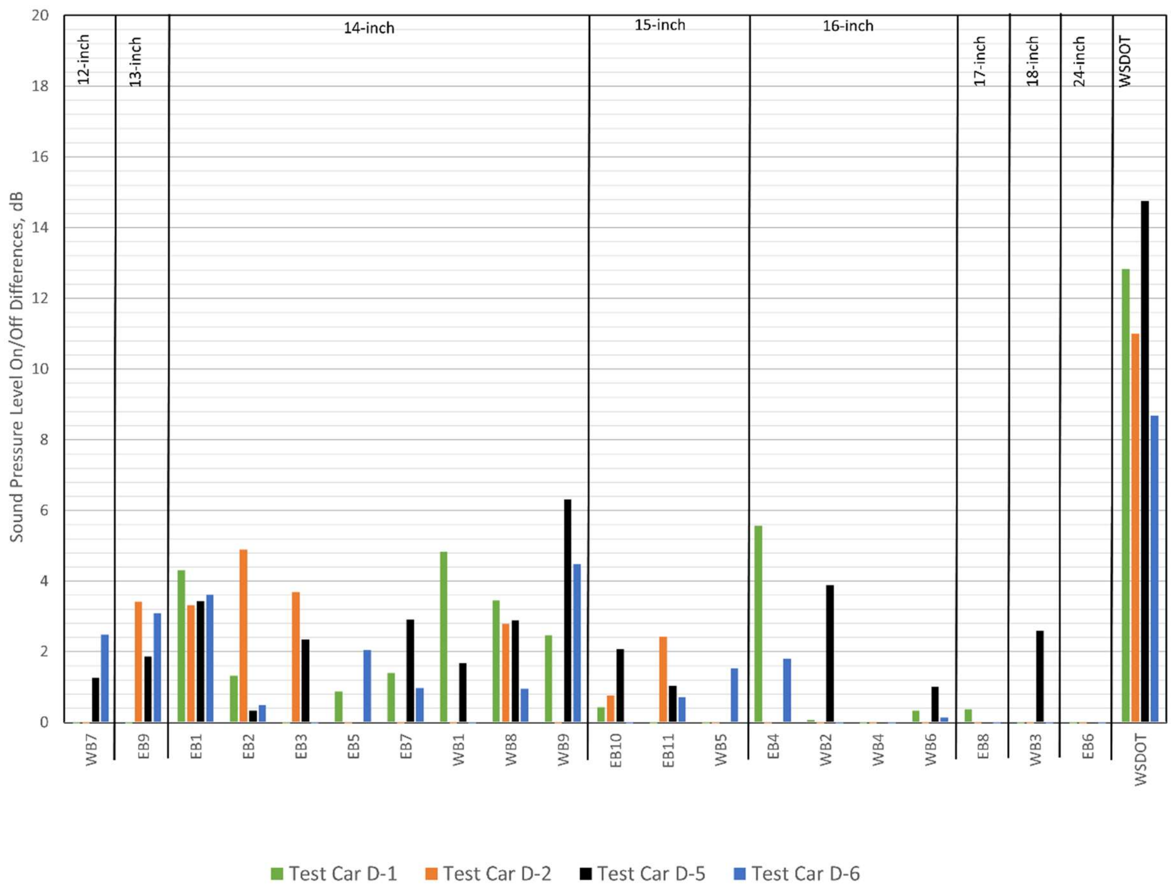



*Figure D-22: Band-passed pass-by noise level differences from 31.5 to 200 Hz between on and off strips at 20 sinusoidal strip sites and the standard WSDOT rumble strips site for all test vehicles*

### 45 mph Pass-by

Pass-by measurements were made at all 20 test sites and at the conventional WSDOT site at a driving speed of 45 mph. The results for 45 mph displayed the same features as the 60 mph with a delay on the maximum one-third octave band relative to the overall A-weighted maximum level. The frequency of the sinusoidal repetition rate is also, accordingly, lowered with the speed reduction. Also, as with the 60 mph results, the maximum pass-by levels off the strips are typically equal to or greater than those on the strips due to the chip seal road surface. An example of a 45 mph spectra plot is shown in Figure D-23 for Test Car D-2 on the 16-inch sinusoidal strip at site EB4.

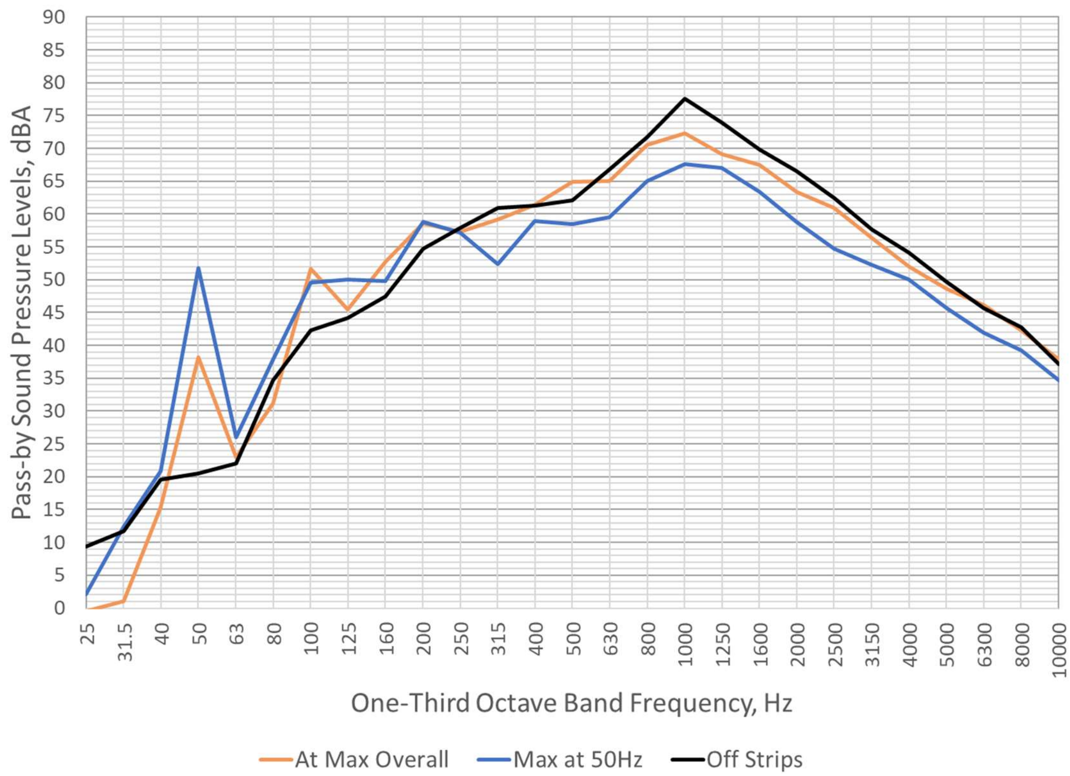



*Figure D-23: Test Car D-2 on 16-inch sinusoidal strips at EB4 for off strips, on strips at maximum overall A-weighted level, and maximum 50 Hz band level for 45 mph*

The 16-inch strip at this site lowers the sinusoidal peak to 50 Hz from 63 Hz at 60 mph. For this case, the peak in the 50 Hz band at the maximum band-passed A-weighted level is 13.6 lower than the 50 Hz band level determined at the 50 Hz maximum. Representative spectra taken at each test site at 45 mph are provided at the end of this appendix for all four test vehicles. Similar to the spectra for 60 mph, the black lines in the figures represent the off strips runs; the orange lines are the spectra that occur at the time of maximum overall level; and the blue and gray lines are the spectra that occur at the maximum driving frequencies.

The band-passed levels summed between 31.5 and 200 Hz for the on and off strip cases for all test vehicles are shown in Figures D-24 to D-27. For each test vehicle, the standard WSDOT rumble strips had band-passed levels ranging from 67 to 71 dBA, which were more than 5 dB higher than the on-strips levels at the sinusoidal test sites. The range of band-passed levels on the sinusoidal sites was from 53 to 62 dBA. This range of band-passed noise levels resulted in less site-to-site variation than at 60 mph, which ranged from about 54 to 70 dBA.

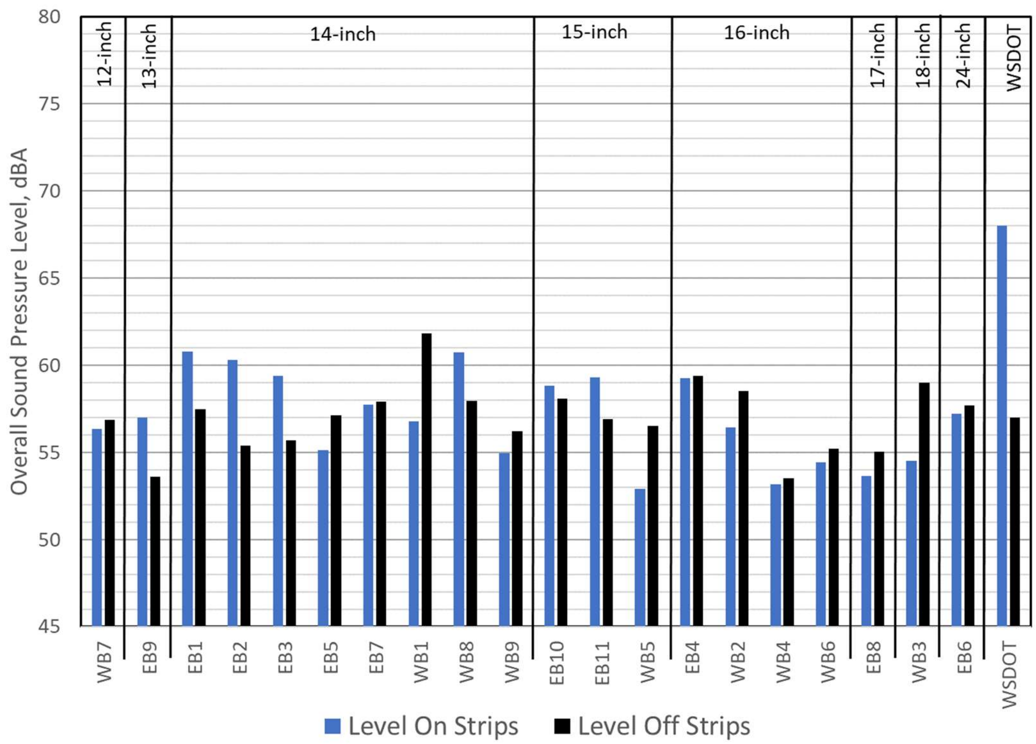



*Figure D-24: Band-passed A-weighted pass-by levels 31.5 to 200 Hz for Test Car D-2 (45 mph)*

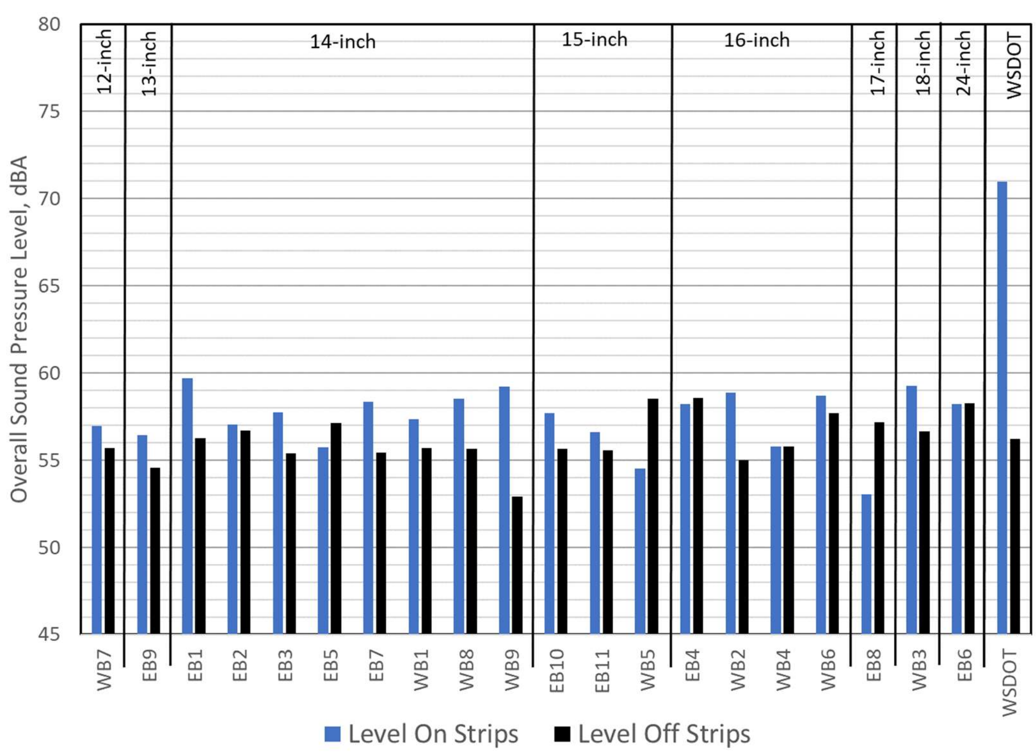



*Figure D-25: Band-passed A-weighted pass-by levels 31.5 to 200 Hz for Test Car D-5 (45 mph)*

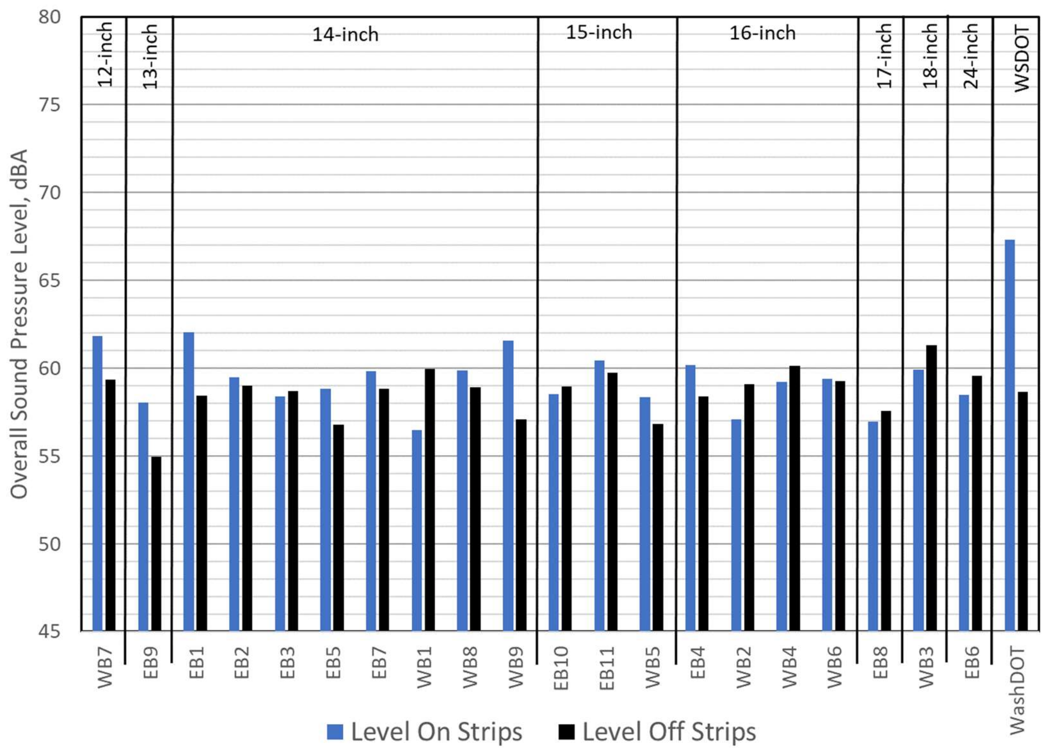



*Figure D-26: Band-passed A-weighted pass-by levels 31.5 to 200 Hz for Test Car D-6 (45 mph)*

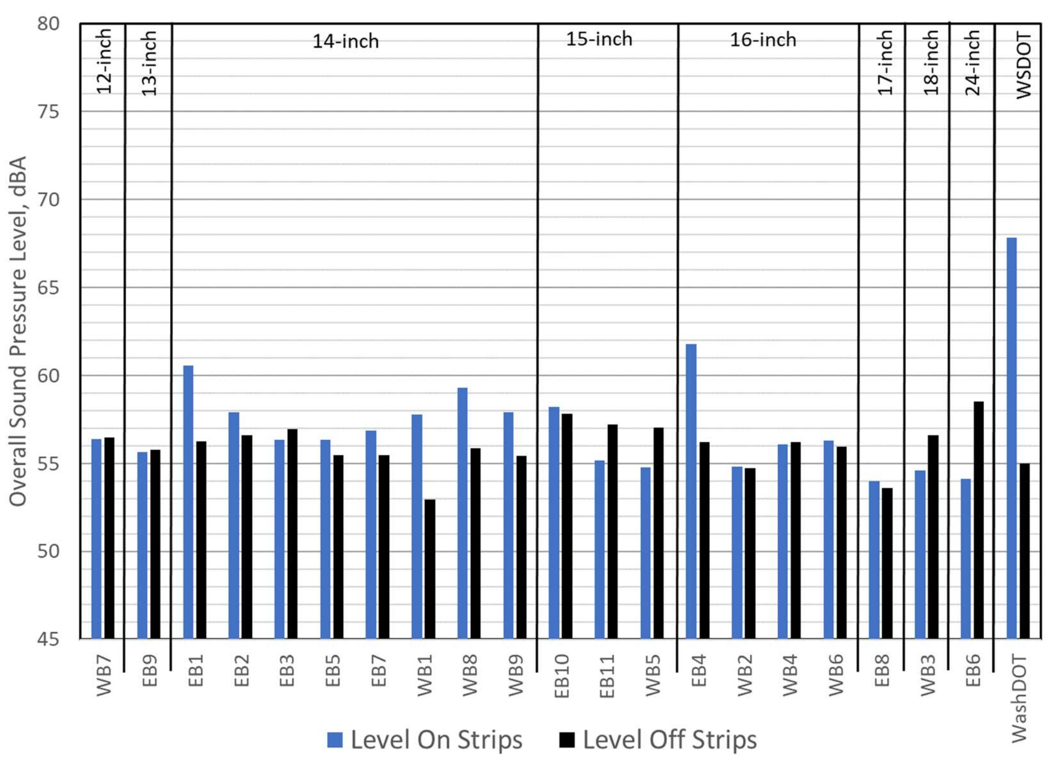



*Figure D-27: Band-passed A-weighted pass-by levels 31.5 to 200 Hz for Test Car D-1 (45 mph)*

The on/off increments, which are calculated by subtracting the band-passed off-strips levels from the maximum band-passed on-strips levels at each site, are shown for all vehicles in Figure D-28. The on/off difference at the conventional WSDOT test site ranged from about 9 to 15 dBA, which is similar to the 60 mph results of about 9 to 19 dBA. For the sinusoidal sites, there were more instances at 45 mph of off strips levels being higher than on strips, not resulting in measurable on/off increments. WB9 (14-inch wavelength) resulted in the highest increments for the large SUV and the mid-size SUV, which ranged from about 4.5 to 6 dB. EB2 (14-inch wavelength) and EB4 (16-inch wavelength) test sites showed the highest increments for the sedan and compact car, respectively. EB1 and WB8 (both 14-inch wavelengths) were the only two sinusoidal test sites that had measurable increments with all four vehicle categories at 45 mph, which ranged from 1 to 4 dB.

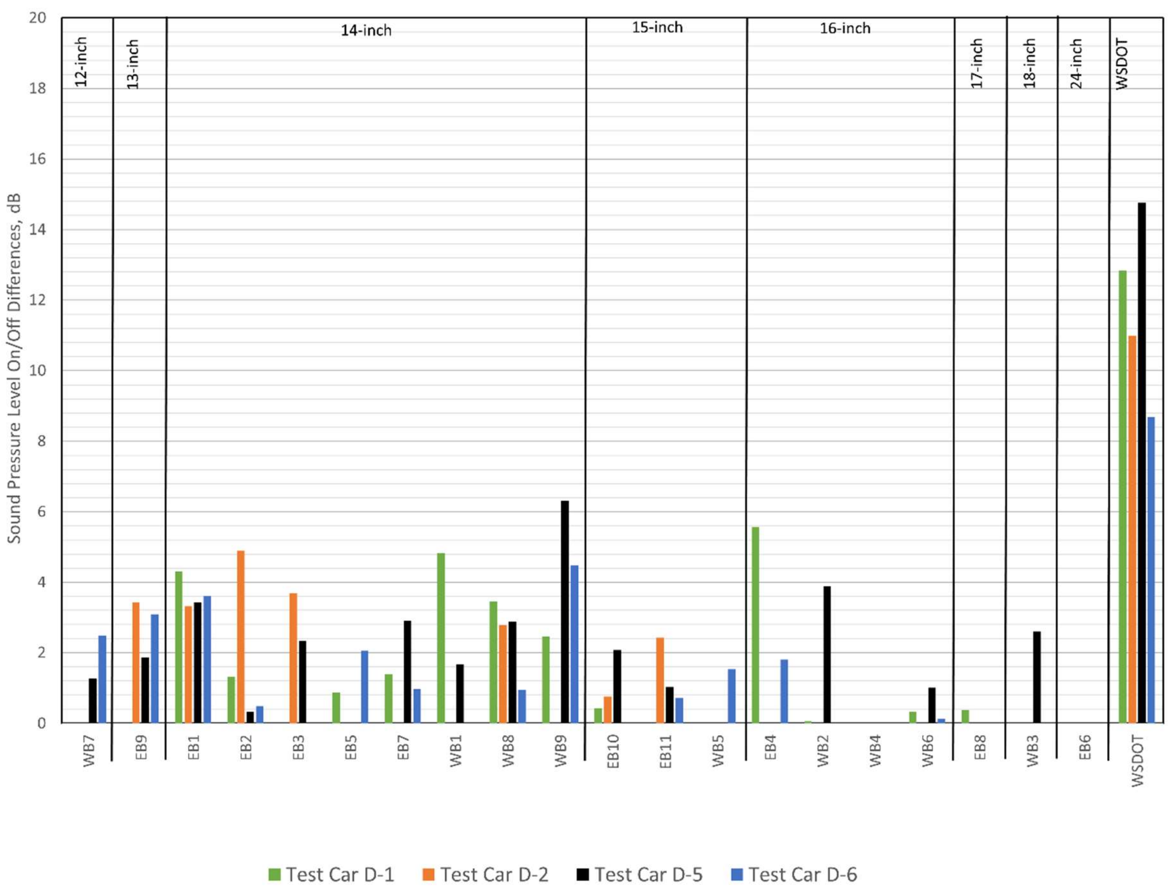



*Figure D-28: Band-passed pass-by noise level differences from 31.5 to 200 Hz between on and off strips at 20 sinusoidal strip sites and the standard WSDOT rumble strips site for all test vehicles*

## Sound Propagation to Surrounding Distances

From the pass-by measurements made at 25 feet, it is apparent that a time lag exists between the maximum A-weighted level and the maximum level of the tone generated by the sinusoidal rumble strips. It was not known if this lag persists to more distant receiver locations or how it would be perceived. More generally, it is not understood how perceptible and potentially annoying the low frequency tone is at greater distances. To address these issues, measurements of on-rumble strip noise were measured and recorded at seven sinusoidal sites and at the standard WSDOT rumble strip site. The pass-by measurements were made at various distances from the roadway to document the propagation rates that could be due to the different rumble strip designs and different topographical and ground cover features. These data were collected at speeds of 60 mph with Test Car D-2. The measurements were typically made at several distances from the rumble strips up to 381 feet.

Distant pass-by measurements were made for seven sinusoidal rumble strips and the standard WSDOT strips. The sinusoidal test sites included EB9 (13-inch wavelength); EB1, WB1, and WB9 (all 14-inch wavelengths); EB11 (15-inch wavelength); WB2 (16-inch wavelength); and EB8 (17-inch wavelength). At each location and each microphone position, one-third octave levels were captured on a sound level meter. In addition, audio recordings were made to assess the audibility of the tones generated by the sinusoidal strips and to provide longer time histories for analysis. Cell phone video and audio was obtained for the sites where a view of the pass-by events was possible.

A set of measurements were at the west end of the locations, which included the 14-inch WB9 and EB1 sites. This included data from three distances from SR 105 on the northbound side of the road, as shown in Figure D-29 from the middle distance. At this location, the distances were 138, 234, and 381 feet from the EB1 sinusoidal strips. Radio communication was used between the vehicle and instrument operator to start measurements when the site was free from other traffic. Travel on the strips began about 100 feet before the line of the measurement locations. The time histories obtained at the three distances are shown in Figures D-30, D-31, and D-32. All three, time histories have a sharp increase in the 80 Hz frequency band level corresponding to the 14-inch sinusoidal strip repetition rate. This occurs at all three distances and indicates the start of the strips just prior to the peak in the overall A-weighted time history. After the initial rise, the 80 Hz levels decrease as the vehicle passes away from the microphone at all three positions. With distance, the difference between overall A-weighted level and 80 Hz band level decreases, indicating that the tonal sound should be more perceptible relative to the overall level.

*Figure D-29: Microphone locations at 234 ft from EB1 sinusoidal strips*

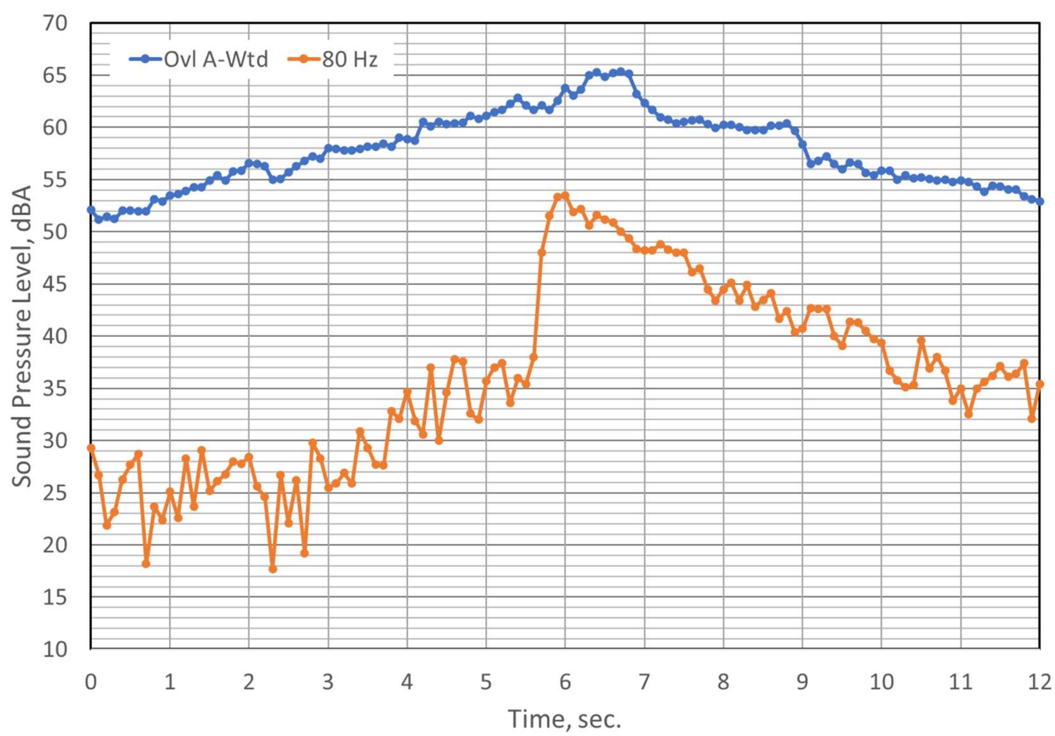



*Figure D-30: Pass-by time history on 14-inch sinusoidal strips of EB1 at 138 ft*

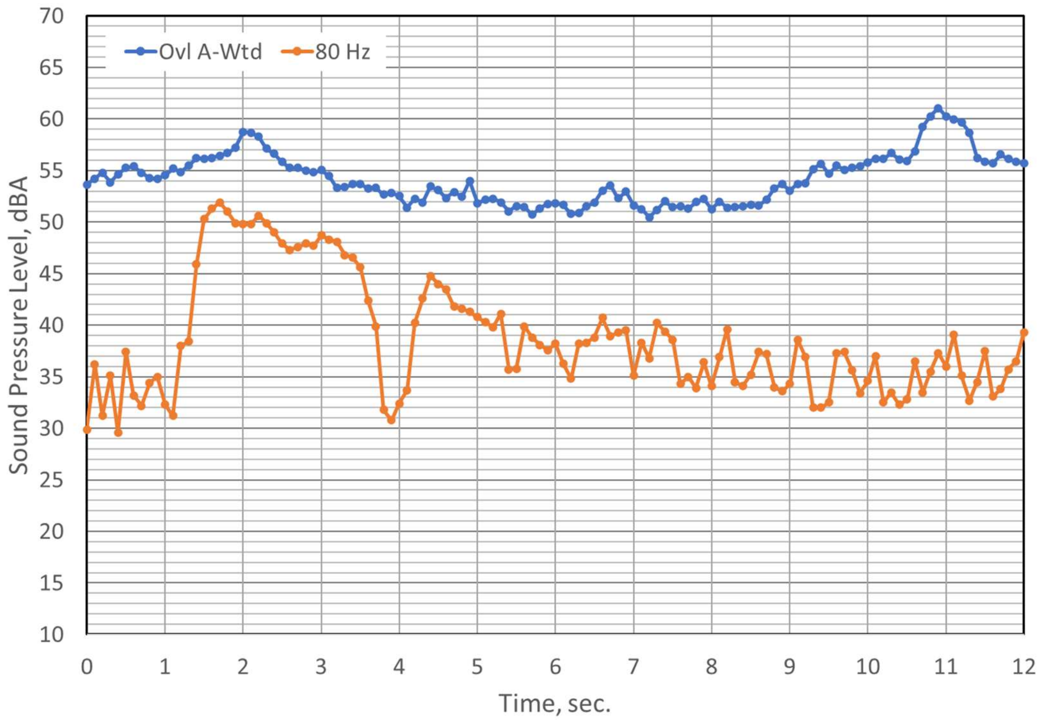



*Figure D-31: Pass-by time history on 14-inch sinusoidal strips of EB1 at 234 ft*

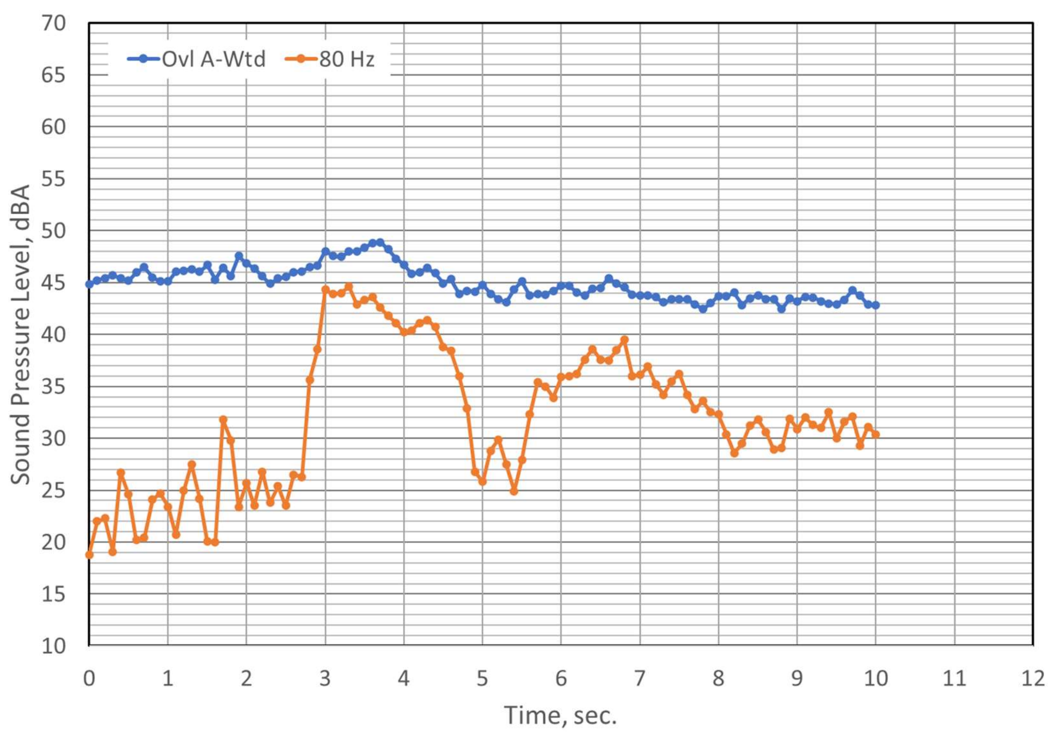



*Figure D-32: Pass-by time history on 14-inch sinusoidal strips of EB1 at 381 ft*

A review of Figures D-30 through D-32 indicates the maximum of the 80 Hz band occurs before the band-passed maximum by 0.7 seconds for the 138- and 381-foot distances and 0.3 seconds for the 234 feet distance. At the time of maximum 80 Hz level, the difference between the band-passed A-weighted level and 80 Hz level is 10.3 dB at 138 feet, 4.5 dB at 234 feet, and 3.2 dB at 381 feet. The spectra at the time of maximum 80 Hz band level are shown in Figure D-33 for these three distances. The tone at 80 Hz produces a level such that it would be classified as a prominent tone under ANSI S12.9[3] for each distance and should be audible. This was subjectively confirmed by listening to the recorded WAV files.

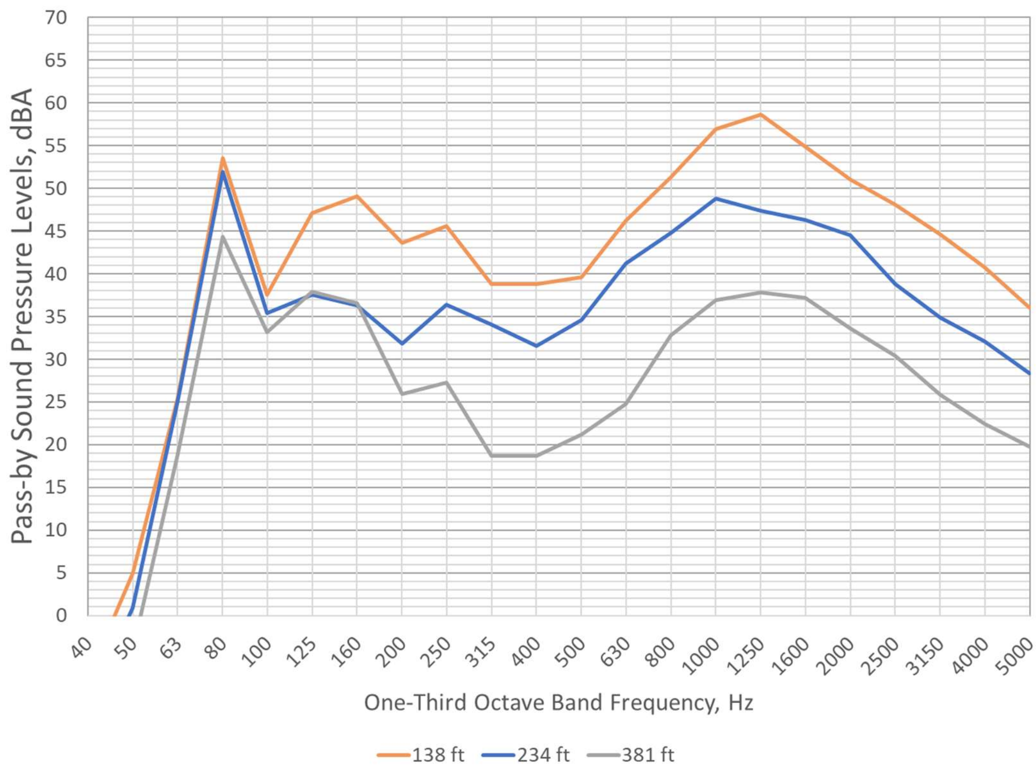



*Figure D-33: Sound pressure spectra at the time of maximum 80 Hz level at Site EB1*

A second example of the distant pass-by measurements is for the 16-inch wavelength sinusoidal strips at site WB2. A photograph of this site is provided in Figure D-34. At this location, the strips are located on the opposite side of SR 105 with the pass-bys going from right to left. The test vehicle used in the pass-by measurement is shown in the foreground during measurement system set-up. Measurements were made 153 and 222 feet from the far shoulder sinusoidal strips. The time histories at these two distances are shown in Figures D-35 and D-36 for the overall A-weighted level and the level in the 80 Hz band. The expected frequency of 16-inch strips of 63 Hz. This shifted into the 80 Hz band due to the doppler effect as the vehicle approached. The 63 Hz band is also plotted in Figures D-35 and D-36 to demonstrate this shift. The spectra at 153 and 222 feet are shown in Figure D-37 at the time at which the maximum level in the 80 Hz band occurred. These WB2 spectra also indicate that the peaks at 80 Hz are prominent, as was seen for the peaks in the figures for Site EB1. Similar to the figures for EB1, the WB2 time histories (Figures D-35 and D-36) show that difference between the overall A-weighted data and the 80 Hz band data is less at further distance (222 feet) than at the closer distance (153 feet). The spectra for the two measurement distances at the time of maximum 80 Hz level are compared in Figure D-37.

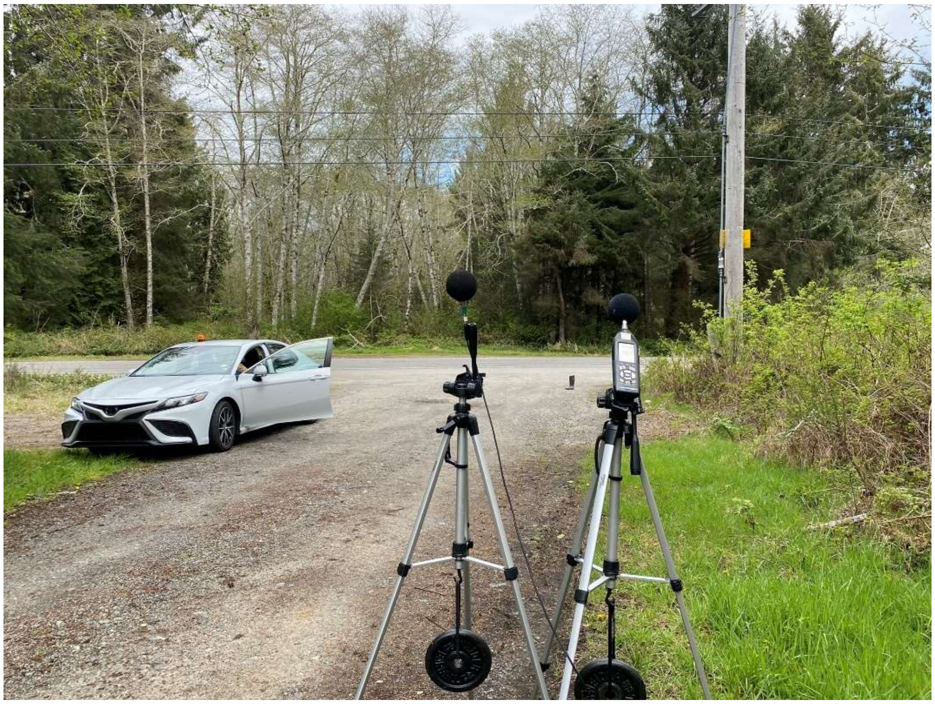


*Figure D-34: Microphone location 153 feet from 16-inch sinusoidal strips at Site WB2*

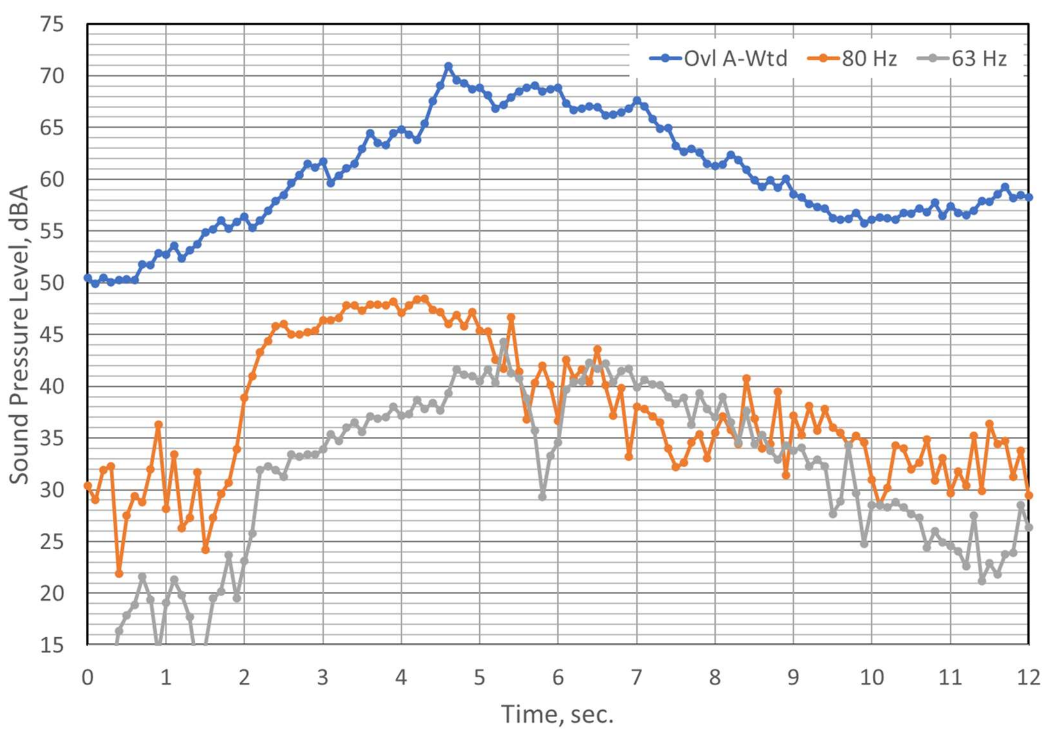



*Figure D-35: Pass-by time history on 16-inch sinusoidal strips of WB2 at 153 ft*

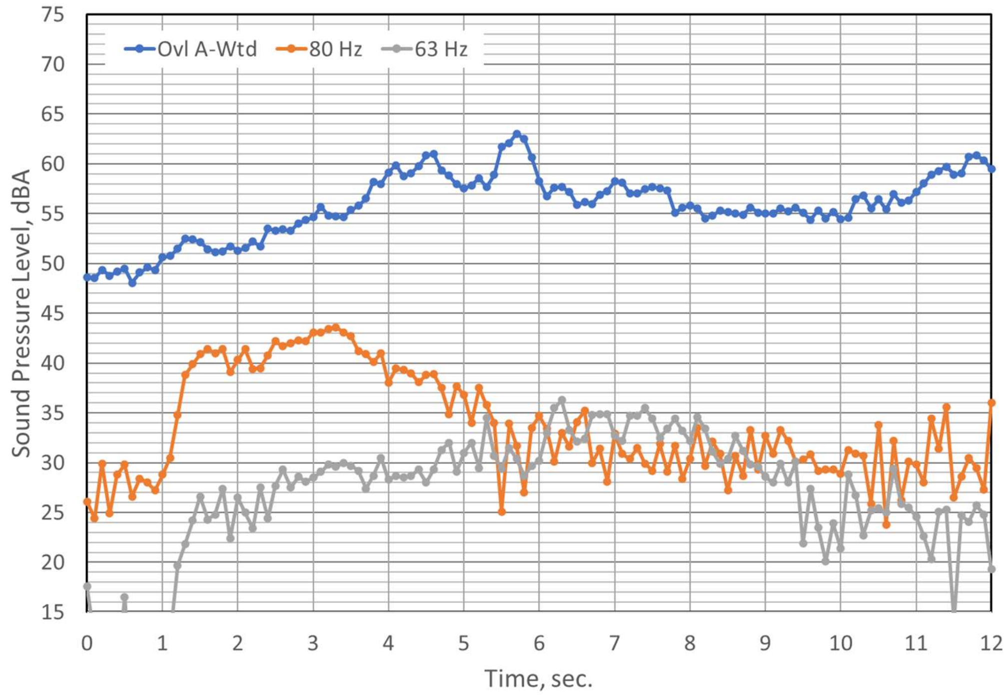



*Figure D-36: Pass-by time history on 16-inch sinusoidal strips of WB2 at 222 ft*

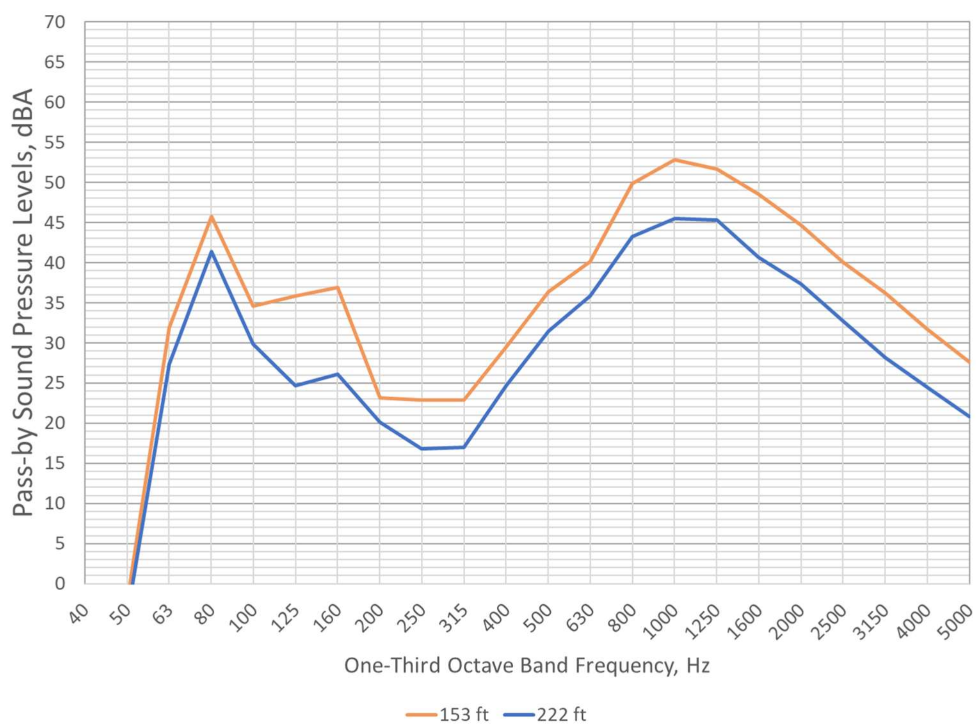



*Figure D-37: Sound pressure spectra at the time of maximum 80 Hz level at Site WB2*

The results for the other sinusoidal strips were similar in nature to those for EB1 and WB2, with the highest level at the sinusoidal repetition rate frequency occurring prior to the maximum band-passed A-weighted level. For the WSDOT strips, the main repetition rate was in the 100 Hz one-third octave band, and the peak in the band-passed A-weighted pass-by time history was accentuated by the terrain between the strips and the measurement location. The microphone location is shown in Figure D-38 for its position 207 feet from the roadway. The microphone was located on a road in a cut from SR 105, which provided shielding from the approach of the test vehicle. When the vehicle was directly opposite the microphone, there was no shielding, and band-passed A-weighted noise levels spiked up accordingly, as shown in the time history of Figure D-39. This spike was centered in the 1,000 Hz one-third octave band. Comparison of the spectra at the time of the maximum pass-by level at 8.4 seconds (see Figure D-39) and at the maximum of the 100 Hz band at 7.1 seconds is shown in Figure D-40. At 7.1 seconds into the pass-by, the level at the 100 Hz repetition rate produces the highest level, while the higher frequencies from 630 to 1,600 Hz are shielded by the terrain. When the test vehicle is directly opposite the microphones and unshielded, the levels in the higher frequencies dominate the spectrum, and the higher harmonics produced by the strips at 200 and 400 Hz also contribute more to the band-passed level. This case also indicates that the longer wavelength of the 100 Hz frequency sound from the strips propagates with less attenuation due to the terrain and vegetation.

*Figure D-38: Microphone locations at 207 ft from WSDOT standard strips*

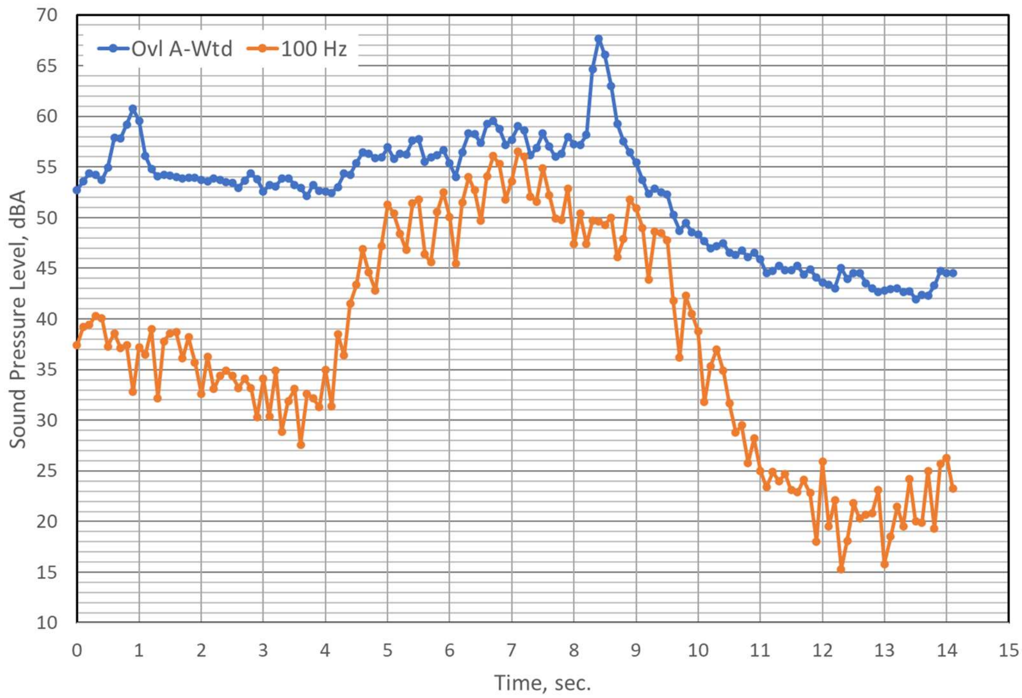



*Figure D-39: Pass-by time history on WSDOT standard strips at 207 ft*

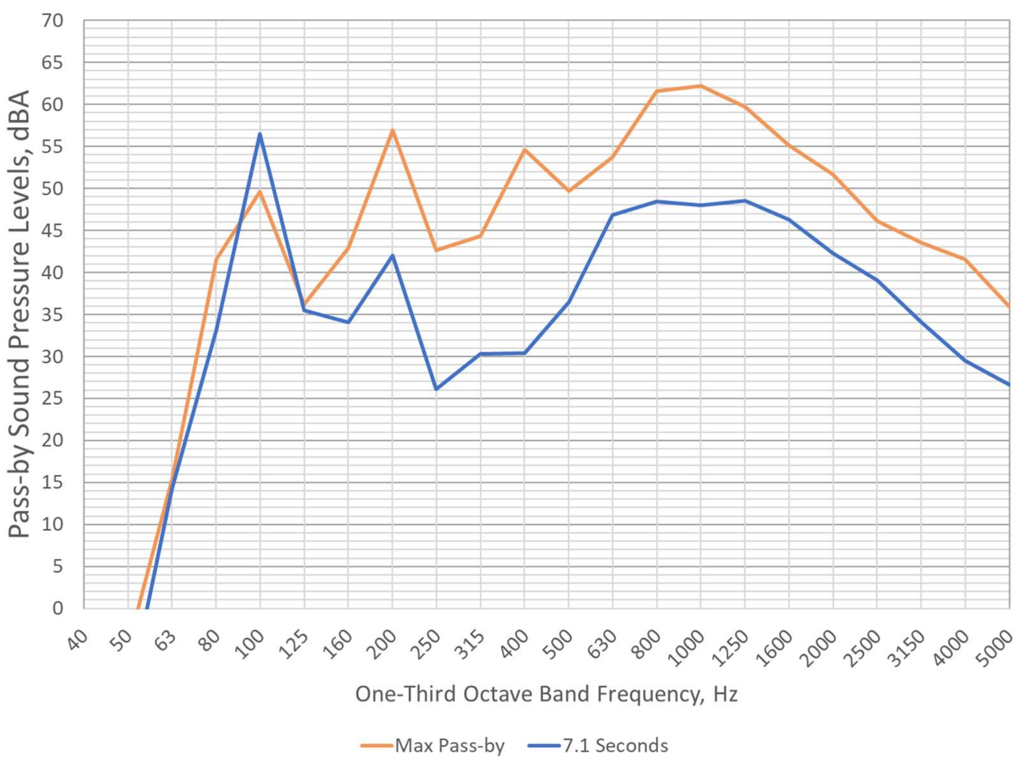



*Figure D-40: Spectra at the time of overall maximum pass-by level and 1.3 prior to maximum*

## INTERIOR NOISE AND VIBRATION MEASUREMENT RESULTS

### 60 mph Interior Noise

Interior noise and vibration data were taken at all 20 sinusoidal tests sites and the conventional WSDOT strips using all four test vehicle types. Ten-second data was taken, collecting overall and spectral information every 0.1 seconds. A minimum of three runs, both on and off strips at 60 and 45 mph, were made at each site. During post-processing, each run was reviewed to select a representative run where the passenger side tires remained consistently on the strips for two continuous seconds. The two seconds of constant data were averaged together for a single spectrum at each site and at each speed, both on and off strips, in each test vehicle.

Interior noise measurements were made at both the primary microphone location (center center [CC]) and the secondary microphone location (forward center [FC]), as defined in Phase I testing. Examples of the interior noise spectra for the CC location are shown in Figures D-41, D-42, D-43, and D-44 on and off the 14-inch sinusoidal strips for Test Car D-4, D-2, D-3, and D-1, respectively. For the 14-inch strips, the repetition rate occurs in the 80 Hz one-third octave band, as shown very clearly for Test Car D-3 (Figure D-41). The other three vehicles also display this peak; however, they also show elevated, higher frequency content up through the 315 Hz band. Similar to the pass-by data, all of the interior noise spectra were band-passed in order to minimize the influence of the chip seal pavement surface. For these data, due to the spectral peaks, the analysis band was 31.5 to 315 Hertz. The sounds of these peaks were quite noticeable inside the test vehicles. Spectra for the remaining test sites and all spectra with the FC microphone are provided at the end of this appendix.

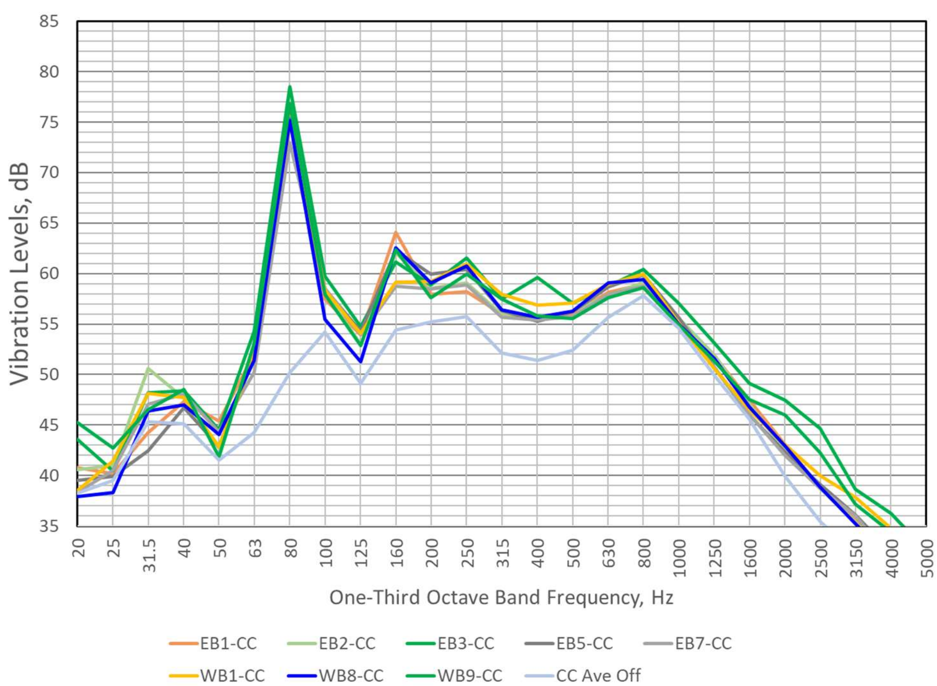


*Figure D-41: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 60 mph – Test Car D-4*

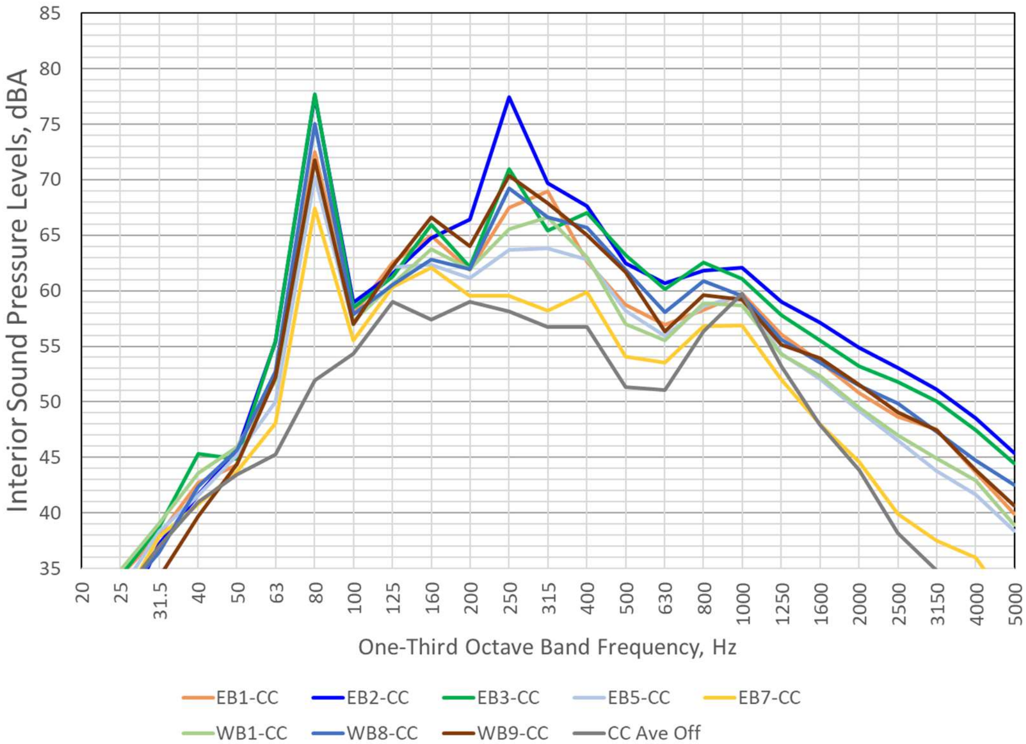



*Figure D-42: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 60 mph – Test Car D-2*

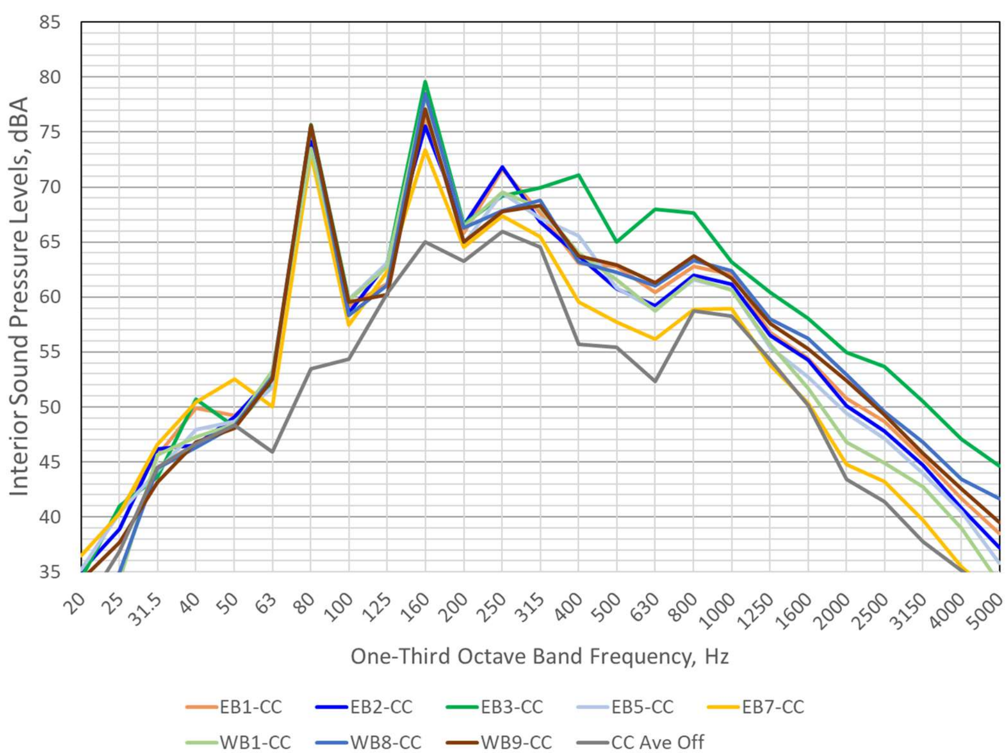


*Figure D-43: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 60 mph – Test Car D-3*

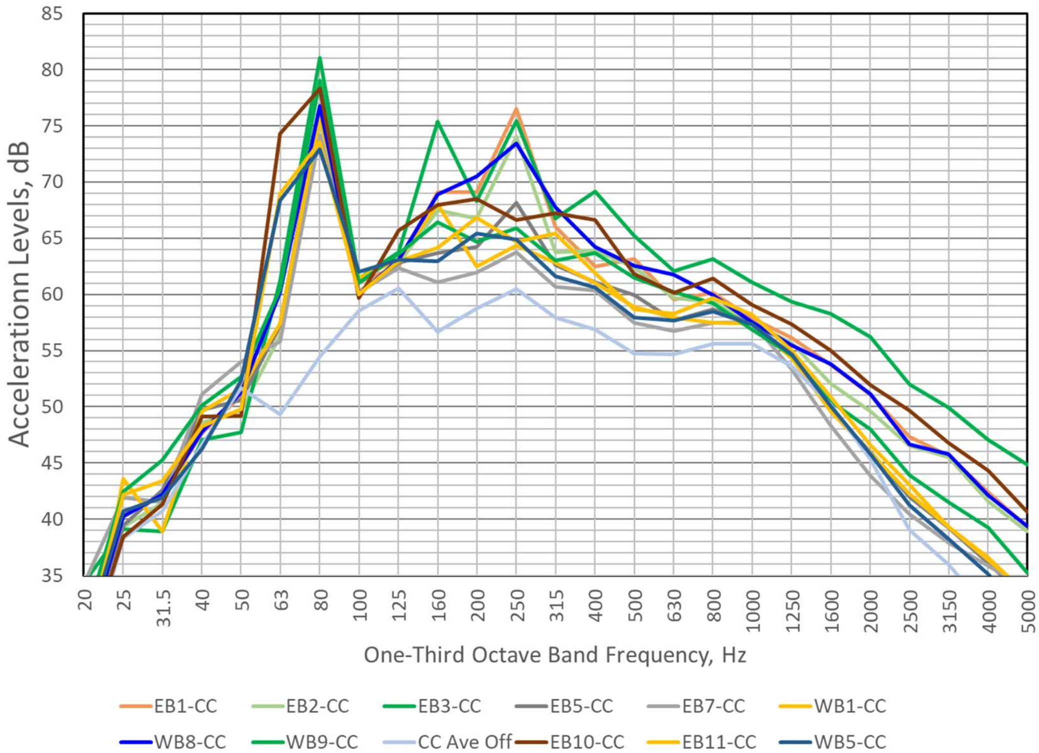



*Figure D-44: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 60 mph – Test Car D-1*

Figures D-45 through D-48 show the measured band-passed noise levels on the sinusoidal test strips for the large SUV, mid-size SUV, sedan, and compact car test vehicles, respectively, as measured from the primary CC microphones (FC data is provided at the end of this appendix). Also shown in each figure are the average off strips levels measured at each site. These band-passed A-weighted noise levels were calculated by summing the energy from 31.5 to 315 Hz.

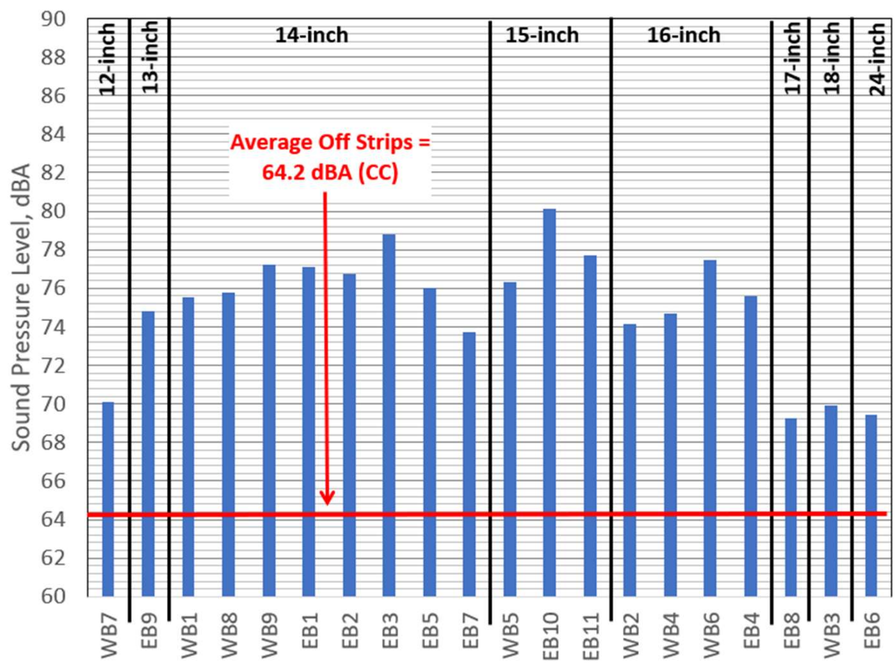



*Figure D-45: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-4 on the strips - CC microphones at 60 mph*

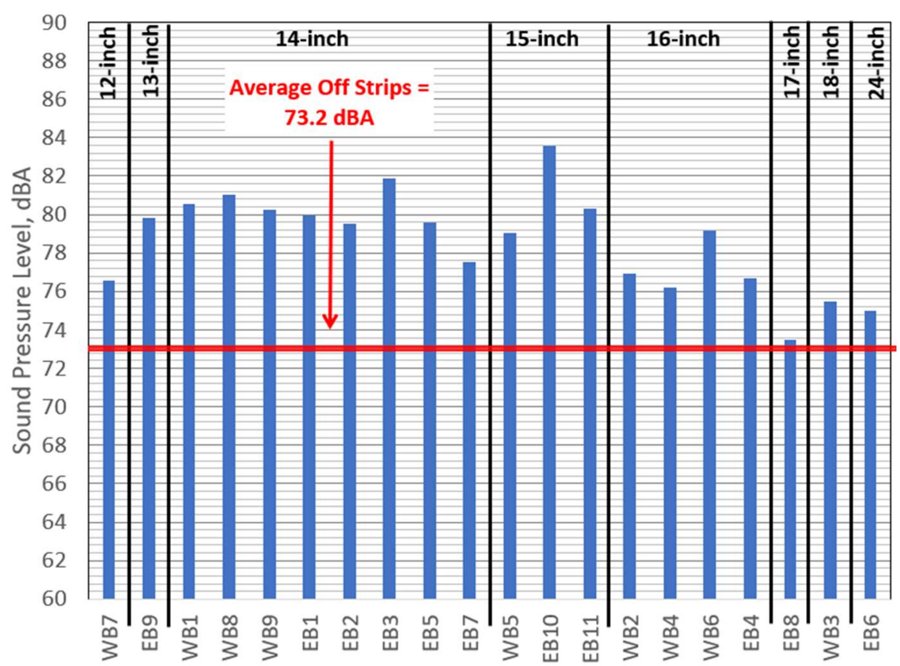



*Figure D-46: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-3 on the strips - CC microphones at 60 mph*

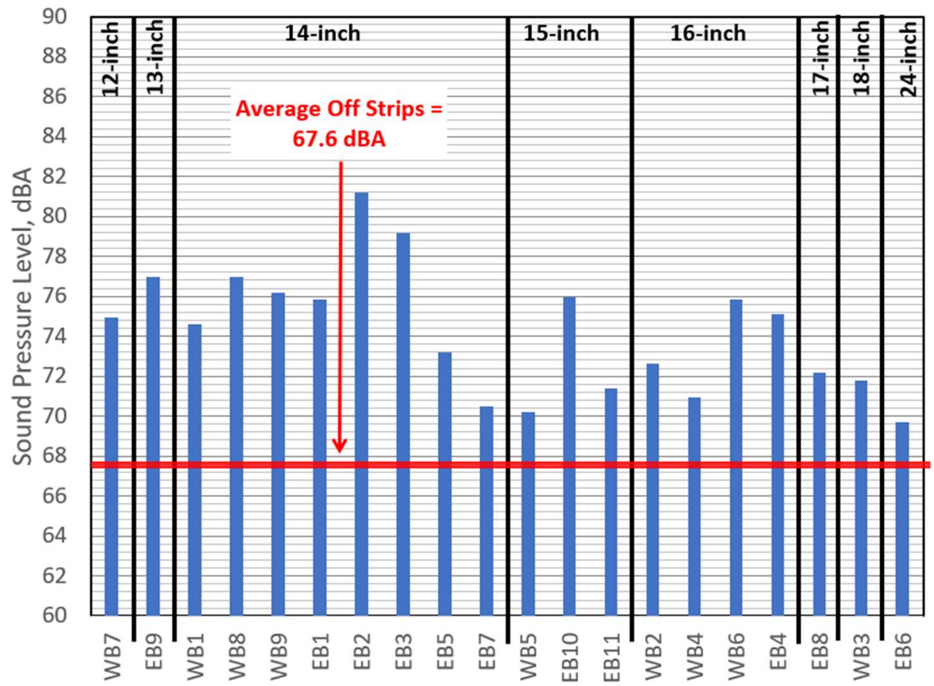



*Figure D-47: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-2 on the strips – CC microphones at 60 mph*

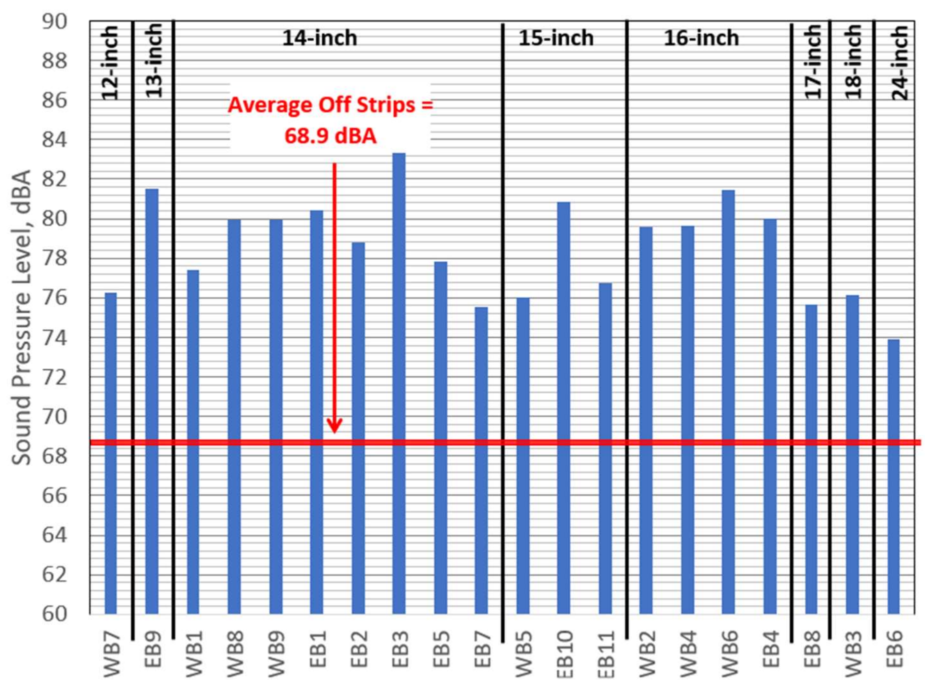



*Figure D-48: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-1 on the strips - CC microphones at 60 mph*

The band-passed levels in Test Car D-4 ranged from about 69 to 80 dBA; in Test Car D-3 ranged from 74 to 84 dBA; in Test Car D-2 ranged from 70 to 81 dBA; and in Test Car D-1 ranged from 74 to 83 dBA. In both SUV categories, the highest band-passed level was measured at EB10 (15-

inch wavelength), and the lowest band-passed level was measured at EB8 (17-inch wavelength). The highest levels in the car categories were measured at EB2 and EB3 (both 14-inch wavelengths), and the lowest levels in the car categories were measured at EB6 (24-inch wavelength). Due to wet weather conditions, interior noise and vibration measurements were made at the conventional WSDOT rumble strips with Test Car D-4 and D-1 only. The band-passed on-strips levels at the conventional WSDOT rumble strips ranged from 75 to 79 dBA in these vehicles. These levels fall within the range of levels measured on the sinusoidal strips.

The on/off increments measured with the CC microphone for each site and all vehicles are shown in Figure D-49 (on/off increments measured with the FC microphone are provided at the end of this appendix). Not one site resulted in a 10 dBA or more difference between on and off strips in all test vehicles. WB8, EB2, and EB3 (14-inch wavelength) and EB10 (15-inch wavelength) had more than a 10 dB difference in three of the four test vehicles, and EB9 (13-inch wavelength), WB9 and EB1 (14-inch wavelengths) and WB2, WB4, WB6, and EB4 (16-inch wavelengths) showed a 10 dB difference in two of the four test vehicles.

Both test vehicles resulted in more than a 10 dBA increment at the conventional WSDOT strips.

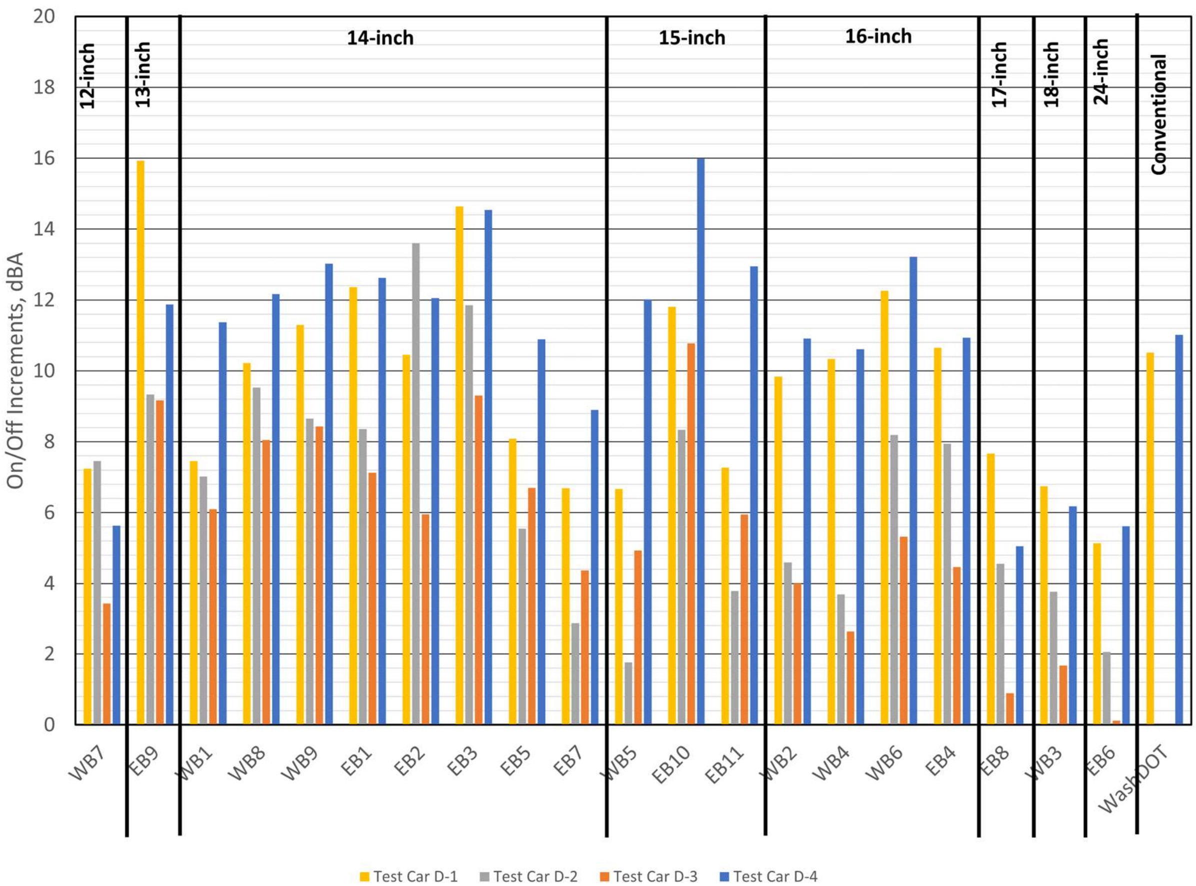



*Figure D-49: On/off increments measured with the CC microphone at all 20 sinusoidal test sites and the conventional WSDOT rumble strips using each test vehicle at 60 mph*

Average band-passed noise levels at the CC microphone were calculated across all vehicles at each test site. These are shown in Figure D-50 (FC is shown in Appendix C). EB3 and EB10 showed the highest band-passed levels of 80 to 81 dB. The lowest average levels were measured at EB6, EB8, and WB3 and were approximately 72 to 73 dB.

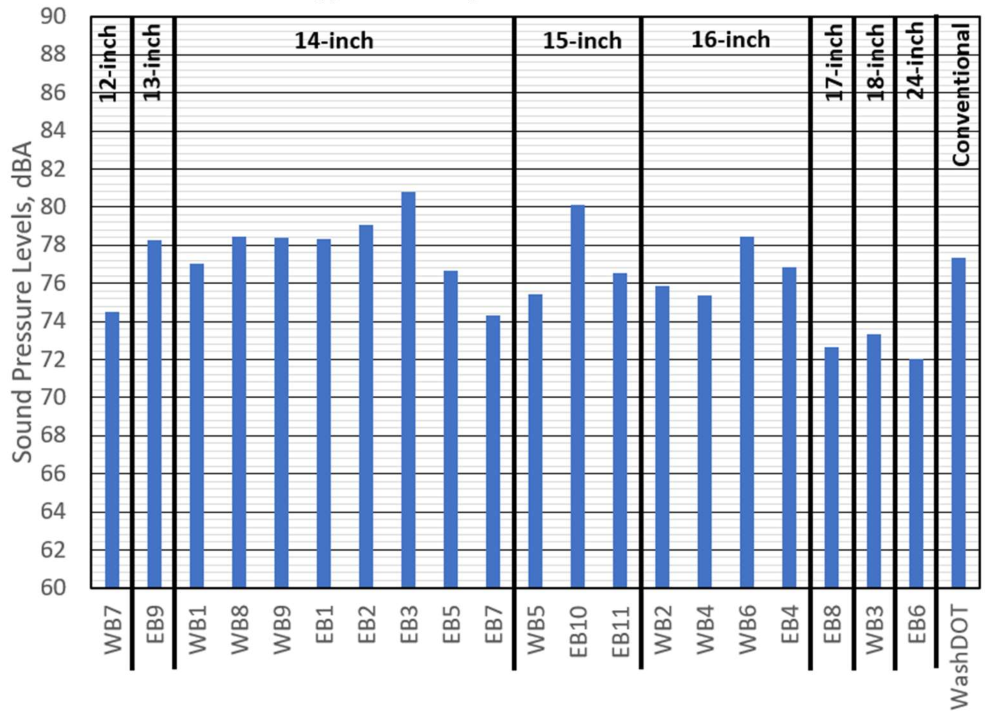



*Figure D-50: Band-passed A-weighted interior sound pressure levels at all test sites averaged across all test vehicle on the strips - CC microphones at 60 mph*

Figure D-51 shows the average on/off increments for all vehicles at the CC microphone (FC is shown at the end of this appendix). Sinusoidal test sites resulting in average on/off increments of 10 dBA or more across all test vehicles include: EB9 (13-inch wavelength); WB8, WB9, EB1, EB2, and EB3 (14-inch wavelengths); EB10 (15-inch wavelength); and WB6 (16-inch wavelength). Table D-8 summarizes the dimensions for each of these sites.

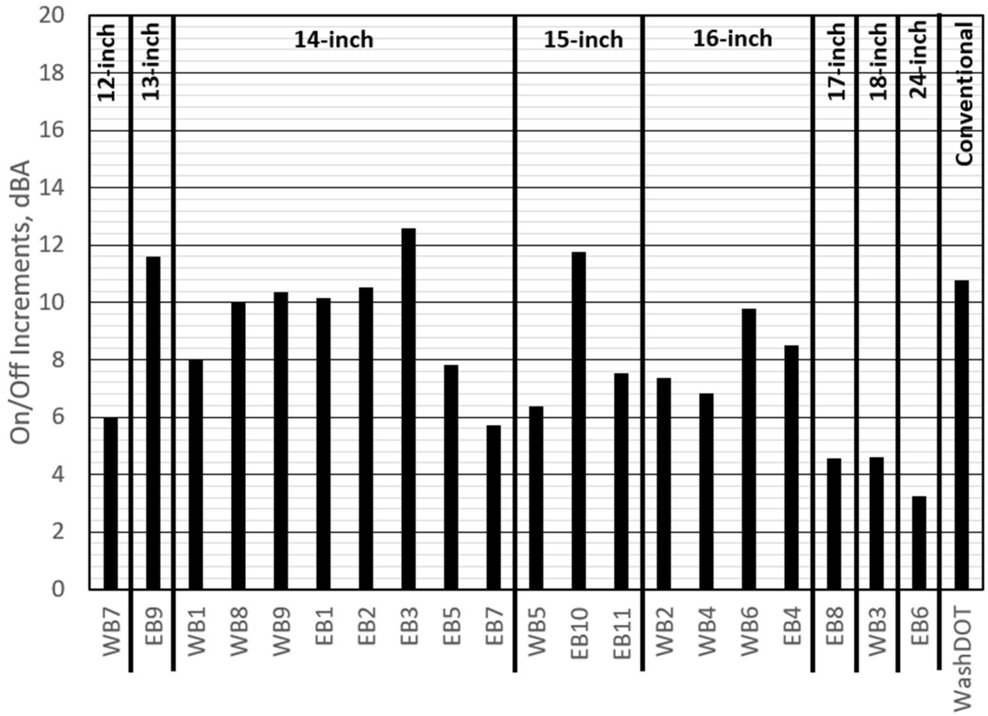



*Figure D-51: Average on/off increments across all test vehicles at the CC microphone traveling at 60 mph*

*Table D-8: Specified and as installed dimensions of the sinusoidal rumble strips that resulted in an average on/off increment of 10 dBA or more at the CC microphone*

| Site | Wavelength, in. | | Amplitude, in. | | Recess, in. | |
|---|---|---|---|---|---|---|
| | Specified | Actual | Specified | Actual | Specified | Actual |
| WB6 | 16 | 16 | 1/2 | 7/16 | 0 | 0-1/16 |
| WB8 | 14 | 14 | 7/16 | 7/16 | 0 | 1/8 |
| WB9 | 14 | 14 | 1/2 | 1/2 | 1/8 | 1/8 |
| EB1 | 14 | 14 | 5/16 | 1/4-5/16 | 0 | 0-1/16 |
| EB2 | 14 | 14 | 3/8 | 5/16 | 0 | 0-1/8 |
| EB3 | 14 | 14 | 1/2 | 7/16-1/2 | 0 | 0-3/8 |
| EB9 | 13 | 13 | 3/8 | 1/4-3/8 | 1/8 | 1/8-3/16 |
| EB10 | 15 | 15 | 1/2 | 7/16-1/2 | 0 | 0-1/16 |

**45 mph Interior Noise**

Examples of the interior noise spectra for the CC location, as measured at 45 mph, are shown in Figures D-52, D-53, D-54, and D-55 on and off the 14-inch sinusoidal strips for Test Car D-4, D-2, D-3, and D-1, respectively. For the 14-inch strips, the repetition rate at 45 mph shifts to 50 and 63 Hz one-third octave bands. The split peaks are shown clearly in Test Car D-2 and D-1 (both smaller car categories), but most of the energy in Test Car D-4 and D-3 (both larger SUV categories) is in the 63 Hz band. The band-passed levels calculated by summing the energy in the bands from 31.5 to 315 Hz are shown in Figures D-56 through D-59 for the large SUV, mid-size

SUV, sedan, and compact car test vehicles, respectively, as measured at the CC microphone. Spectra for the remaining test sites and all spectra and band-passed levels measured with the FC microphone are provided at the end of this appendix.

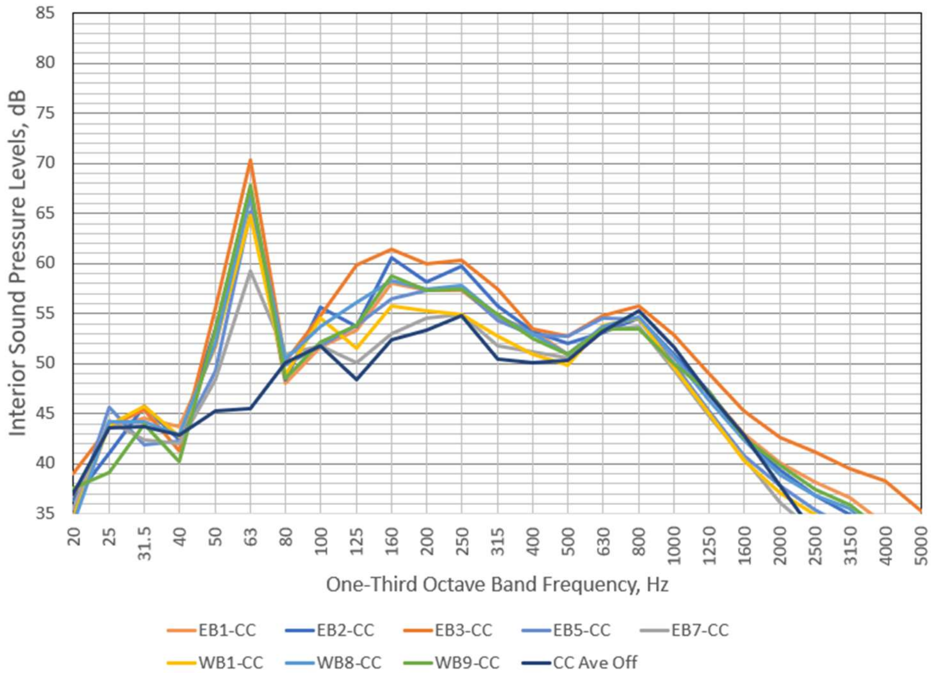



*Figure D-52: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 45 mph – Test Car D-4*

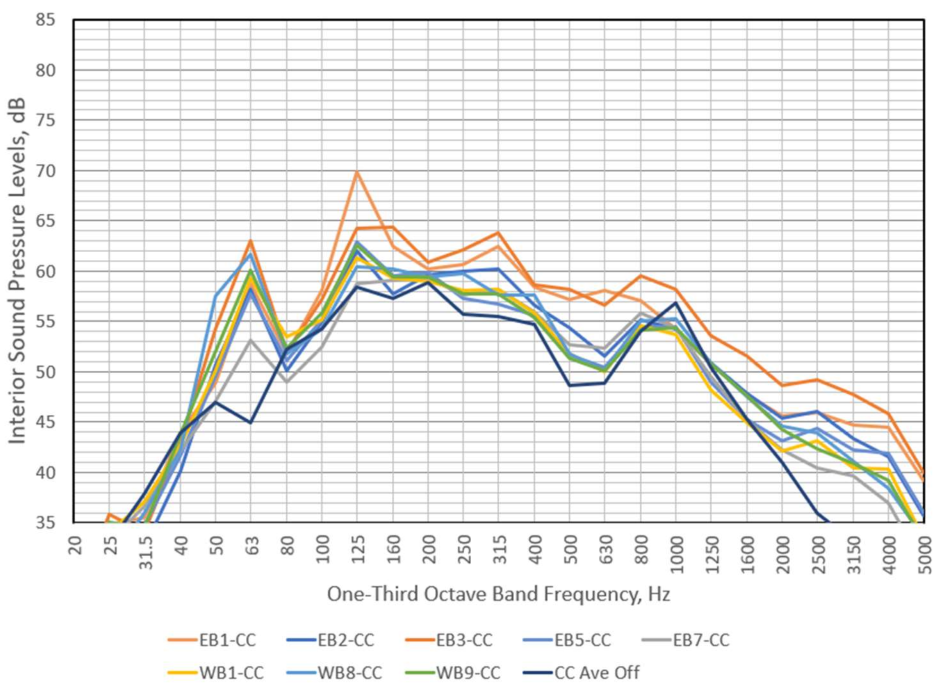



*Figure D-53: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 45 mph – Test Car D-2*

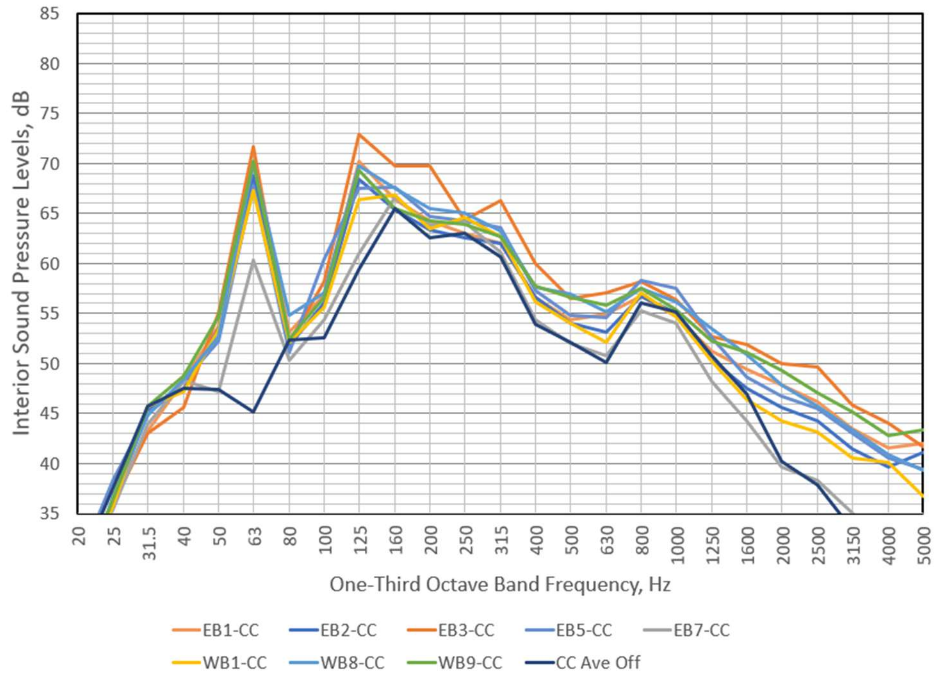



*Figure D-54: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 45 mph – Test Car D-3*

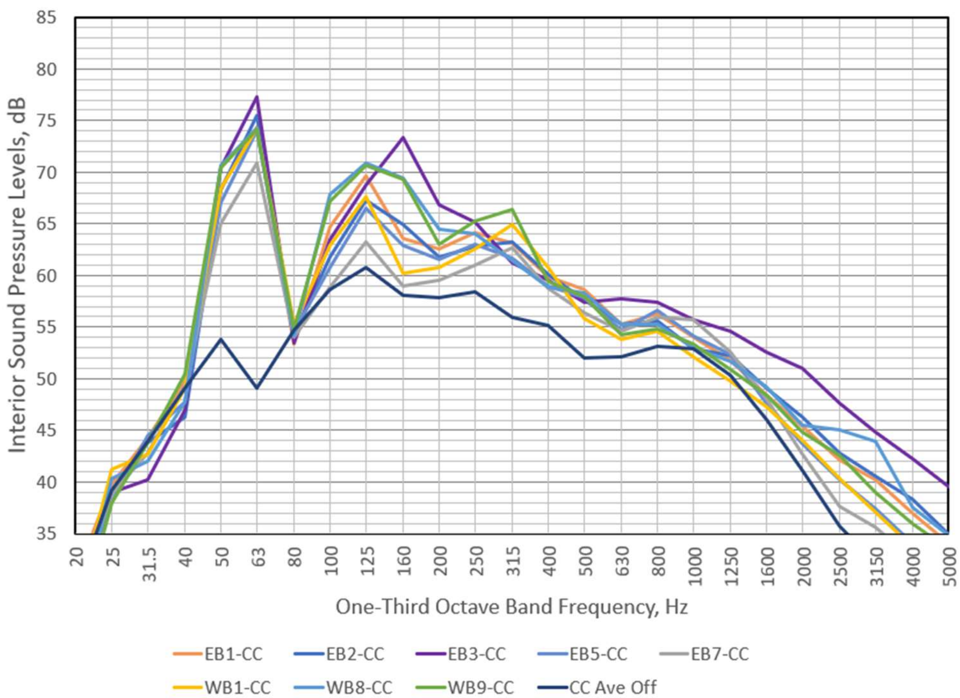



*Figure D-55: Interior noise spectra on 14-inch sinusoidal strips with the CC microphone at 45 mph – Test Car D-1*

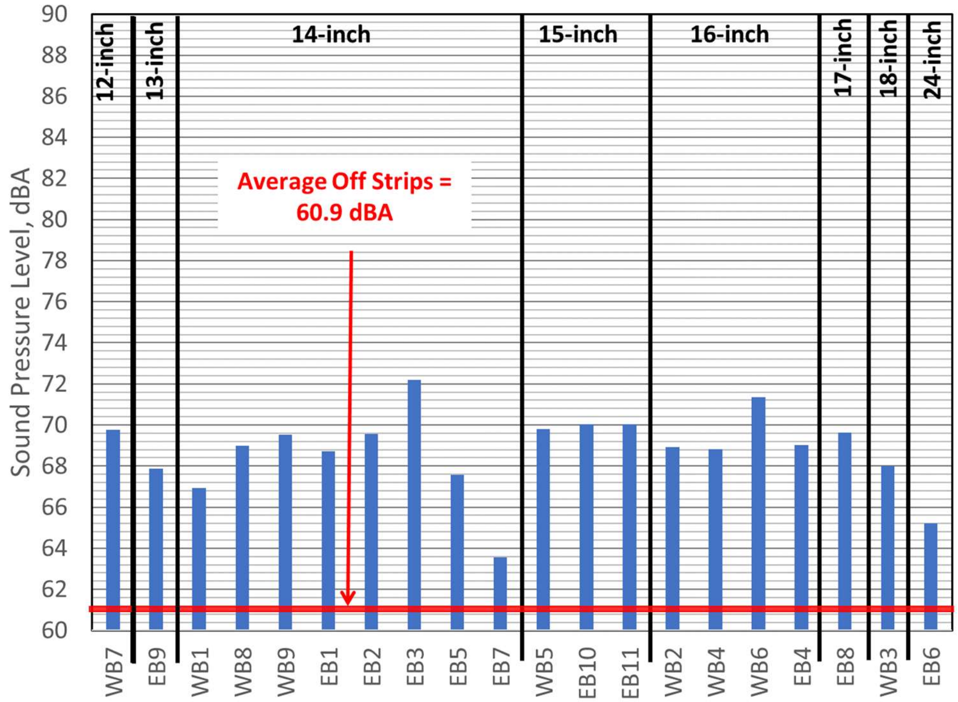



*Figure D-56: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-4 on the strips - CC microphones at 45 mph*

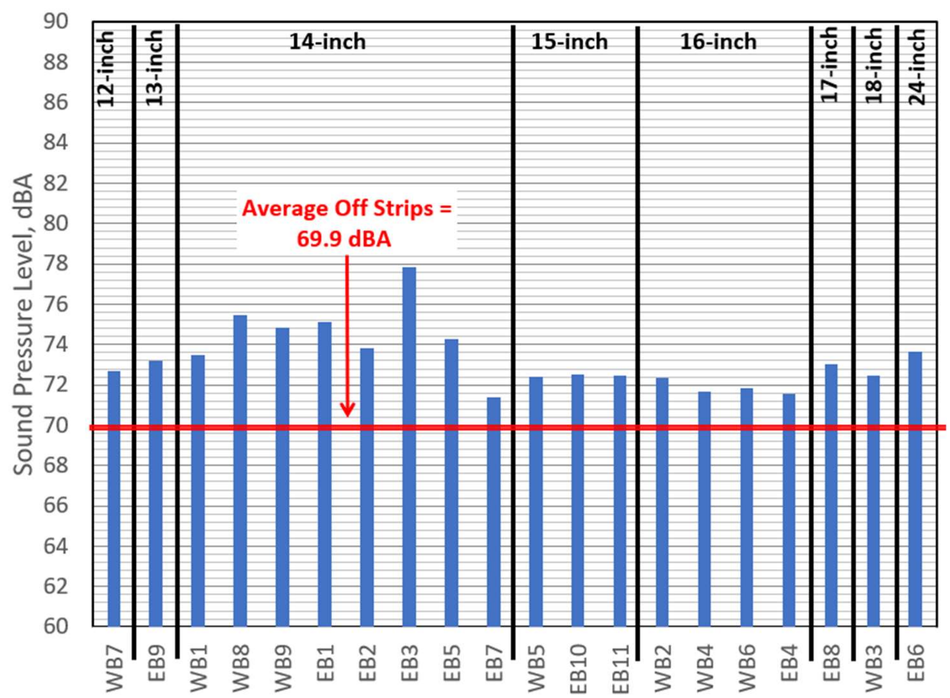



*Figure D-57: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-3 on the strips - CC microphones at 45 mph*

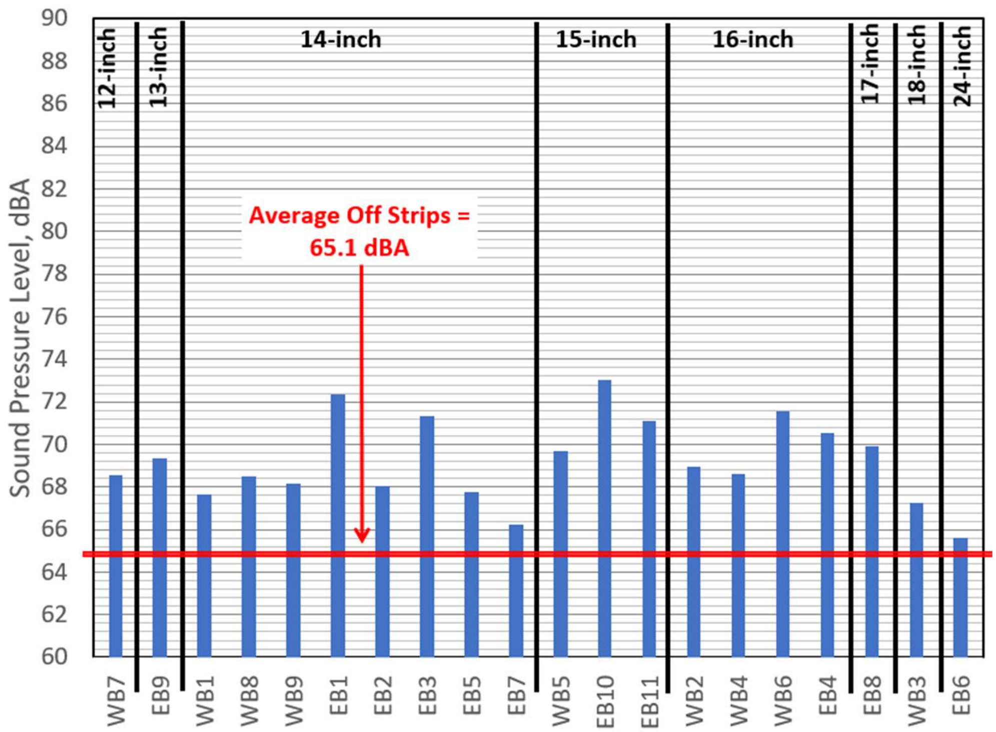



*Figure D-58: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-2 on the strips - CC microphones at 45 mph*

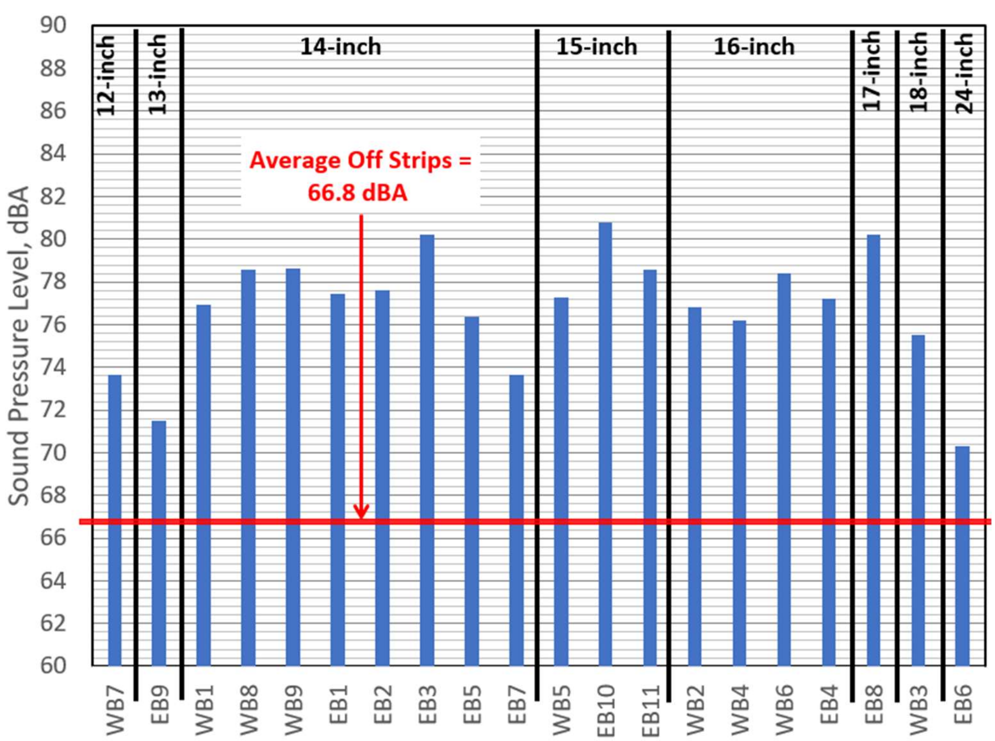



*Figure D-59: Band-passed A-weighted interior sound pressure levels at all test sites using Test Car D-1 on the strips - CC microphones at 45 mph*

The highest band-passed levels measured at 45 mph in the SUVs (Test Car D-3 and D-4) occurred at the EB3 (14-inch wavelength) test site, and the lowest levels in these categories occurred at EB7 (14-inch wavelength). In the passenger car categories (Test Car D-1 and D-2), the highest levels occurred at EB10 (15-inch wavelength), and the lowest levels occurred at EB6 (24-inch wavelength). The highest levels at 60 mph occurred at EB2, EB3, and EB10. The lowest levels at 60 mph occurred at EB8 and EB6.

Figure D-60 shows the on/off increments measured at 45 mph with the CC microphones for each site and all vehicles (FC is shown at the end of this appendix). At 45 mph, increments of 10 dBA or more were measured in Test Car D-4 and D-1 only. EB3 (14-inch wavelength), EB10 (15-inch wavelength), and WB6 (16-inch wavelength) test sites showed increments of 10 dB or more in both of these vehicles. Additional sites resulting in increments of 10 dB or more with Test Car D-1 include WB8, WB9, EB1, and EB2 (14-inch wavelengths), EB11 (15-inch wavelength), EB4 (16-inch wavelength), and EB8 (17-inch wavelength). The conventional WSDOT rumble strips also resulted in 10 dB increments with Test Car D-4 and D-1.

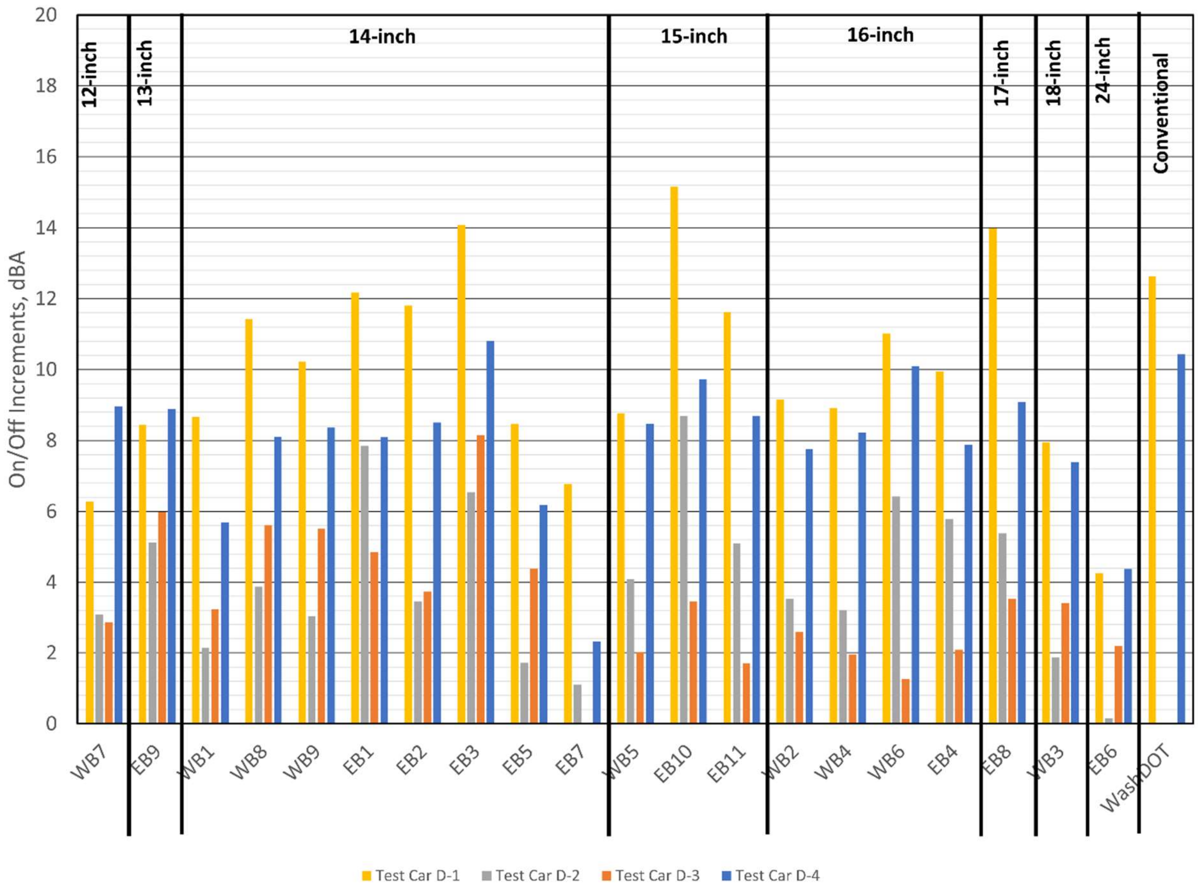



*Figure D-60: On/off increments measured with the CC microphone at all 20 sinusoidal test sites and the conventional WSDOT rumble strips using each test vehicle at 45 mph*

Average band-passed noise levels at the CC microphone were calculated across all vehicles at each test site at 45 mph. These are shown in Figure D-61 (FC is shown at the end of this appendix). Just like at 60 mph, EB3 and EB10 showed the highest band-passed levels of 74 to 75 dB. The lowest average levels were measured at EB6 and EB7 and were approximately 68 to 69 dB.

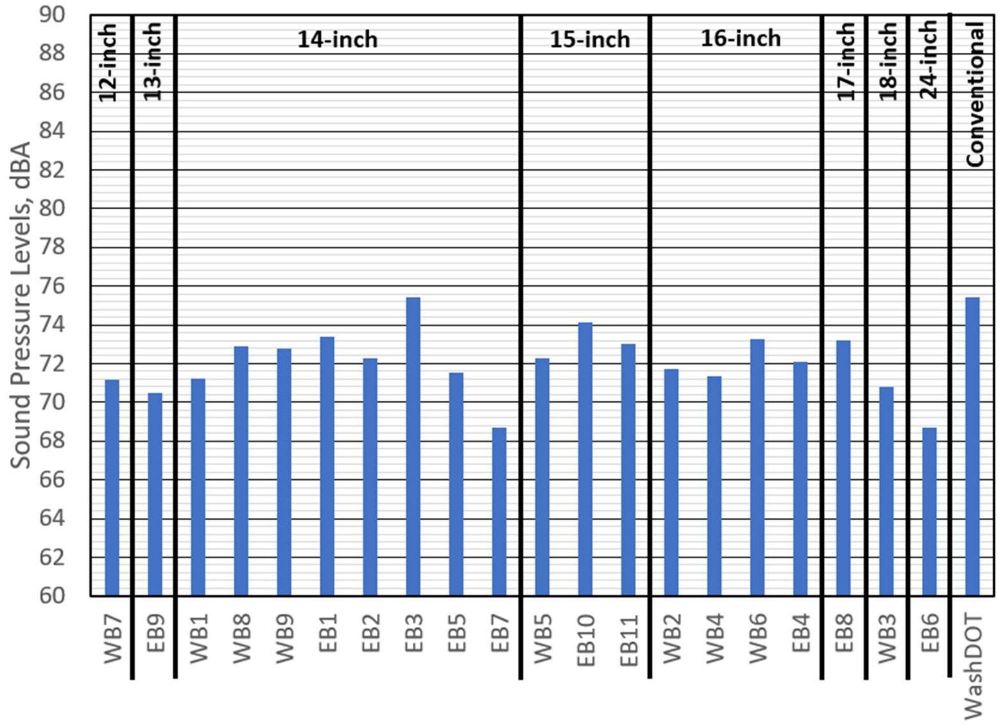



*Figure D-61: Band-passed A-weighted interior sound pressure levels at all test sites averaged across all test vehicle on the strips - CC microphones at 45 mph*

Figure D-62 shows the average on/off increments for all vehicles at the CC microphone (FC is shown at the end of this appendix) at 45 mph. Only one sinusoidal test site resulted in average on/off increments of 10 dBA or more at 45 mph: EB3 (14-inch wavelength).

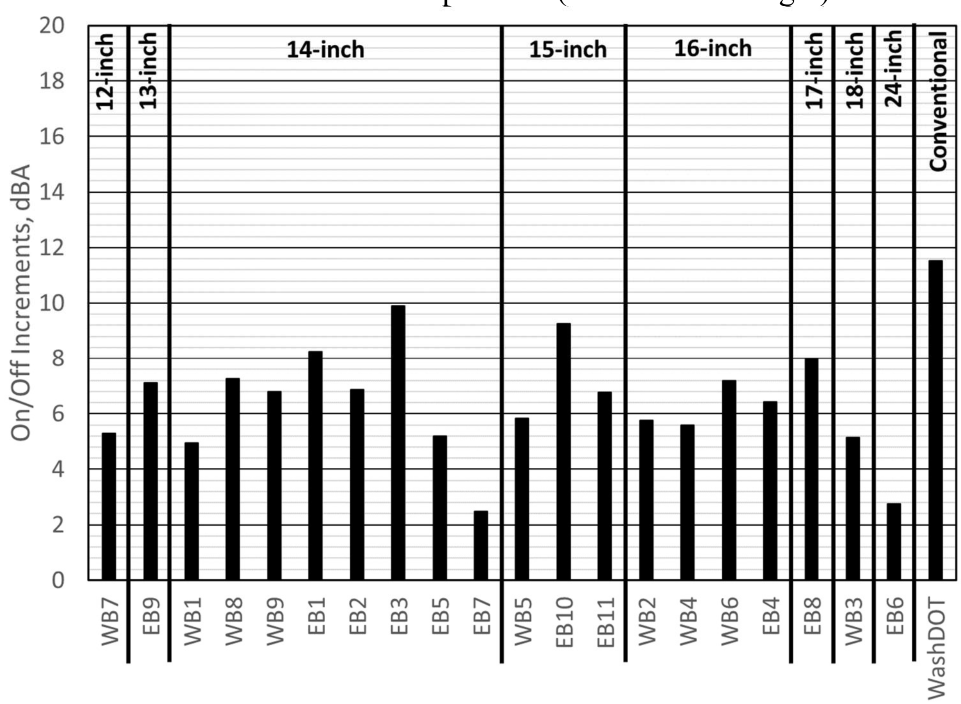


*Figure D-62: Average on/off increments across all test vehicles at the CC microphone traveling at 45 mph*

**60 mph Interior Vibration**

Vibration measurements were made at both the primary accelerometer location (seat track [ST]) and the secondary accelerometer location (steering column [SC]), which were selected in Phase I. As determined in Phase I, the combination of vibration levels in all three directions (the x-plane, the y-plane, and the z-plane) resulted in the most consistent correlation with tactile response to rumble strips. Therefore, all results in this section reflect the combination of vibration levels from all three planes.

Examples of the interior vibration spectra for the primary ST location are shown in Figures D-63, D-64, D-65, and D-66 on and off the 14-inch sinusoidal strips for Test Car D-4, D-2, D-3, and D-1, respectively. The 80 Hz one-third octave band at the 14-inch wavelength sinusoidal test strips are very apparent in each of the vehicles. Both of the passenger cars showed elevated levels at ST in the 400 to 630 Hz range. Spectra for the remaining test sites and all spectra with the SC microphone are provided at the end of this appendix.

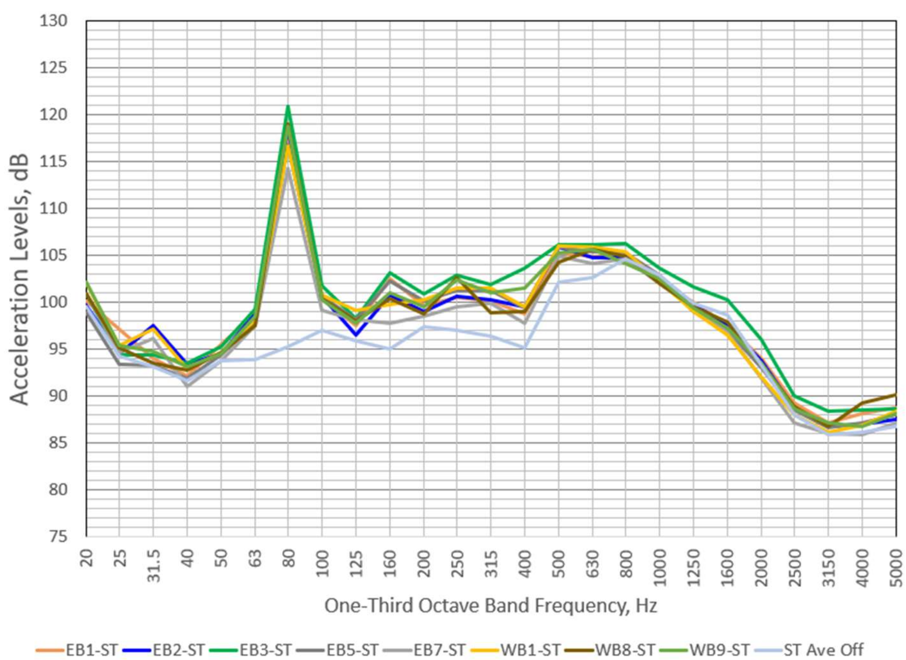



*Figure D-63: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 60 mph – Test Car D-4*

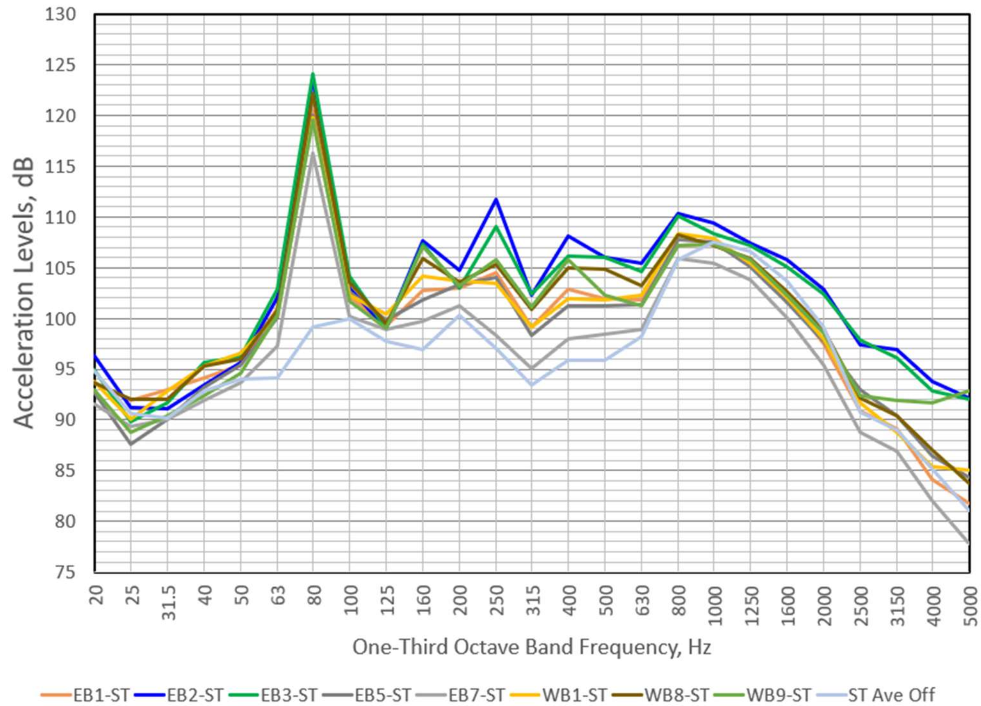



*Figure D-64: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 60 mph – Test Car D-2*

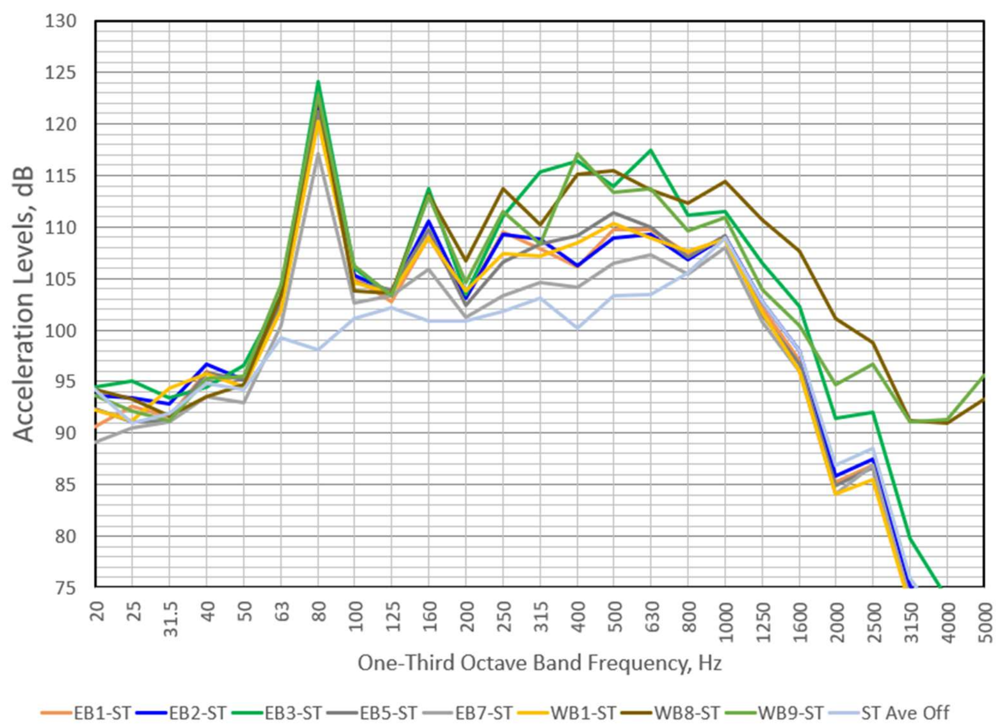



*Figure D-65: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 60 mph – Test Car D-3*

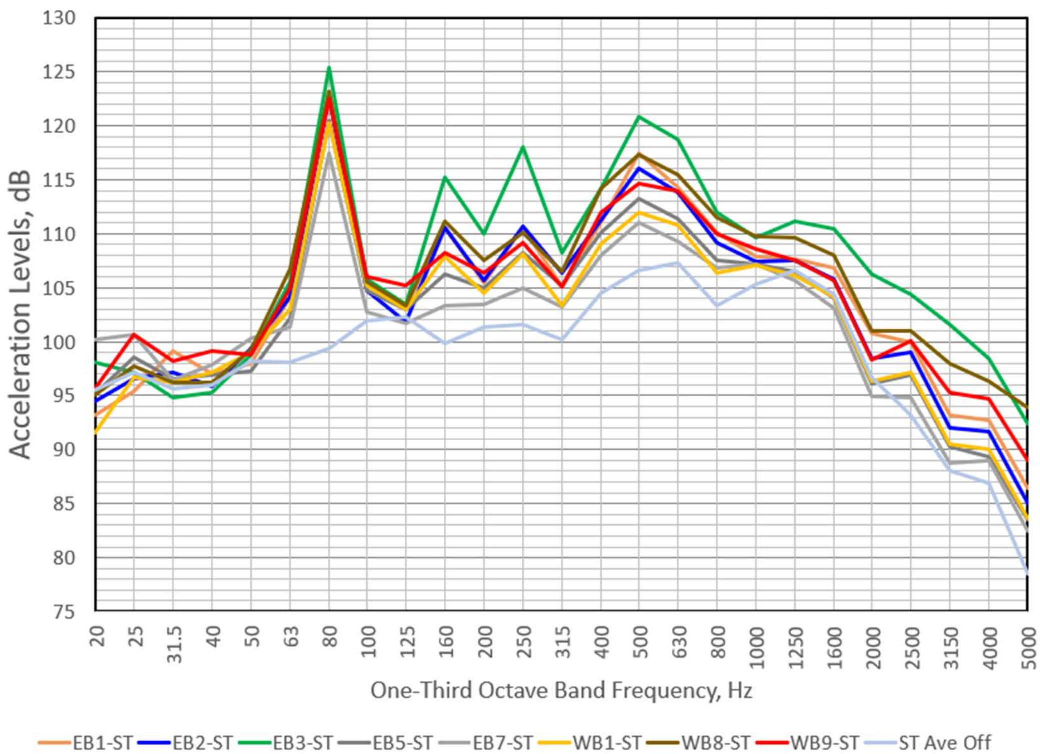



*Figure D-66: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 60 mph – Test Car D-1*

Figures D-67 through D-60 show the measured band-passed noise levels on the sinusoidal test strips for the large SUV, mid-size SUV, sedan, and compact car test vehicles, respectively, as measured from the ST accelerometer (SC results are provided at the end of this appendix). Also shown in each figure are the average off strips levels measured at each site. Similar to the interior noise measurements, the band-passed noise levels were calculated by summing the energy from 31.5 to 315 Hz.

The highest vibration levels were measured at WB6 (16-inch wavelength) in the Test Car D-4; at EB10 (15-inch wavelength) in Test Car D-3; and at EB3 (14-inch wavelength) in Test Car D-2 and Test Car D-1. The lowest levels were measured at the test sites with 12-, 17-, 18-, and 24-inch wavelengths.

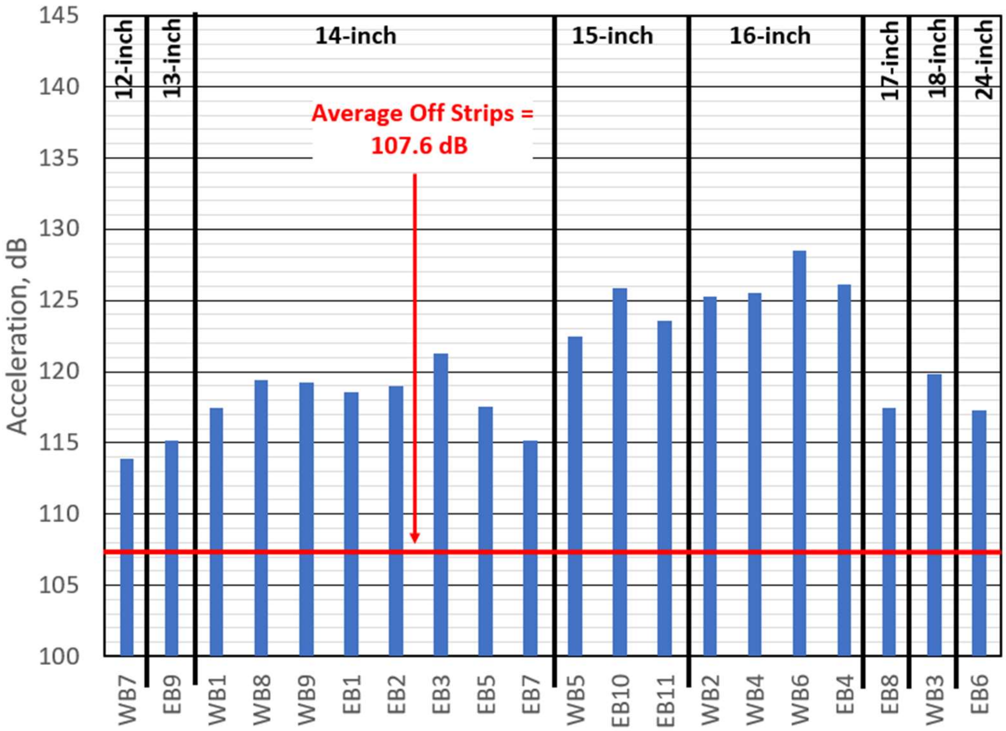



*Figure D-67: Band-passed interior vibration levels at all test sites using Test Car D-4 on the strips with the ST sensor at 60 mph*

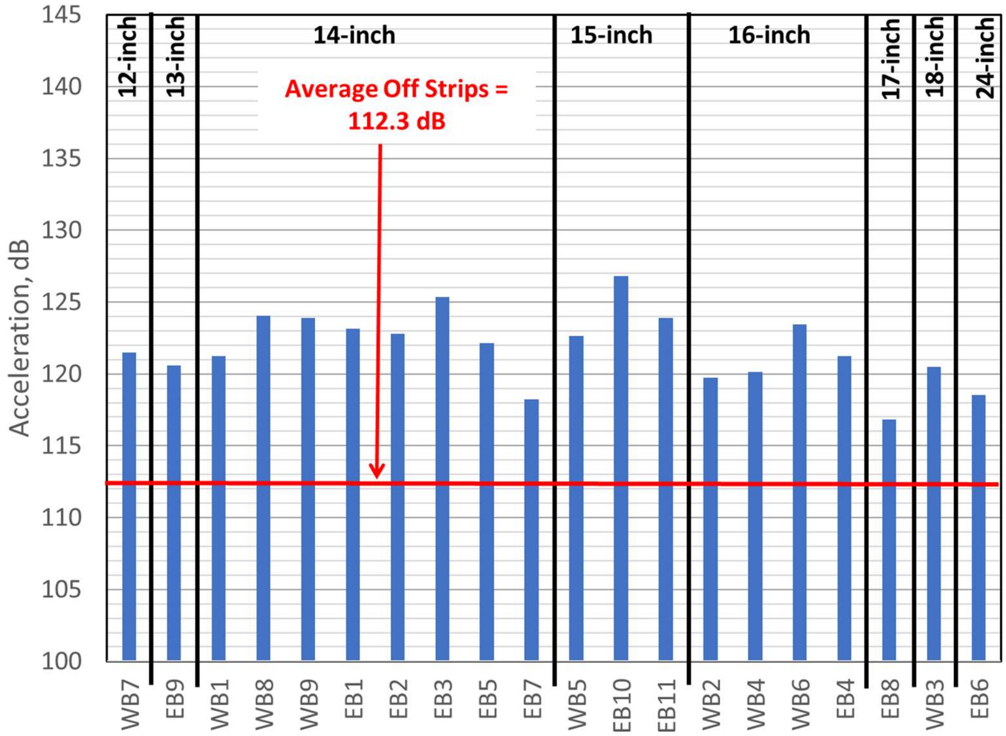



*Figure D-68: Band-passed interior vibration levels at all test sites using Test Car D-3 on the strips with the ST sensor at 60 mph*

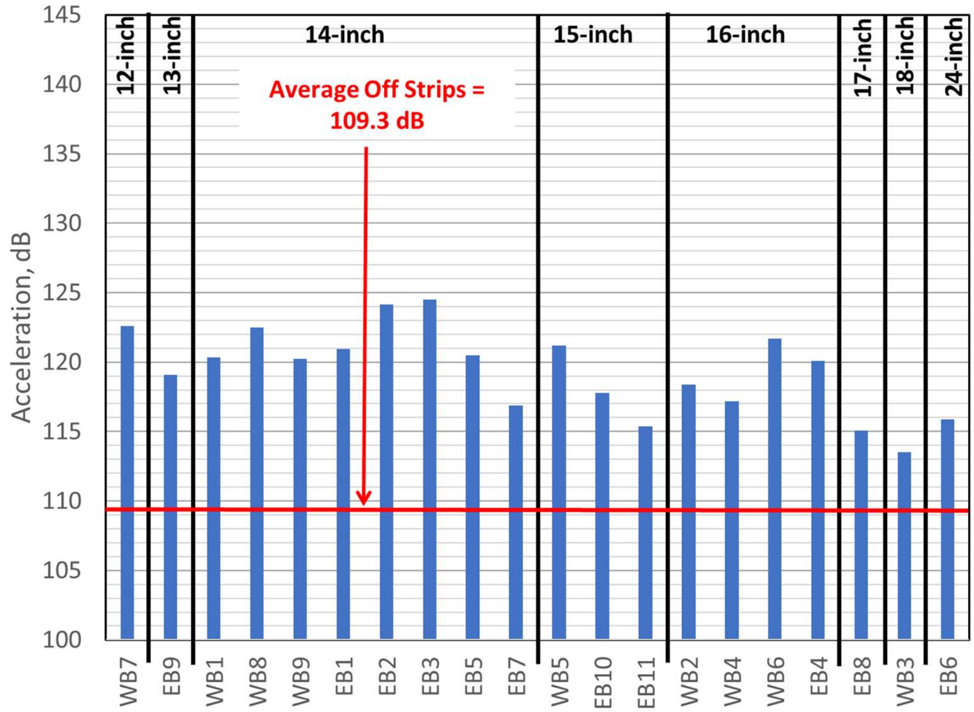



*Figure D-69: Band-passed interior vibration levels at all test sites using Test Car D-2 on the strips with the ST sensor at 60 mph*

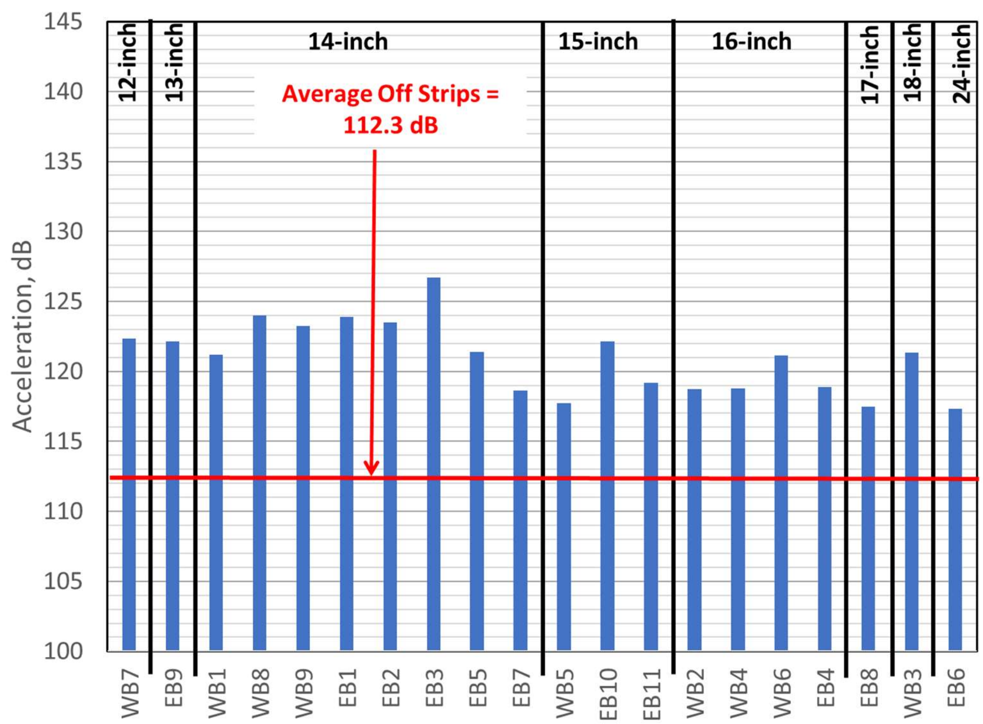



*Figure D-70: Band-passed interior vibration levels at all test sites using Test Car D-1 on the strips with the ST sensor at 60 mph*

The on/off increments measured with the ST sensor for each site and all vehicles are shown in Figure D-71. The on/off increments measured with the SC sensor are shown at the end of this appendix. A 10 dBA or more difference between on and off strips was calculated in all test vehicles at WB8, WB9, EB1, EB2, and EB3 (all 14-inch wavelength) test sites with the ST sensor.

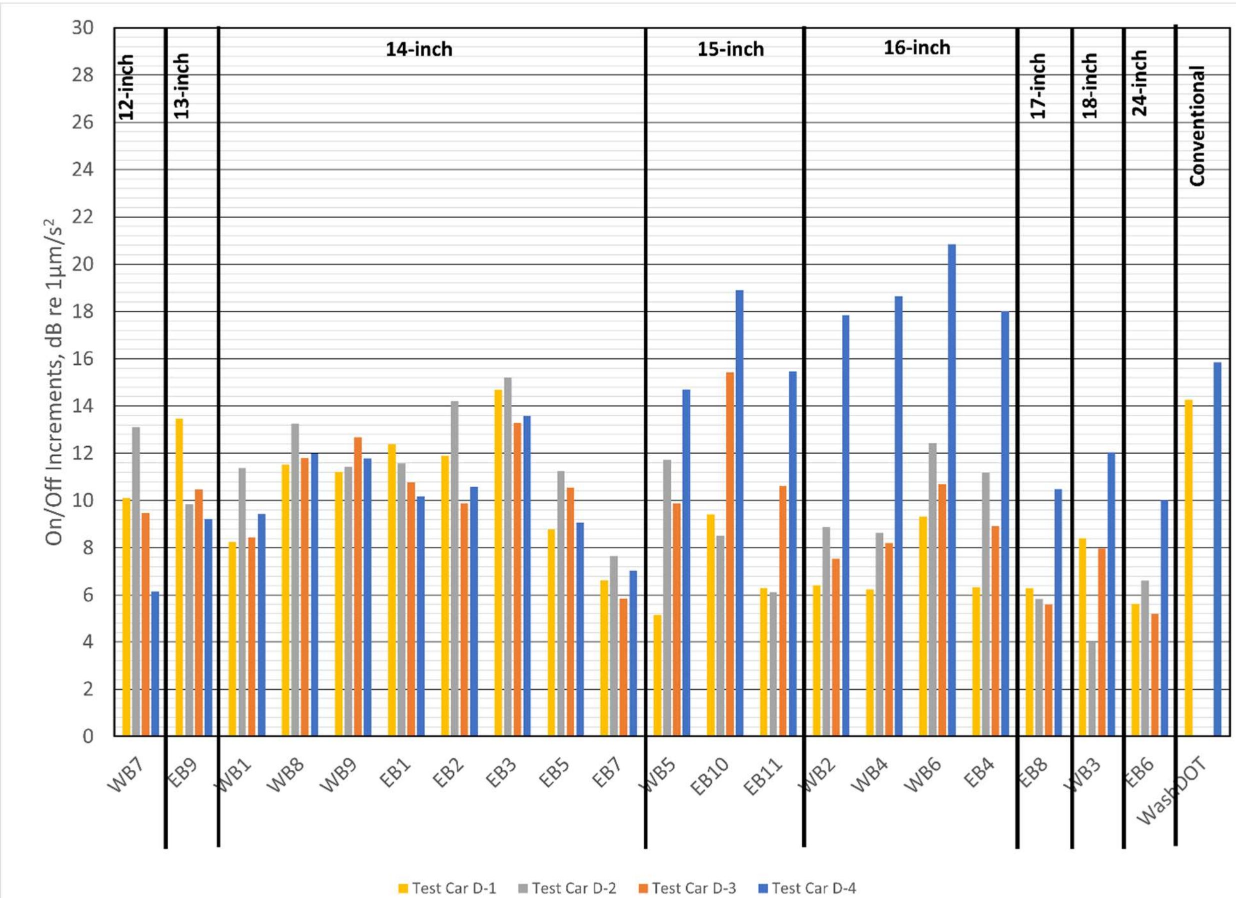



*Figure D-71: On/off increments measured with the ST sensor at all 20 sinusoidal test sites and the conventional WSDOT rumble strips using each test vehicle at 60 mph*

Average band-passed vibration levels at the ST accelerometer were calculated across all vehicles at each test site. These are shown in Figure D-72 (SC is shown at the end of this appendix). EB3, WB8, and EB10 showed the highest band-passed levels of 128 to 131 dB. The lowest average levels were measured at WB3 and EB7 and were approximately 121 to 123 dB.

Figure D-73 shows the average on/off increments for all vehicles at the ST accelerometer (SC is shown at the end of this appendix). Sinusoidal test sites resulting in average on/off increments of 10 dBA or more across all test vehicles include: WB7 (12-inch wavelength); EB9 (13-inch wavelength); WB8, WB9, EB1, EB2, EB3, and EB5 (14-inch wavelengths); WB5, EB10, and EB11 (15-inch wavelengths); and WB2, WB4, WB6, and EB4 (16-inch wavelengths).

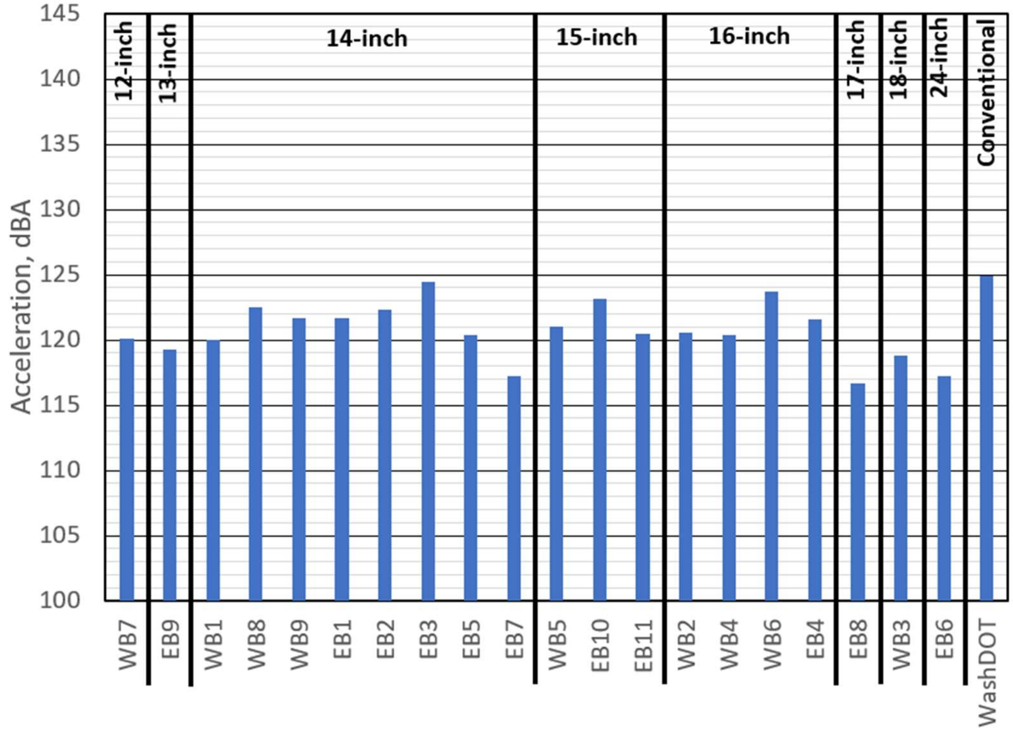



*Figure D-72: Band-passed interior vibration levels at all test sites averaged across all test vehicle on the strips – ST accelerometer at 60 mph*

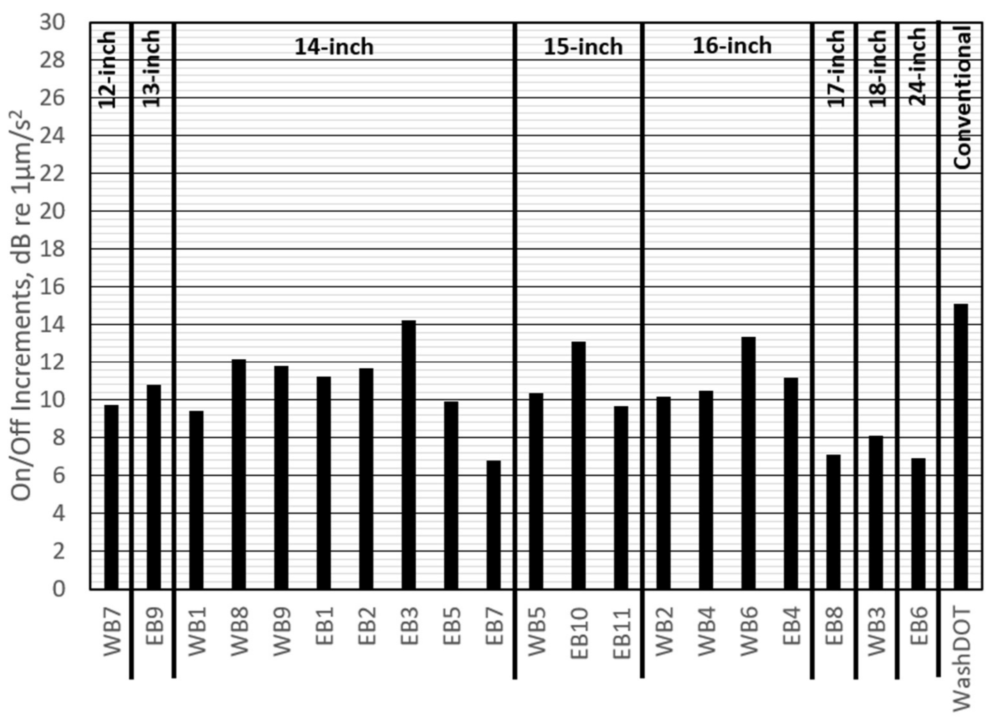



*Figure D-73: Average on/off increments across all test vehicles at the ST accelerometer traveling at 60 mph*

**45 mph Interior Vibration**

Examples of the interior vibration spectra at 45 mph measured at the primary ST location are shown in Figures D-74, D-75, D-76, and D-77 on and off the 14-inch sinusoidal strips for Test Car D-4, D-2, D-3, and D-1, respectively. Similar to the spectra measured with the interior microphones, the split peaks at 50 and 63 Hz are clearly shown in Test Car D-1 and D-2 (both smaller car categories), but most of the energy in Test Car D-3 and D-4 (both larger SUV categories) is in the 63 Hz band. Spectra for the remaining test sites and all spectra and band-passed levels measured with the SC accelerometer are provided at the end of this appendix.

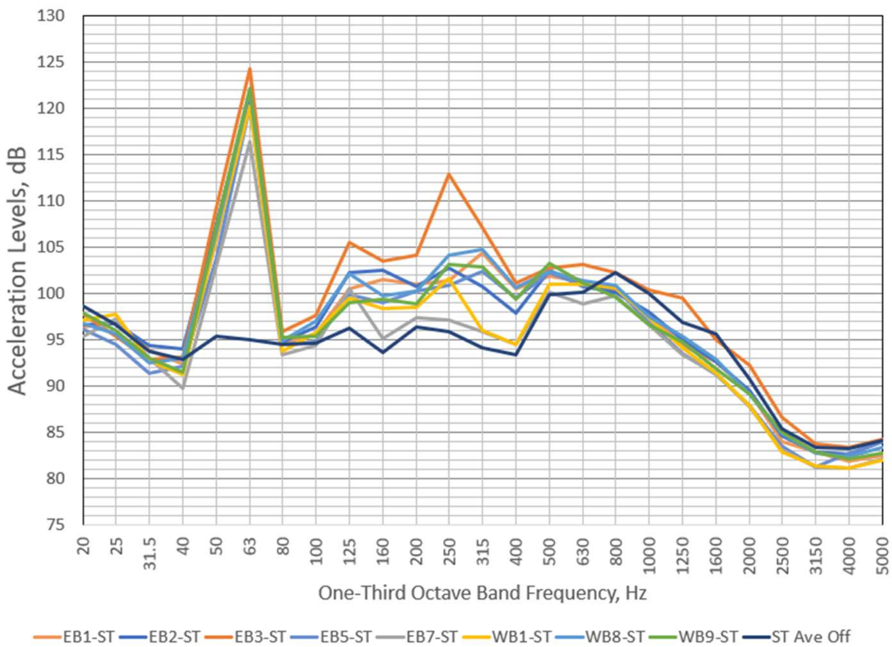



*Figure D-74: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 45 mph – Test Car D-4*

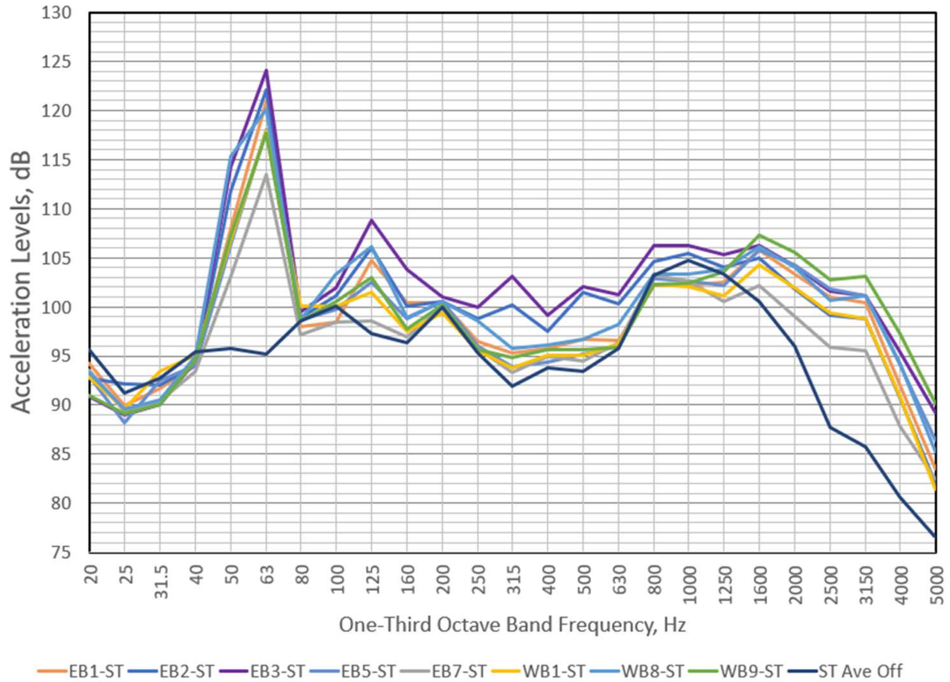



*Figure D-75: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 45 mph – Test Car D-2*

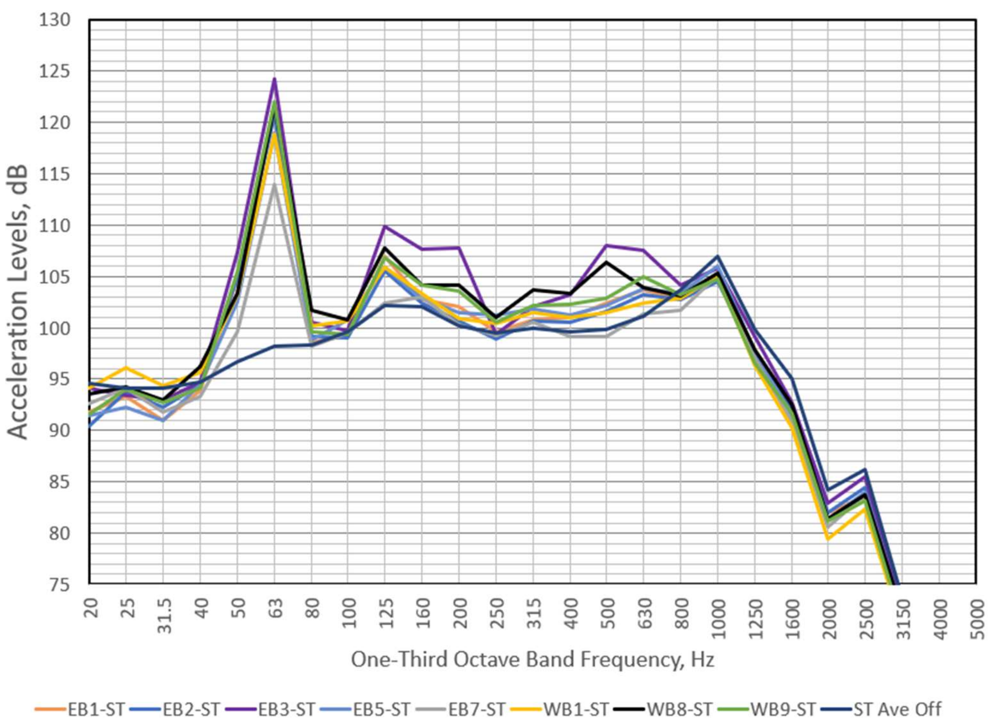



*Figure D-76: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 45 mph – Test Car D-3*

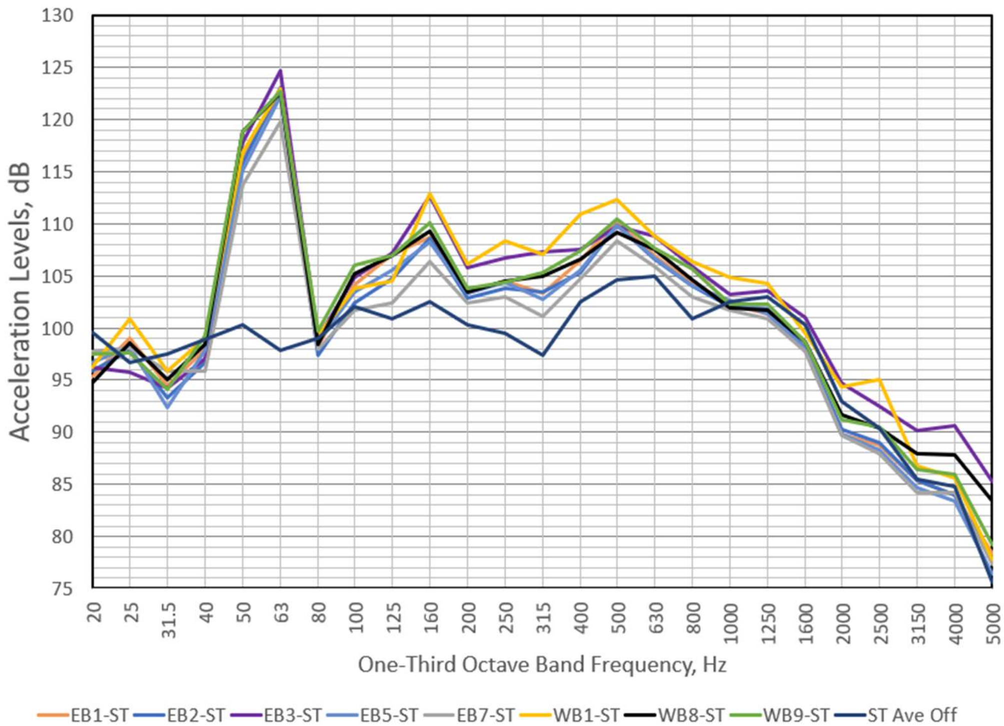



*Figure D-77: Interior vibration spectra on 14-inch sinusoidal strips with the ST accelerometer at 45 mph – Test Car D-1*

The band-passed levels calculated by summing the energy in the bands from 31.5 to 315 Hz are shown in Figures D-78 through D-81 for the large SUV, mid-size SUV, sedan, and compact car test vehicles, respectively, as measured at the ST accelerometer. The average off strips levels measured at each site with both sensors are also identified in each figure. The highest vibration levels were measured at EB10 (15-inch wavelength) test site in Test Car D-4 and D-1 and at EB3 (14-inch wavelength) test site in Test Car D-3 and D-2. These levels ranged from about 124 to 126 dB.

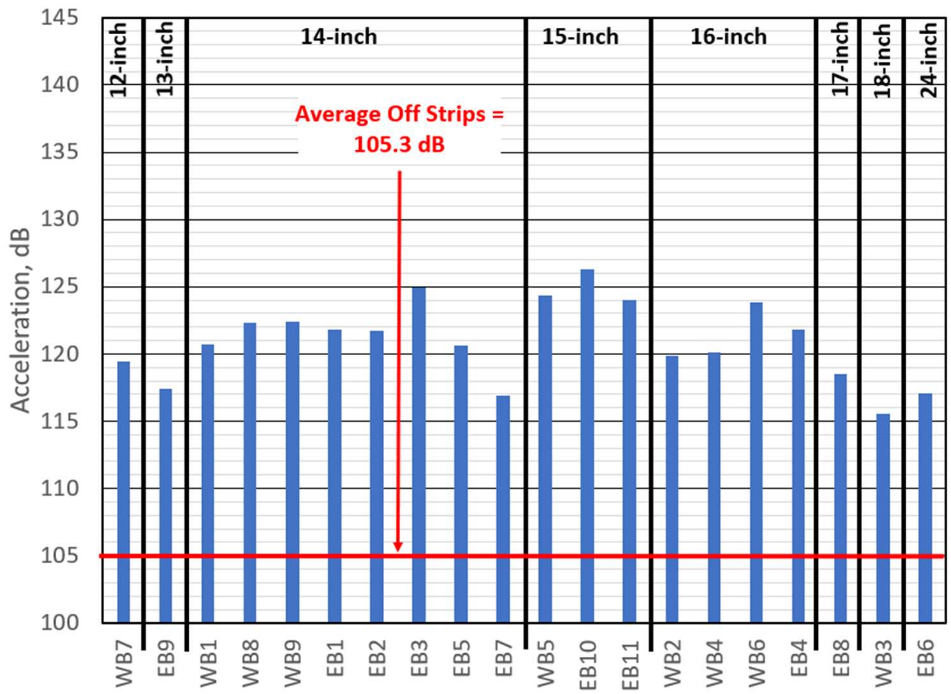



*Figure D-78: Band-passed interior vibration levels at all test sites using Test Car D-4 on the strips with the ST sensor at 45 mph*

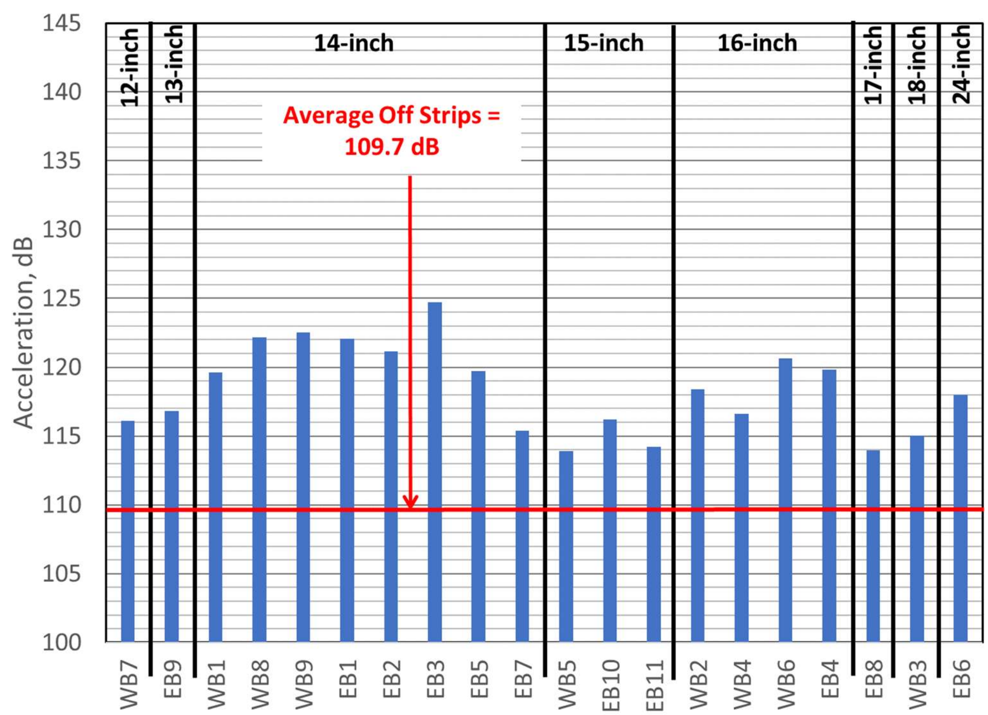



*Figure D-79: Band-passed interior vibration levels at all test sites using Test Car D-3 on the strips with the ST sensor at 45 mph*

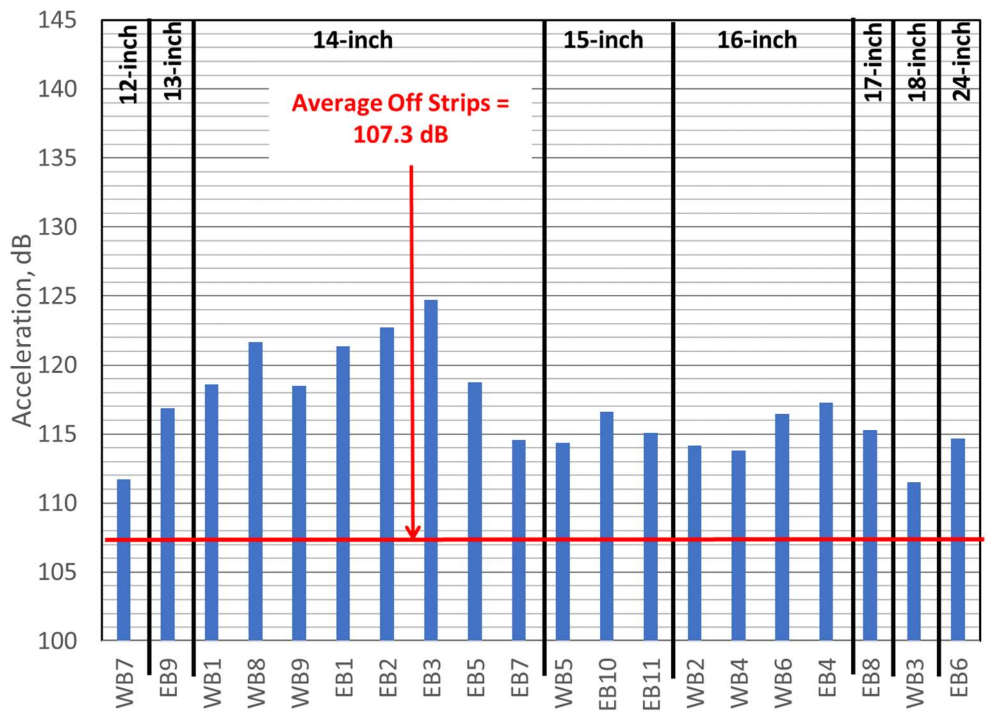



*Figure D-80: Band-passed interior vibration levels at all test sites using Test Car D-2 on the strips with the ST sensor at 45 mph*

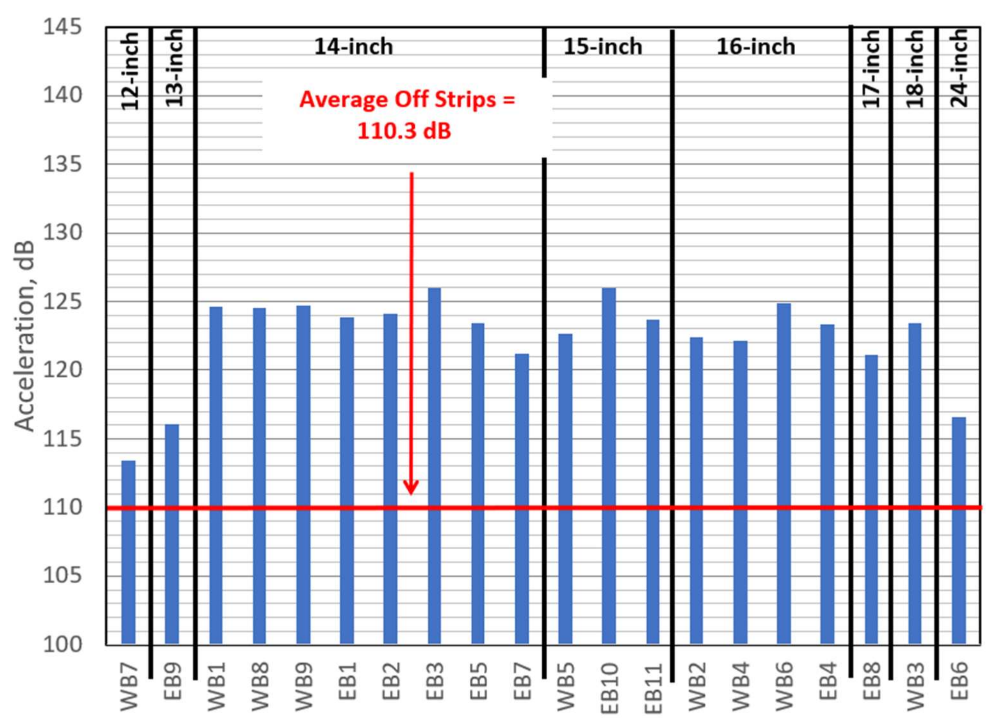



*Figure D-81: Band-passed interior vibration levels at all test sites using Test Car D-1 on the strips with the ST sensor at 45 mph*

Figure D-82 shows the on/off increments measured at 45 mph with the ST accelerometer for each site and all vehicles. At 45 mph, increments of 10 dB or more were measured at each site with Test Car D-4. Increments of 10 dB or more were measured with all four vehicles at the ST sensor at WB8, WB9, EB1, EB2, EB3, and EB5 (14-inch wavelength) and EB4 (16-inch wavelength).

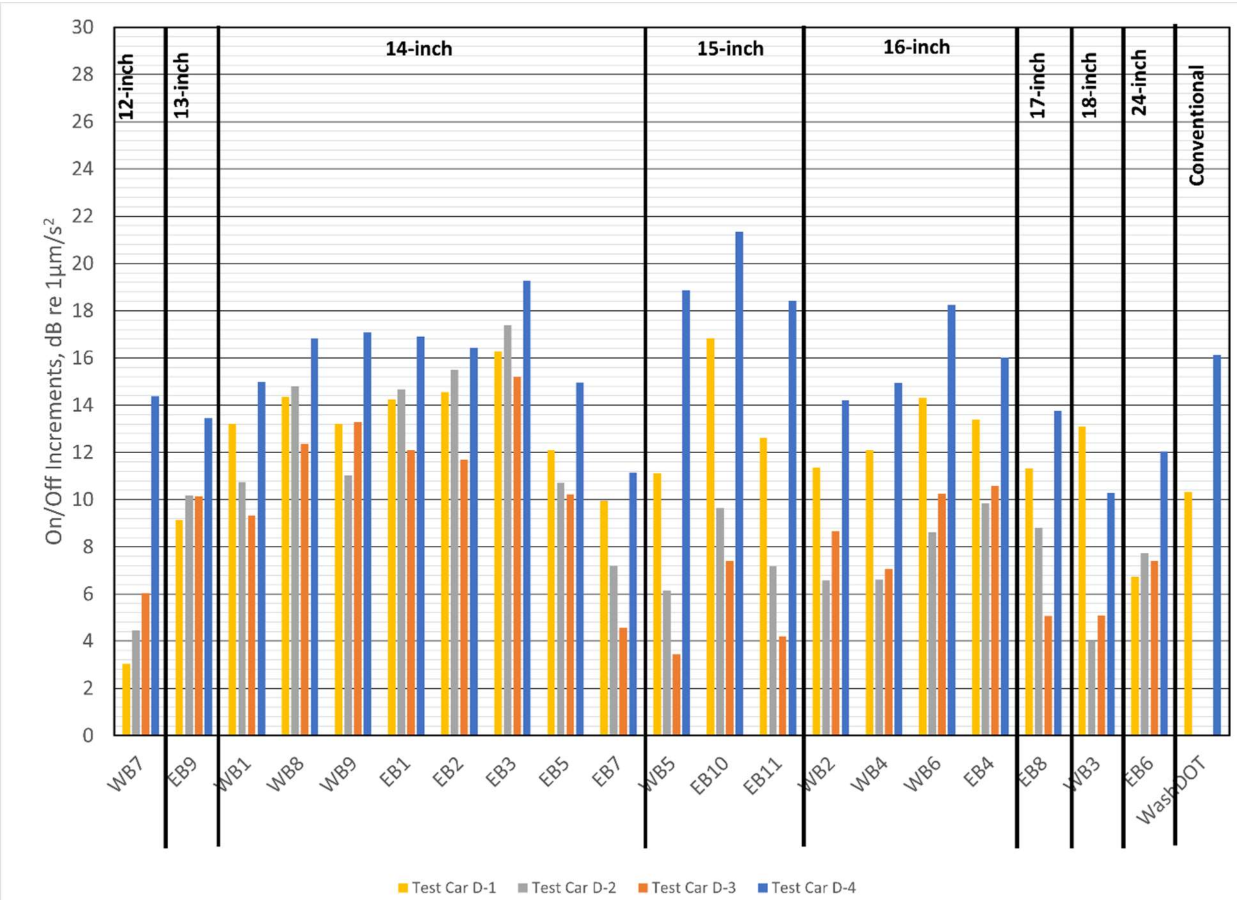



*Figure D-82: On/off increments measured with the ST accelerometer at all 20 sinusoidal test sites and the conventional WSDOT rumble strips using each test vehicle at 45 mph*

Average band-passed vibration levels at the ST accelerometer were calculated across all vehicles at each test site. At 45 mph, these are shown in Figure D-83 (SC is shown at the end of this appendix). WB8, WB9, EB1, EB2, and EB3 showed the highest band-passed levels of 122 to 125 dB. The lowest average levels were measured at WB7 and were approximately 115 dB.

Figure D-84 shows the average on/off increments for all vehicles at the ST accelerometer (SC is shown at the end of this appendix). Sinusoidal test sites resulting in average on/off increments of 10 dBA or more across all test vehicles include: EB9 (13-inch wavelength); WB1, WB8, WB9, EB1, EB2, EB3, and EB5 (14-inch wavelengths); WB5, EB10, and EB11 (15-inch wavelengths); WB2, WB4, WB6, and EB4 (16-inch wavelengths); and EB8 (17-inch wavelength).

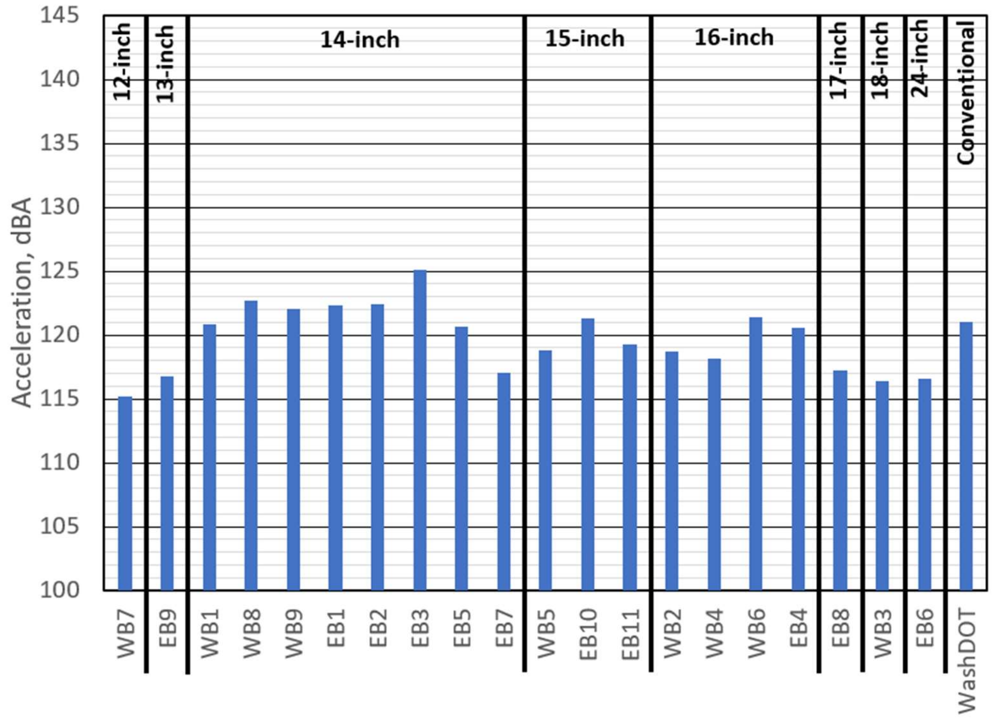



*Figure D-83: Band-passed interior vibration levels at all test sites averaged across all test vehicle on the strips – ST accelerometer at 45 mph*

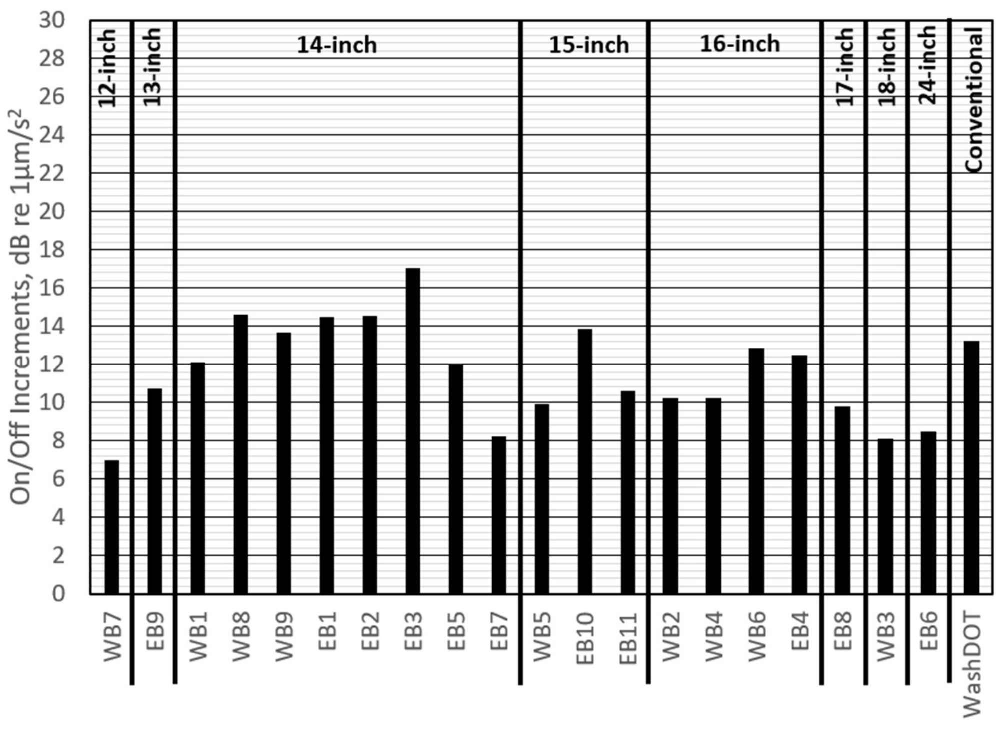



*Figure D-84: Average on/off increments across all test vehicles at the ST accelerometer traveling at 45 mph*

## COMPARISON TO PREVIOUS MEASUREMENTS

All four categories of vehicles (large SUV, mid-size SUV, sedans, and compact cars) were used to measure the sinusoidal rumble strips in California, Indiana, Michigan, and Washington states. This chapter compares the results of the exterior pass-by measurements and the interior noise and vibration measurements measured in Washington with the measurements made in previous tasks.

### Comparison to Previous Pass-by Results

For comparison, the results for a mid-size sedan are shown here, with comparisons for the other three vehicle groupings included at the end of this appendix. Figure D-85 shows the spectra measured at 60 mph for all eight sites with 14-inch wavelengths in Washington compared to the 14-inch test sites in California and Michigan. These spectra were occurring at the time of maximum band-passed level. The 80 Hz peaks at the 14-inch sites in California and Michigan fall within the range of 80 Hz peak levels at the Washington sites. The higher orders of repetition rate (160 and 250 Hz) are more distinct in California and Michigan than at the Washington sites. This may indicate the importance of more uniform installation of the sinusoidal design in California and Michigan. The 12- and 18-inch strips in Indiana and Washington had more roughness, and the sinusoidal design was less distinct. In California and Michigan, however, the sinusoidal design was more defined, which may increase the prevalence of the repetition rates. Both the California and Michigan sites consisted of DGAC pavement of different ages. These data show high levels in the upper frequencies similar to the Washington sites. These higher levels were not measured in the off-strips spectra in California and Michigan, however, as they were in Washington.

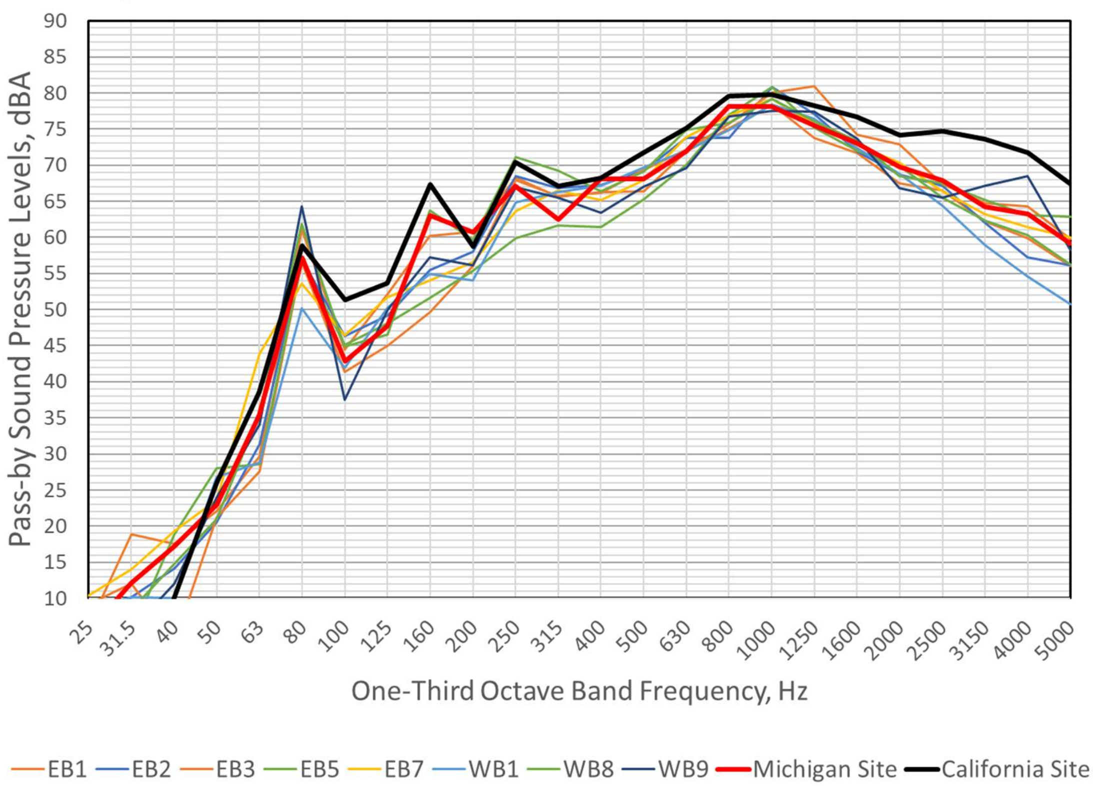


*Figure D-85: Spectra for 14-inch Washington Sites vs. 14-inch California and Michigan Sites*

Spectra for the 12-inch wavelength of WB7 compared to the 12-inch site in Indiana are shown in Figure D-86; spectra for the 18-inch wavelength strips of WB3 and the 18-inch strips from Indiana are shown in Figure D-87; and those for the 24-inch wavelength of EB6 are compared to the 24-inch site in Indiana in Figure D-88. The peaks at the driving frequencies at the 12-inch site are more distinct than at the 18- and 24-inch sites, but the peak in Indiana is more discernable than at the Washington site. Additionally, both spectra do show elevated levels in the higher frequency bands, which would help to mask the peaks at the driving frequencies. The 12-inch sites in Indiana and Washington were both overlayed with chip seal pavement. While it should be noted that the chip seal was installed over the rumble strips in Indiana but were not installed over the rumble strips in Washington, the pass-by measurements would have included the two driver-side tires on the chip seal pavement and the two passenger-side tires on the rumble strips. Therefore, the effect of the chip seal pavement in both spectra would be expected.

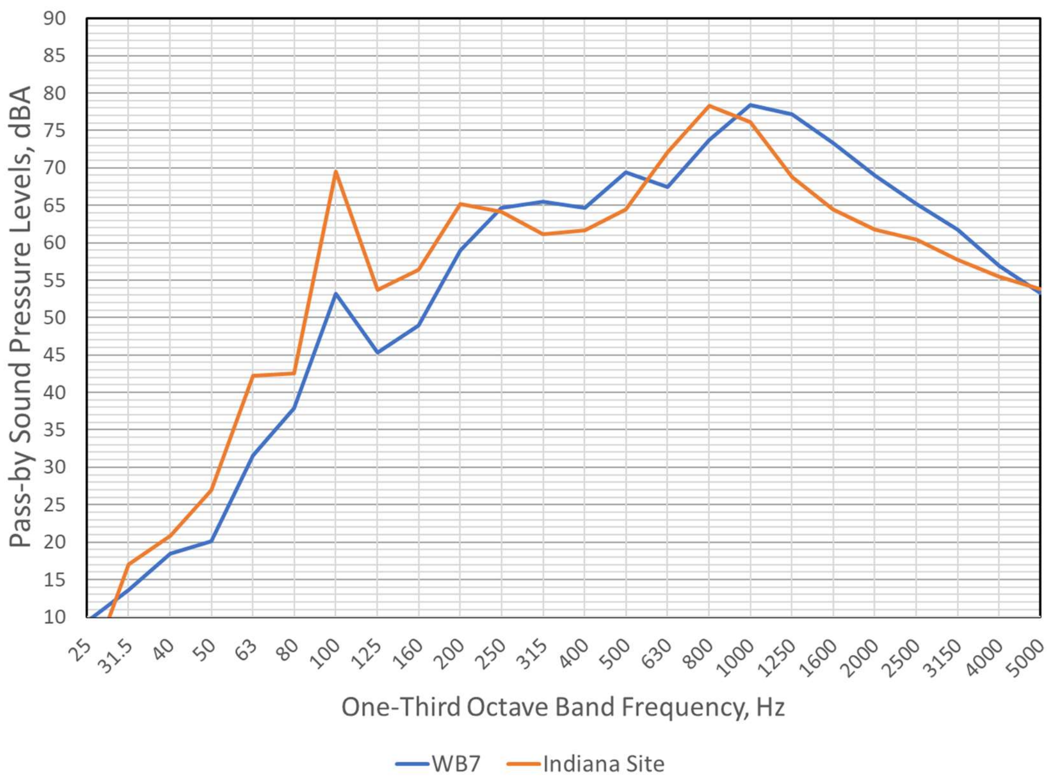



*Figure D-86: Spectra for 12-inch Washington Site vs. 12-inch Indiana Site*

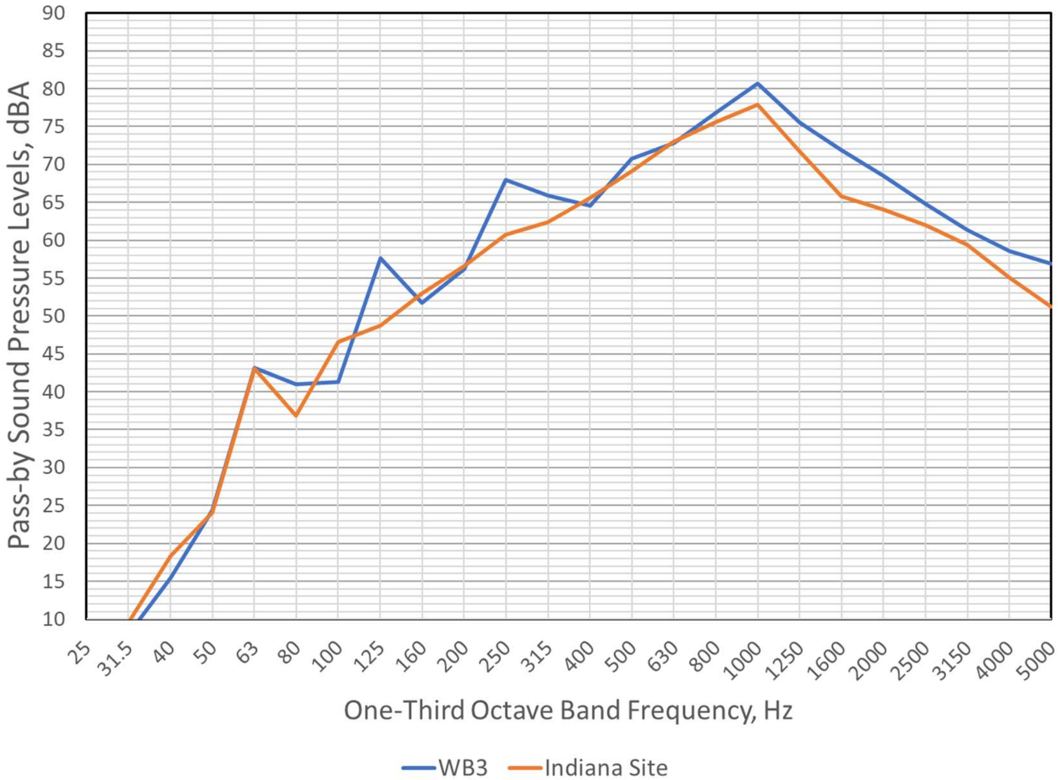



*Figure D-87: Spectra for 18-inch Washington Site vs. 18-inch Indiana Site*

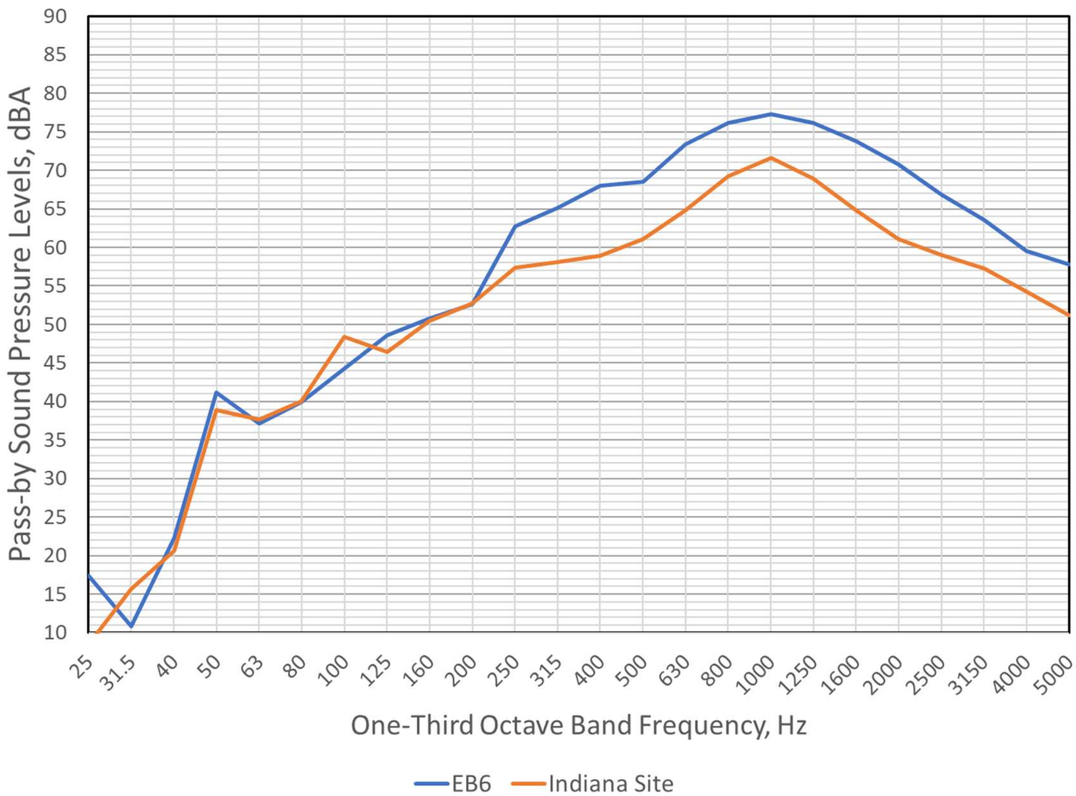



*Figure D-88: Spectra for 24-inch Washington Site vs. 24-inch Indiana Site*

While peaks are observed at the driving frequencies of the 18- and 24-inch sites in both Washington and Indiana, the peaks are not as distinct as at the 12- and 14-inch sites. Further, levels at the frequency bands above the driving frequency are higher and would help to mask the noise generated by the sinusoidal strips. This consistency in both Washington and Indiana indicates that sinusoidal rumble strips with wavelengths of 18- and 24-inch would generate minimal pass-by levels, regardless of the pavement since the 24-inch site in Indiana was an aged DGAC pavement.

To compare with the band-passed pass-by levels from the WSDOT test sites, which were calculated by summing the energy from 31.5 to 200 Hz, previous data was recalculated accordingly. The band-passed levels, on and off strips for all vehicle categories, are shown in Figure D-89 for vehicles in the large SUV category. The band-passed 31.5 to 200 Hz levels for the mid-size SUV, sedan, and compact car categories are shown in Figures D-90, D-91, and D-92, respectively. Across each test vehicle category, the conventional rumble strips in Washington and California, the 12-inch sinusoidal strips in Indiana, and the 14-inch sinusoidal strips in California resulted in the highest on-strips levels. The lowest levels occurred at the 18- and 24-inch sites; however, in some cases, the off-strips levels were higher at these sites than the on-strips levels. The next lowest levels were found on the 14-inch sites in Washington identified as EB7 and EB5.

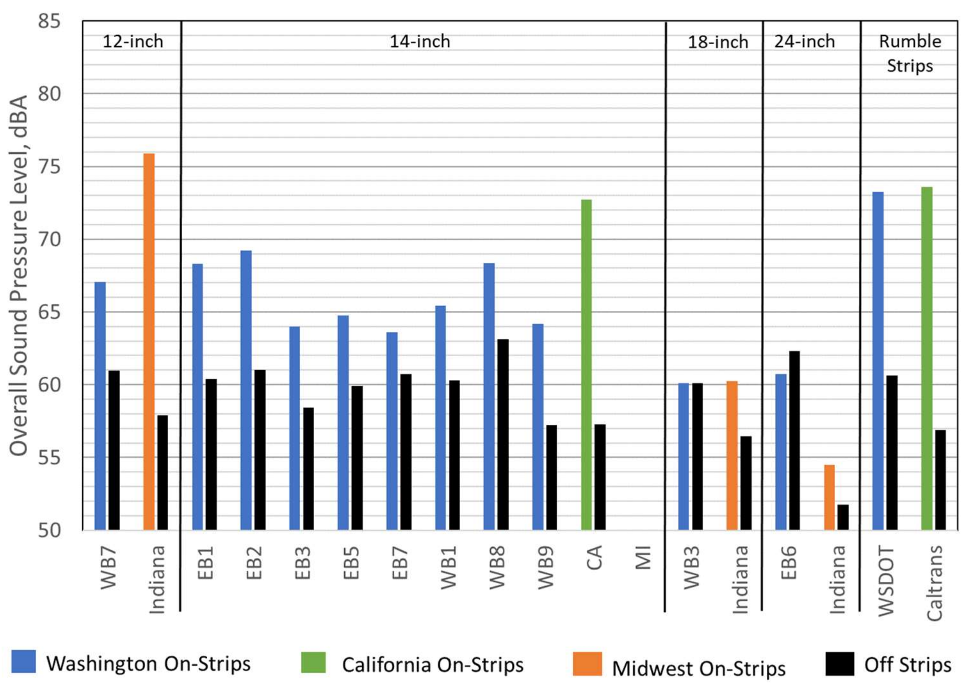



*Figure D-89: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the large SUV category*

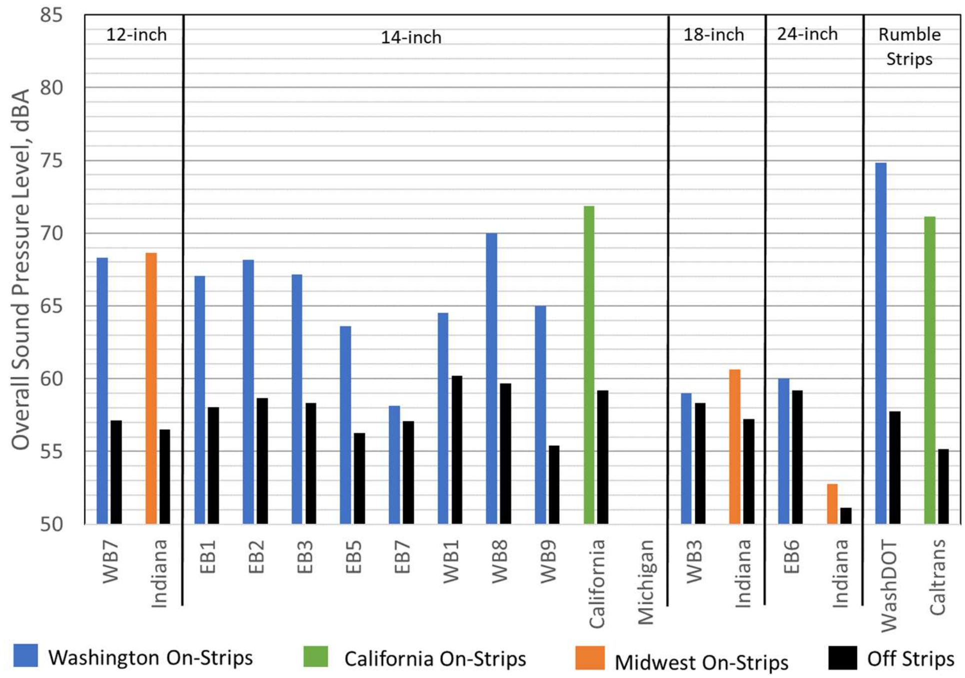



*Figure D-90: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the mid-size SUV category*

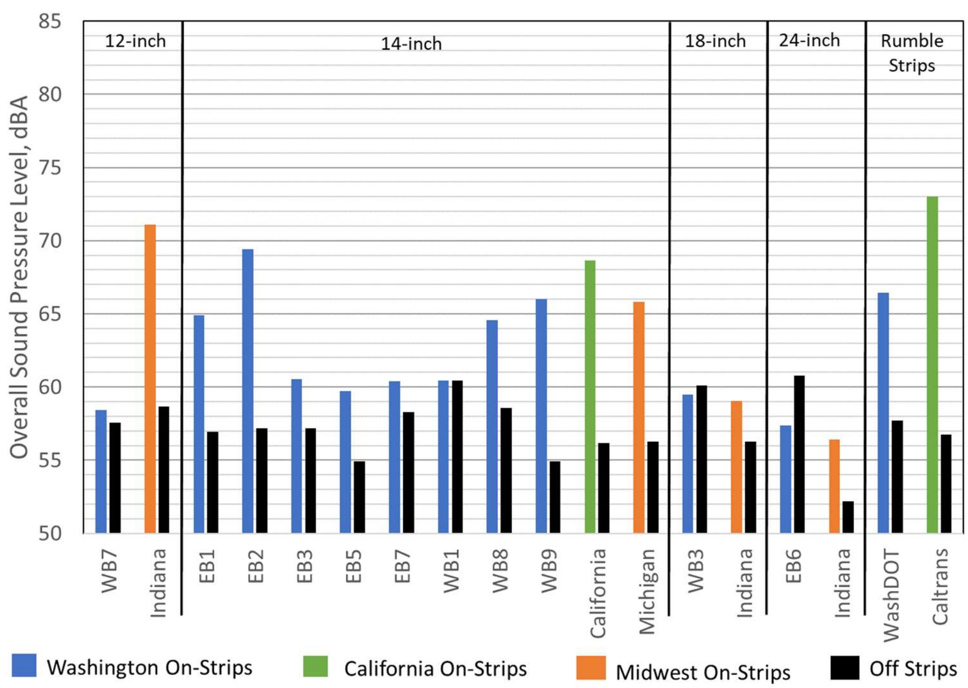



*Figure D-91: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the full/mid-size sedan category*

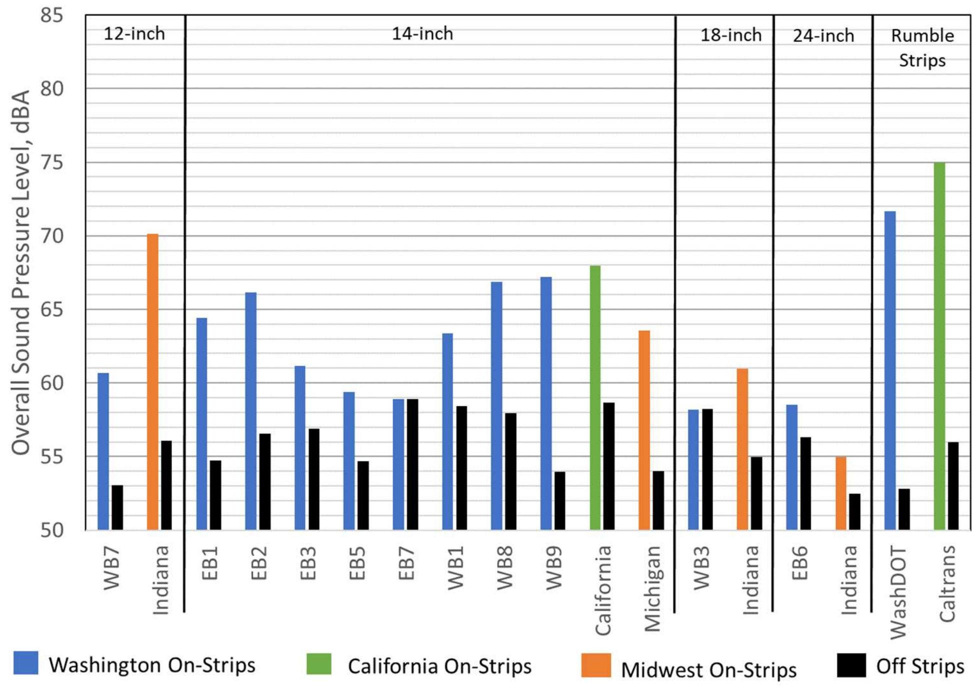



*Figure D-92: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the compact car category*

The on/off increments, which are calculated by subtracting the band-passed off-strips levels from the maximum band-passed on-strips levels at each site, are shown for all vehicles in Figure D-93. The same sites that resulted in the highest on-strips levels also resulted in the highest on/off differences. Aside from the Washington sites that resulted in off-strips levels higher than on-strips levels (i.e., 18- and 24-inch sites), the test site with the lowest on/off difference, which would be barely perceptible at receptors along the wayside, is the 14-inch site in Washington identified as EB7.

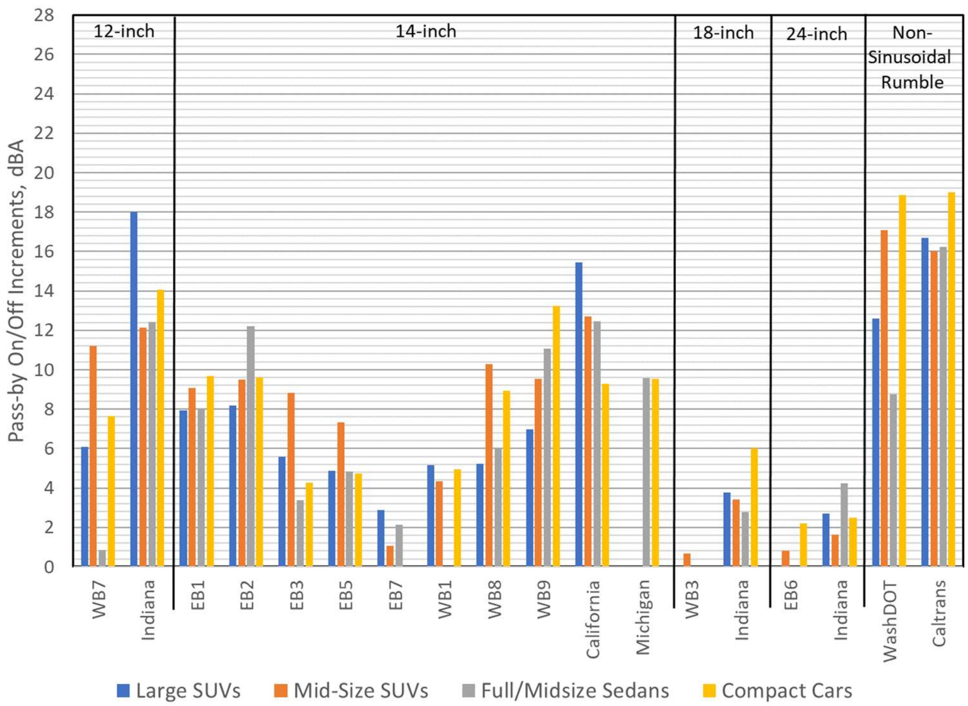



*Figure D-93: Band-passed pass-by noise level differences between on and off strips in Washington, California, Indiana, and Michigan for all vehicle categories*

To better compare the various test sites, the band-passed on-strips levels were averaged for all vehicles at each site. The highest average band-passed levels on the sinusoidal sites were measured at the 12-inch Indiana site and the 14-inch California site. The lowest average levels were measured on the 18- and 24-inch sites, as well as the 14-inch site in Washington identified as EB7. The average band-passed levels are shown in Figure D-94. The average on/off increments are shown in Figure D-95. The highest and lowest average on/off increments coincide with the same sites as the highest and lowest on-strips levels.

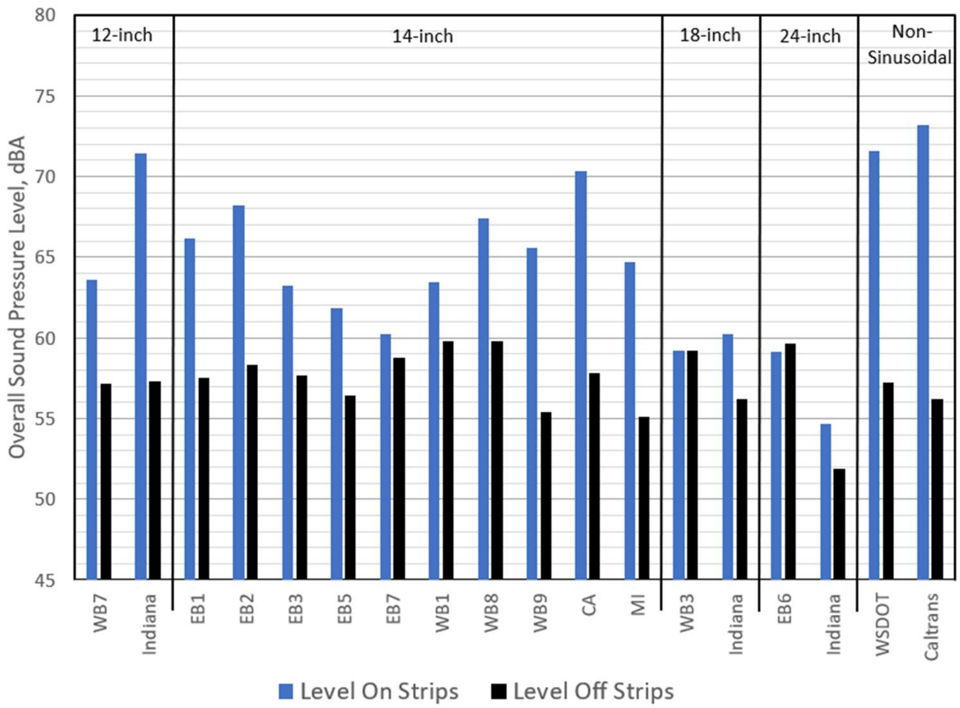



*Figure D-94: Vehicle average band-passed A-weighted pass-by sound pressure levels at Washington test sites compared to measurements made in California and the Midwest – 60 mph*

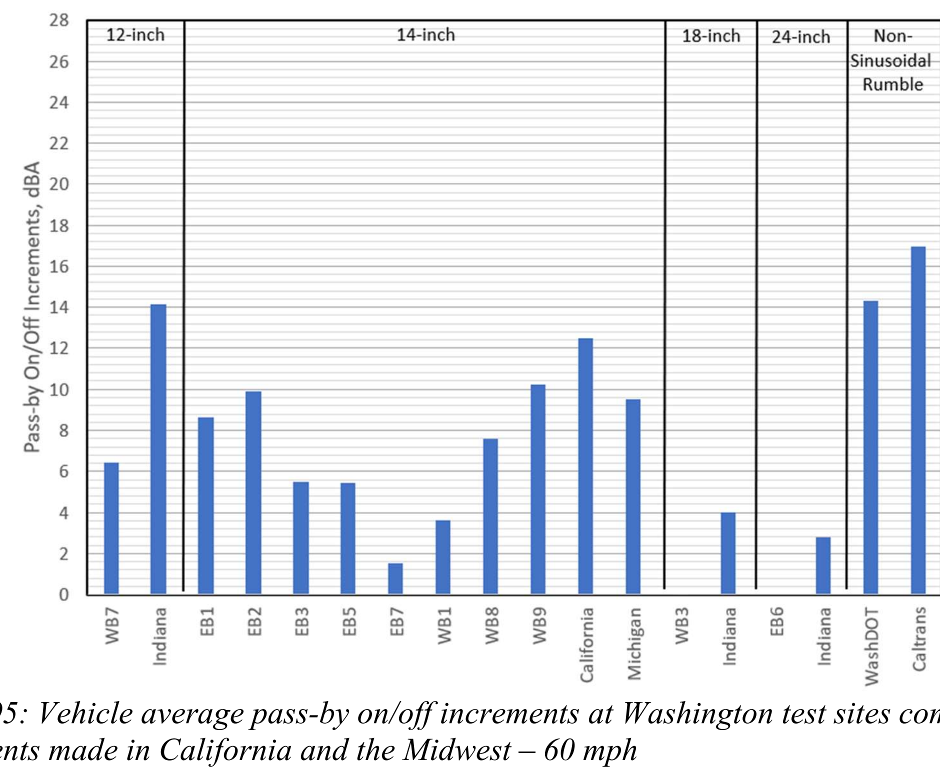



*Figure D-95: Vehicle average pass-by on/off increments at Washington test sites compared to measurements made in California and the Midwest – 60 mph*

The band-passed pass-by levels at 45 mph are compared to the data from previous tasks in Figures D-96 through D-99 for vehicles in the large SUV, mid-size SUV, mid-size sedan, and compact car categories, respectively. The band-passed pass-by levels at the 12-inch site in Indiana was higher than the Washington site by 3 to 5 dB at each vehicle category, and the 24-inch site in Indiana was lower than the Washington site by 2 to 7 dB. However, results varied at the 14- and 18-inch sites. The band-passed levels at the 14-inch site in California was 3 to 9 dB lower than the Washington sites in the large SUV category, was 2 to 6 dB lower than the Washington sites in the mid-size SUV category and was up to 6 dB lower in the sedan category; however, in the compact cars, band-passed levels in California were 5 to 9 dB higher than the Washington sites. Only two vehicle types were tested in Michigan, and both were 4 to 9 dB higher than the 14-inch Washington sites. Both large and mid-size SUVs were 2 to 3 dB lower at the 18-inch site in Indiana than in Washington, and both the sedan and compact cars were 1 to 2 dB higher in Indiana than in Washington.

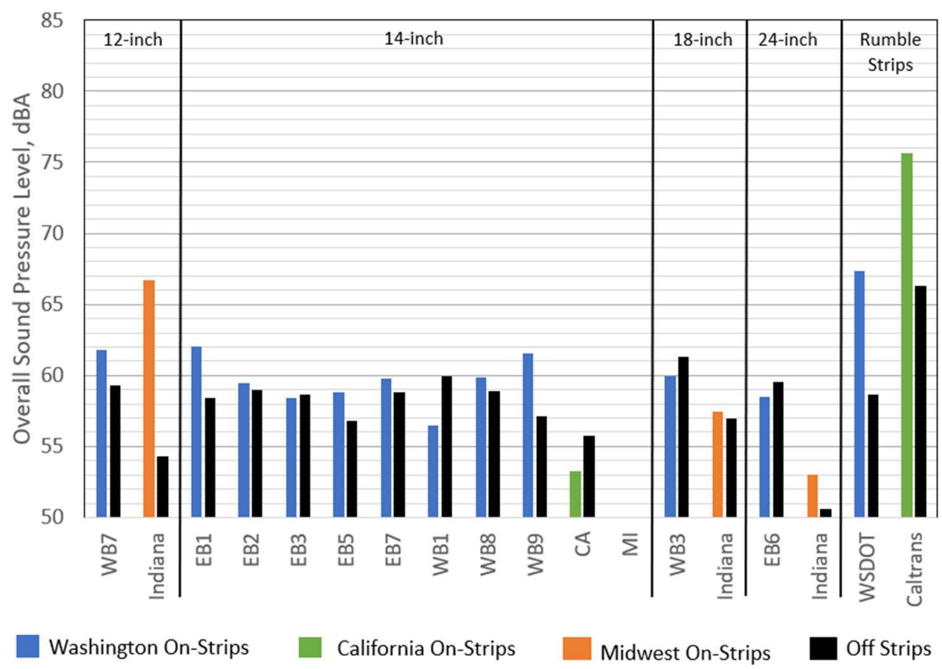



*Figure D-96: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the large SUV category at 45 mph*

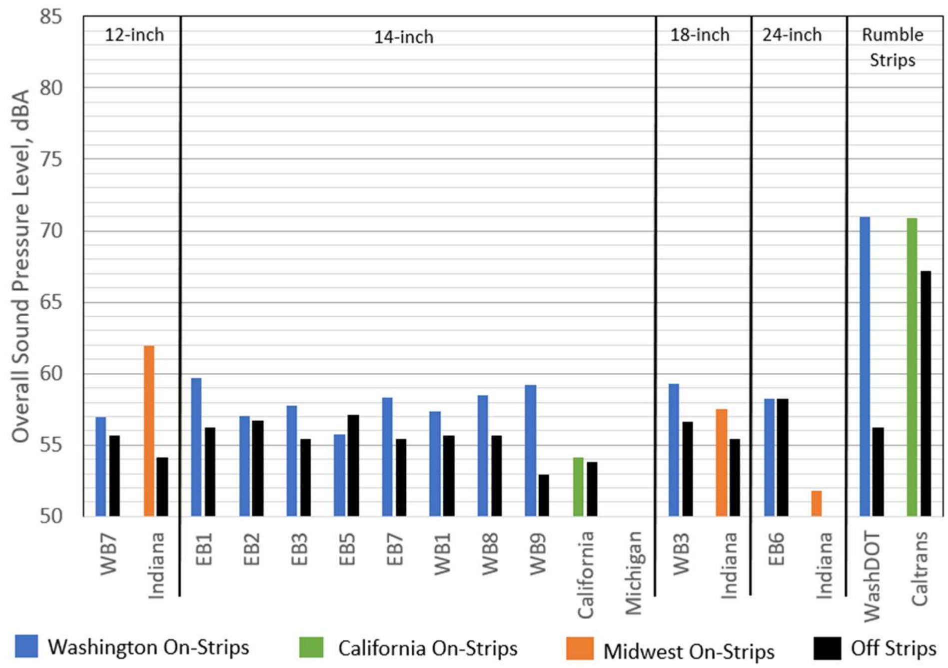



*Figure D-97: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the mid-size SUV category at 45 mph*

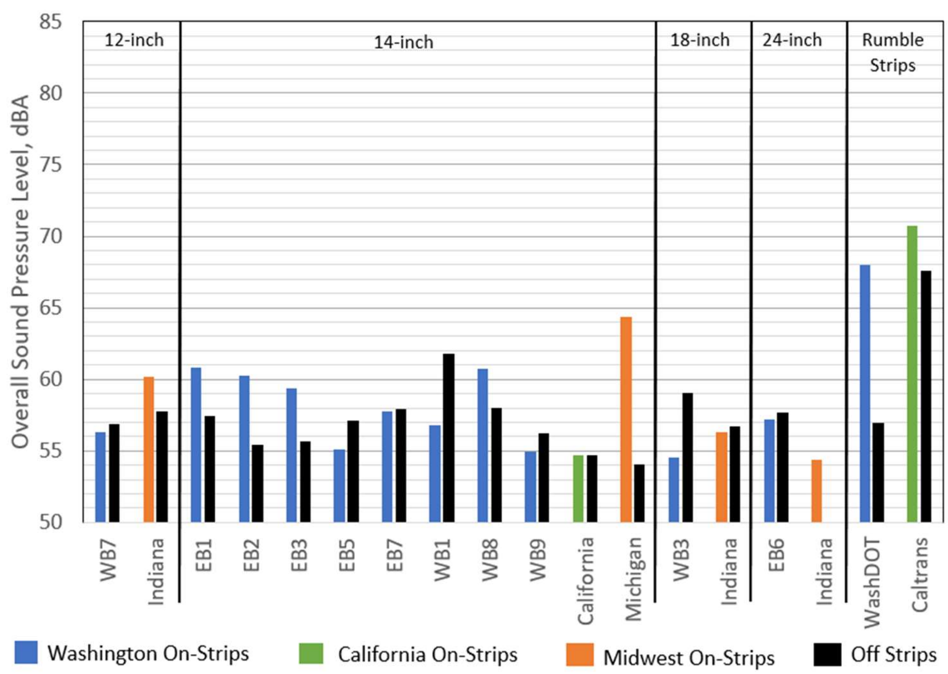



*Figure D-98: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the full/mid-size sedan category at 45 mph*

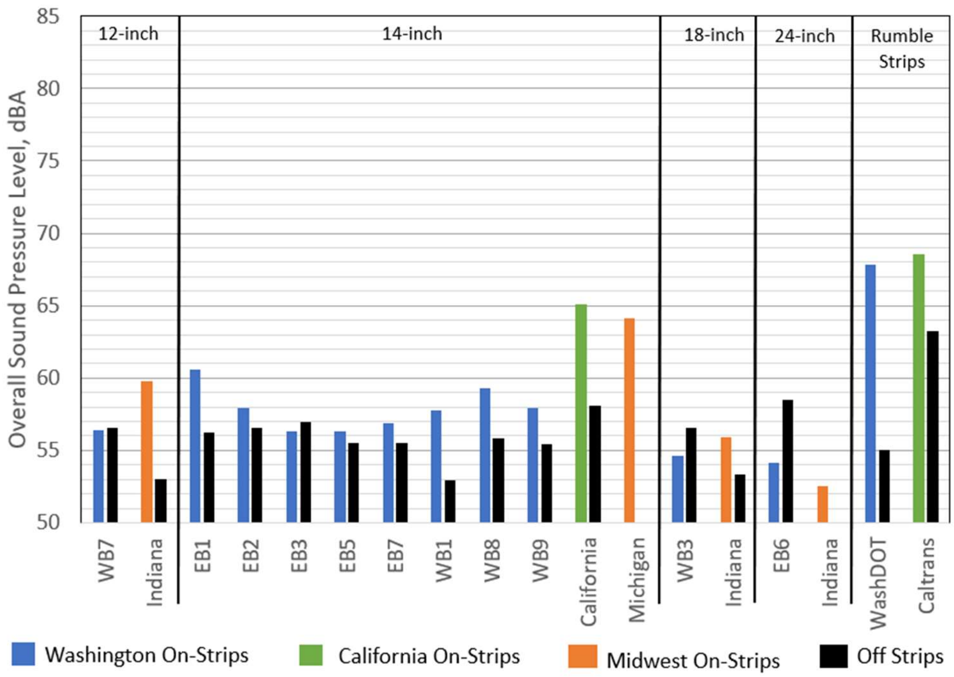



*Figure D-99: Band-passed A-weighted pass-by levels on and off rumble strips in Washington, California, Indiana, and Michigan for the compact car category at 45 mph*

The on/off increments measured at 45 mph are shown for all vehicles in Figure D-100. Each of the sinusoidal sites in Washington resulted in increments of 6 dB or less across all vehicles; however, the Midwest sites with 12- and 14-inch sites reached increments up to 12 dB and up to 16 dB, respectively. The 14-inch site in California had increments up to 7 dB. The 18- and 24-inch sites in Indiana had increments below 6 dB. The pass-by increments at the conventional Washington site ranged from 8 to 14 dB, while the conventional California site had increments of 3 to 9 dB.

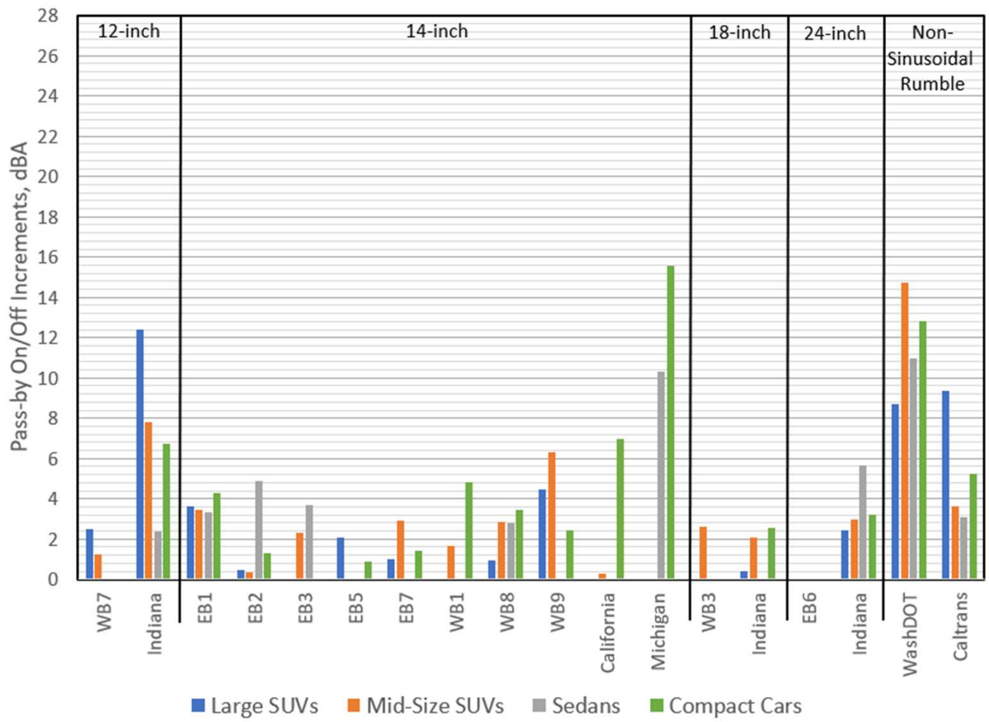



*Figure D-100: Band-passed pass-by noise level differences between on and off strips in Washington, California, Indiana, and Michigan for all vehicle categories at 45 mph*

The average band-passed levels across all vehicles at 45 mph are shown in Figure D-101. The highest average band-passed levels on the sinusoidal sites were measured at the 12-inch Indiana site and the 14-inch California site, just like at 60 mph. The lowest average levels were measured on the 24-inch site in Indiana. The average on/off increments at 45 mph are shown in Figure D-102. The highest increments at sinusoidal strips were measured at the 12- and 14-inch sites in Indiana and Michigan. The lowest average on/off increments of 2 dB or less were measured on the 12-inch strips at WB3, on the 14-inch strips at EB2, EB3, EB5, EB7, WB1, and WB8, on the 18-inch strips in Indiana and Washington, and on the 24-inch strips at EB6.

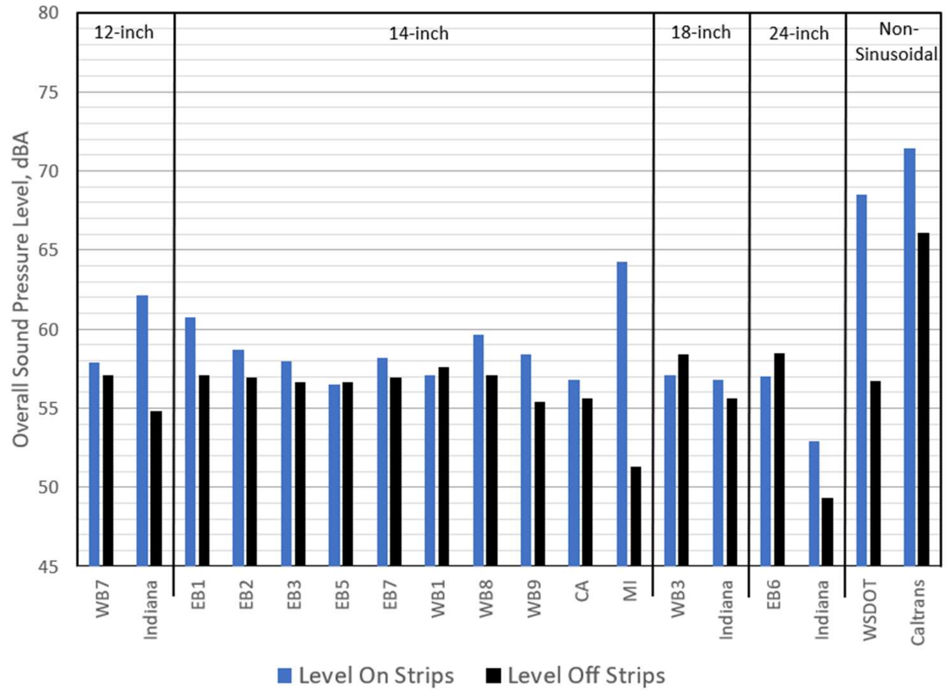



*Figure D-101: Vehicle average band-passed A-weighted pass-by sound pressure levels at Washington test sites compared to measurements made in California and the Midwest – 45 mph*

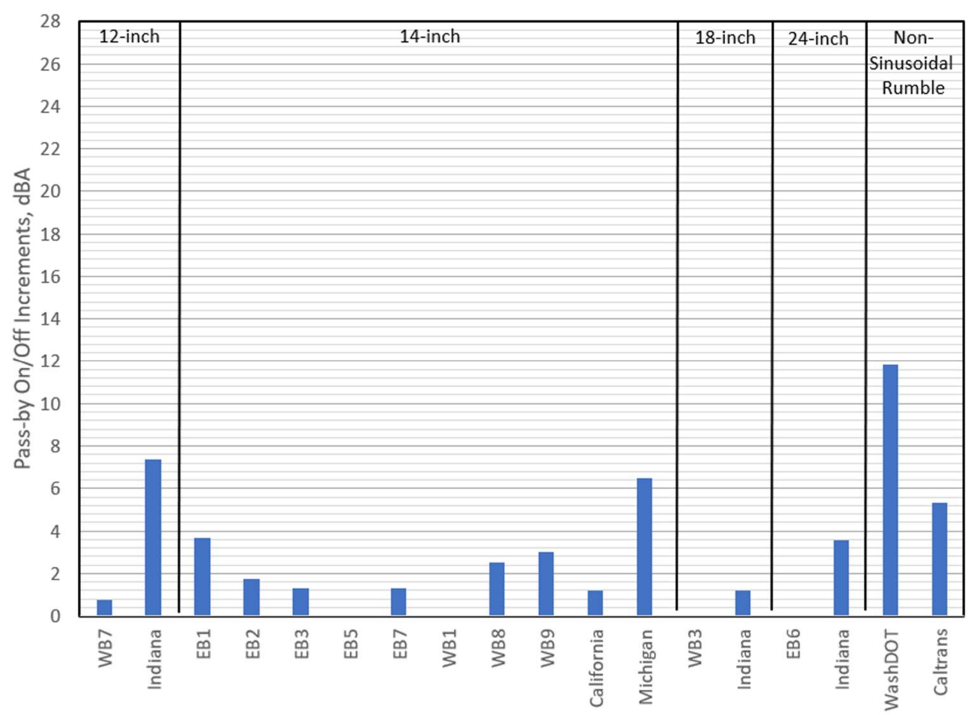



*Figure D-102: Vehicle average pass-by on/off increments at Washington test sites compared to measurements made in California and the Midwest – 45 mph*

**Comparison to Previous Interior Noise Results**

Figures D-103 through D-106 show the spectra comparisons in the mid-size sedans for the sites with 14-, 12-, 18-, and 24-inch wavelengths in Washington, the Midwest, and California when traveling at 60 mph for the CC microphone.

The 80 Hz peak at the 14-inch site in California falls within the range of 80 Hz peak levels at the Washington sites, but the 80 Hz peak at the Michigan site shows energy split with energy at 63 Hz, which is due to the as installed actual wavelength being about 15 inches (see Project 15-68 Task I Report). The repetition rate at the 12-inch Indiana site is higher than the 12-inch Washington site, while the repetition rate at the 18-inch Indiana site was barely perceptible compared to the Washington site. The repetition rate at the 24-inch sites in Indiana and Washington are very similar. The spectra for the other vehicles and all results with the FC microphone are provided at the end of this appendix.

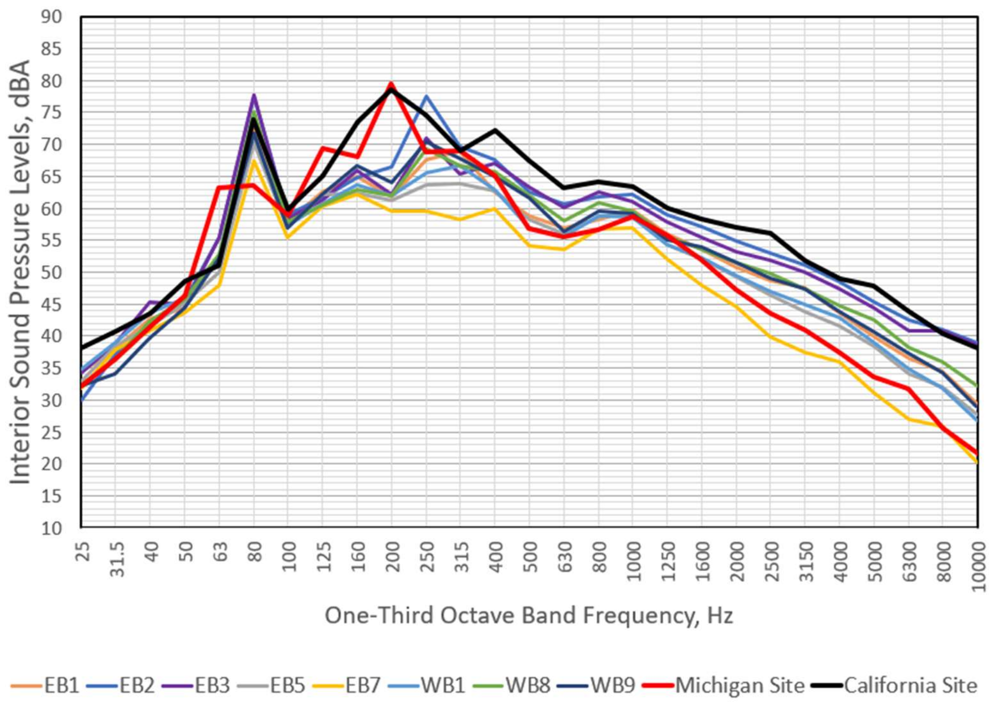



*Figure D-103: Interior noise spectra for 14-inch Washington Sites vs. 14-inch California and Michigan Sites measured with the CC microphone at 60 mph*

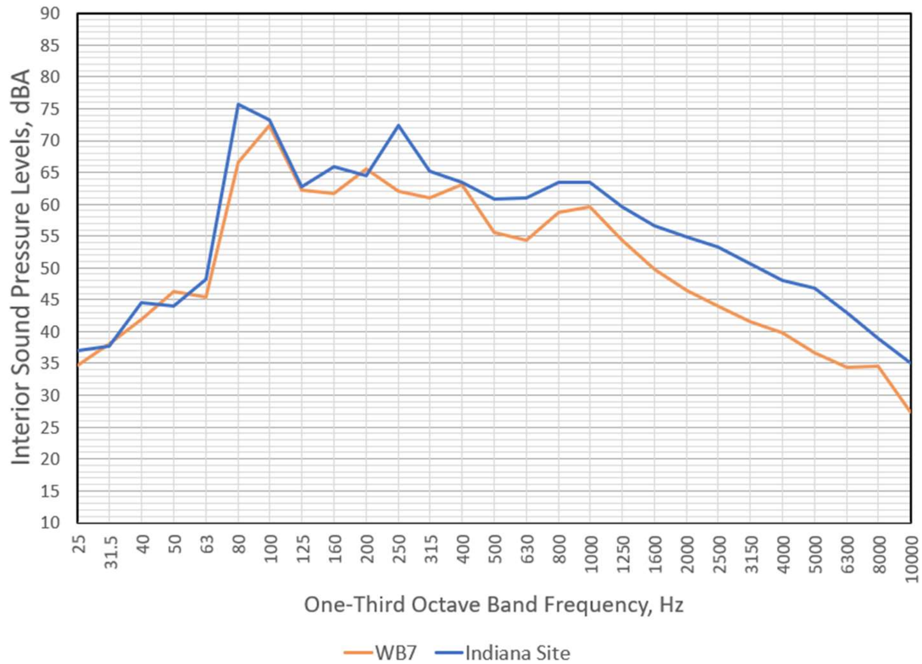



*Figure D-104: Interior noise spectra for 12-inch Washington Sites vs. 12-inch Indiana Site measured with the CC microphone at 60 mph*

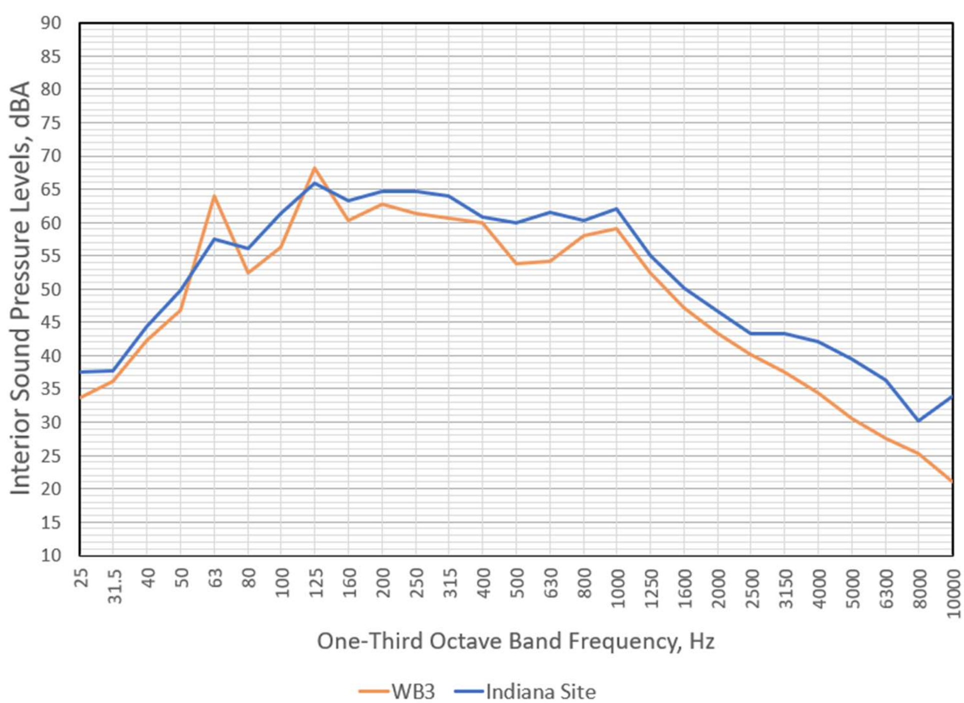



*Figure D-105: Interior noise spectra for 18-inch Washington Sites vs. 18-inch Indiana Site measured with the CC microphone at 60 mph*

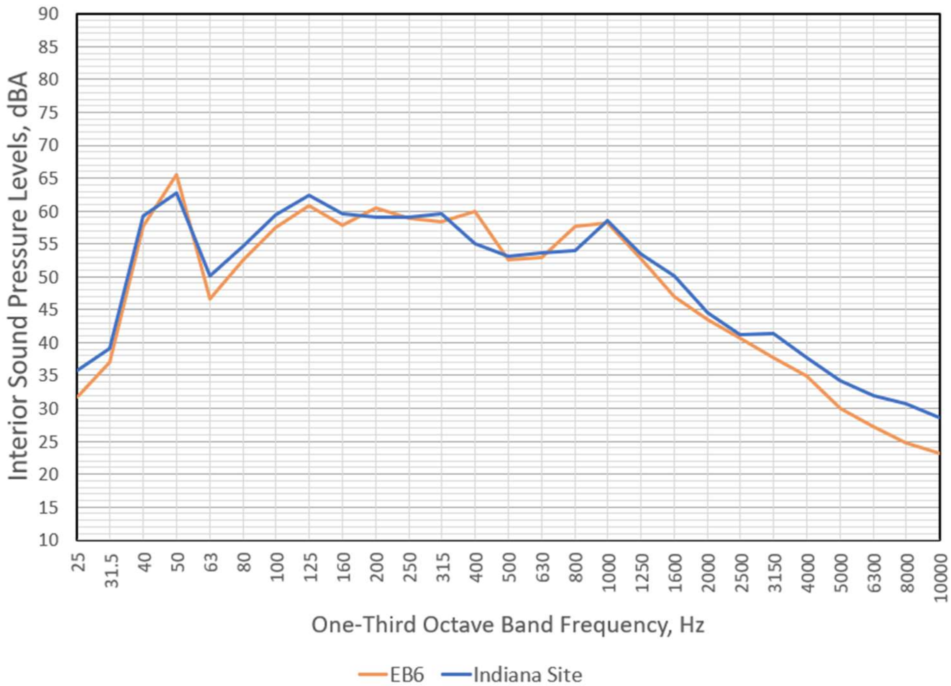


*Figure D-106: Interior noise spectra for 24-inch Washington Sites vs. 24-inch Indiana Site measured with the CC microphone at 60 mph*

The band-passed interior noise levels summed from 31.5 to 315 Hz at the Washington test sites are compared to the Midwest and California sites in Figures D-107, D-108, D-109, and D-110 for the large SUVs, mid-size SUVs, sedans, and compact cars, respectively, measured at the CC microphone. WB3 (18-inch wavelength) consistently resulted in the highest levels across all vehicle categories. High on-strips levels were also measured at the 14-inch California site in the large SUV and sedan categories; at EB1 (14-inch wavelength) site in the mid-size SUV and compact car categories; at EB3 (14-inch wavelength) in the sedan category; and at EB5 (14-inch wavelength) in the compact car category.

The 24-inch Indiana site consistently resulted in the lowest levels across all vehicle categories. Low on-strips levels were also measured at EB6 (24-inch wavelength) in the large SUV and compact car categories; at the 18-inch Indiana site in the mid-size SUV category; and at WB1 (14-inch wavelength) in the sedan category.

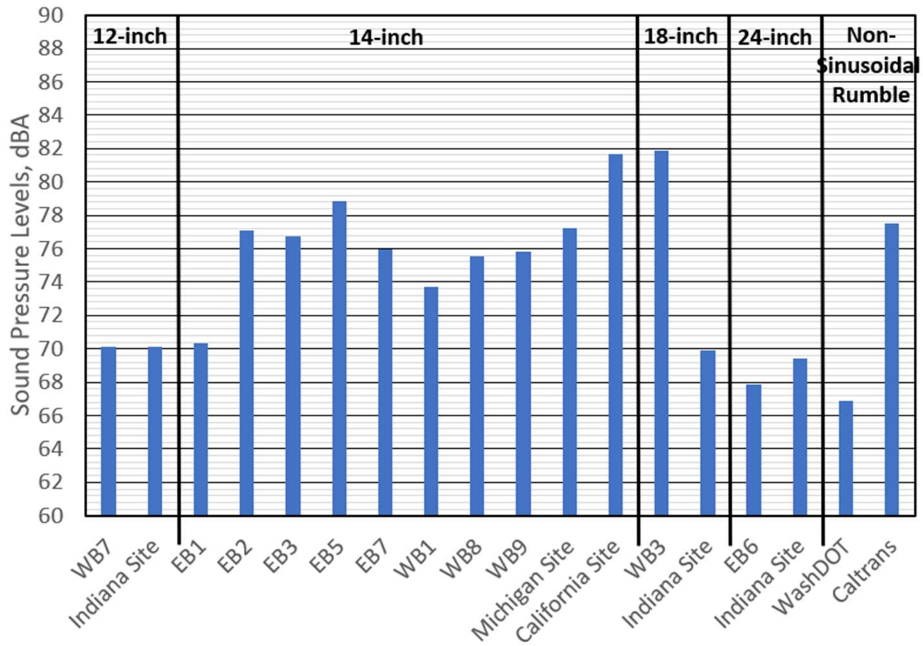



*Figure D-107: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the large SUV category measured with the CC microphone at 60 mph*

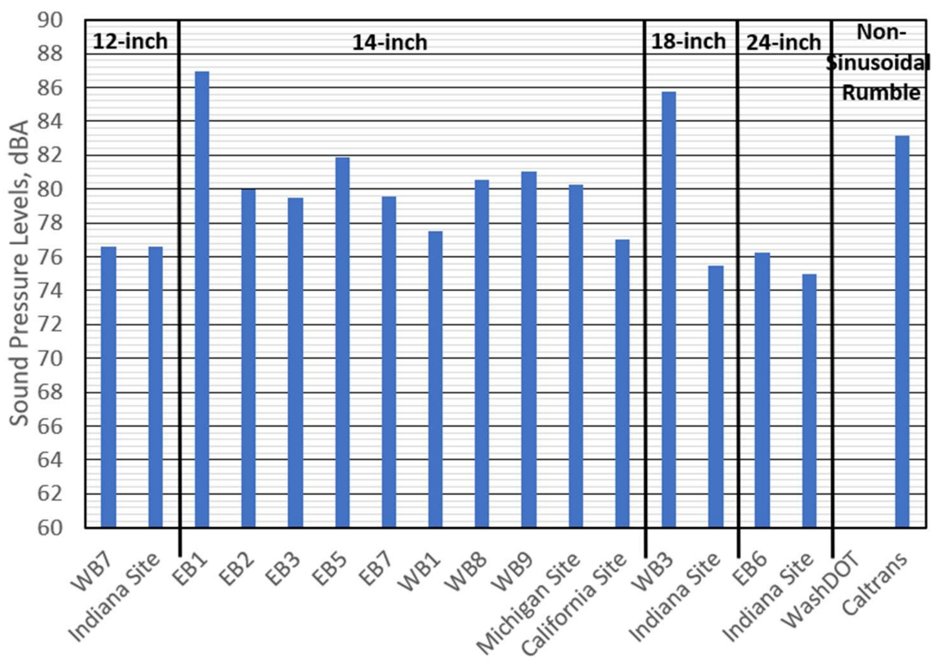



*Figure D-108: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the mid-size SUV category measured with the CC microphone at 60 mph*

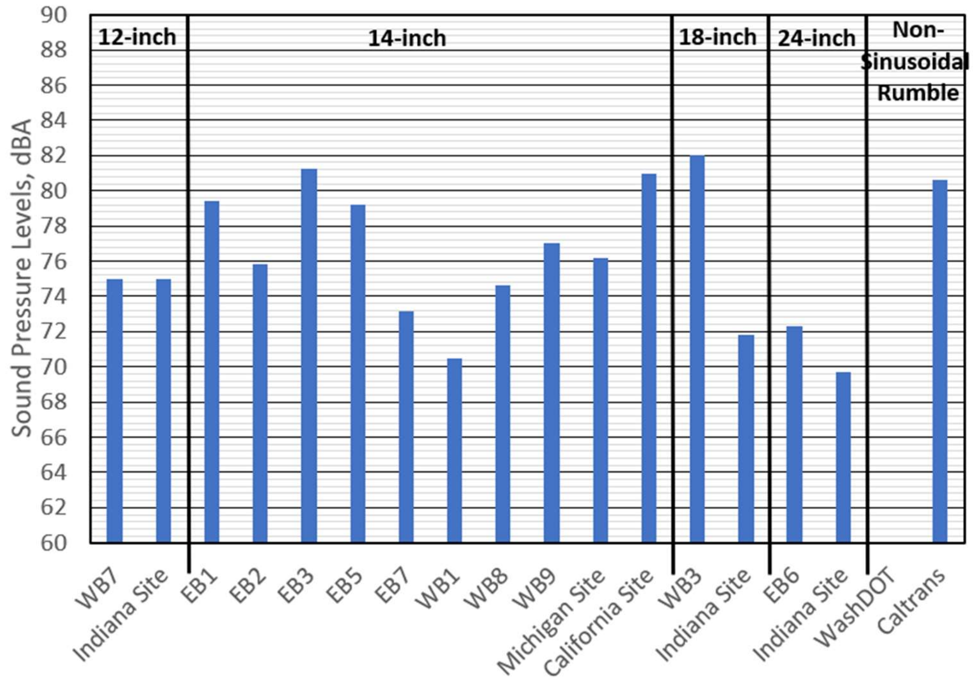



*Figure D-109: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the sedan category measured with the CC microphone at 60 mph*

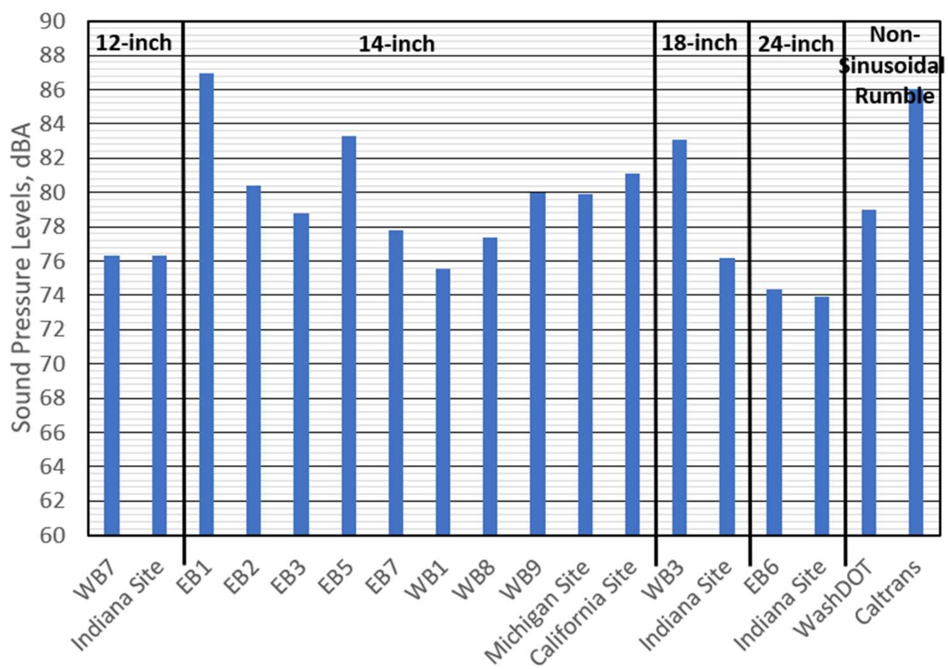



*Figure D-110: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the compact car category measured with the CC microphone at 60 mph*

The on/off increment comparisons measured at 60 mph with the CC microphone are shown for all vehicles in Figure D-111. On/off increments of 10 dBA or more were measured across all vehicles at the 14-inch Michigan site and at WB3 (18-inch wavelength). Additionally, 10 dB or more increments were measured at three vehicle categories at EB1, EB3, and EB5 (14-inch wavelengths), and at the 14-inch California site.

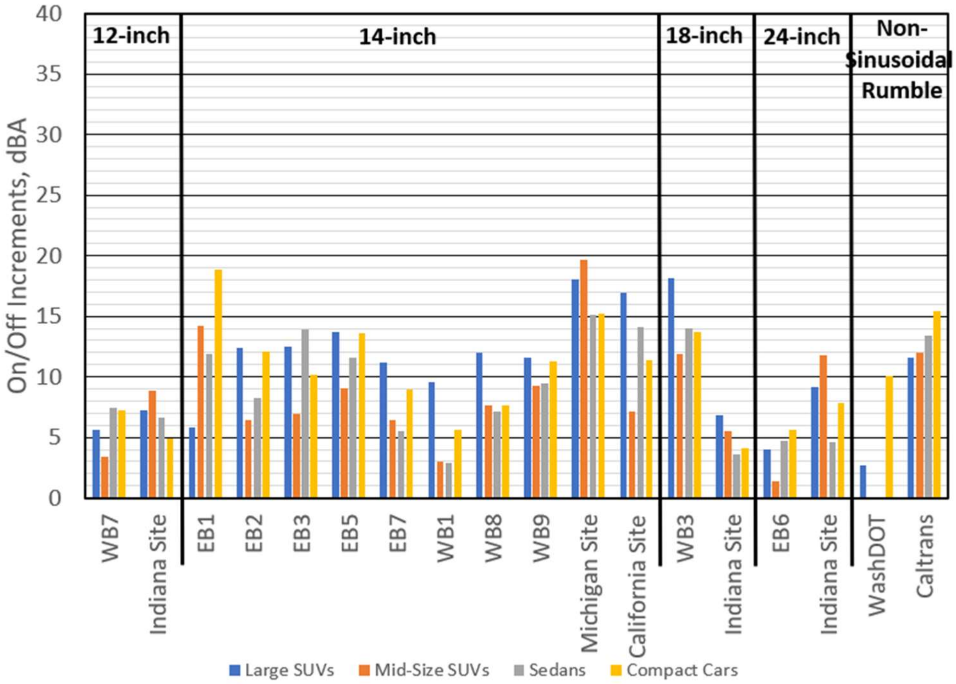



*Figure D-111: Band-passed interior noise level differences between on and off strips in Washington, California, Indiana, and Michigan for all vehicle categories measured with the CC microphone at 60 mph*

Figure D-112 shows the band-passed on-strips levels averaged across all vehicles at 60 mph. The highest average band-passed level on the sinusoidal sites was 83 dB and measured at WB3 (18-inch wavelength). Additionally, on-strips levels of 80 to 81 dB were measured at EB1 and EB5 (14-inch wavelengths) and the 14-inch site in California. The lowest average levels were measured at EB6 (24-inch wavelength) and at the 18- and 24-inch sites in Indiana.

The average on/off increments at 60 mph are shown in Figure D-113. Increments of 10 dB or more were measured at EB1, EB2, EB3, EB5, and WB9 (14-inch wavelengths), the 14-inch sites in Michigan and California, and WB3 (18-inch wavelength).

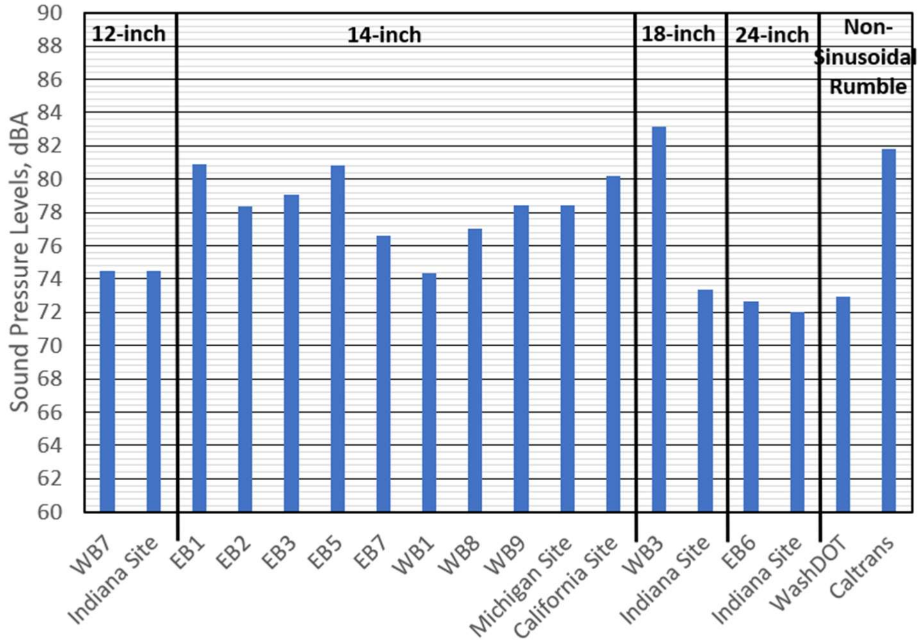



*Figure D-112: Average band-passed A-weighted interior sound pressure levels at Washington test sites compared to measurements made in California and the Midwest measured with the CC microphone – 60 mph*

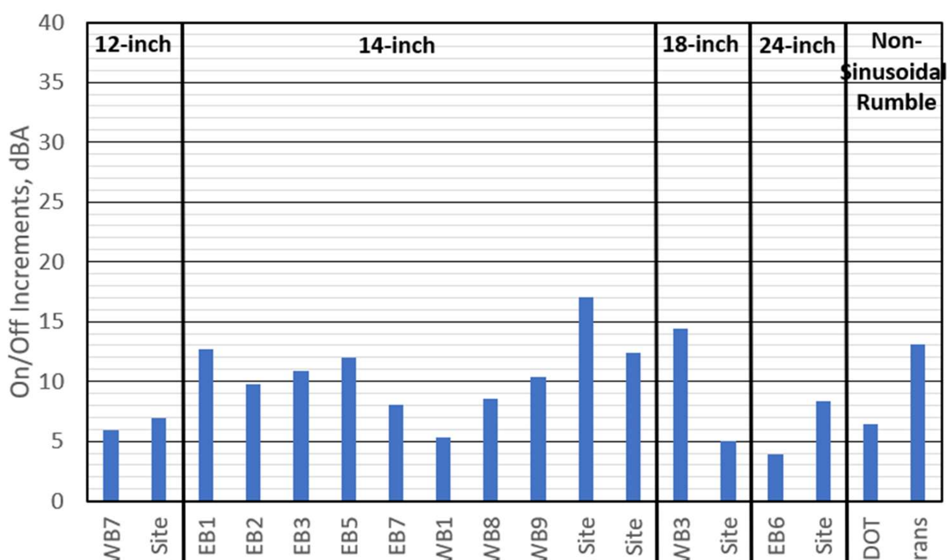



*Figure D-113: Vehicle average interior on/off increments at Washington test sites compared to measurements made in California and the Midwest measured with the CC microphone – 60 mph*

The band-passed interior noise levels summed from 31.5 to 315 Hz at the Washington test sites are compared to the Midwest and California sites at 45 mph in Figures D-114, D-115, D-116, and D-117 for the large SUVs, mid-size SUVs, sedans, and compact cars measured at the CC microphone. The 14-inch California site consistently resulted in the highest levels across all vehicle categories. High on-strips levels were also measured at EB3 (14-inch wavelength) site in the large SUV and mid-size SUV categories; and at the 14-inch Indiana site in the mid-size SUV, sedan, and compact car categories.

EB7 (14-inch wavelength) site consistently resulted in the lowest levels across all vehicle categories. Low on-strips levels were also measured at EB6 (24-inch wavelength) in the large SUV, sedan, and compact car categories; WB7 (12-inch wavelength) and WB3 (18-inch wavelength) sites in the mid-size SUV category; and at the 24-inch site in Indiana in the compact car category.

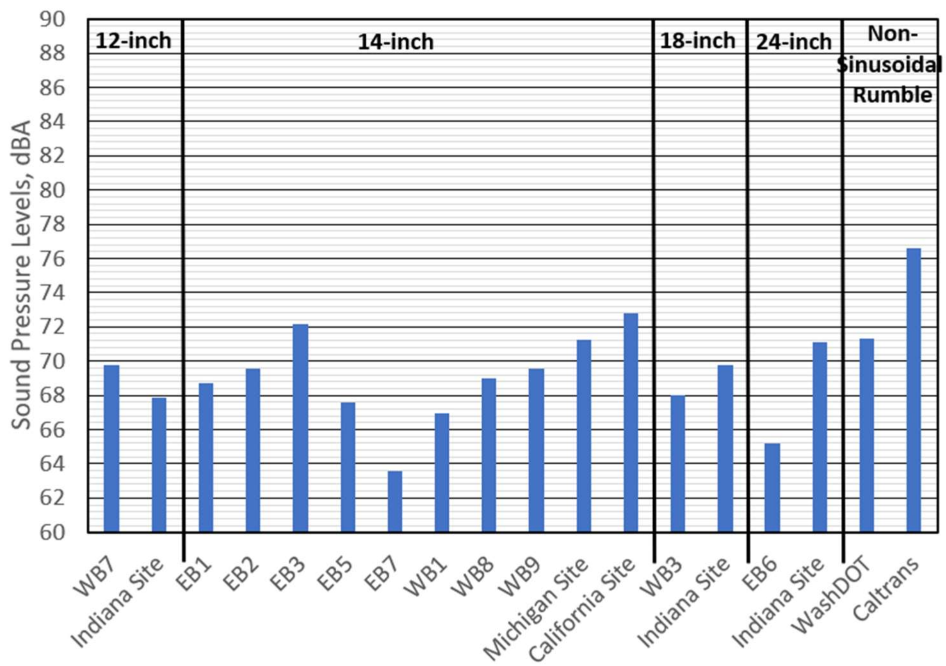



*Figure D-114: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the large SUV category measured with the CC microphone at 45 mph*

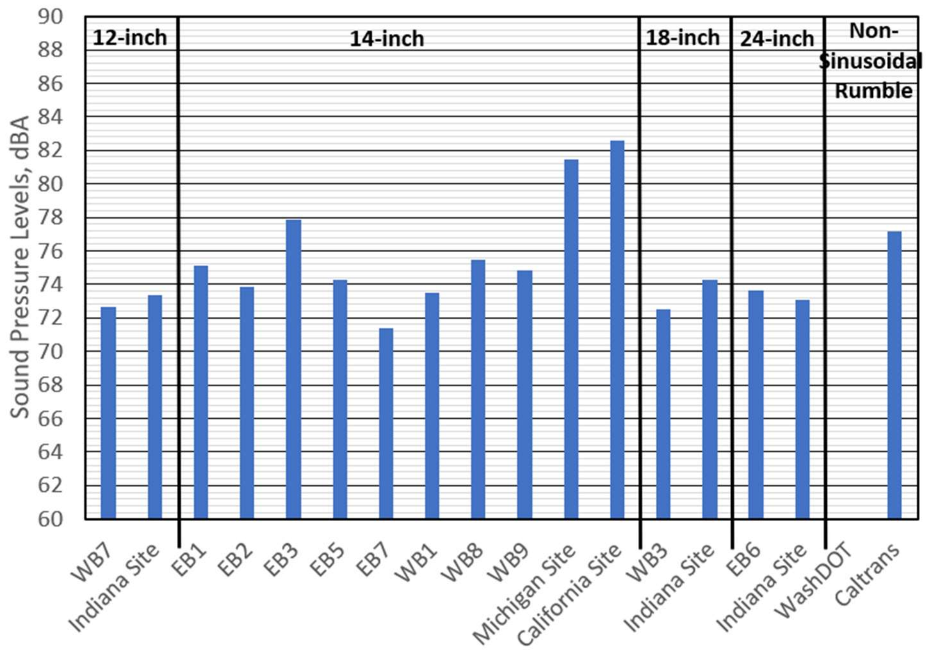



*Figure D-115: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the mid-size SUV category measured with the CC microphone at 45 mph*

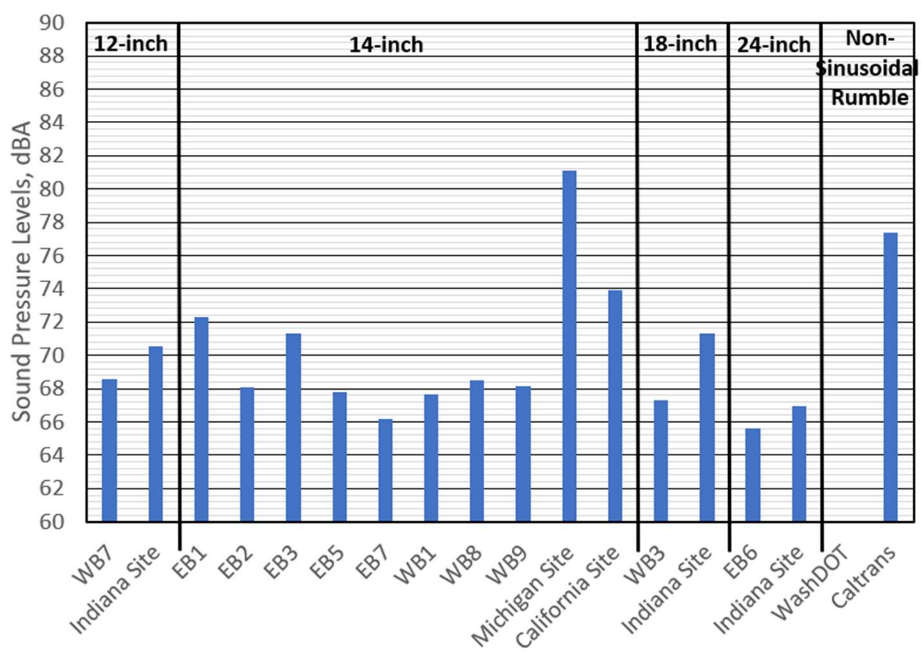



*Figure D-116: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the sedan category measured with the CC microphone at 45 mph*

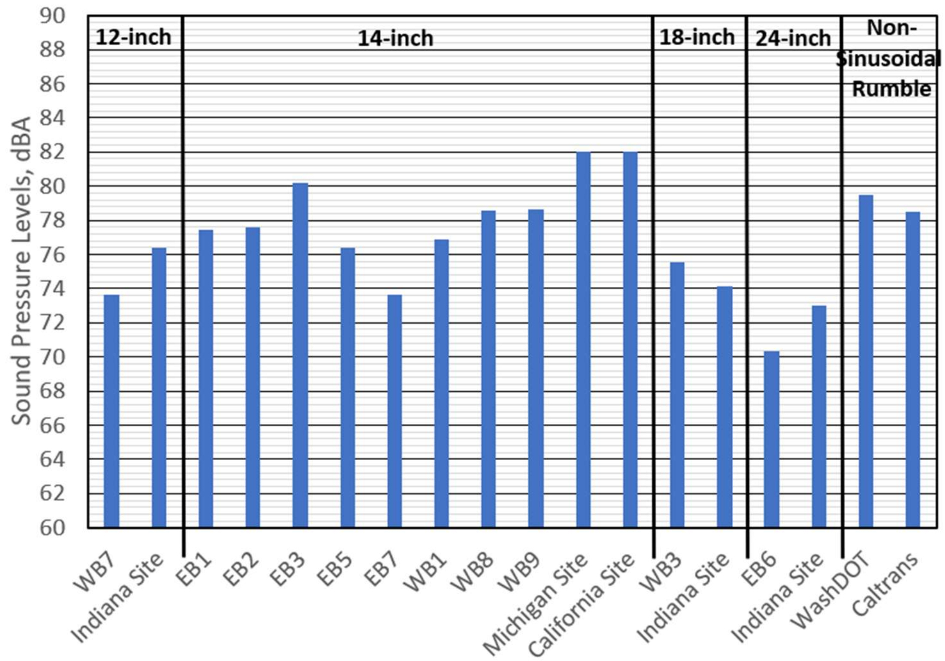



*Figure D-117: Band-passed A-weighted interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the compact car category measured with the CC microphone at 45 mph*

The on/off increment comparisons measured at 45 mph with the CC microphone are shown for all vehicles in Figure D-118. On/off increments of 10 dBA or more were measured across all vehicles at the 14-inch sites in California and Michigan. Additionally, 10 dB or more increments were measured at three vehicle categories at the 24-inch site in Indiana.

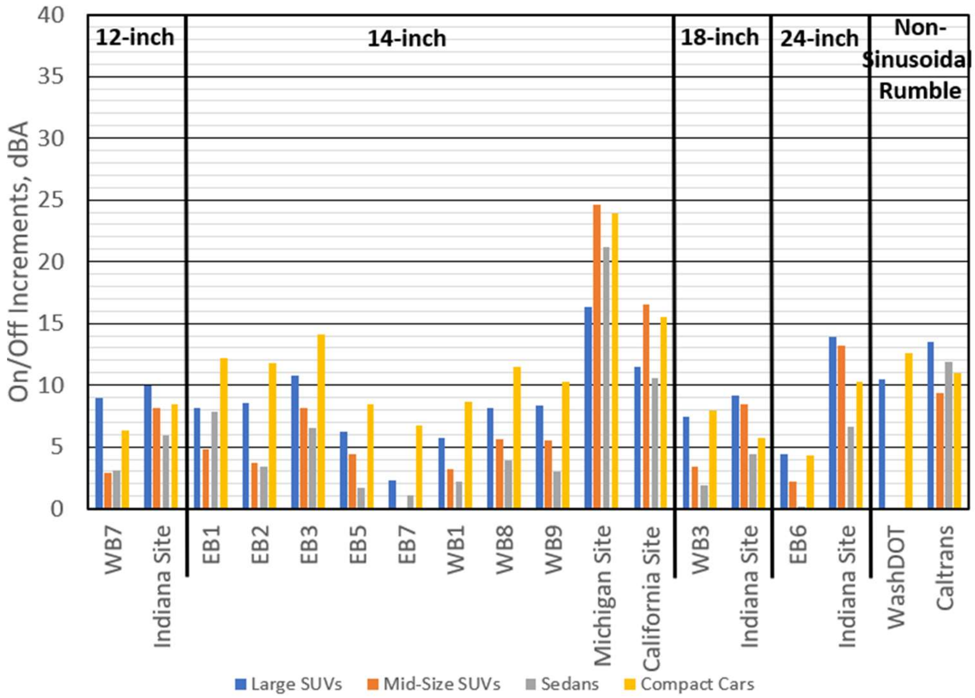



*Figure D-118: Band-passed interior noise level differences between on and off strips in Washington, California, Indiana, and Michigan for all vehicle categories measured with the CC microphone at 45 mph*

Figure D-119 shows the band-passed on-strips levels averaged across all vehicles at 45 mph. The highest average band-passed levels on the sinusoidal sites ranged from 78 to 79 dB on the 14-inch sites in California and Michigan. The lowest average levels were measured at EB6 (24-inch wavelength) and EB7 (14-inch wavelength).

The average on/off increments at 45 mph are shown in Figure D-120. Increments of 10 dB or more were measured at EB3 (14-inch wavelength), the 14-inch sites in Michigan and California, and the 24-inch site in Indiana.

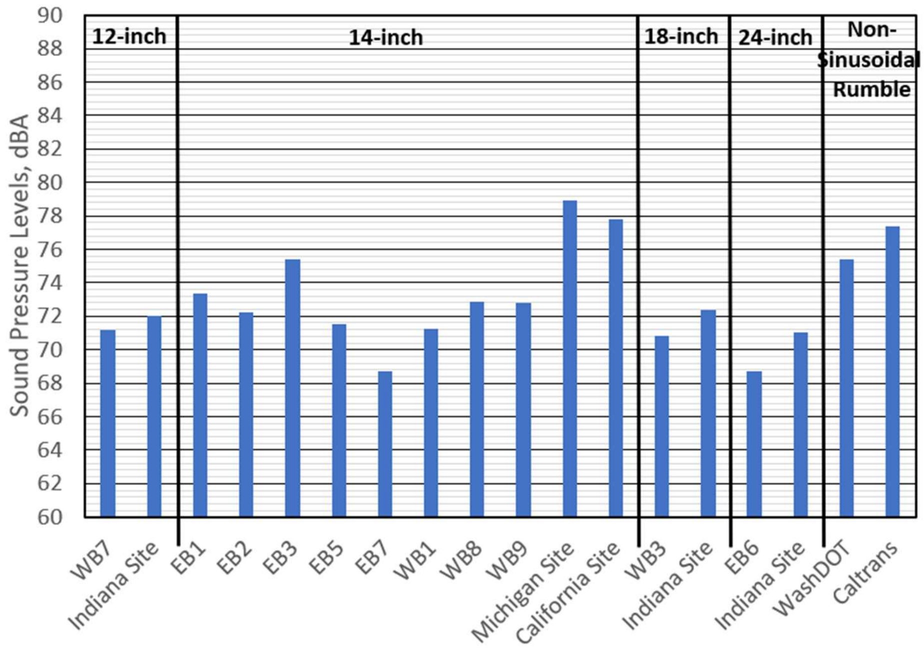



*Figure D-119: Average band-passed A-weighted interior sound pressure levels at Washington test sites compared to measurements made in California and the Midwest measured with the CC microphone – 45 mph*

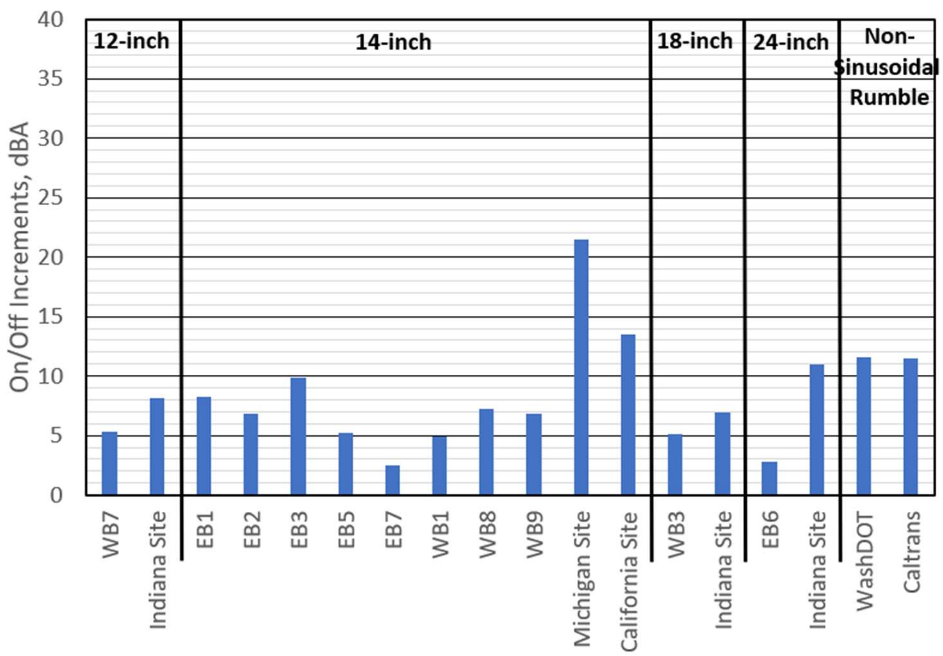



*Figure D-120: Vehicle average interior on/off increments at Washington test sites compared to measurements made in California and the Midwest measured with the CC microphone – 45 mph*

**Comparison to Previous Interior Vibration Results**

Figures D-121 through D-124 show the spectra comparisons in the mid-size sedans for the sites with 14-, 12-, 18-, and 24-inch wavelengths, respectively, in Washington, the Midwest, and California when traveling at 60 mph for the ST accelerometer.

The 80 Hz peak at the 14-inch site in California is 8 dB or higher than all other sites. Similar to the 80 Hz peak level measured at the Michigan site with the CC microphone, the 80 Hz peak with the ST sensor shows energy split with energy at 63 Hz. The split repetition rate at the 12-inch Indiana site is higher in the 80 Hz band, while in Washington, it was higher in the 100 Hz band. At the 18-inch sites, the peak at the repetition rate in Indiana was approximately 10 dB higher than in Washington. Similar to the CC microphone, the spectra at each of the Washington and Indiana 24-inch sites are similar. The spectra for the other vehicles and all results with the SC accelerometer are provided at the end of this appendix.

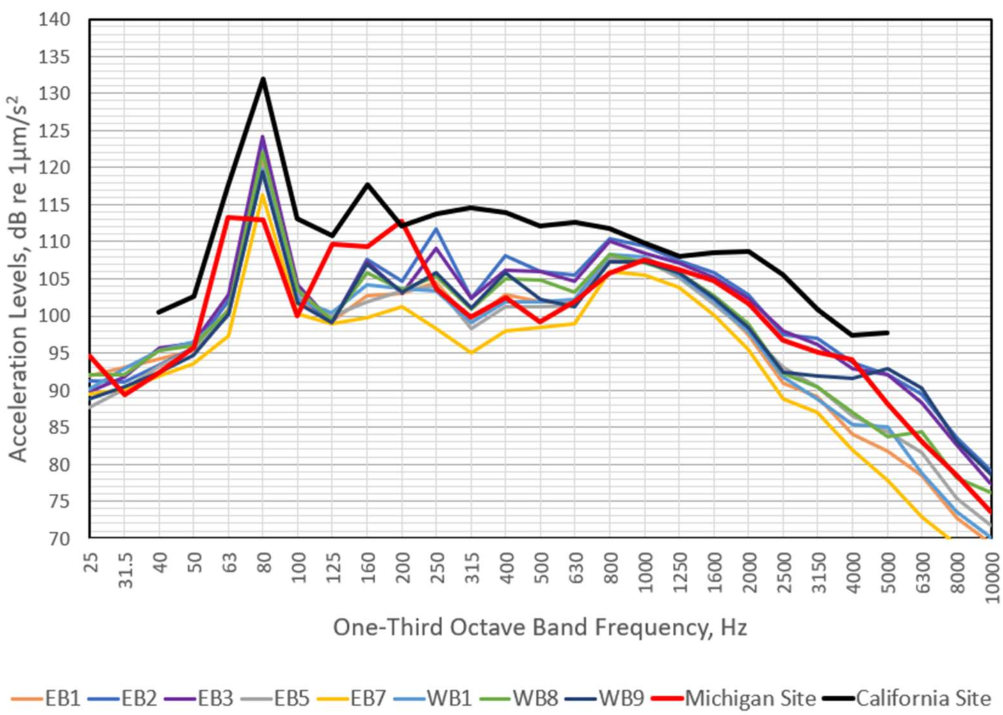



*Figure D-121: Interior vibration spectra for 14-inch Washington Sites vs. 14-inch California and Michigan Sites measured with the ST accelerometer at 60 mph*

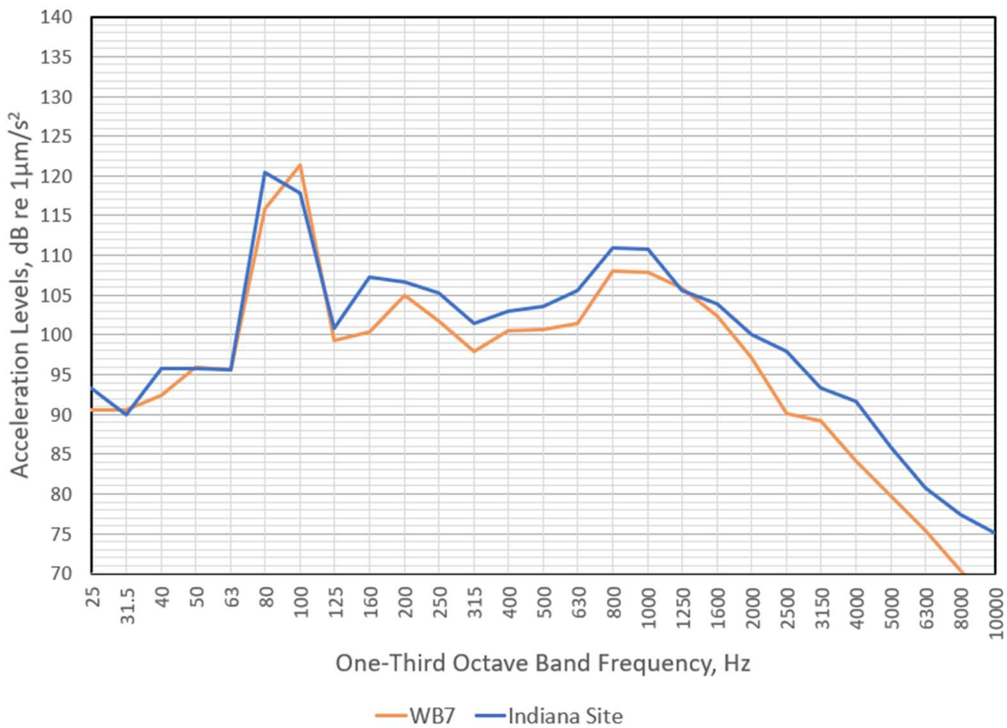



*Figure D-122: Interior vibration spectra for 12-inch Washington Sites vs. 12-inch Indiana Site measured with the ST accelerometer at 60 mph*

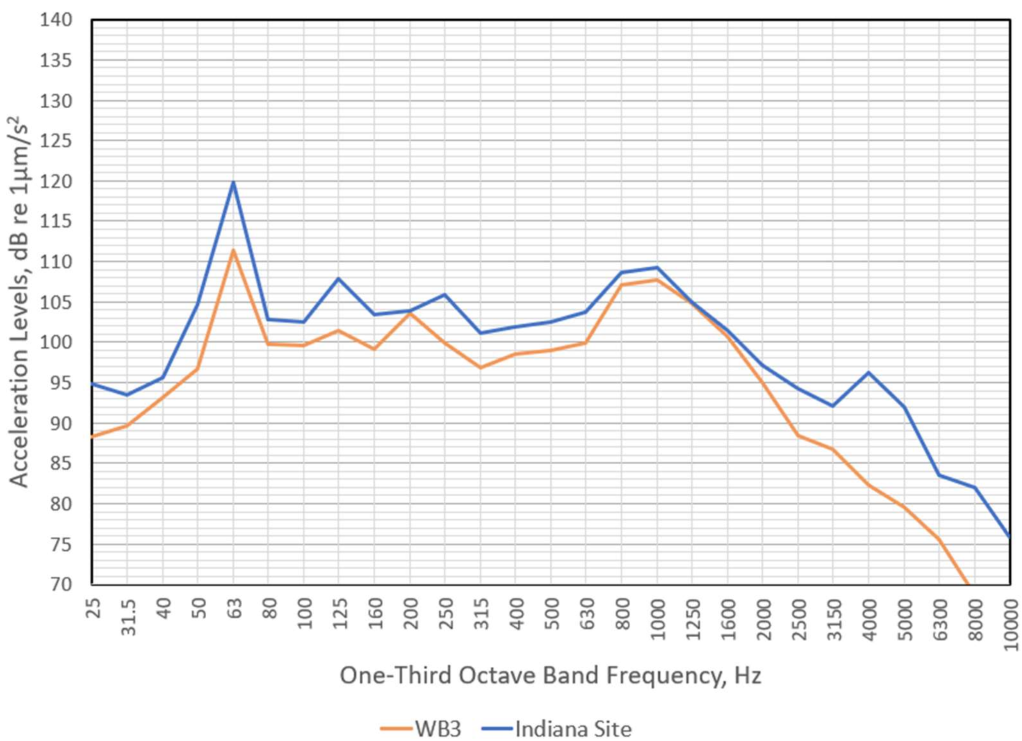



*Figure D-123: Interior vibration spectra for 18-inch Washington Sites vs. 18-inch Indiana Site measured with the ST accelerometer at 60 mph*

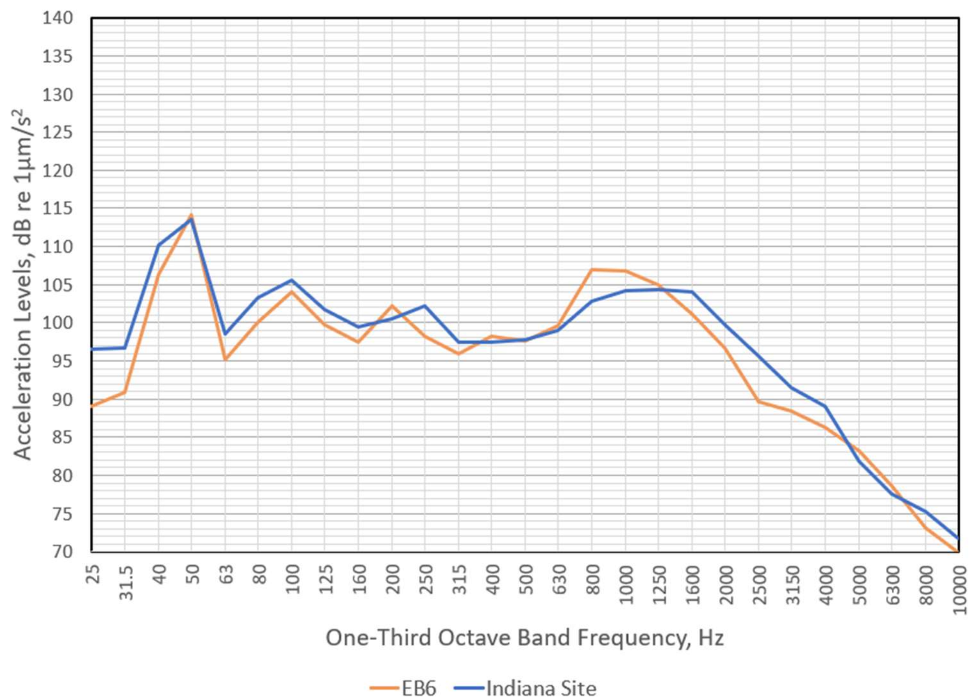



*Figure D-124: Interior vibration spectra for 24-inch Washington Sites vs. 24-inch Indiana Site measured with the ST accelerometer at 60 mph*

The band-passed interior noise levels summed from 31.5 to 315 Hz at the Washington test sites are compared to the Midwest and California sites in Figures D-125, D-126, D-127, and D-128 for the large SUVs, mid-size SUVs, sedans, and compact cars measured at the ST accelerometer, respectively. The 14-inch site in California consistently resulted in the highest levels across all vehicle categories. High on-strips levels were also measured at the 12-inch site in Indiana in the compact car category.

The lowest on-strips levels were measured at EB7 (14-inch wavelength) in the large SUV, mid-size SUV, and compact car categories; at the 24-inch Indiana site in the large SUV and mid-size SUV categories; at EB6 (24-inch wavelength) site in the mid-size SUV and compact car categories; at WB3 (18-inch wavelength) site in the sedan category; and at the 18-inch Indiana site in the compact car category.

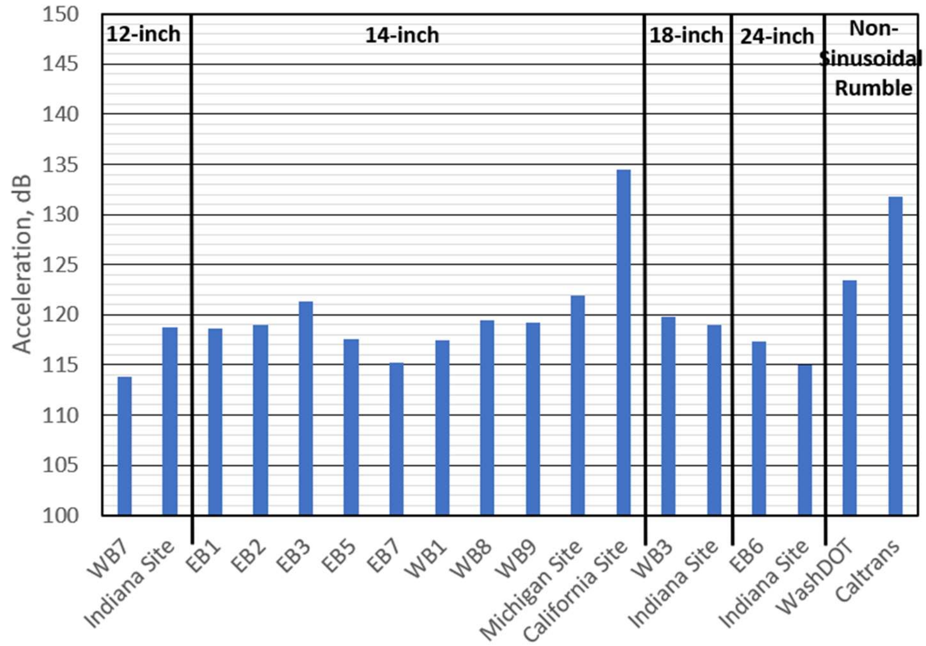



*Figure D-125: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the large SUV category measured with the ST accelerometer at 60 mph*

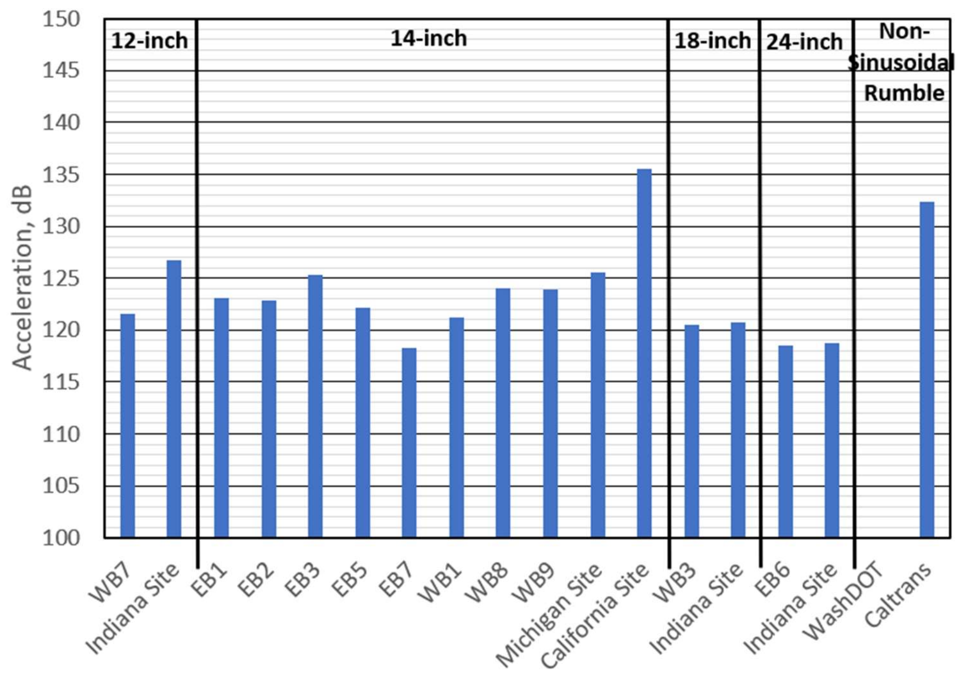



*Figure D-126: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the mid-size SUV category measured with the ST accelerometer at 60 mph*

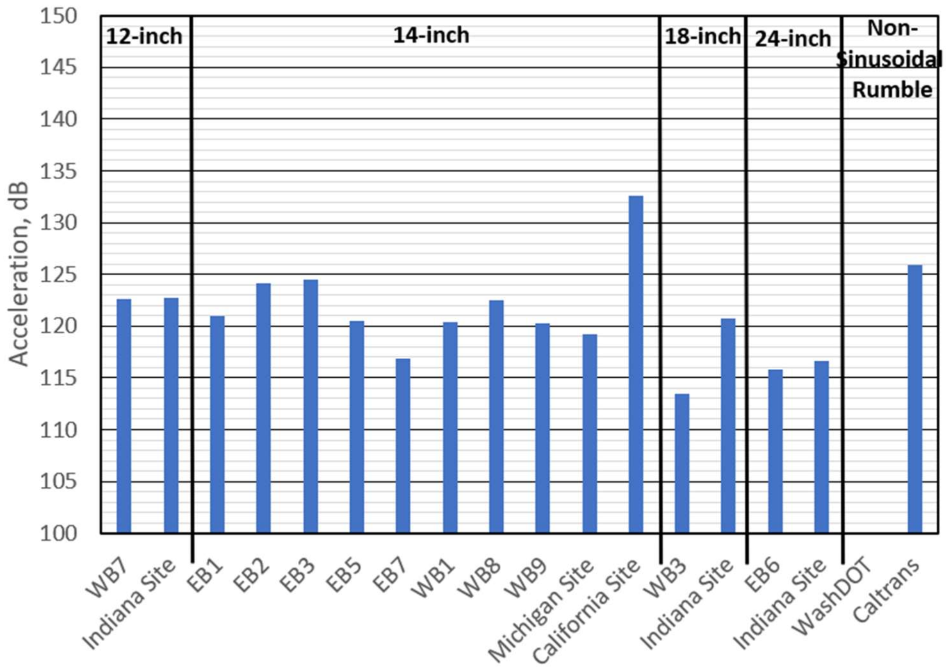



*Figure D-127: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the sedan category measured with the ST accelerometer at 60 mph*

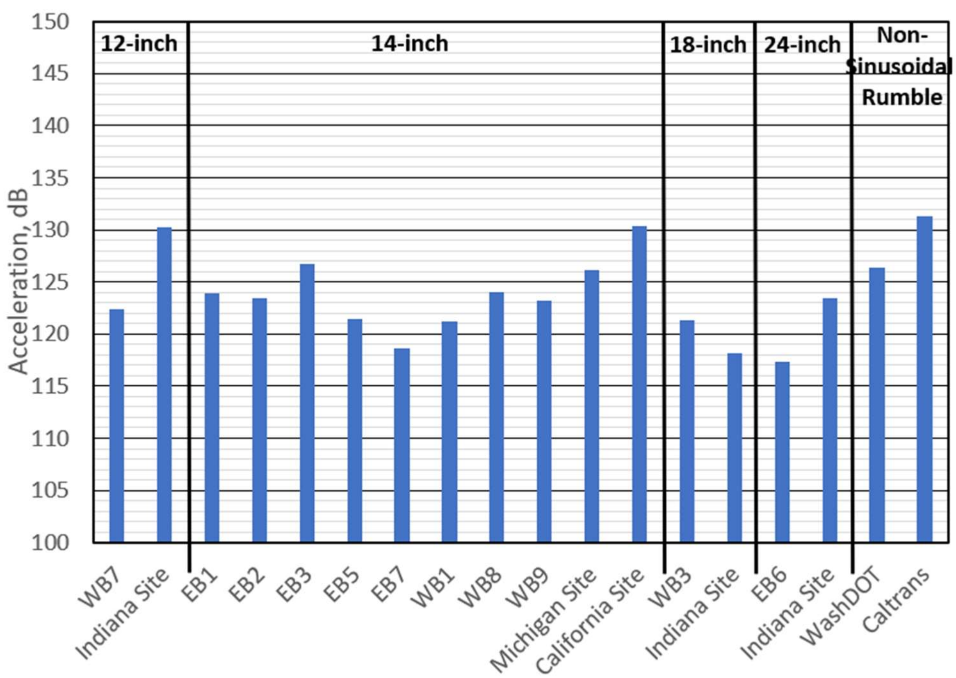



*Figure D-128: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the compact car category measured with the ST accelerometer at 60 mph*

The on/off increment comparisons measured at 60 mph with the ST sensor are shown for all vehicles in Figure D-129. On/off increments of 10 dBA or more were measured across all vehicles at the following sites: the 12-inch Indiana site; EB1, EB2, EB3, WB8, and WB9 (14-inch wavelength) sites and the 14-inch sites in California and Michigan; and the 24-inch site in Indiana.

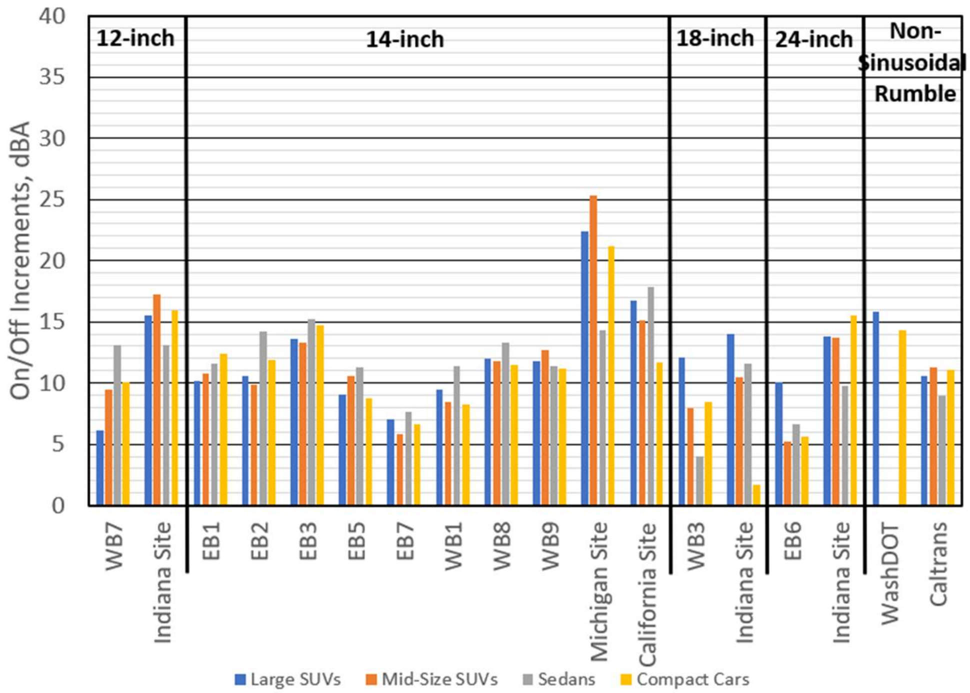



*Figure D-129: Band-passed interior vibration level differences between on and off strips in Washington, California, Indiana, and Michigan for all vehicle categories measured with the ST accelerometer at 60 mph*

Figure D-130 shows the band-passed on-strips levels averaged across all vehicles at 60 mph at the ST accelerometer. The highest average band-passed level on the sinusoidal sites was about 133 dB at the 14-inch California site. The lowest average levels were measured at EB6 (24-inch wavelength), EB7 (14-inch wavelength), and at the 24-inch site in Indiana.

The average on/off increments at 60 mph are shown in Figure D-131. Increments of 10 dB or more were measured at the following sites: WB7 (12-inch wavelength) and the 12-inch Indiana site; EB1, EB2, EB3, EB5, WB8, and WB9 (14-inch wavelengths) and the 14-inch sites in Michigan and California; and the 24-inch site in Indiana.

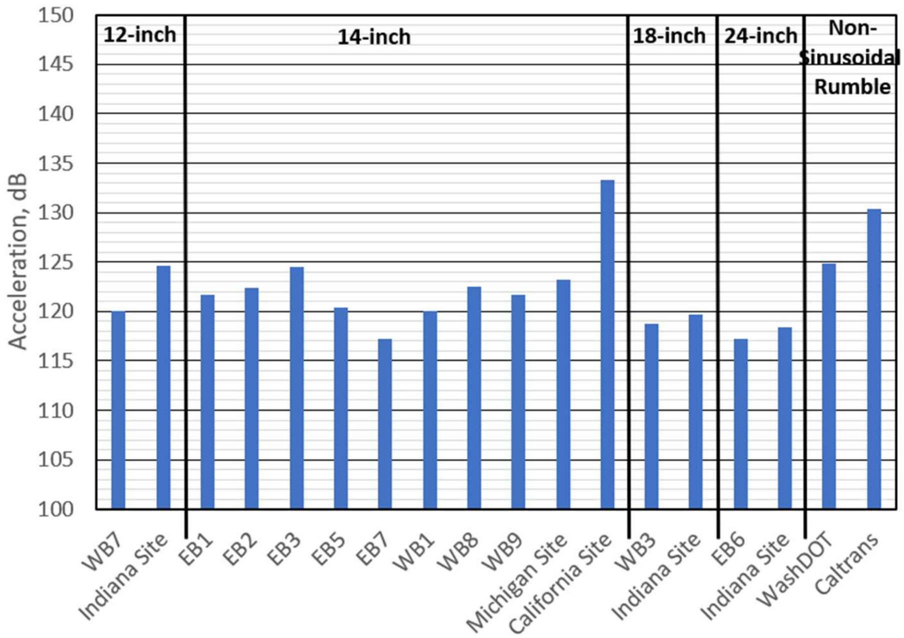



*Figure D-130: Vehicle average band-passed A-weighted interior vibration levels at Washington test sites compared to measurements made in California and the Midwest measured with the ST accelerometer – 60 mph*

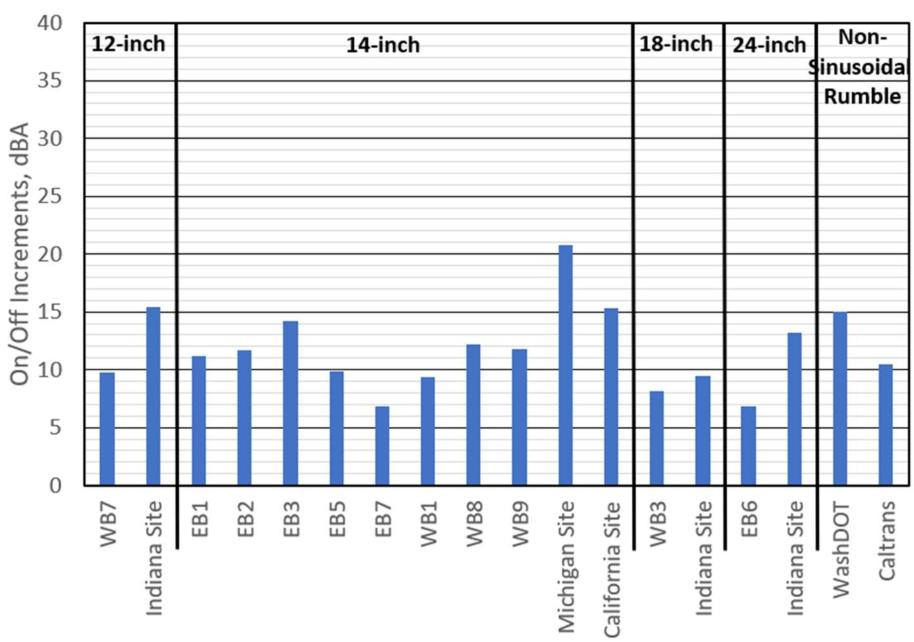



*Figure D-131: Vehicle average interior on/off increments at Washington test sites compared to measurements made in California and the Midwest measured with the ST accelerometer – 60 mph*

The band-passed interior noise levels summed from 31.5 to 315 Hz at the Washington test sites are compared to the Midwest and California sites at 45 mph in Figures D-132, D-133, D-134, and D-135 for the large SUVs, mid-size SUVs, sedans, and compact cars, respectively, measured at the ST sensor. The 14-inch California site consistently resulted in the highest levels across all vehicle categories, just like at the CC microphone. High on-strips levels were also measured at EB3 (14-inch wavelength) site in the large SUV, mid-size SUV, and sedan categories; and at the 14-inch Michigan site in the mid-size SUV and sedan categories.

The lowest on-strips levels were also measured at the 18-inch Indiana site in the large SUV and the mid-size SUV categories; WB7 (12-inch wavelength) in the mid-size SUV, sedan, and compact car categories; WB3 (18-inch wavelength) in the mid-size SUV and sedan categories; the 24-inch site in Indiana in the mid-size SUV category; and EB6 (24-inch wavelength) in the compact car category.

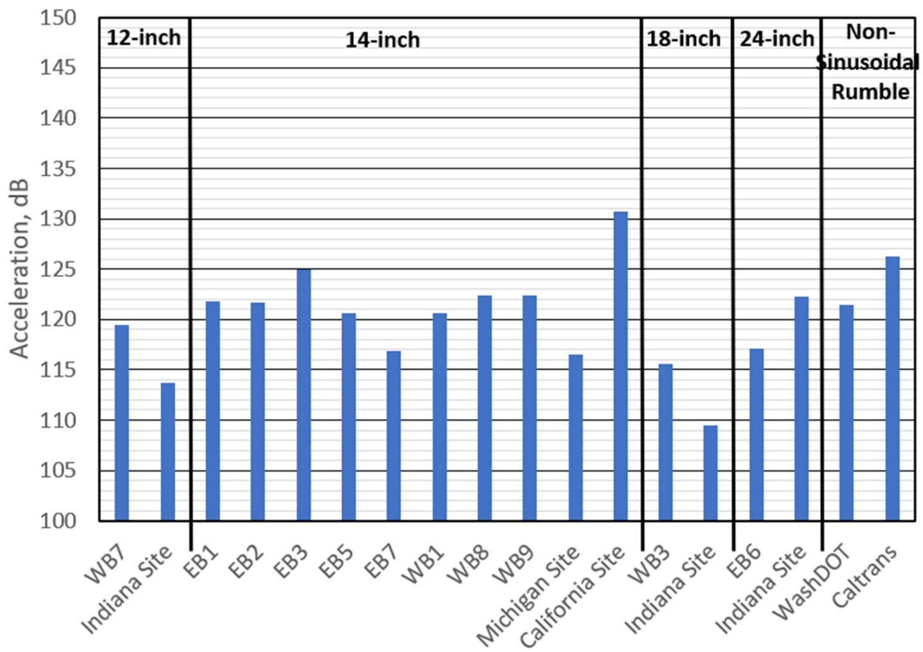



*Figure D-132: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the large SUV category measured with the ST accelerometer at 45 mph*

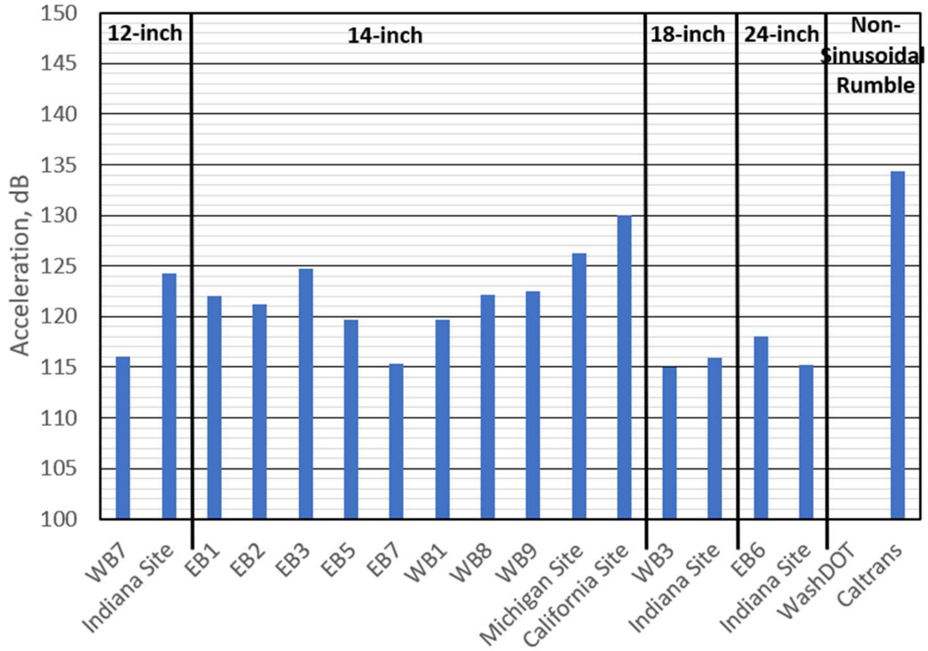



*Figure D-133: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the mid-size SUV category measured with the ST accelerometer at 45 mph*

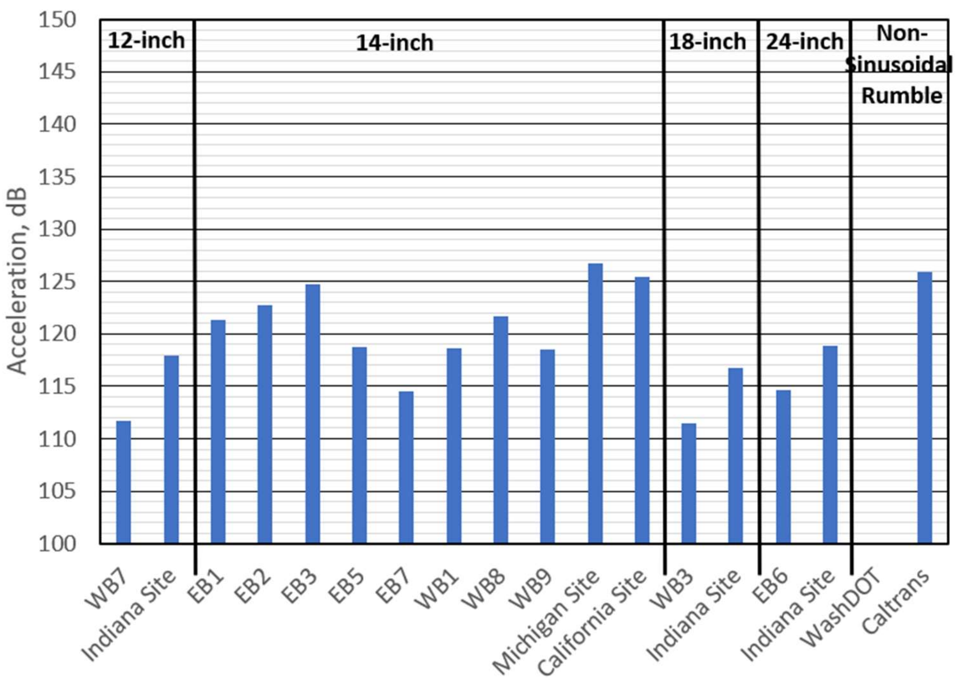



*Figure D-134: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the sedan category measured with the ST accelerometer at 45 mph*

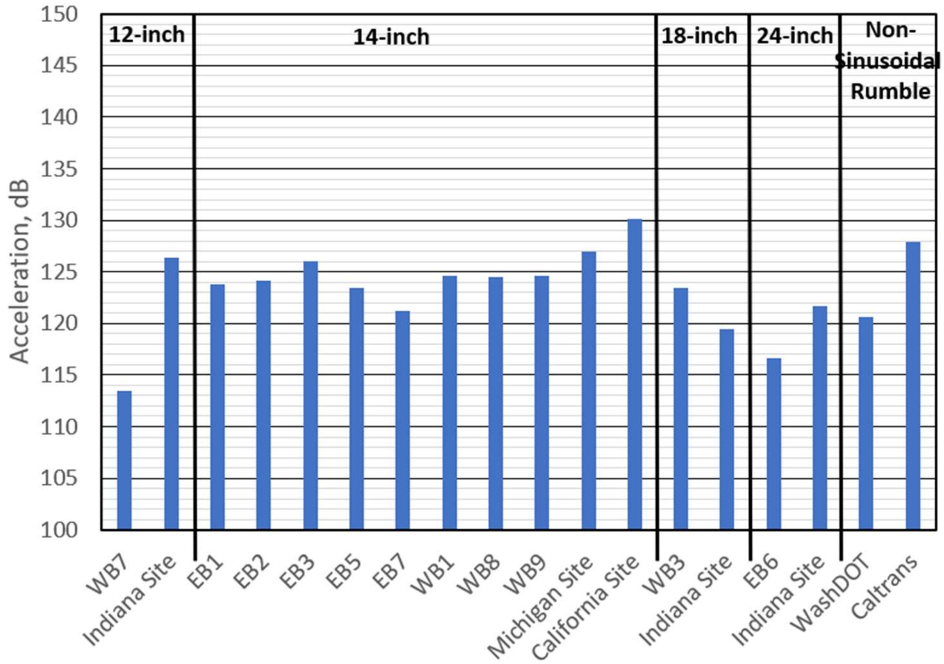



*Figure D-135: Band-passed interior levels on sinusoidal rumble strips in Washington, California, Indiana, and Michigan for the compact car category measured with the ST accelerometer at 45 mph*

The on/off increment comparisons measured at 45 mph with the ST accelerometer are shown for all vehicles in Figure D-136. On/off increments of 10 dBA or more were measured across all vehicles at the following sites: the 12-inch Indiana site; EB1, EB2, EB3, EB5, WB8, and WB9 (14-inch wavelength) and the 14-inch sites in California and Michigan; and at the 24-inch site in Indiana.

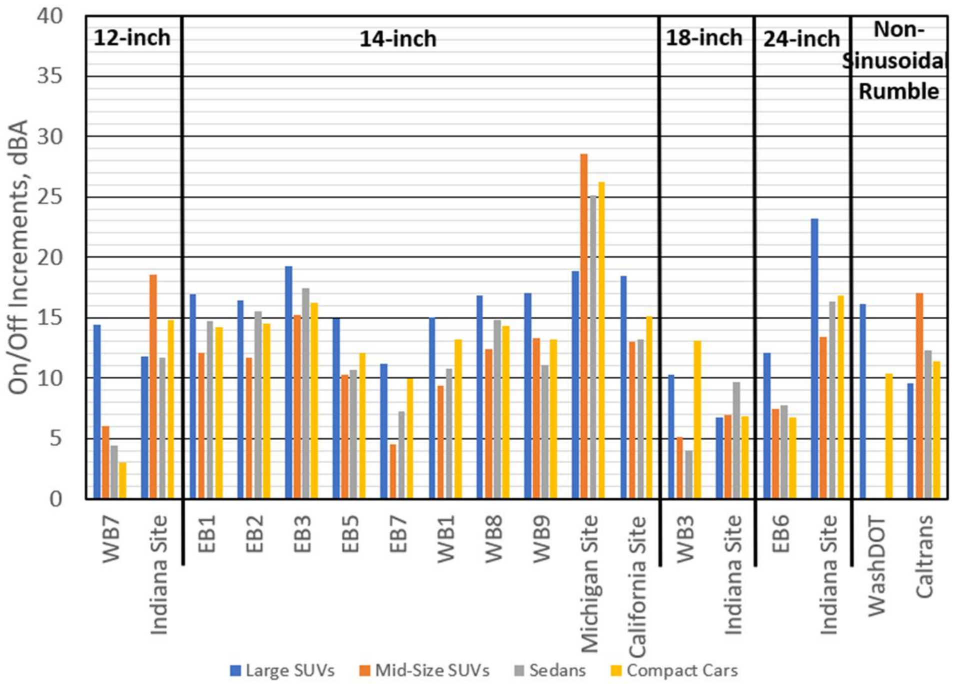



*Figure D-136: Band-passed interior vibration level differences between on and off strips in Washington, California, Indiana, and Michigan for all vehicle categories measured with the ST accelerometer at 45 mph*

Figure D-137 shows the band-passed on-strips levels averaged across all vehicles at 45 mph. The highest average band-passed levels on the sinusoidal sites were measured at the 14-inch site in California and at EB3 (14-inch wavelength). The lowest average levels were measured at WB7 (12-inch wavelength), WB3 (18-inch wavelength), the 18-inch site in Indiana, and EB6 (24-inch wavelength).

The average on/off increments at 45 mph are shown in Figure D-138. Increments of 10 dB or more were measured at the following sites: the 12-inch Indiana site; EB1, EB2, EB3, EB5, WB1, WB8, and WB9 (14-inch wavelength) and the 14-inch sites in California and Michigan; and at the 24-inch site in Indiana.

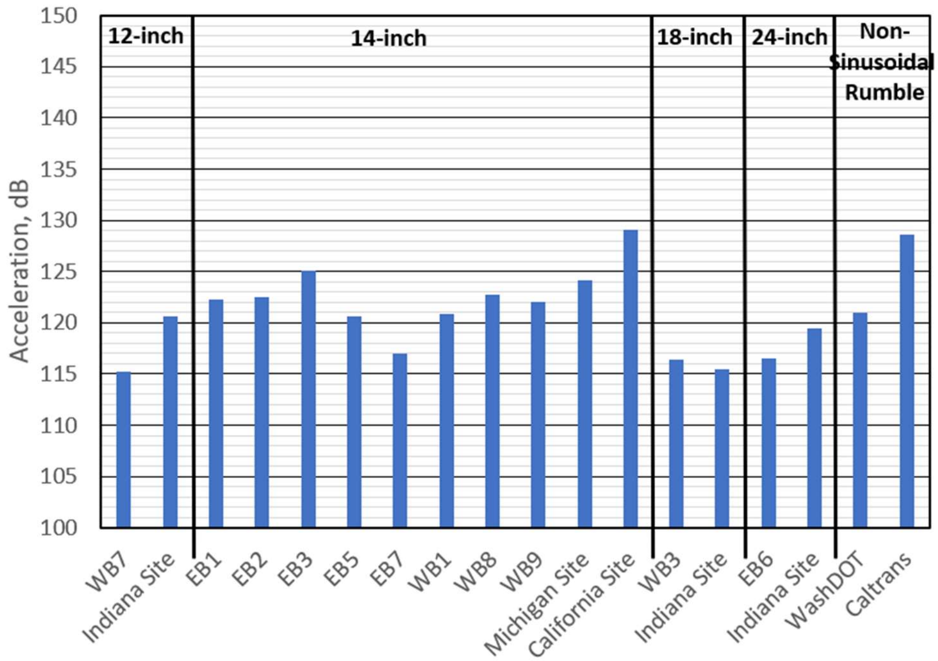



*Figure D-137: Vehicle average band-passed interior vibration levels at Washington test sites compared to measurements made in California and the Midwest measured with the ST accelerometer – 45 mph*

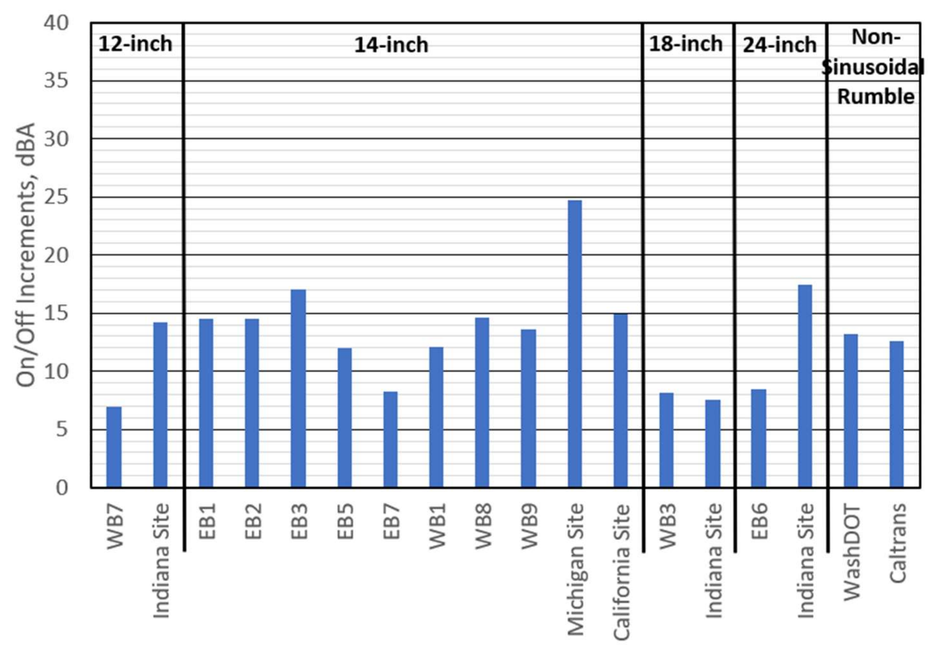



*Figure D-138: Vehicle average interior on/off increments at Washington test sites compared to measurements made in California and the Midwest measured with the ST accelerometer – 45 mph*

## SUMMARY AND CONCLUSIONS

Twenty different experimental sinusoidal rumble strip designs were installed on State Route 105 (SR 105) in Washington State near Aberdeen as part of a WSDOT roadway safety project. The strip wavelength varied from 12 to 24 inches, spanning the range of wavelengths tested in previous measurement periods in California, Indiana, and Michigan. The Washington sinusoidal strips produced on/off pass-by increments lower than or equal to the other comparable sinusoidal strips at the other test sites measured in the other states and to the conventional bump-grind strips at 60 mph and for all except the California sinusoidal strips at 45 mph. For interior noise, five Washington sinusoidal strips produced on/off increments equal to or greater than 10 dB at 60 mph and one equal to 10 dB at 45 mph. For seat track vibration, 12 of the Washington sinusoidal strips produced increments over 12 dB at 60 mph, and 14 produced increments over 10 dB at 45 mph. The Washington testing also produced the following findings and conclusions:

- The tire/pavement noise levels off the strips need to be accounted for in evaluating the on/off performance of the strip design.
- Peak levels at the sinusoidal strip repetition rates are delayed relative to the peak band-passed A-weighted level by an average of 0.7 to 0.8 seconds and should considered in evaluating the strips.
- The level at the sinusoidal strip repetition rate also precedes the maximum of the band-passed A-weighted level for more distant measurement locations than 25 feet.
- The roughness in the finished grind may be a factor in producing lower on/off increments.
- For a given wavelength of the sinusoidal strip design, on/off performance can show considerable variation depending on other design parameters.

## REFERENCES


1. "Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method," T 360, American Association of State Highway and Transportation Officials, 444 North Capitol Street N.W., Suite 249, January 1, 2016. Washington, D.C.
2. "Standard Method of Test for Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-By (SIP) Method" AASHTO TP-98 American Association of State Highway and Transportation Officials, 444 North Capitol Street N.W., Suite 249, 2012.
3. ANSI S12.9/Part 3-1993 American National Standard Quantities and Procedures for Description of Measurement of Environmental Sound Part 3: Short-Term Measurements with an Observer Present.