NCHRP Project 15-68(01)

EFFECTIVE LOW-NOISE RUMBLE STRIPS

APPENDIX E:
RUMBLE STRIP DESIGN RECOMMENDATION DEVELOPMENT

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

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APPENDIX E

RUMBLE STRIP DESIGN RECOMMENDATION DEVELOPMENT

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INTRODUCTION

This appendix contains the NCHRP Rumble Strip Project rumble strip design recommendation development, completed in 2022.

INSTALLED RUMBLE STRIP PARAMETERS

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 and Michigan test sites. Table F-1 summarizes the nominal site dimensions of the 20 sinusoidal sites, as well as the installed dimensions. 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 profiles for all 20 of the sinusoidal rumble strips were provided in the Task 3 report. For the wavelength parameter, 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 Indiana 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. For this parameter, the nominal specification was used based on visual inspection of the strip photographs.

Table F-1: Specified and as installed dimensions of the sinusoidal rumble strips

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

Site	Wavelength, in.		Amplitude, in.		Recess, in.	
	Specified	Measured	Specified	Measured	Specified	Measured
EB8	17	17	3/8	3/8	1/8	0
EB9	13	13	3/8	5/16	1/8	0
EB10	15	15	1/2	7/16	0	0
EB11	15	15	3/8	5/16	1/8	1/8

COMPARISON OF INTERIOR MEASUREMENTS

Established criteria indicates a minimum difference of 10 dB between on and off rumble strips for interior measurements would effectively alert drivers of lane departure. Interior noise and vibration on/off increments were used for each of the 20 design parameters to determine effectiveness in alerting the drivers, consistency of results, and limits for each of the parameters.

Interior Noise and Vibration Measurements – Wavelength Discussion

Figures F-1 and F-2 show the on/off increments for all test vehicles measured at each of the 20 sinusoidal test sites with the center center (CC) microphone and seat track (ST) accelerometer, respectively, versus the wavelength of the individual sites at 60 mph. The overall levels used to calculate the on/off increments reflect the energy from 31.5 to 315 Hz to reduce the impact of the chip seal pavement in calculating the overall levels.

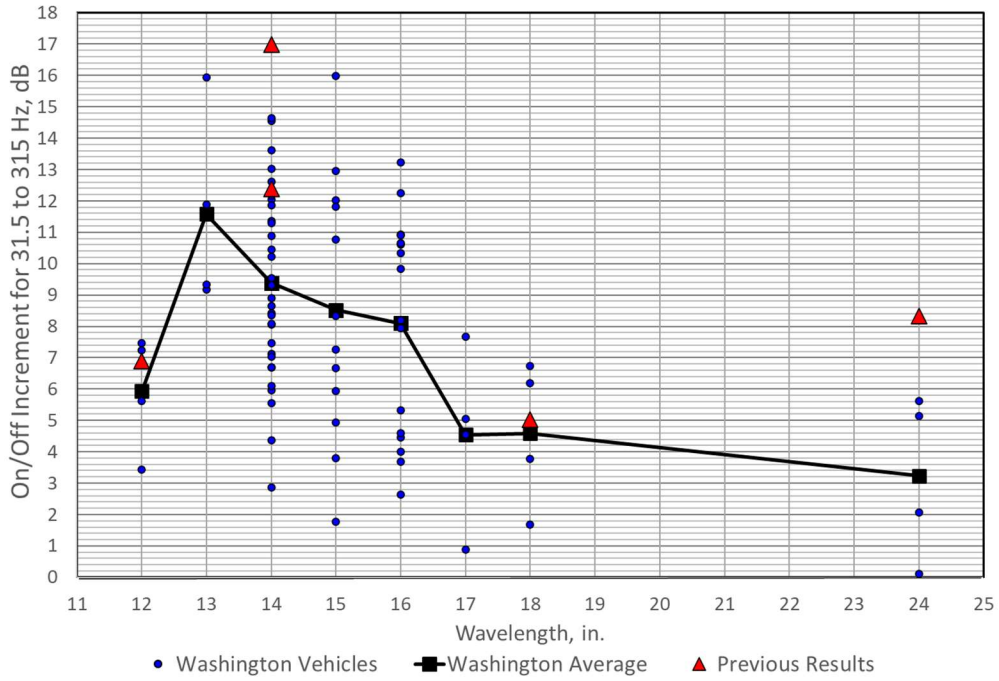

Figure F-1: On/off increments measured with the CC microphone versus wavelength of rumble strips for all test vehicles at all test sites, 60 mph

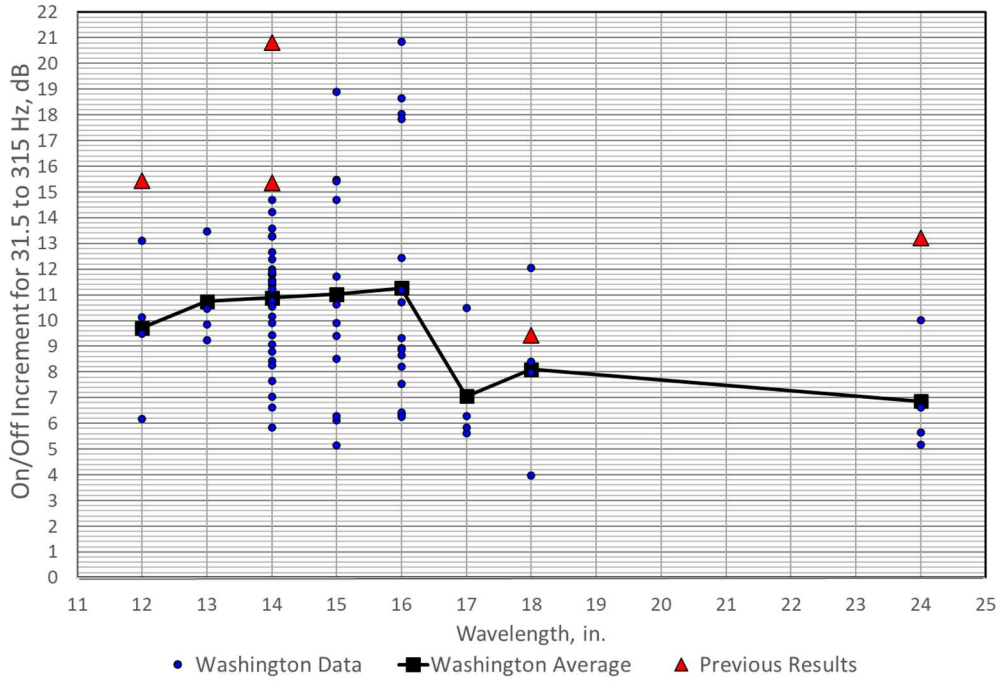

Figure F-2: On/off increments measured with the ST accelerometer versus wavelength of rumble strips for all test vehicles at all test sites, 60 mph

In both figures, all data collected at the 20 Washington test sites are shown in blue, while the average at each wavelength is shown in black. The red triangles represent the average increment for all test vehicles at the Midwest and California test sites. Each of the average increments from the previous sites were higher than the average at each wavelength measured in Washington. On average, the wavelengths that resulted in the interior on/off increment requirement of 10 dB or more at the ST sensor were 13-, 14-, 15-, and 16-inch sites, while only the average 13-inch wavelength resulted in a 10 dB or more increment at the CC microphone.

Figures F-3 and F-4 show the increments versus wavelength for all sites at 45 mph. None of the average increments resulted in 10 dB or more at the CC microphone when grouped by wavelengths 45 mph. However, individual vehicles or sites with wavelengths of 14, 15, and 16 inches did have increments of 10 dB or more. At the ST sensor, average increments of 10 dB or more were measured at the 13-, 14-, 15-, and 16-inch sites.

Consistently, sites with 13-, 14-, 15-, and 16-inch wavelengths provided interior noise level increments of 10 dB or more at both the primary microphone (CC) and the primary accelerometer (ST) when tested at 45 mph. These would be the most effective wavelength designs for meeting the requirement of alerting the driver of lane departure.

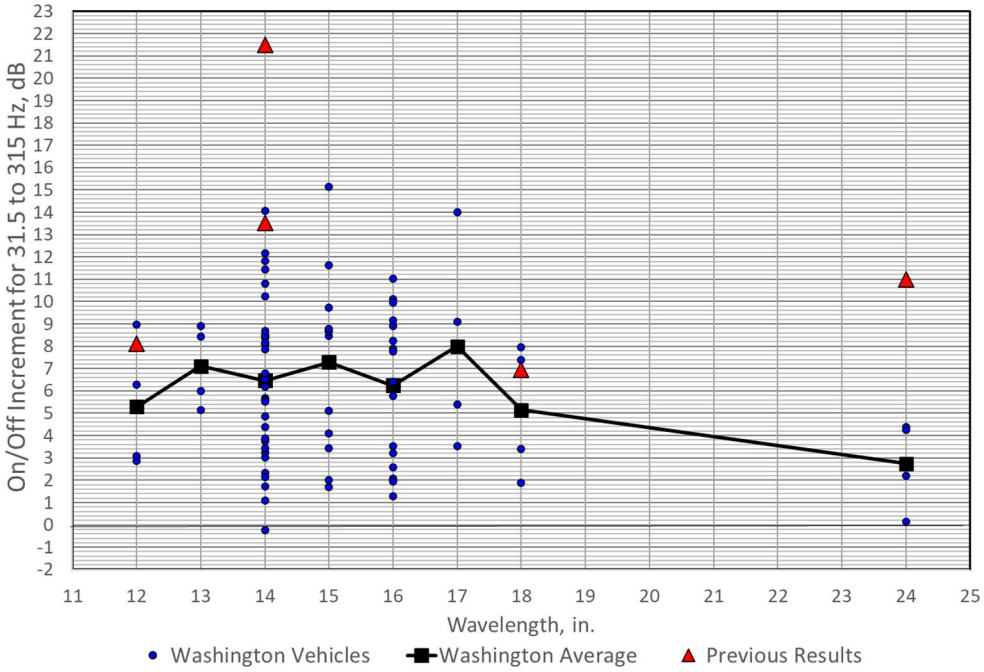

Figure F-3: On/off increments measured with the CC microphone versus wavelength of rumble strips for all test vehicles at all test sites, 45 mph

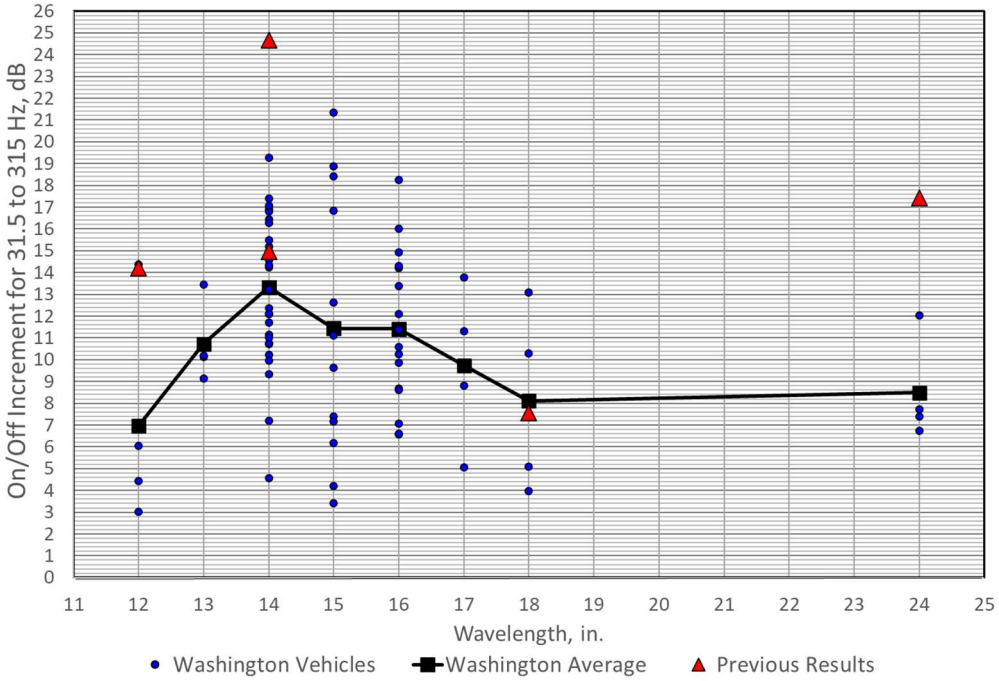

Figure F-4: On/off increments measured with the ST accelerometer versus wavelength of rumble strips for all test vehicles at all test sites, 45 mph

Interior Noise and Vibration Measurements – Amplitude Discussion

Figures F-5 and F-6 show the increments versus amplitude for all test sites, as measured at the CC microphone and ST sensor, respectively, at 60 mph. At the CC microphone, average peak-to-peak amplitudes of 7/16 (0.4375) and ½ (0.5) inches resulted in increments of 10 dB or more. At the ST sensor, average peak-to-peak amplitudes of 5/16 (0.3125), 7/16, and ½ inches resulted in increments of 10 dB or more.

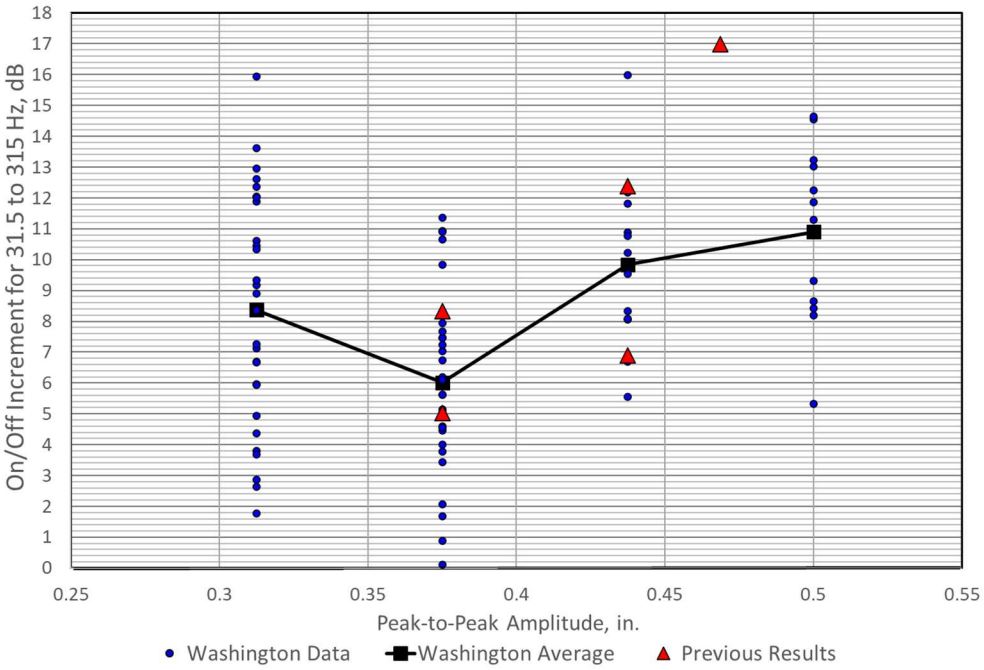

Figure F-5: On/off increments measured with the CC microphone versus amplitude of the rumble strips for all test vehicles at all test sites, 60 mph

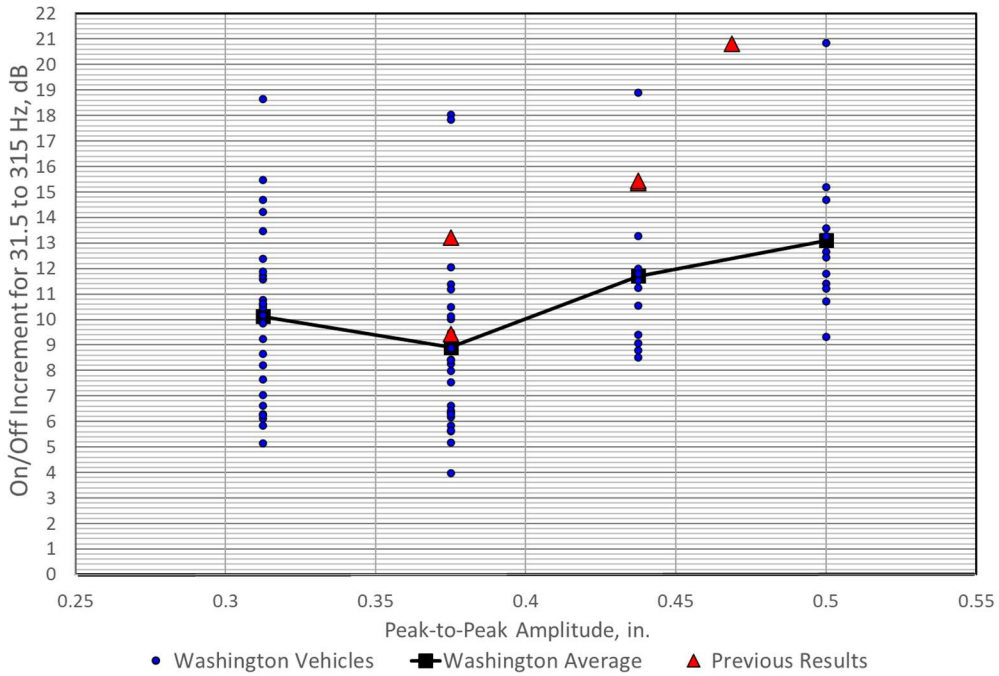

Figure F-6: On/off increments measured with the ST accelerometer versus amplitude of the rumble strips for all test vehicles at all test sites, 60 mph

Figures F-7 and F-8 show the increments versus amplitude for all test sites, as measured at the CC microphone and ST sensor, respectively, at 45 mph. While none of the average peak-to-peak amplitudes resulted in increments of 10 dB or more at the CC microphone at 45 mph, individual vehicles at each amplitude showed increments of 10 dB or more. At the ST sensor, average peak-to-peak amplitudes of 5/16, 7/16, and ½ inches resulted in increments of 10 dB or more, similar to the 60 mph results.

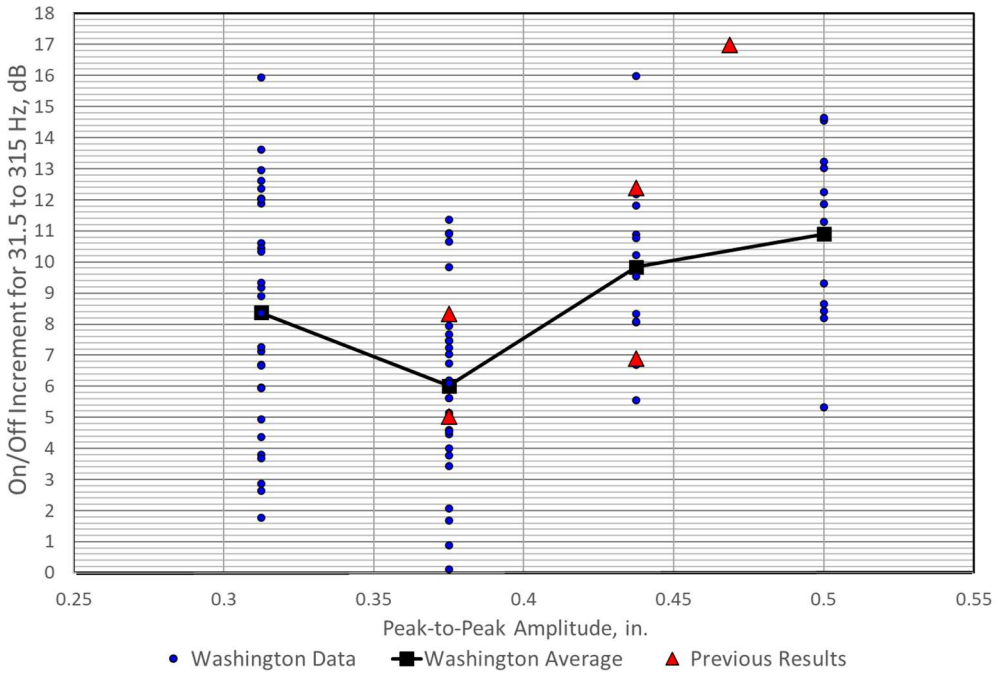

Figure F-7: On/off increments measured with the CC microphone versus amplitude of the rumble strips for all test vehicles at all test sites, 45 mph

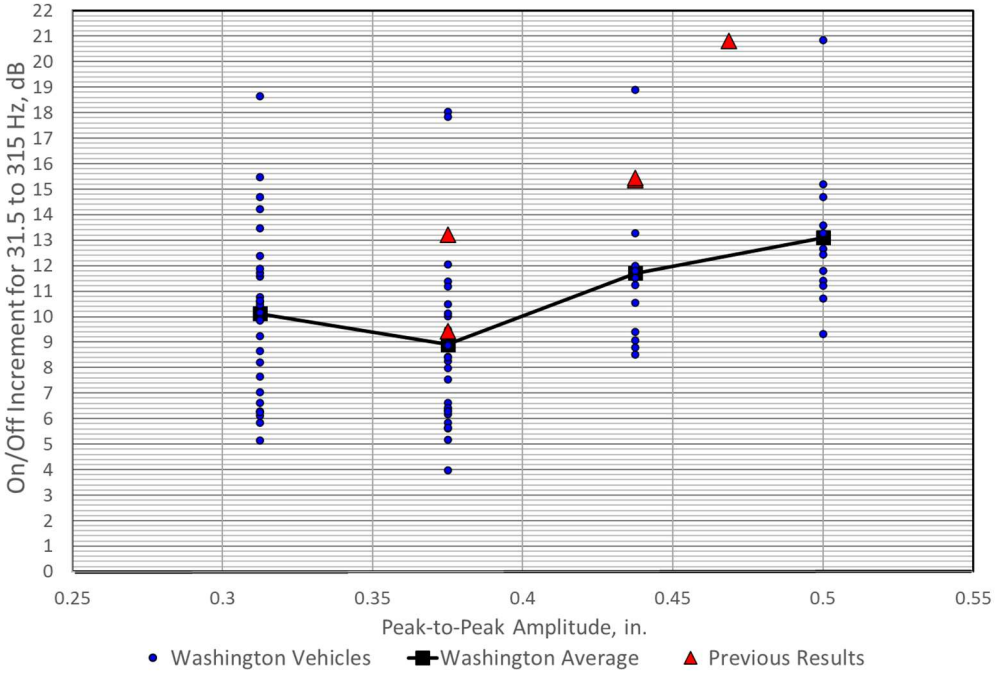

Figure F-8: On/off increments measured with the ST accelerometer versus amplitude of the rumble strips for all test vehicles at all test sites, 45 mph

From Figures F-1 to F-4, it was determined above that sites with wavelengths of 13, 14, 15, and 16 inches would be the optimal design for notifying the driver of lane departure, Washington test sites with these wavelengths only were isolated to compare the other design parameters. Figures F-9 and F-10 show increments versus peak-to-peak amplitudes for all test vehicles at sites with wavelengths of 13, 14, 15, and 16 inches only, as measured at the CC microphone and ST accelerometer, respectively, at 60 mph. At the CC microphone, amplitudes of 7/16 and ½ inches resulted in averages increments of 10 dB or more, while amplitudes of 5/16 and 3/8 (0.375) inches resulted in average increments of about 8 dB. At the ST sensor, all peak-to-peak amplitudes resulted in averages increments of 10 dB or more.

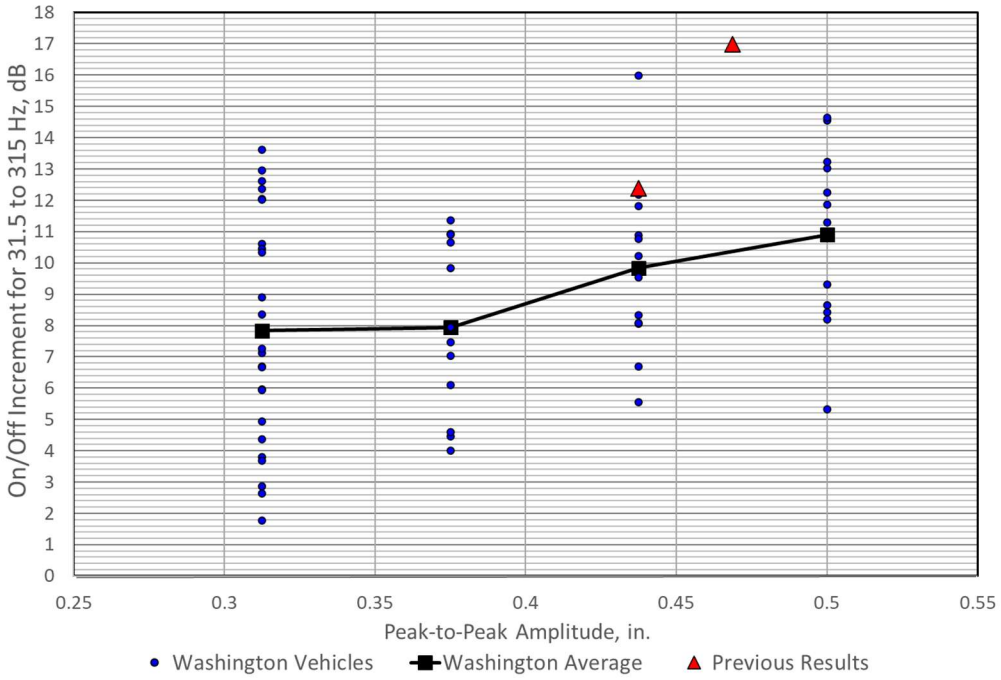

Figure F-9: On/off increments measured with the CC microphone versus amplitude of the rumble strips for all test vehicles at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 60 mph

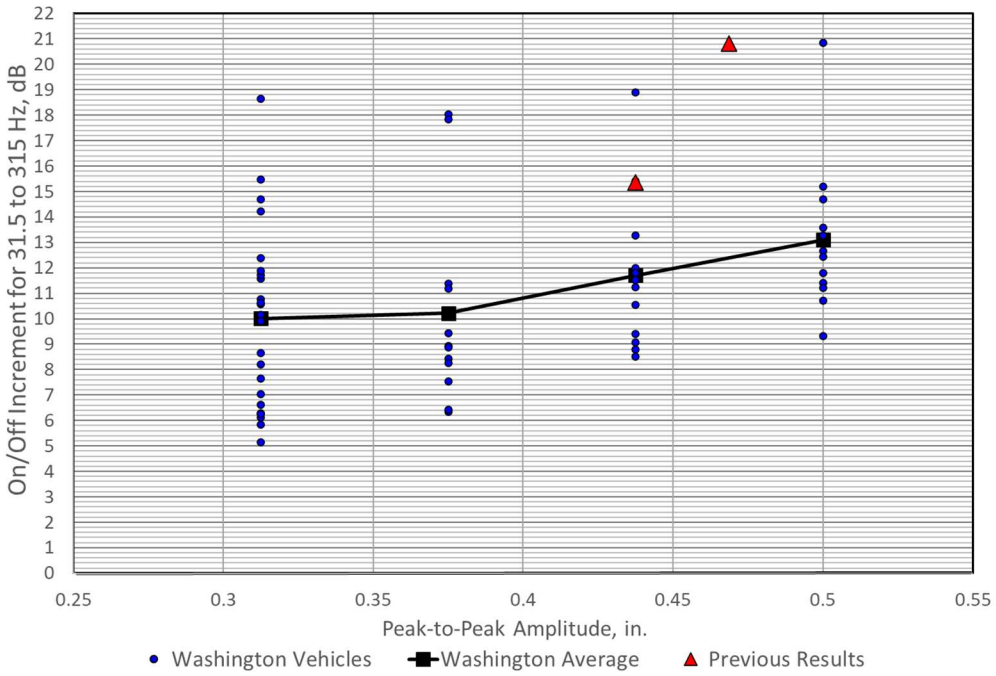

Figure F-10: On/off increments measured with the ST accelerometer versus amplitude of the rumble strips for all test vehicles at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 60 mph

Figures F-11 and F-12 show increments versus peak-to-peak amplitudes for all test vehicles at sites with wavelengths of 13, 14, 15, and 16 inches only, as measured at the CC microphone and ST accelerometer, respectively, at 45 mph. While all amplitudes show average increments of 10 dB or more at the ST sensor, none result in 10 dB or more increments at the CC microphone.

In general, the peak-to-peak amplitudes of 7/16 and ½ inches show the highest on/off increments on the vehicle interior.

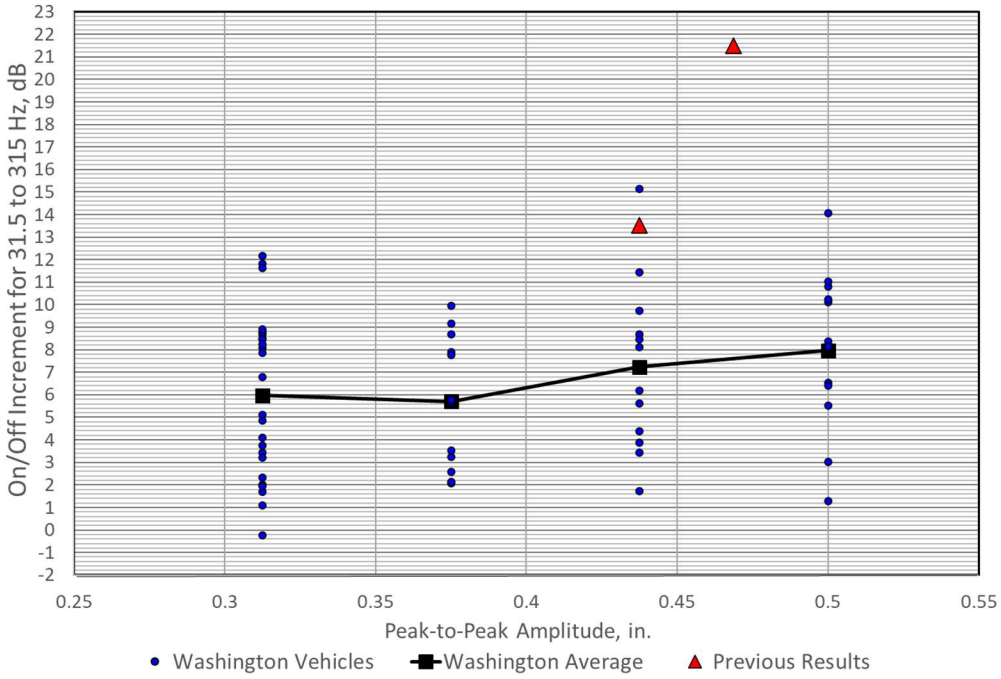

Figure F-11: On/off increments measured with the CC microphone versus amplitude of the rumble strips for all test vehicles at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 45 mph

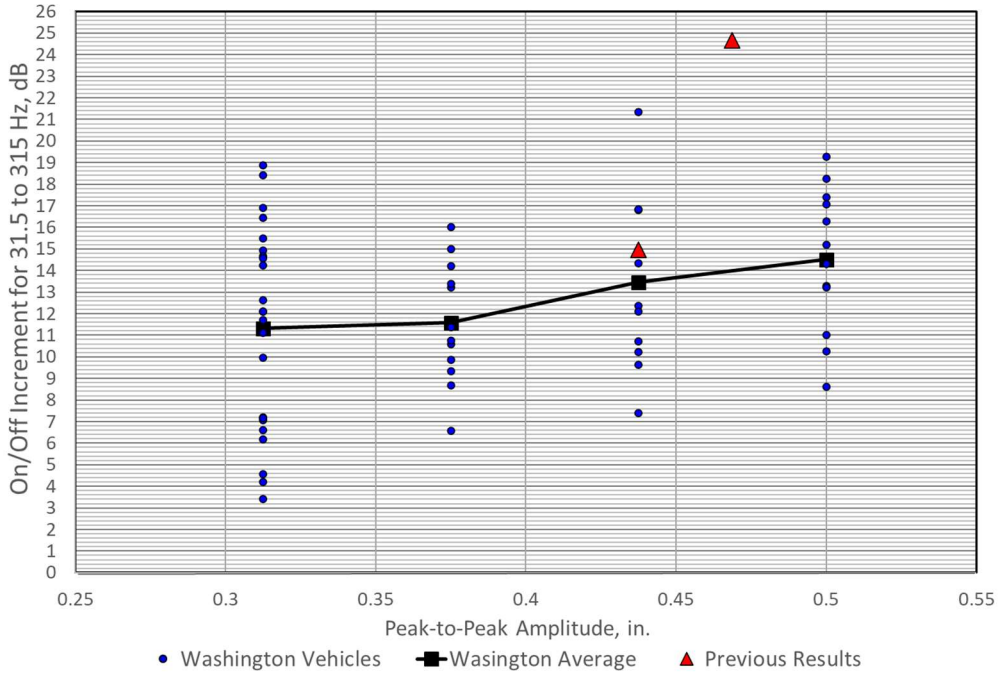

Figure F-12: On/off increments measured with the ST accelerometer versus amplitude of the rumble strips for all test vehicles at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 45 mph

Interior Noise and Vibration Measurements – Recess Discussion

The recess design parameter relates to the distance below the pavement surface that the entire sinusoidal strip is set. From the figures of the pavement, a 0-inch recess would mean the peak of the sinusoidal wave would be flush with the pavement surface, while a 1/8-inch recess means the peak of the wave would be 1/8 inch below the pavement surface.

Figures F-13 and F-14 show the on/off increments for all test vehicles measured at each of the 20 sinusoidal test sites with the CC microphone and ST accelerometer, respectively, versus the recess at 60 mph. Figures F-15 and F-16 show the same at 45 mph.

Overall, the average increment at each recess value is within 2 dB of each other, which is not statistically relevant. At both sensors and at both speeds, the 0-inch recess was slightly higher than the 1/8-inch recess. While it does not appear that this design parameter correlates to the on/off increments, a 0-inch recess would be better for bicycle safety and easier to install. Therefore, a recess of 0 inches is recommended.

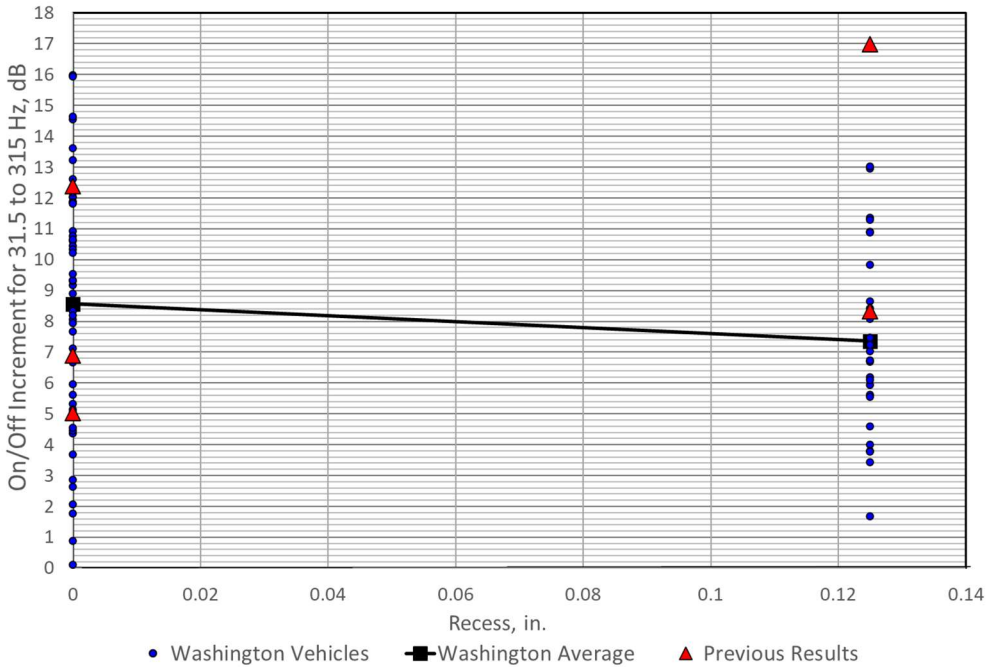

Figure F-13: On/off increments measured with the CC microphone versus recess of rumble strips for all test vehicles at all test sites, 60 mph

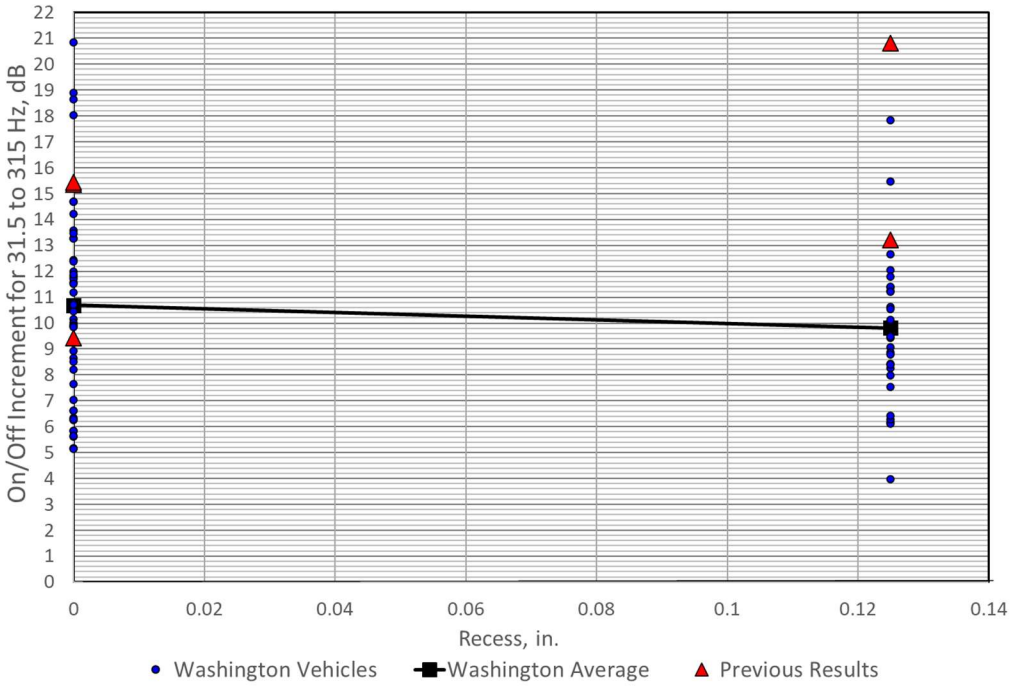

Figure F-14: On/off increments measured with the ST accelerometer versus recess of rumble strips for all test vehicles at all test sites, 60 mph

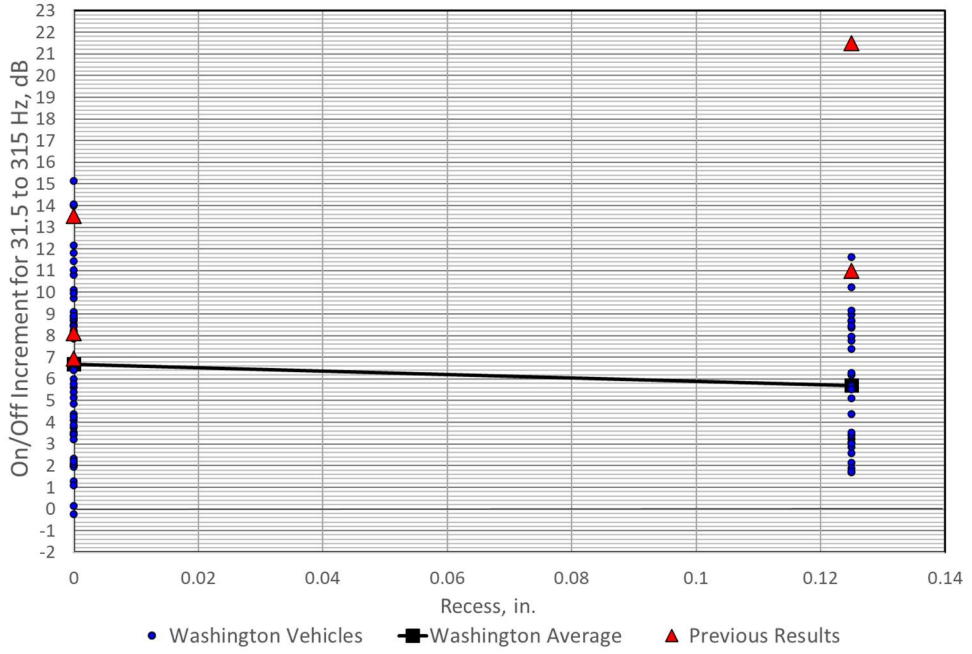

Figure F-15: On/off increments measured with the CC microphone versus recess of rumble strips for all test vehicles at all test sites, 45 mph

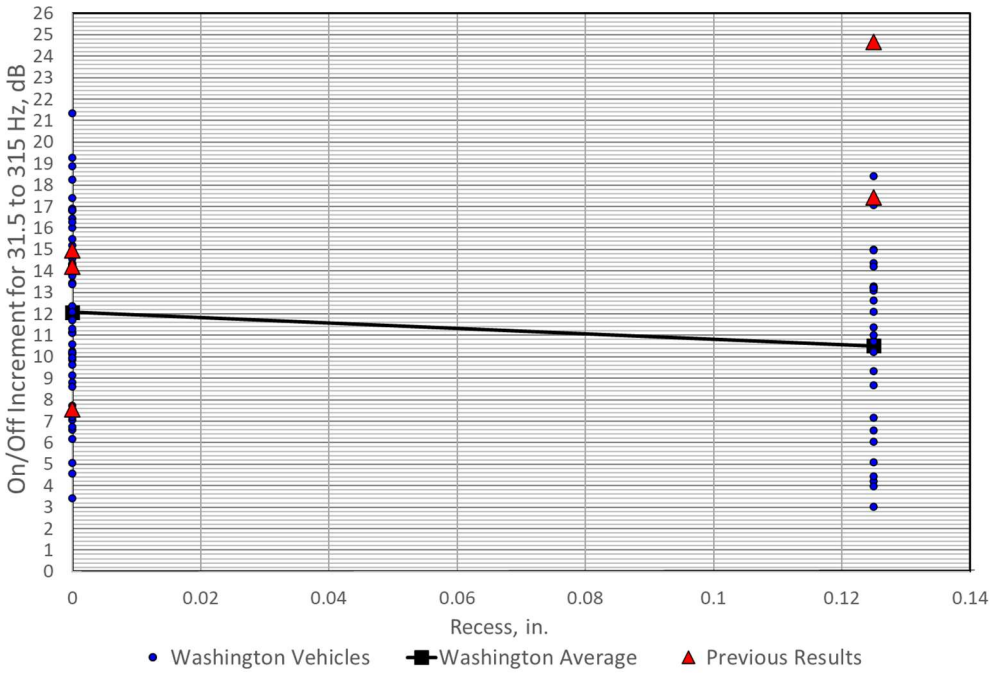

Figure F-16: On/off increments measured with the ST accelerometer versus recess of rumble strips for all test vehicles at all test sites, 45 mph

Interior Noise and Vibration Measurements – Spectra Discussion

As discussed in the Task 3 report, comparing the amplitudes at the excited frequencies of the spectra for each test site is critical, especially at the Washington test sites since the off-strips pavement is chip seal.

Figures F-17 through F-20 show the spectra for the 13-, 14-, 15-, and 16-inch sites, respectively, as measured at the CC microphone. Comparing the amplitudes at excited frequencies for each site, the highest peak levels for each wavelength at the CC microphone occur at: EB9 (13-inch wavelength); EB3 (14-inch wavelength); EB10 (15-inch wavelength); and WB6 (16-inch wavelength).

Figure F-17: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 13-inch wavelengths, 60 mph

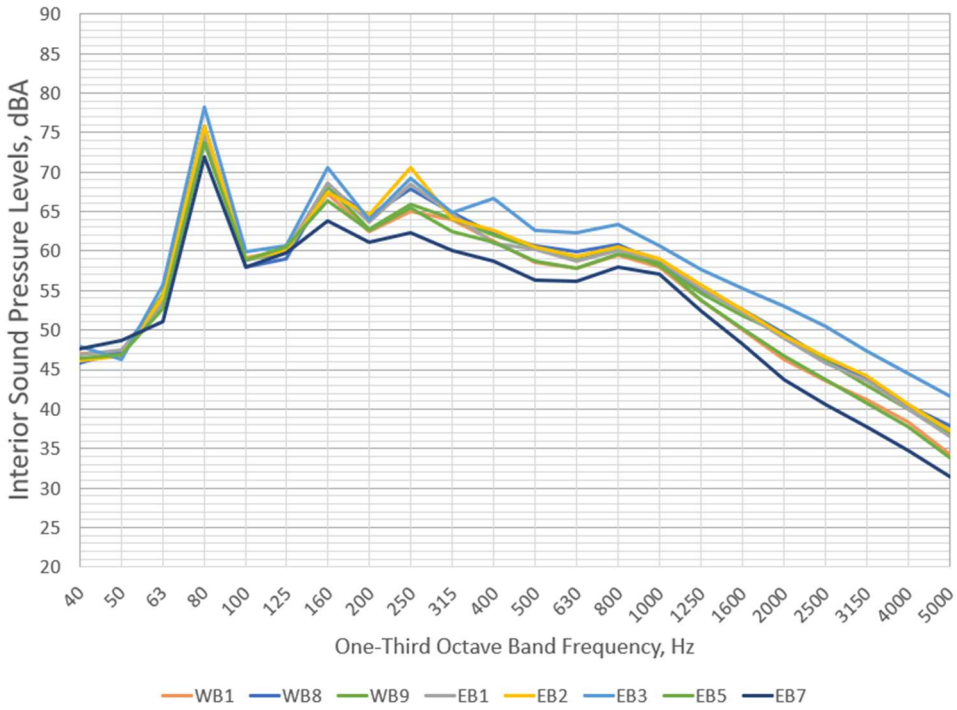

Figure F-18: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 14-inch wavelengths, 60 mph

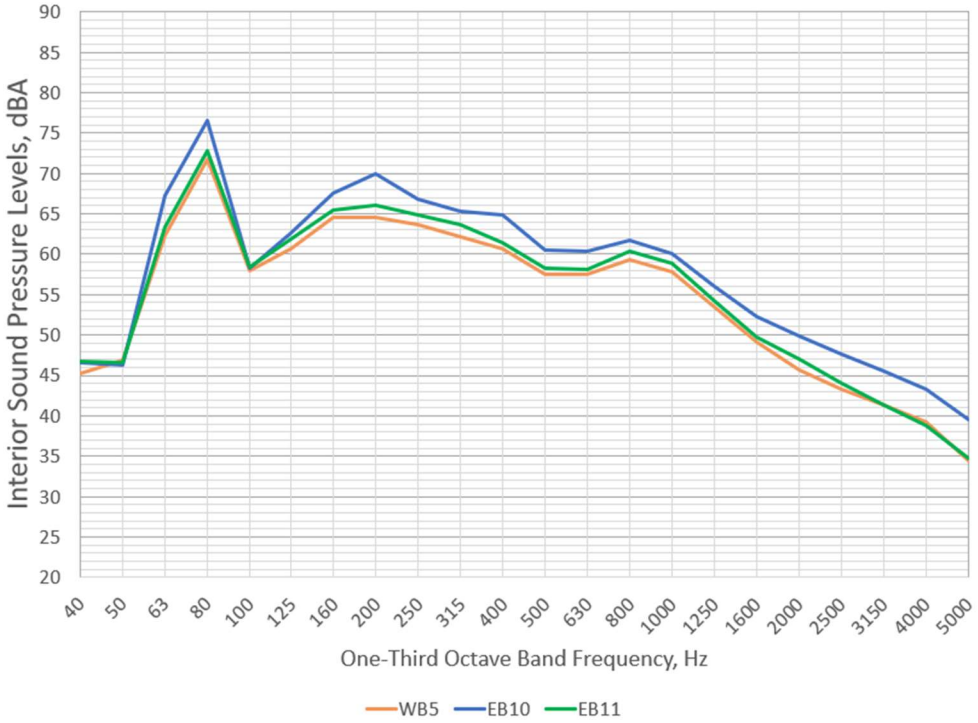

Figure F-19: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 15-inch wavelengths, 60 mph

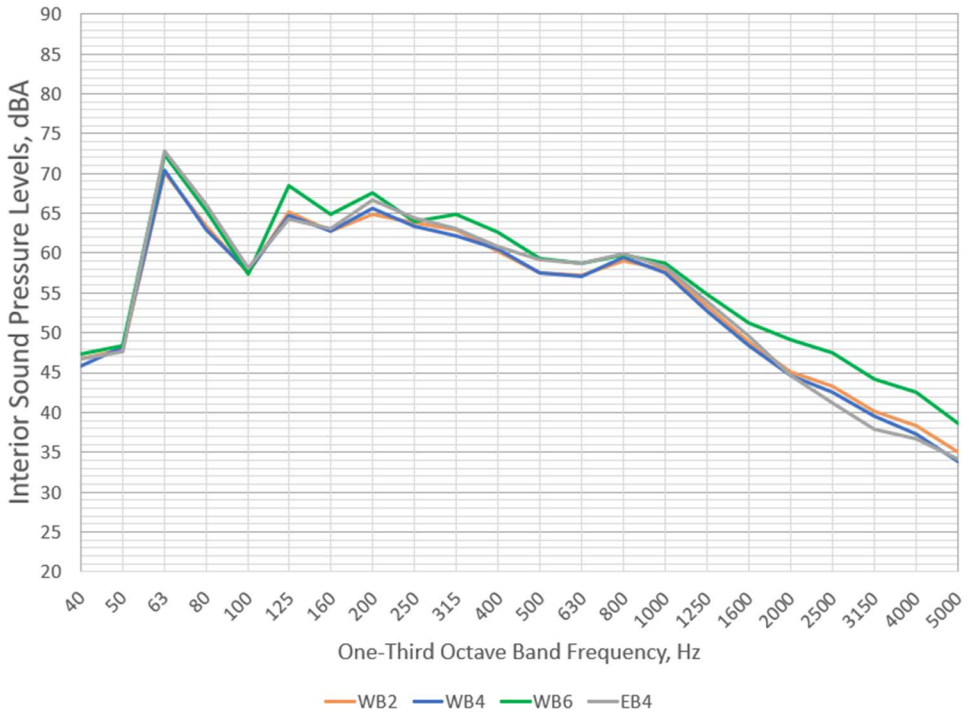

Figure F-20: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 16-inch wavelengths, 60 mph

Figures F-21 through F-24 show the spectra for the 13-, 14-, 15-, and 16-inch sites, respectively, as measured at the ST accelerometer. Comparing the amplitudes at excited frequencies for each site, the highest peak levels for each wavelength at the ST accelerometer again occur at: EB9 (13-inch wavelength); EB3 (14-inch wavelength); EB10 (15-inch wavelength); and WB6 (16-inch wavelength).

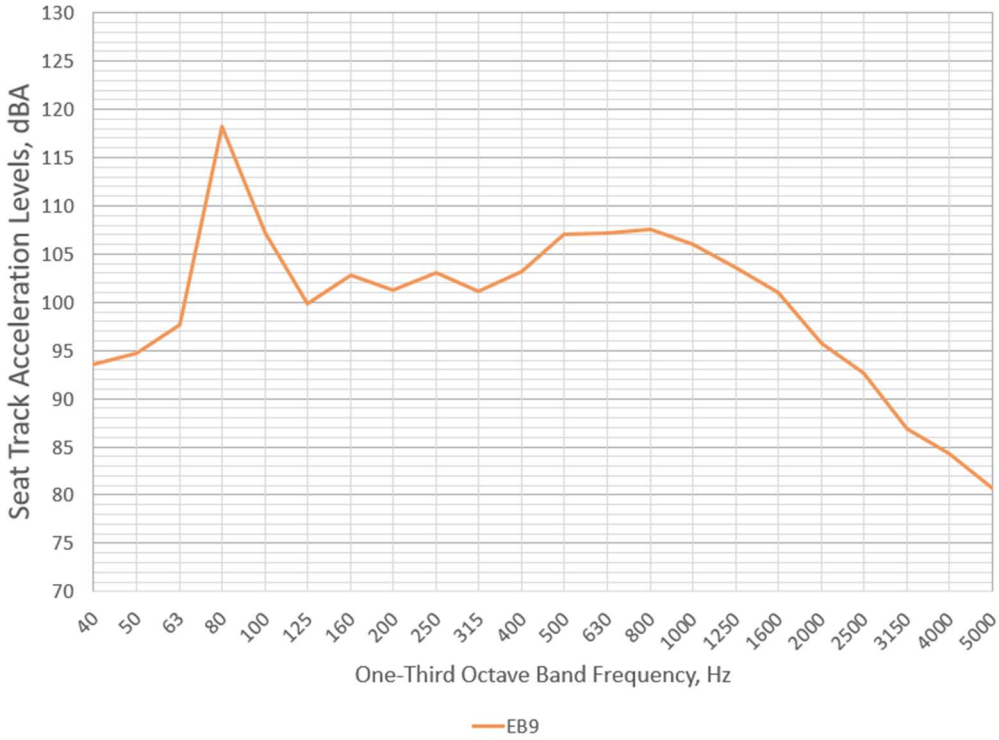

Figure F-21: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 13-inch wavelengths, 60 mph

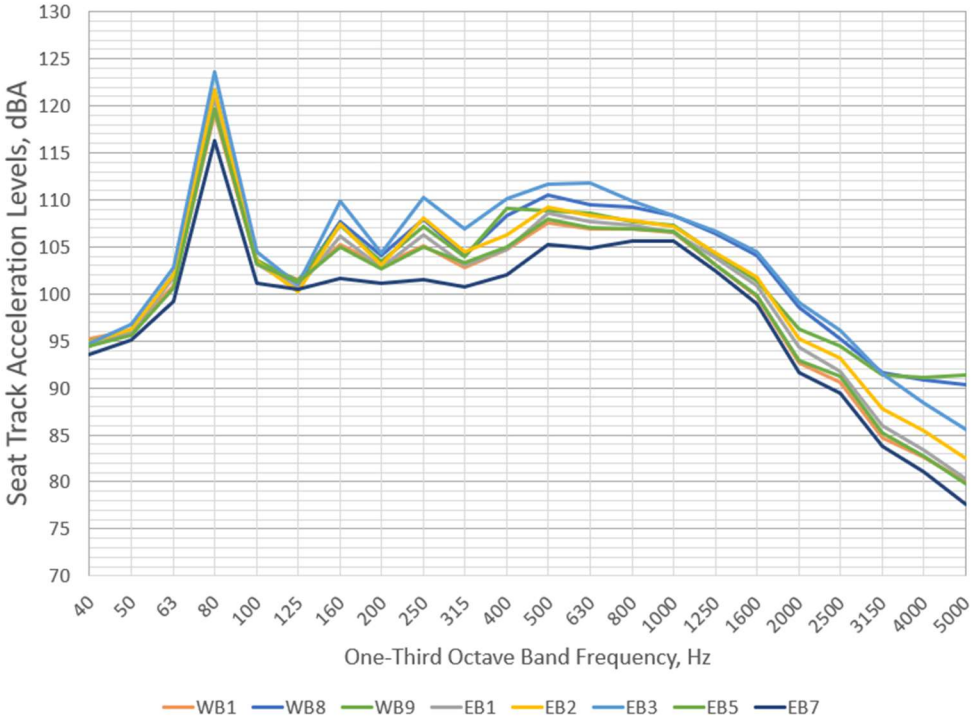

Figure F-22: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 14-inch wavelengths, 60 mph

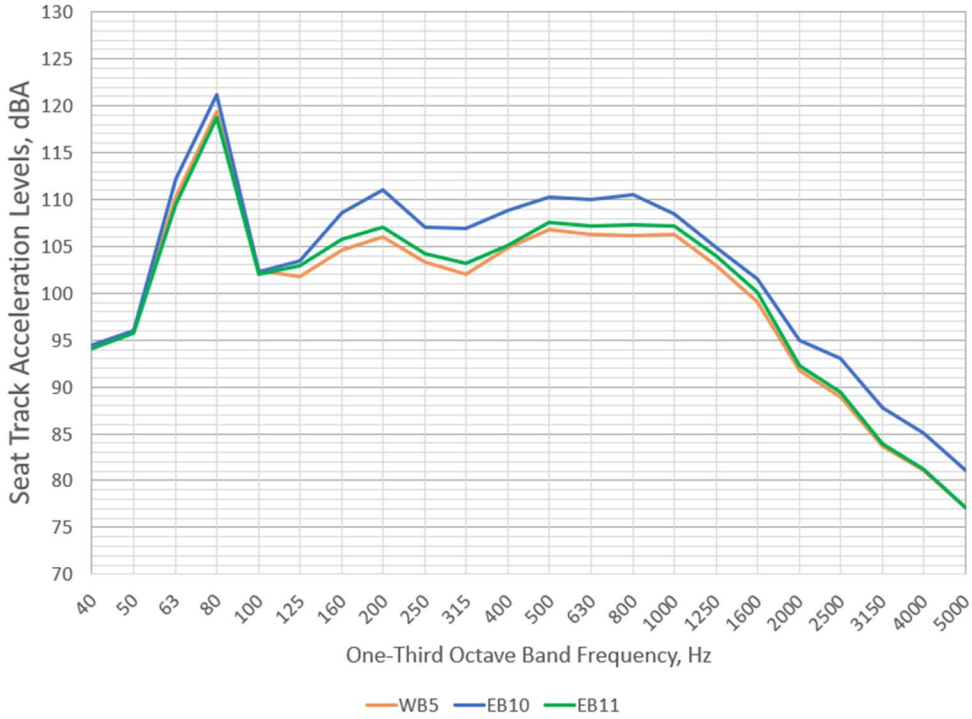

Figure F-23: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 15-inch wavelengths, 60 mph

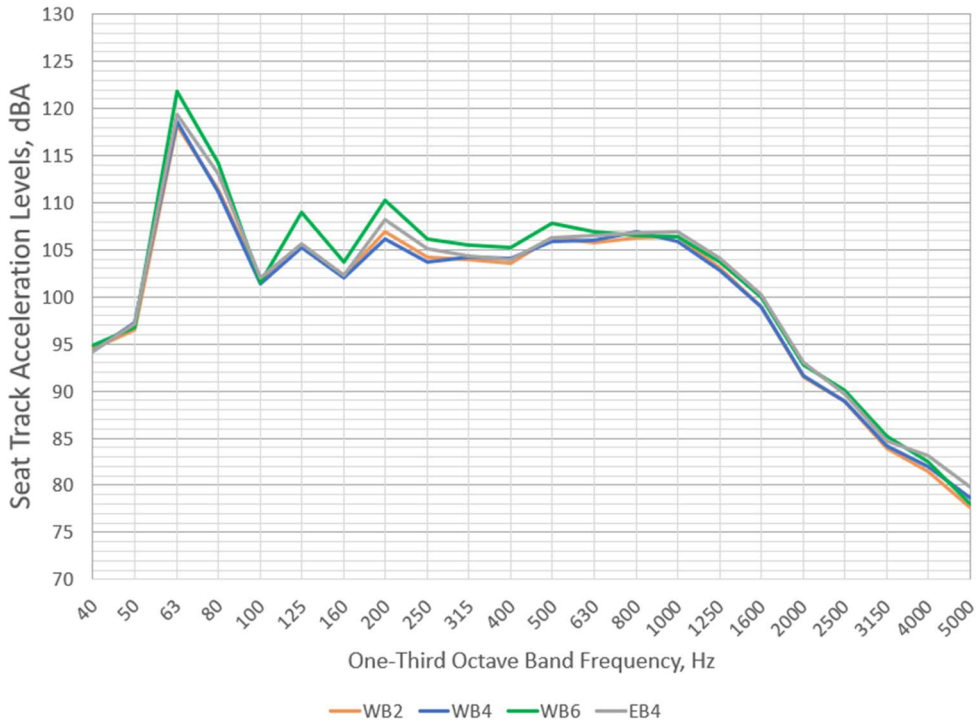

Figure F-24: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 16-inch wavelengths, 60 mph

Both the CC microphone and ST accelerometer had spectra with the highest peak levels occurring at the same sites: EB9 (13-inch wavelength); EB3 (14-inch wavelength); EB10 (15-inch wavelength); and WB6 (16-inch wavelength). Table F-2 summarizes the dimensions for these four sites. Figures E-25 and E-26 show the spectra for each of these sites on a single plot for the CC and ST sensors, respectively, at 60 mph. Both sensors have the highest peak level at EB3 (14-inch wavelength).

Table F-2: Installed dimensions of the sinusoidal rumble strips for the optimal designs as observed from the interior spectra data at 60 mph

Site	Measured Wavelength	Measured Amplitude	Measured Recess
WB6	16 inches	1/2 inches	0 inches
EB3	14 inches	1/2 inches	0 inches
EB9	13 inches	5/16 inches	0 inches
EB10	15 inches	7/16 inches	0 inches

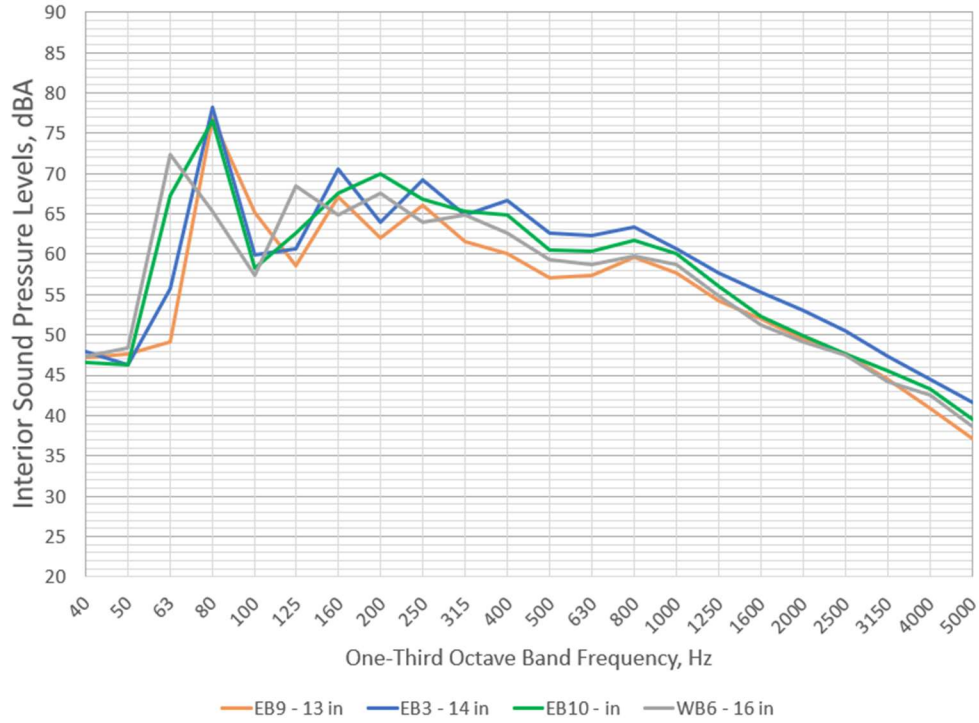

Figure F-25: Best average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 60 mph

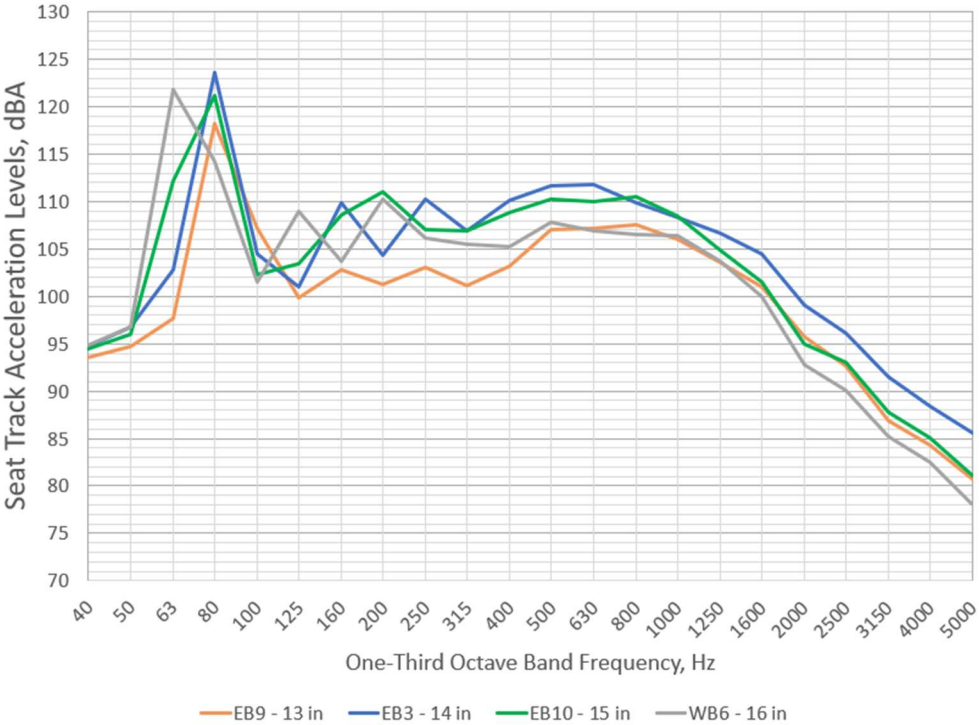

Figure F-26: Best average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 60 mph

Figures F-27 through F-30 show the spectra for the 13-, 14-, 15-, and 16-inch sites, respectively, as measured at the CC microphone at 45 mph. Comparing the amplitudes at excited frequencies for each site, the highest peak levels for each wavelength at the CC microphone occur at: EB9 (13-inch wavelength); EB3 (14-inch wavelength); EB10 (15-inch wavelength); and WB6 (16-inch wavelength). These are the same sites that were identified for the 60 mph spectra.

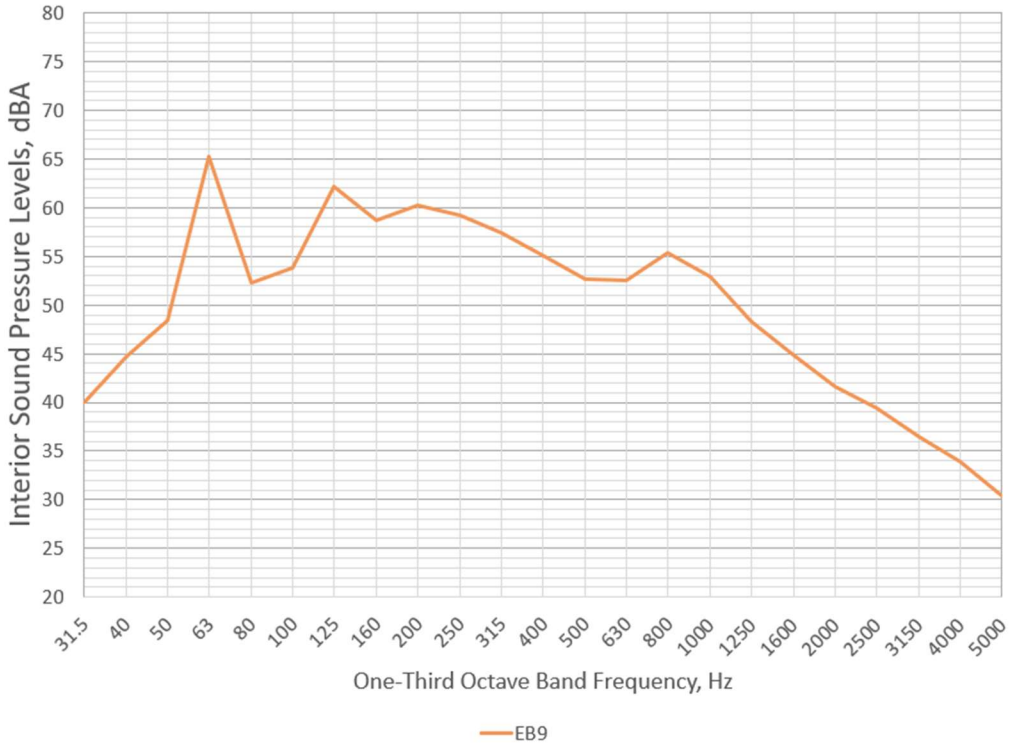

Figure F-27: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 13-inch wavelengths, 45 mph

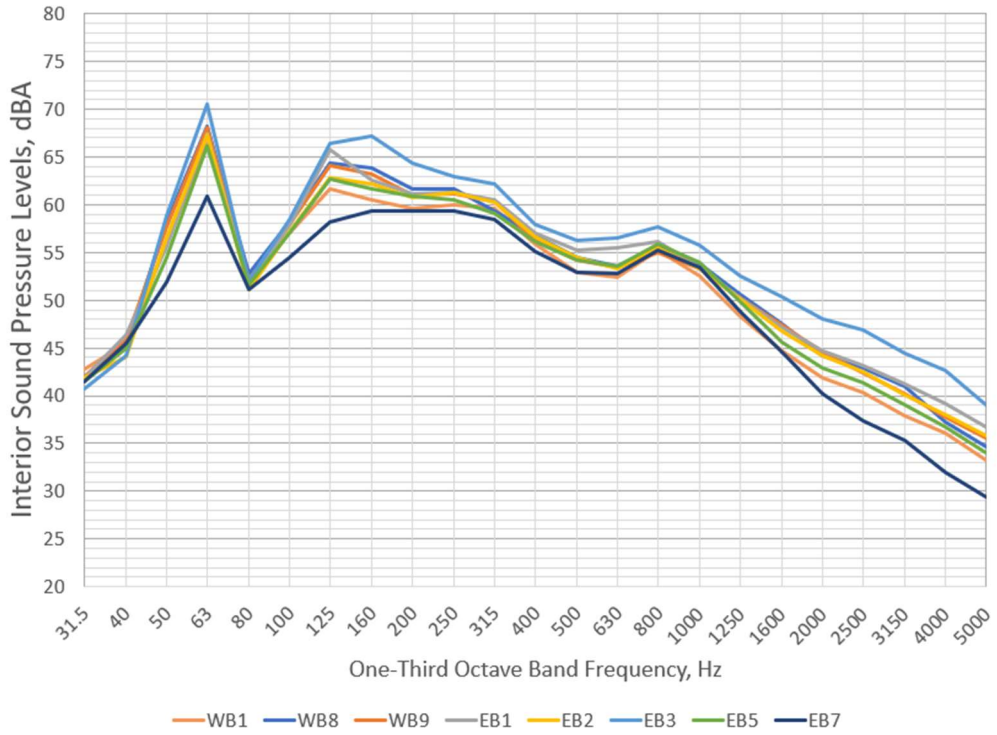

Figure F-28: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 14-inch wavelengths, 45 mph

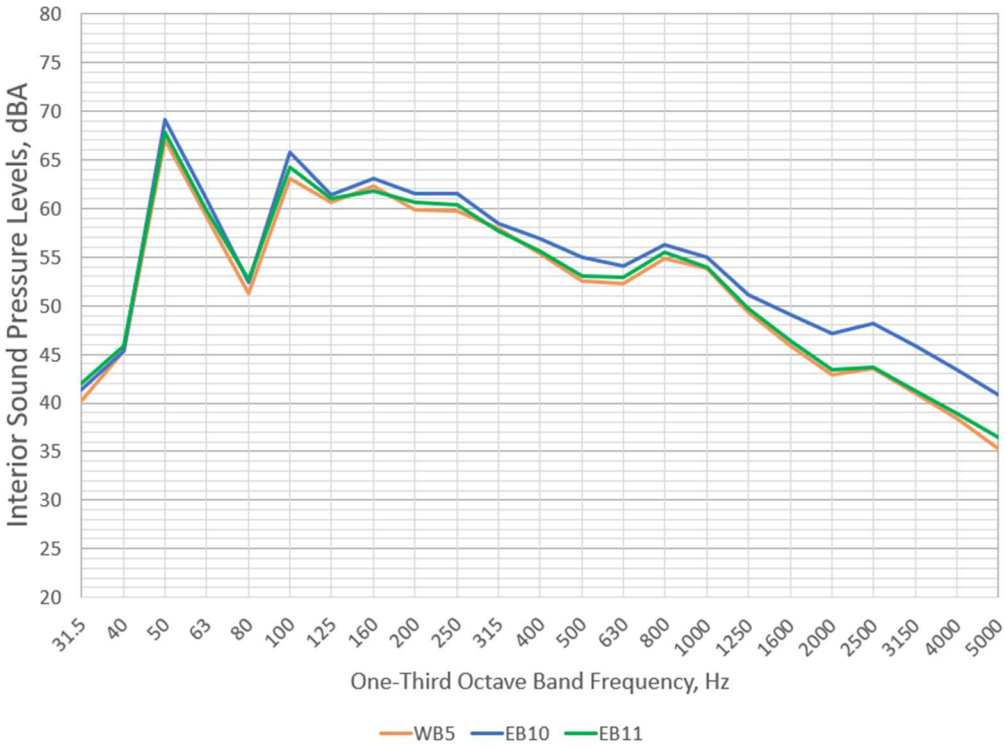

Figure F-29: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 15-inch wavelengths, 45 mph

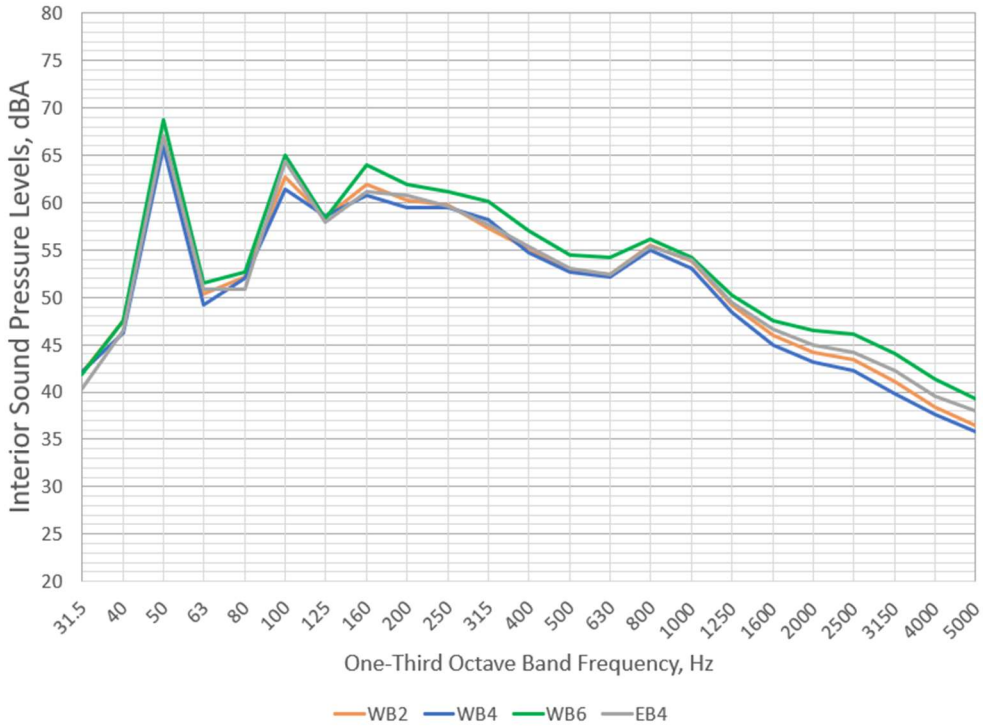

Figure F-30: Average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 16-inch wavelengths, 45 mph

Figures F-31 through F-34 show the spectra for the 13-, 14-, 15-, and 16-inch sites, respectively, as measured at the ST accelerometer. Comparing the amplitudes at excited frequencies for each site, the highest peak levels for each wavelength at the ST accelerometer occur at: EB9 (13-inch wavelength); EB3 (14-inch wavelength); EB10 (15-inch wavelength); and WB6 (16-inch wavelength). These are same as observed at 60 mph.

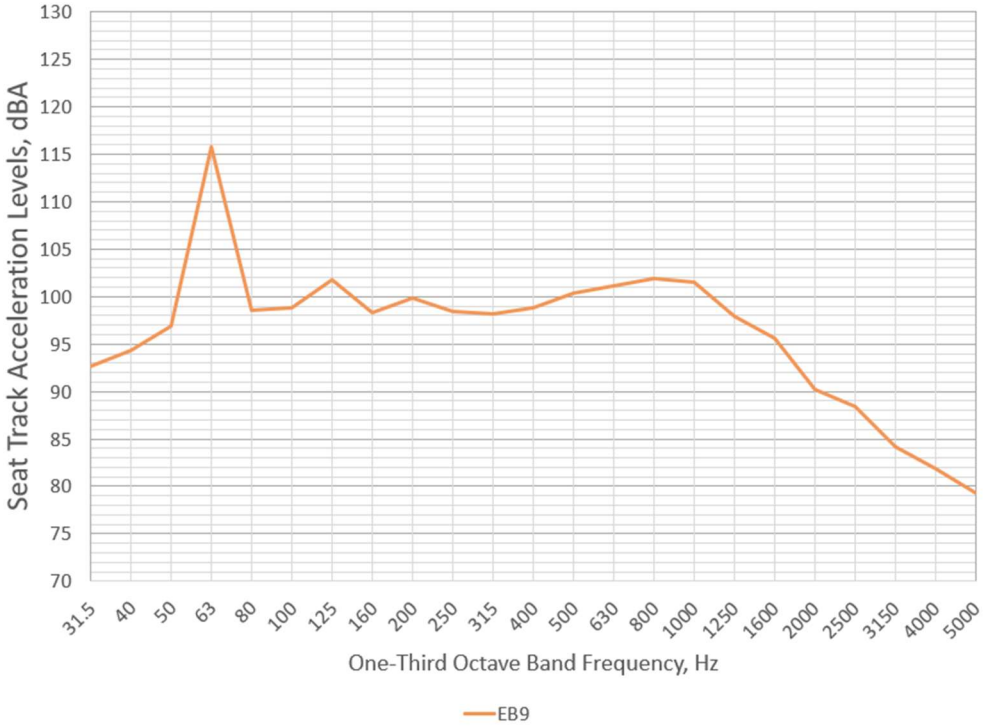

Figure F-31: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 13-inch wavelengths, 45 mph

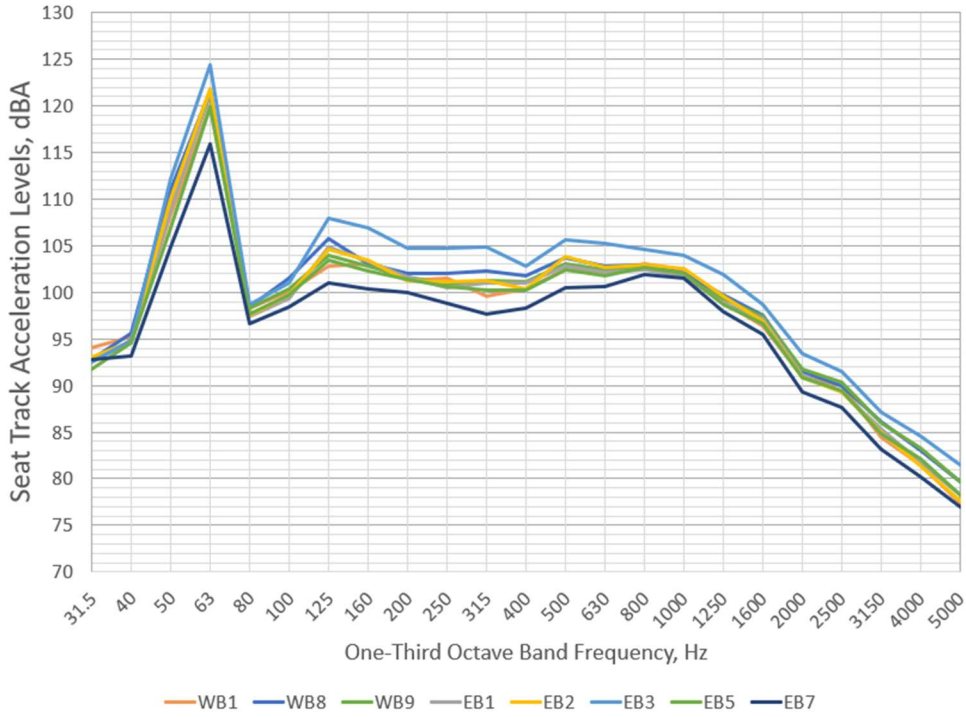

Figure F-32: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 14-inch wavelengths, 45 mph

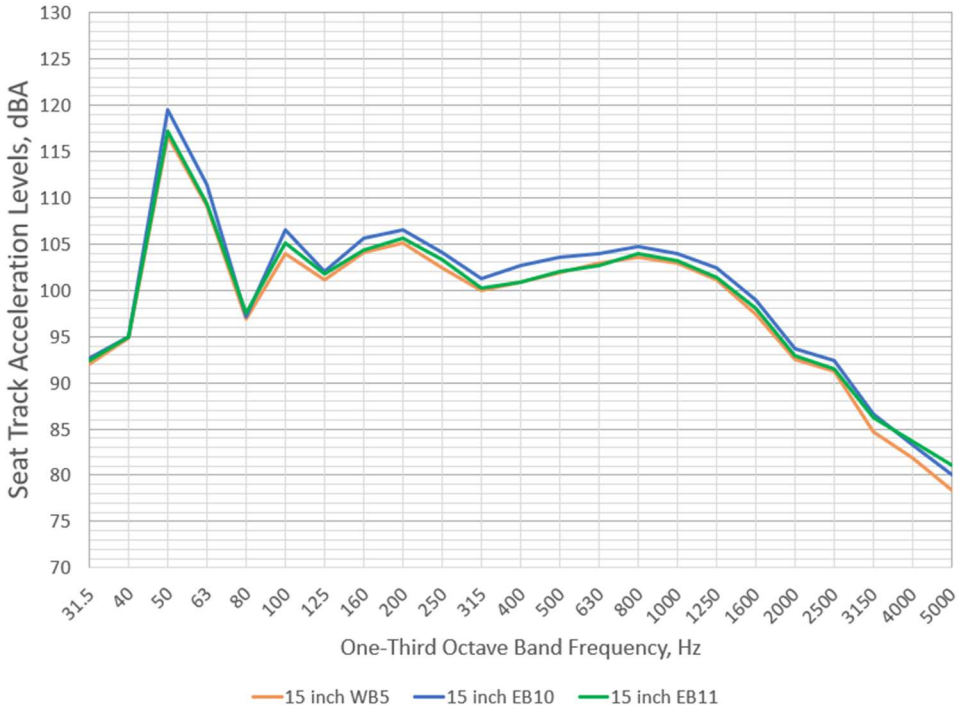

Figure F-33: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 15-inch wavelengths, 45 mph

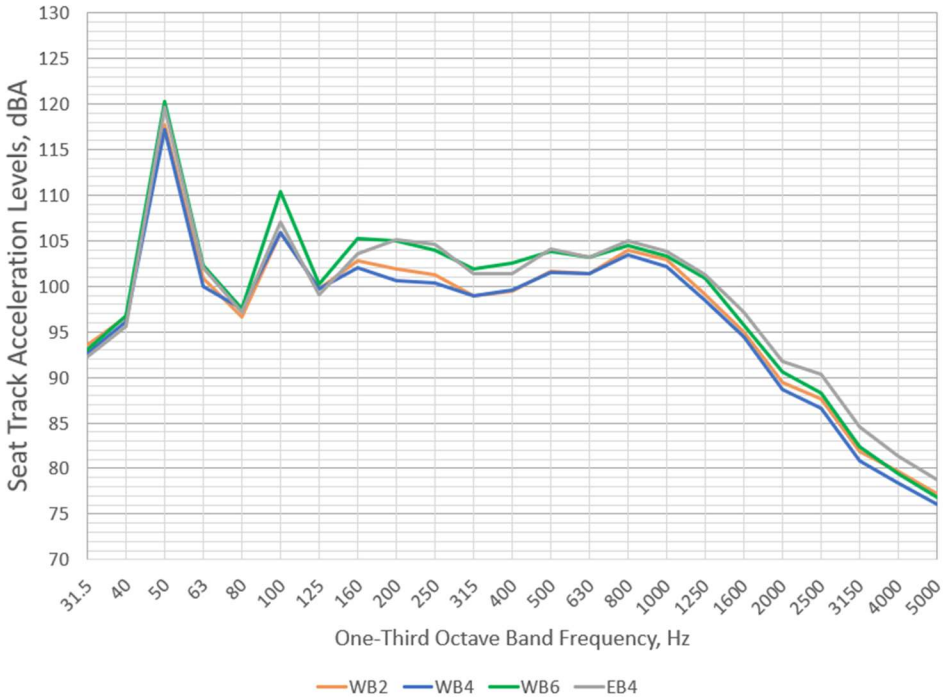

Figure F-34: Average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 16-inch wavelengths, 45 mph

Both the CC microphone and ST accelerometer had spectra with the highest peak levels occurring at the same sites: EB9 (13-inch wavelength); EB3 (14-inch wavelength); EB10 (15-

inch wavelength); and WB6 (16-inch wavelength). These are the same sites identified at 60 mph. Table E-2 summarizes the dimensions for these four sites. Figures F-35 and F-36 show the spectra for each of these sites on a single plot for the CC and ST sensors, respectively, at 45 mph. Both sensors have the highest peak level at EB3 (14-inch wavelength).

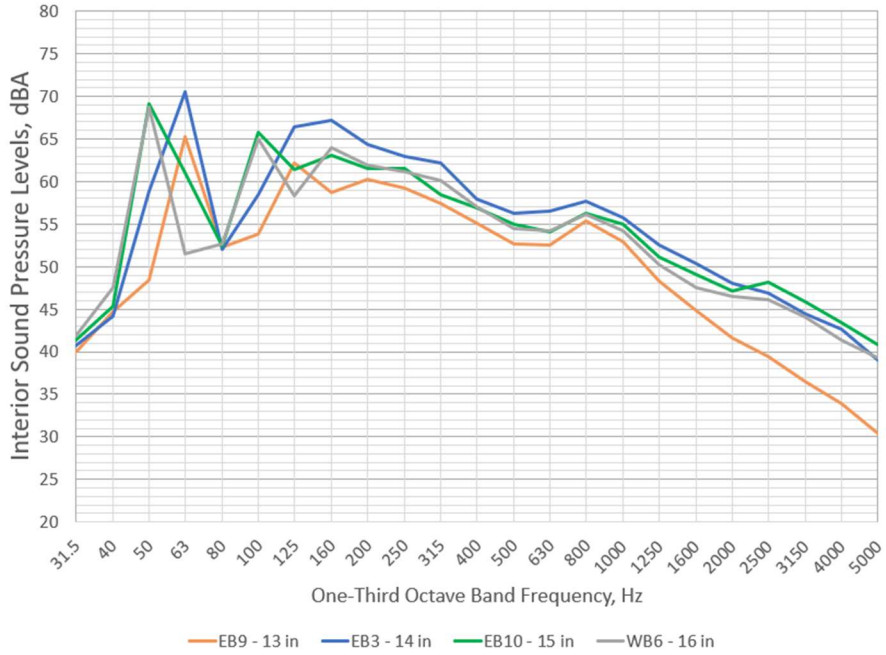

Figure F-35: Best average one-third octave band spectra measured with the CC microphone on the rumble strips at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 45 mph

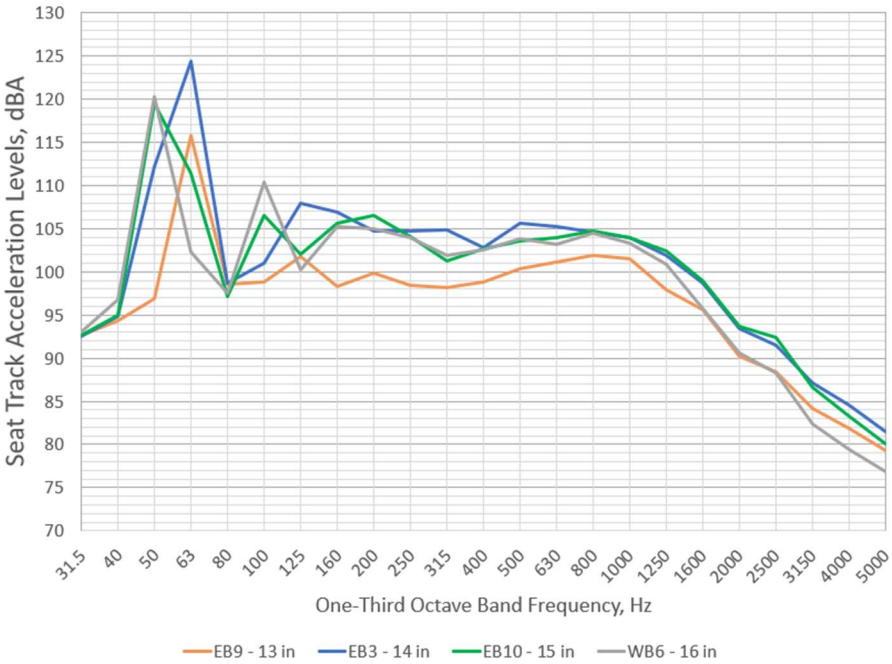

Figure F-36: Best average one-third octave band spectra measured with the ST accelerometer on the rumble strips at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 45 mph

Optimal Designs for Interior Noise and Vibration

Table F-3 summarizes all the sites and dimensions, as well as the average on/off increments calculated across all test vehicles for both the CC microphone and the ST accelerometer at 60 mph. Table F-4 shows the same for 45 mph. In both tables, the bold rows depict the sites where an average on/off increment of 10 dB or higher was calculated at both sensors. These rumble strip designs would meet the interior on/off difference of 10 dB or more. Note that none of the sites meet the criteria at 45 mph; however, EB3 has increments of over 10 dB at the ST sensor and 9.9 dB at the CC microphone. This is the closest site to meeting both criteria.

Table F-3: Installed dimensions of the sinusoidal rumble strips with average on/off increments for all test vehicles, 60 mph

Site	Measured Dimensions			On/Off Increments	
	Wavelength, in.	Amplitude, in.	Recess, in.	CC Microphone	ST Accelerometer
WB1	14	3/8	1/8	8.0	9.4
WB2	16	3/8	1/8	7.3	10.2
WB3	18	3/8	1/8	4.6	8.1
WB4	16	5/16	0	6.8	10.4
WB5	15	5/16	0	6.3	10.4
WB6	16	1/2	0	9.7	13.3
WB7	12	3/8	1/8	5.9	9.7
WB8	**14**	**7/16**	**0**	**10.0**	**12.1**
WB9	**14**	**1/2**	**1/8**	**10.3**	**11.8**
EB1	**14**	**5/16**	**0**	**10.1**	**11.2**
EB2	**14**	**5/16**	**0**	**10.5**	**11.6**
EB3	**14**	**1/2**	**0**	**12.6**	**14.2**
EB4	16	3/8	0	8.5	11.1
EB5	14	7/16	1/8	7.8	9.9
EB6	24	3/8	0	3.2	6.9
EB7	14	5/16	0	5.7	6.8
EB8	17	3/8	0	4.5	7.1
EB9	**13**	**5/16**	**0**	**11.6**	**10.8**
EB10	**15**	**7/16**	**0**	**11.7**	**13.1**
EB11	15	5/16	1/8	7.5	9.6

Table F-4: Installed dimensions of the sinusoidal rumble strips with average on/off increments for all test vehicles, 45 mph

Site	Measured Dimensions			On/Off Increments	
	Wavelength, in.	Amplitude, in.	Recess, in.	CC Microphone	ST Accelerometer
WB1	14	3/8	1/8	4.9	12.1
WB2	16	3/8	1/8	5.8	10.2
WB3	18	3/8	1/8	5.2	8.1
WB4	16	5/16	0	5.6	10.2
WB5	15	5/16	0	5.8	9.9
WB6	16	1/2	0	7.2	12.9
WB7	12	3/8	1/8	5.3	7.0
WB8	14	7/16	0	7.3	14.6
WB9	14	1/2	1/8	6.8	13.6
EB1	14	5/16	0	8.2	14.5
EB2	14	5/16	0	6.9	14.5
EB3	14	1/2	0	9.9	17.0
EB4	16	3/8	0	6.4	12.5
EB5	14	7/16	1/8	5.2	12.0
EB6	24	3/8	0	2.7	8.5
EB7	14	5/16	0	2.5	8.2
EB8	17	3/8	0	8.0	9.7
EB9	13	5/16	0	7.1	10.7
EB10	15	7/16	0	9.3	13.8
EB11	15	5/16	1/8	6.8	10.6

COMPARISON OF EXTERIOR PASS-BY MEASUREMENTS

Reducing noise levels propagated to the wayside is one of the main objectives of this study. Acceptable noise level reductions or on/off increment levels to meet this objective have not been established. However, the lower the on/off increments at the 25-foot pass-by microphone, the better. Since the foremost purpose of rumble strips is to alert drivers of lane departure, that should be considered when evaluating the pass-by results. The pass-by noise levels are intended to confirm lower levels than measured on the standard rectangular rumble strip design. Note that all increments for pass-by provided in this chapter reflect overall levels calculated by summing the energy between 31.5 and 200 Hz to reduce the impact of the chip seal pavement on the results.

Exterior Pass-by Noise Measurements – Wavelength Discussion

Figure F-37 shows the on/off increments for all test vehicles measured at each of the 20 sinusoidal test sites from a microphone positioned 25 feet from the center of the test vehicle, as well as the previous average data taken in the Midwest and California. Sites with 12-, 13-, and 14-inch wavelengths have average pass-by on/off increments of 5.5 to 7 dB, which are the highest of all the sites. Sites with 15- and 16-inch wavelengths had average increments of about 1.5 to 3 dB. The lowest average levels occurred at sites with 17-, 18-, and 24-inch wavelengths and were about 1 dB or less, which would likely not be audible differences to people along the wayside. While sites with 17-, 18-, and 24-inch wavelengths did have the lowest average increments, which would be optimal for pass-by results, these rumble strip designs are not optimal from an interior noise and vibration perspective since a 10 dB on/off difference was not measured on the vehicle interior.

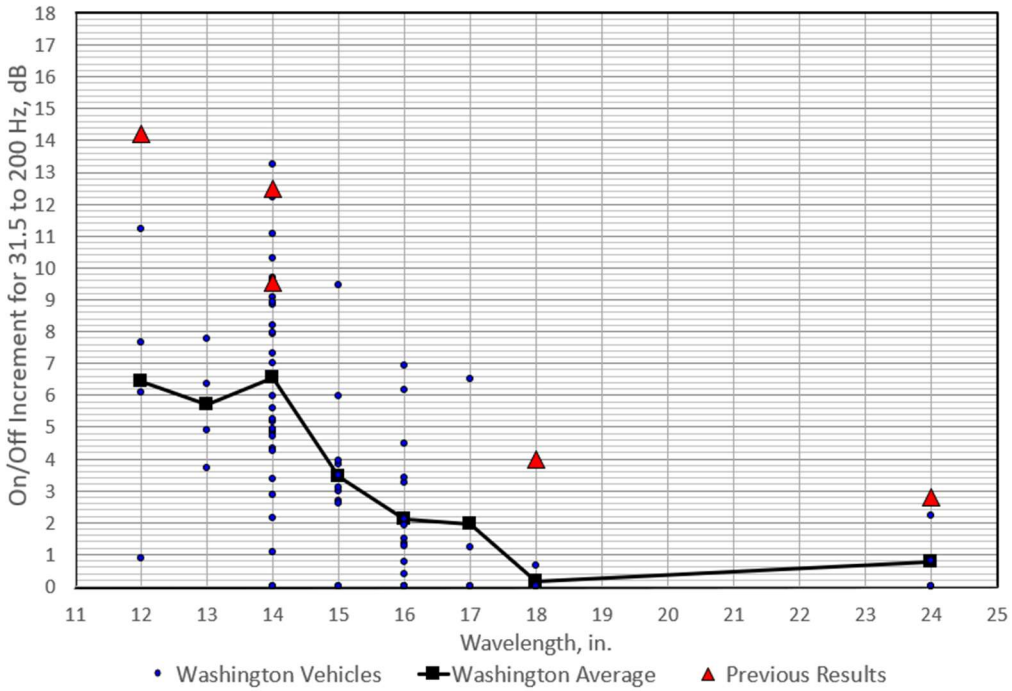

Figure F-37: On/off pass-by increments calculated at the maximum overall level versus wavelength of rumble strips for all test vehicles at all test sites, 60 mph

Figure F-38 shows the on/off increments for all test vehicles and at all test sites at 45 mph, as well as the previous average data taken in the Midwest and California. At 45 mph, the average pass-by on/off increments for all wavelengths were 2 dB or below, which would be barely perceptible.

On average, the 14-inch wavelength sites generate the highest on/off differences along the wayside at 60 mph, while 13-inch wavelength sites generate the highest at 45 mph. Sites with 15- and 16-inch wavelengths resulted in average on/off differences that would have little to no perceptibility along the wayside at both speeds.

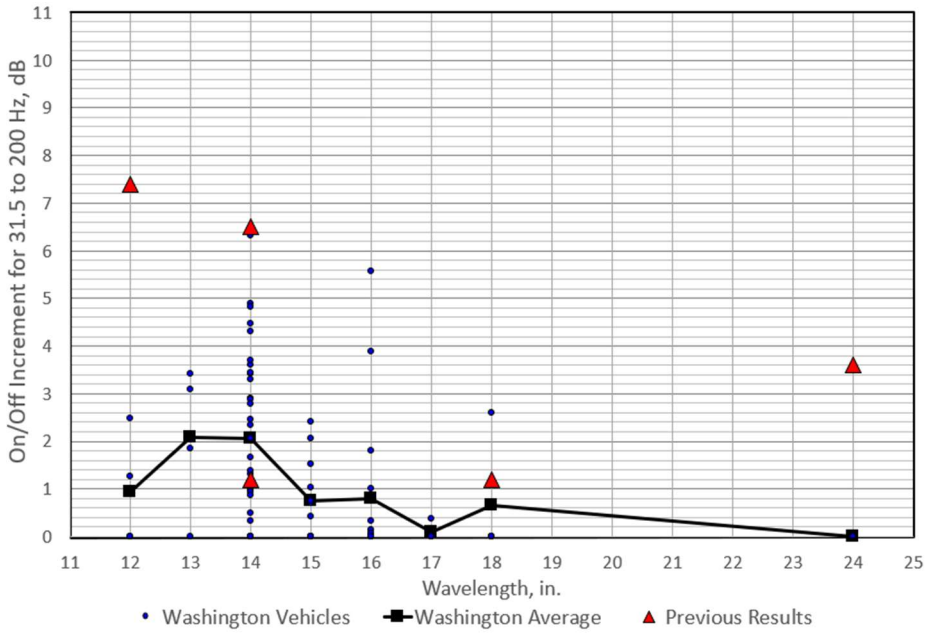

Figure F-38: On/off pass-by increments calculated at the maximum overall level versus wavelength of rumble strips for all test vehicles at all test sites, 45 mph

Exterior Pass-by Noise Measurements – Amplitude Discussion

Figure F-39 shows the on/off increments for all test vehicles and at all test sites, as well as the previous average data taken in the Midwest and California, versus amplitude at 60 mph. The increments in Figure F-39 were calculated at the time of the maximum overall level during the pass-by event. As identified for the vehicle interior measurements, sites with 3/8-inch peak-to-peak amplitudes had the lowest average on/off increments of about 2 dB. The highest average increments of 6 dB were measured at the sites with amplitudes of 7/16 and ½ inches.

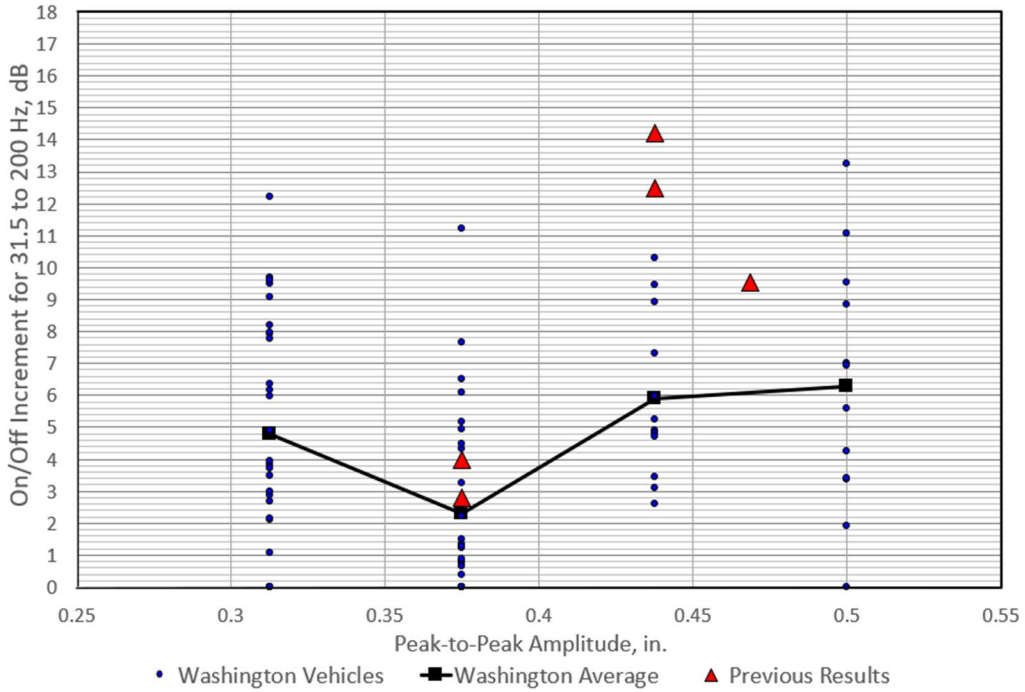

Figure F-39: On/off pass-by increments calculated at the maximum overall level versus peak-to-peak amplitude of rumble strips for all test vehicles at all test sites, 60 mph

Figure F-40 shows the on/off increments for all test vehicles and at all test sites, as well as the previous average data taken in the Midwest and California, versus amplitude at 45 mph. These increments were calculated at the time of the maximum overall level during the pass-by event. The average increments were below 2 dB for all amplitudes.

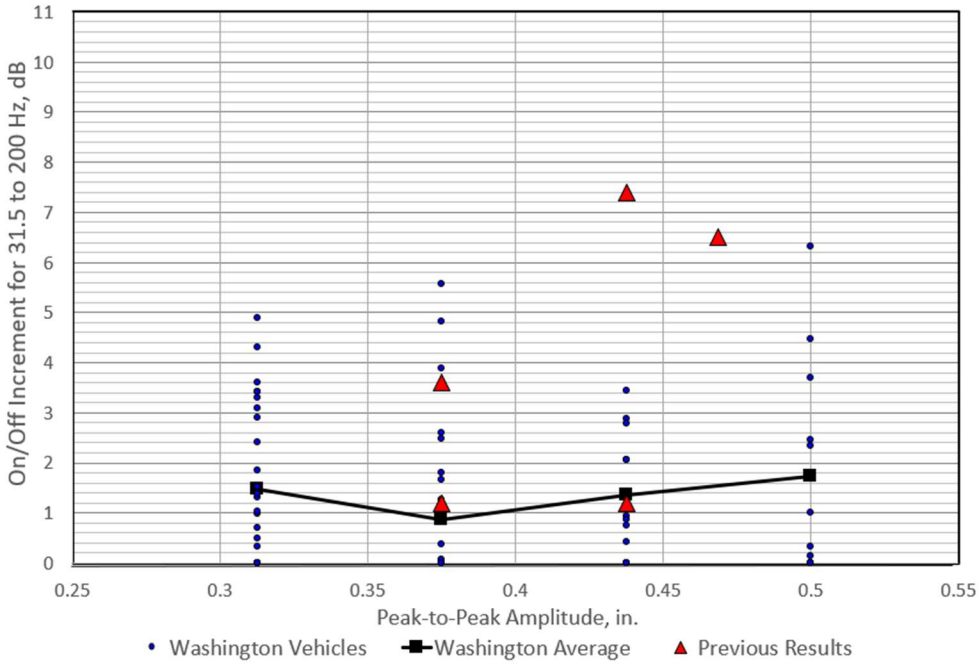

Figure F-40: On/off pass-by increments calculated at the maximum overall level versus peak-to-peak amplitude of rumble strips for all test vehicles at all test sites, 45 mph

Exterior Pass-by Noise Measurements – Recess Discussion

Figures F-41 and F-42 show the on/off increments versus the recess of each site at 60 and 45 mph, respectively. While the average increments at both recesses were within 2 dB of each other at 60 mph, which is statistically unremarkable, lower average increments were found at the 0-inch recess sites. Note, higher average increments were measured at the 0-inch recess sites on the vehicle interior. This provides the optimal results: lower on/off increments along the wayside and higher on/off increments on the vehicle interior.

The average increments at both 0- and 1/8-inch recesses at 45 mph were virtually 0 dB.

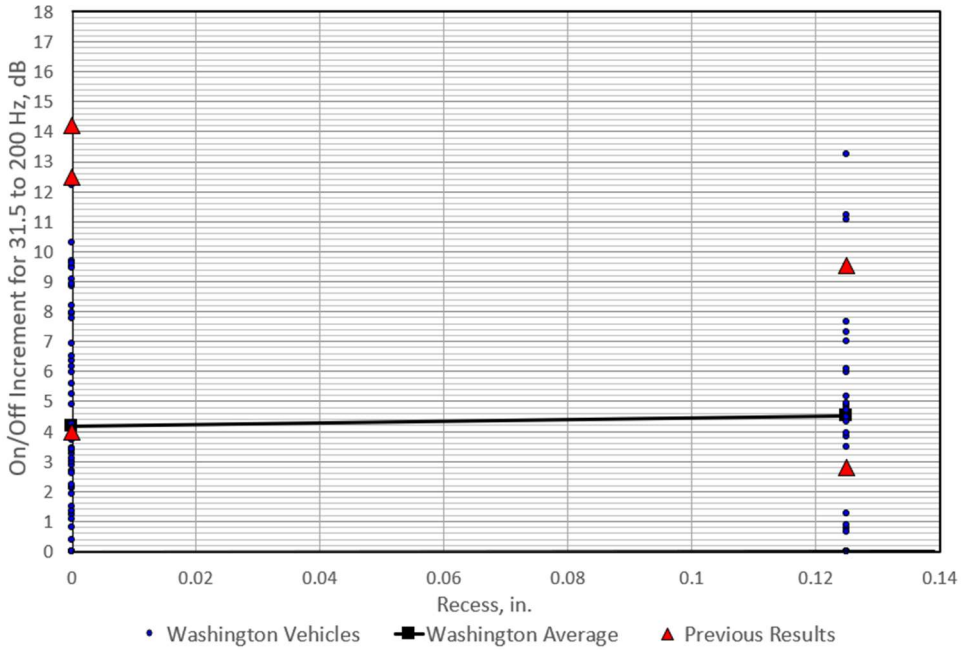

Figure F-41: On/off pass-by increments calculated at the maximum overall level versus recess of rumble strips for all test vehicles at all test sites, 60 mph

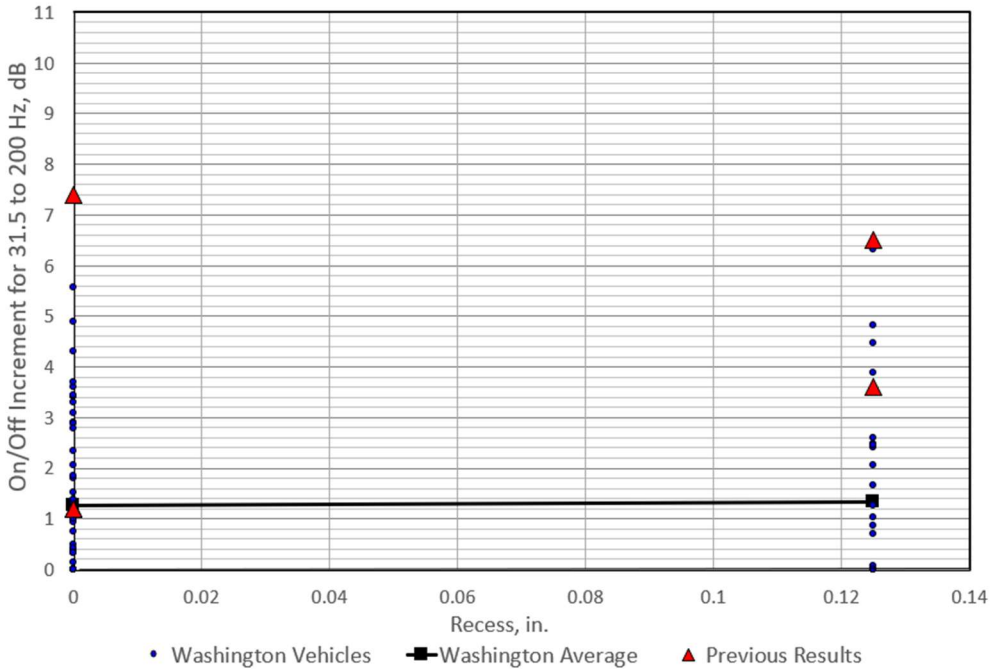

Figure F-42: On/off pass-by increments calculated at the maximum overall level versus recess of rumble strips for all test vehicles at all test sites, 45 mph

Exterior Pass-by Measurements – Spectra Discussion

Figures F-43 through F-44 show the spectra for the 13-, 14-, 15-, and 16-inch sites, respectively, as measured at the 25-foot pass-by microphone at 60 mph. Comparing the amplitudes at excited frequencies for each site, the lowest peak levels for each wavelength at the pass-by location occur at: EB9 (13-inch wavelength); EB7 (14-inch wavelength); EB11 (15-inch wavelength); and WB4 (16-inch wavelength).

Figure F-45 shows the optimal spectra for each wavelength from a pass-by perspective. Considering the peaks at the excited frequency bands, the optimal results were found at the 16-inch wavelength site (WB4). Table F-5 summarizes the installed dimensions for each of the optimal spectra shown in Figure F-45.

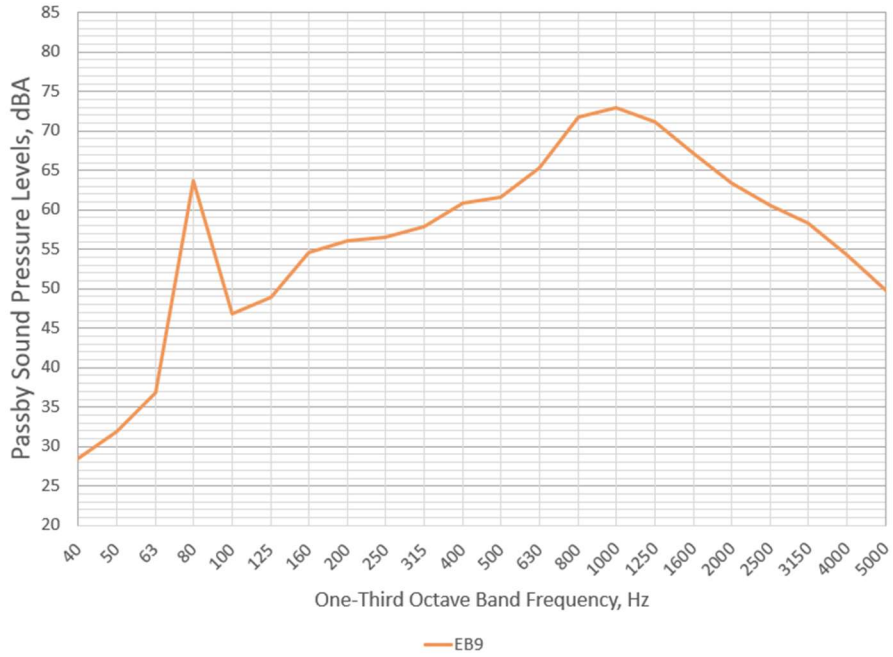

Figure F-43: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 13-inch wavelengths, 60 mph

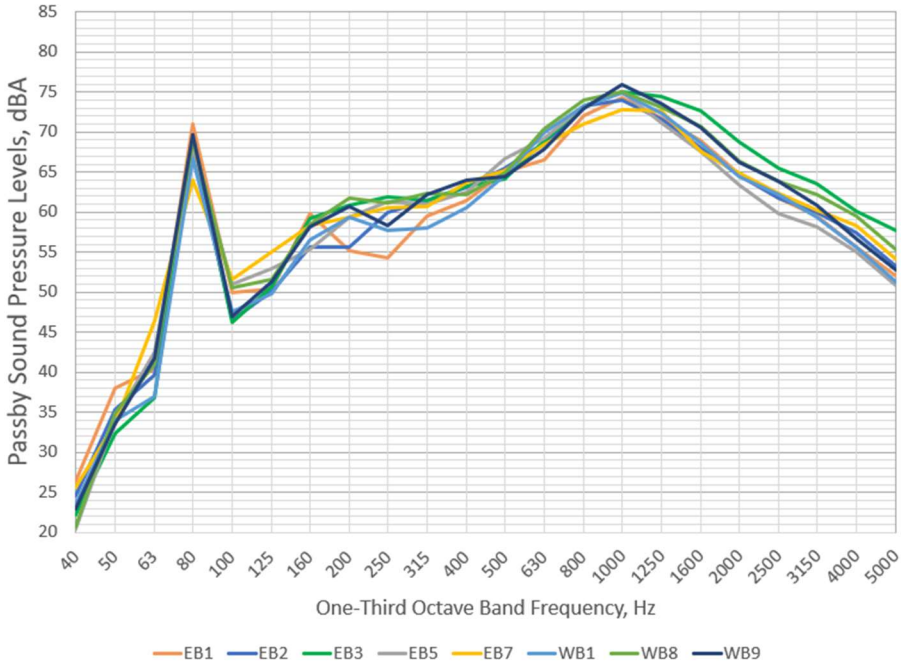

Figure F-44: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 14-inch wavelengths, 60 mph

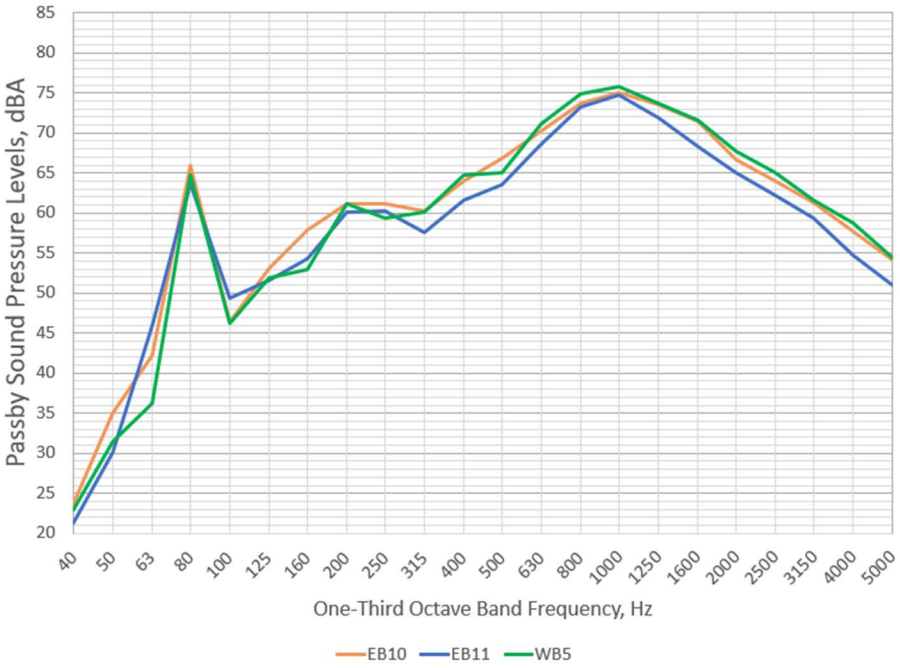

Figure F-45: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 15-inch wavelengths, 60 mph

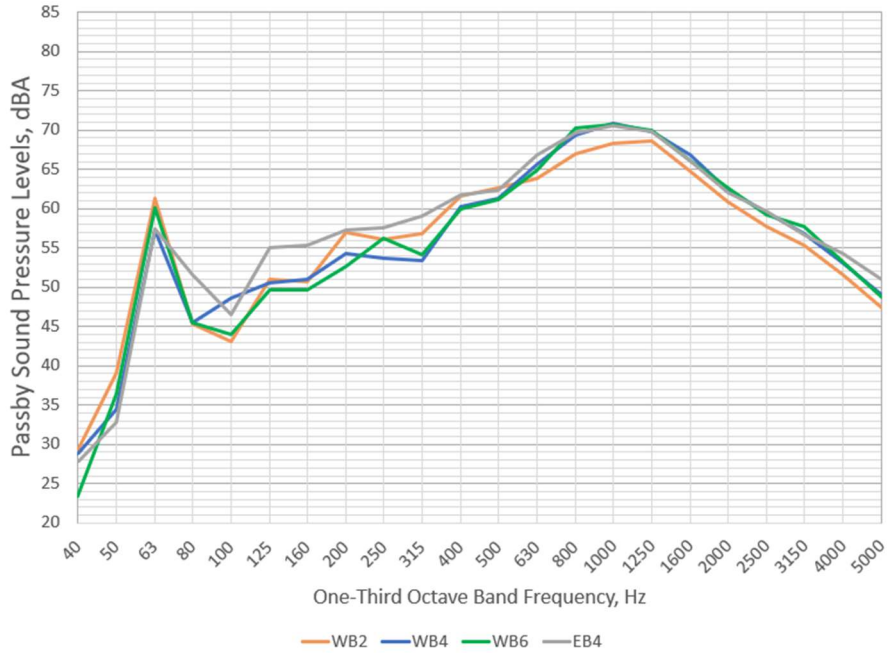

Figure F-46: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 16-inch wavelengths, 60 mph

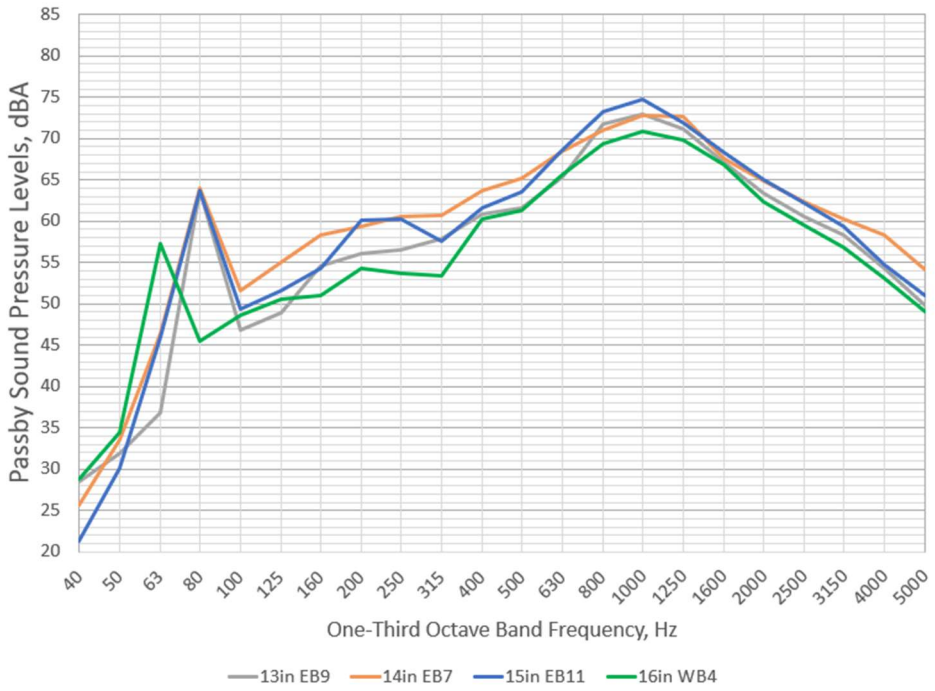

Figure F-47: Best average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 60 mph

Table F-5: Installed dimensions of the sinusoidal rumble strips for the optimal designs as observed from the exterior spectra data at 60 mph

Site	Measured Wavelength	Measured Amplitude	Measured Recess
WB4	16 inches	5/16 inches	0 inches
EB7	14 inches	5/16 inches	0 inches
EB9	13 inches	5/16 inches	0 inches
EB11	15 inches	5/16 inches	1/8 inches

Figures F-48 through F-51 show the spectra for the 13-, 14-, 15-, and 16-inch sites, respectively, as measured at the pass-by microphone at 45 mph. Comparing the amplitudes at excited frequencies for each site, the lowest peak levels for each wavelength occur at: EB9 (13-inch wavelength); EB7 (14-inch wavelength); EB10 (15-inch wavelength); and EB4 (16-inch wavelength).

Figure F-52 shows the optimal spectra for each wavelength from a pass-by perspective at 45 mph. Considering the peaks at the excited frequency bands, the optimal results were found at the 16-inch wavelength site (EB4). Table F-6 summarizes the installed dimensions for each of the optimal spectra shown in Figure F-52.

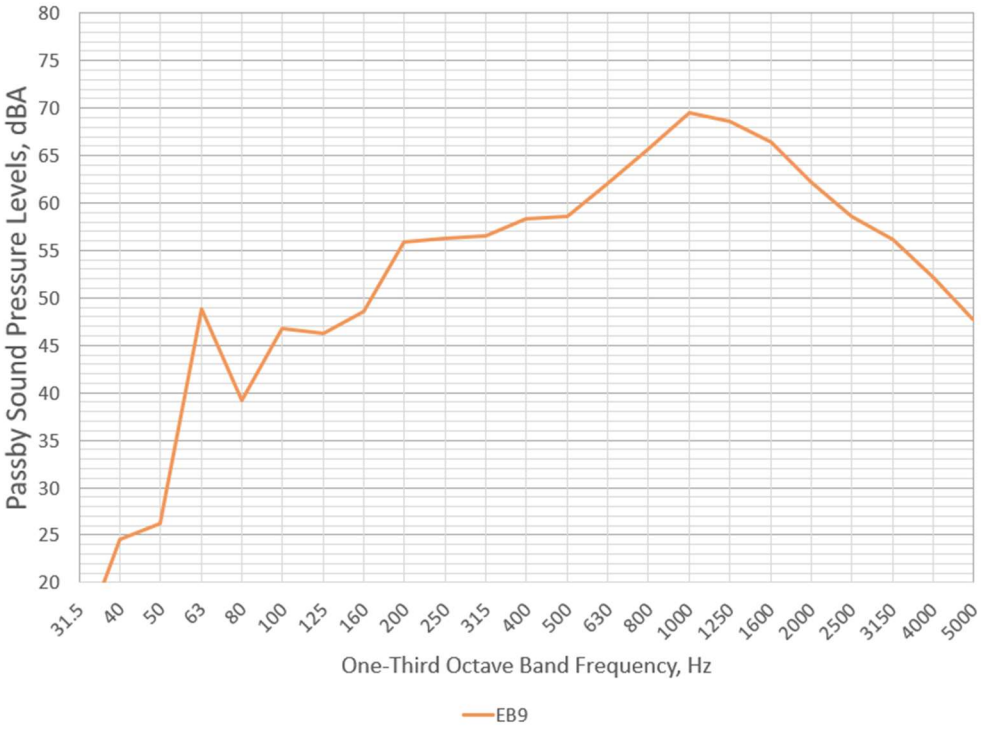

Figure F-48: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 13-inch wavelengths, 45 mph

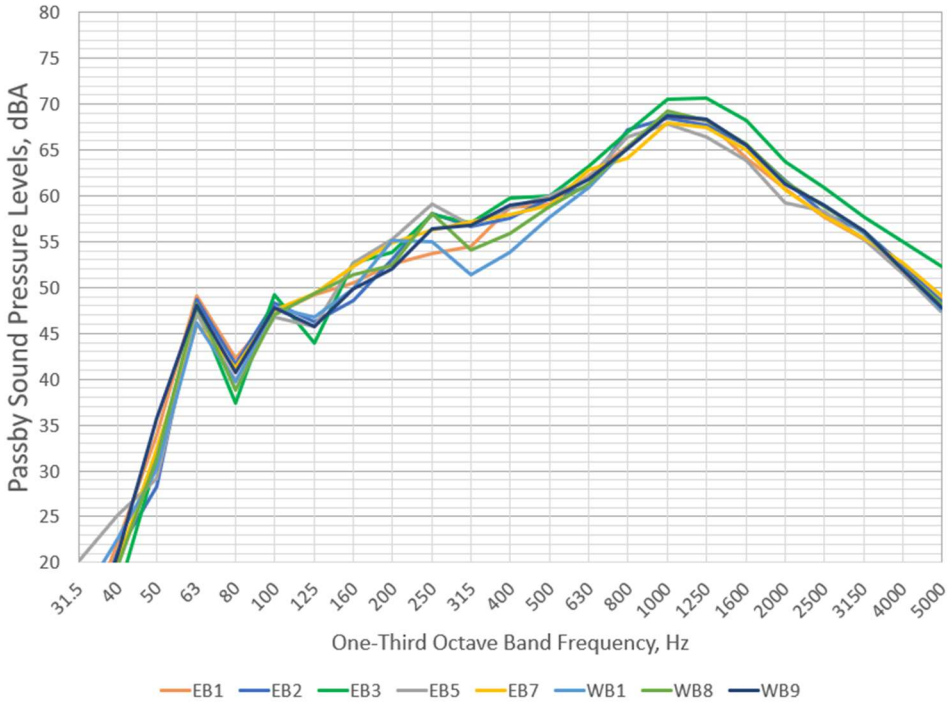

Figure F-49: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 14-inch wavelengths, 45 mph

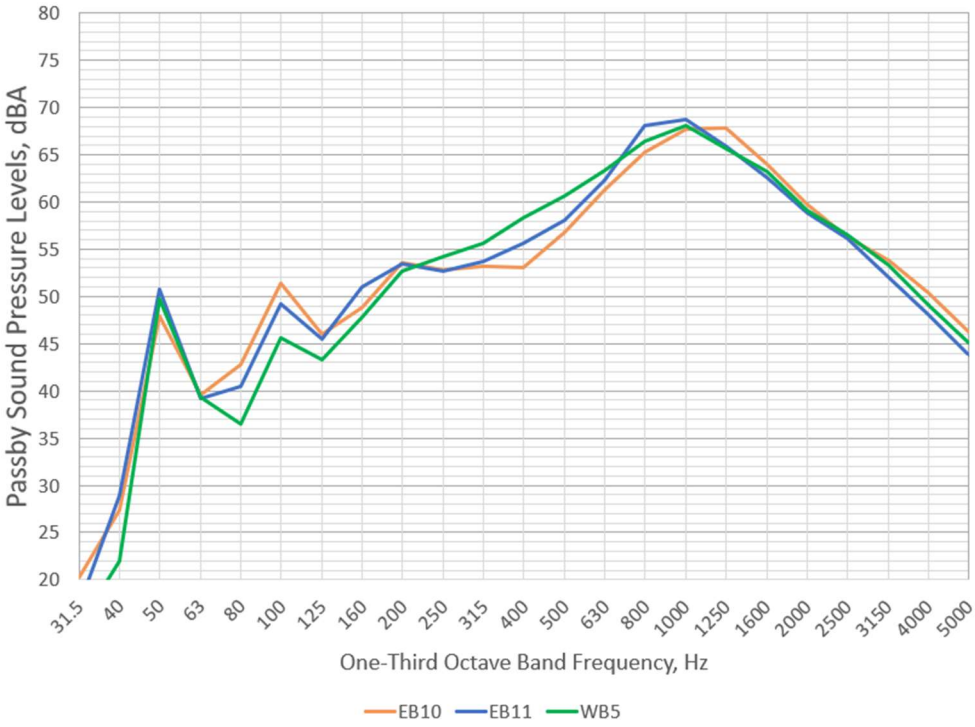

Figure F-50: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 15-inch wavelengths, 45 mph

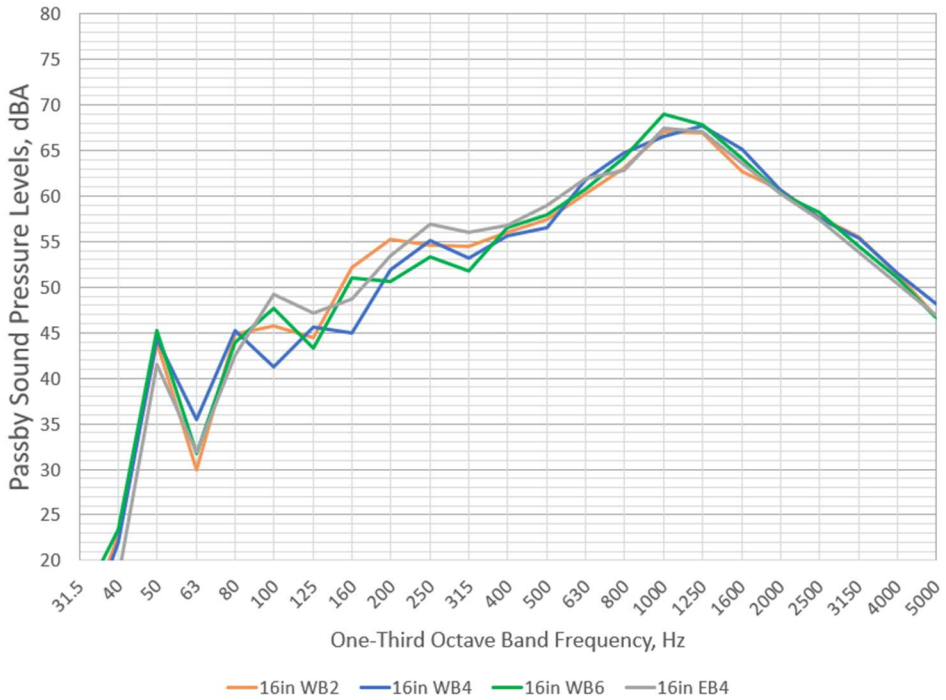

Figure F-51: Average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 16-inch wavelengths, 45 mph

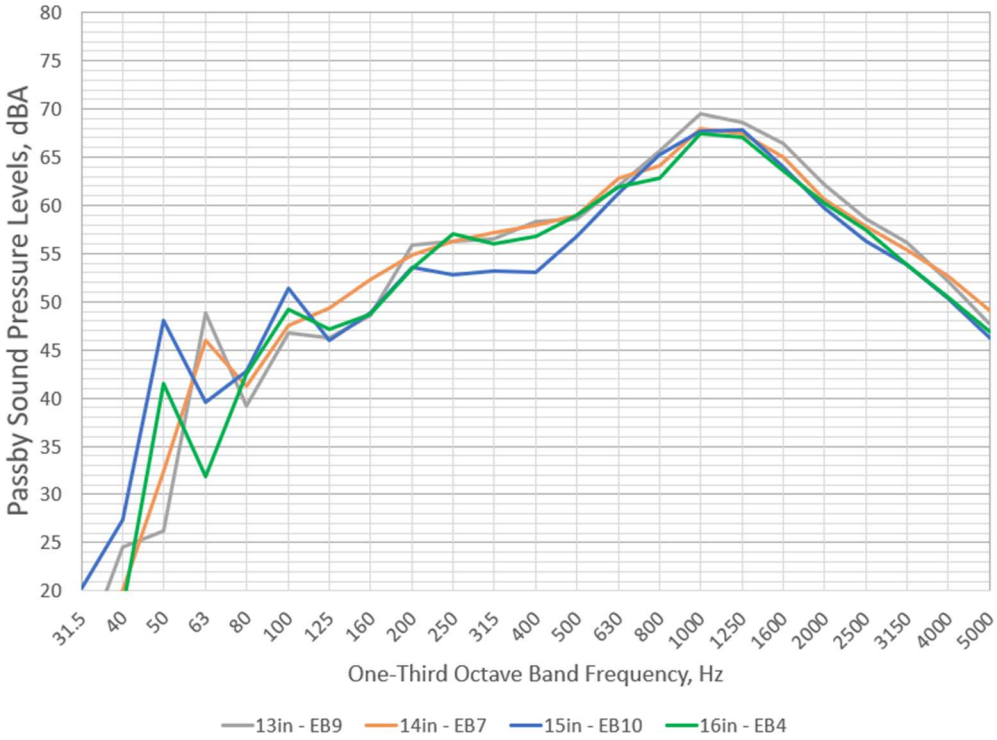

Figure F-52: Best average one-third octave band spectra measured at the pass-by location on the rumble strips at test sites with 13-, 14-, 15-, and 16-inch wavelengths, 45 mph

Table F-6: Installed dimensions of the sinusoidal rumble strips for the optimal designs as observed from the exterior spectra data at 45 mph

Site	Measured Wavelength	Measured Amplitude	Measured Recess
EB4	16 inches	3/8 inches	0 inches
EB7	14 inches	5/16 inches	0 inches
EB9	13 inches	5/16 inches	0 inches
EB10	15 inches	7/16 inches	0 inches

Optimal Designs for Exterior Noise

Table F-7 summarizes all the sites and dimensions, as well as the average on/off increments calculated across all test vehicles for the pass-by microphone and both interior sensors at 60 mph. Table F-8 shows the same for 45 mph. In both tables, the bold rows depict the sites where an average on/off increment of about 10 dB or higher was calculated at both interior sensors and about 5 dB or less was measured at the pass-by microphone. These rumble strip designs would meet the interior on/off difference of about 10 dB or more and an exterior on/off difference of 5 dB or less. At 60 mph, one site meets both criteria absolutely: EB10 (15-inch wavelength), which has peak-to-peak amplitude of 7/16 inches and a recess of 0 inches. At 45 mph, no site meets both criteria absolutely; however, 9.9 dB at the CC microphone is pretty close to the 10 dB threshold. The one site that is close to meeting both criteria is EB3, which has a 14-inch wavelength with ½-inch amplitude and 0-inch recess.

Table F-7: Installed dimensions of the sinusoidal rumble strips with average on/off increments for all test vehicles, 60 mph

Site	Measured Dimensions			On/Off Increments		
	Wavelength, in.	Amplitude, in.	Recess, in.	CC Mic.	ST Accel.	Pass-by Mic.
WB1	14	3/8	1/8	8.0	9.4	3.6
WB2	16	3/8	1/8	7.3	10.2	0.6
WB3	18	3/8	1/8	4.6	8.1	0.0
WB4	16	5/16	0	6.8	10.4	1.4
WB5	15	5/16	0	6.3	10.4	0.8
WB6	16	1/2	0	9.7	13.3	2.7
WB7	12	3/8	1/8	5.9	9.7	6.4
WB8	14	7/16	0	10.0	12.1	7.6
WB9	14	1/2	1/8	10.3	11.8	10.2
EB1	14	5/16	0	10.1	11.2	8.7
EB2	14	5/16	0	10.5	11.6	9.9
EB3	14	1/2	0	12.6	14.2	5.5
EB4	16	3/8	0	8.5	11.1	1.6
EB5	14	7/16	1/8	7.8	9.9	5.4
EB6	24	3/8	0	3.2	6.9	0.0
EB7	14	5/16	0	5.7	6.8	1.5
EB8	17	3/8	0	4.5	7.1	0.9
EB9	13	5/16	0	11.6	10.8	5.7
EB10	**15**	**7/16**	**0**	**11.7**	**13.1**	**4.7**
EB11	15	5/16	1/8	7.5	9.6	4.3

Table F-8: Installed dimensions of the sinusoidal rumble strips with average on/off increments for all test vehicles, 45 mph

Site	Measured Dimensions			On/Off Increments		
	Wavelength, in.	Amplitude, in.	Recess, in.	CC Mic.	ST Accel.	Pass-by Mic.
WB1	14	3/8	1/8	4.9	12.1	0
WB2	16	3/8	1/8	5.8	10.2	0
WB3	18	3/8	1/8	5.2	8.1	0
WB4	16	5/16	0	5.6	10.2	0
WB5	15	5/16	0	5.8	9.9	0
WB6	16	1/2	0	7.2	12.9	0.2
WB7	12	3/8	1/8	5.3	7.0	0.8
WB8	14	7/16	0	7.3	14.6	2.5
WB9	14	1/2	1/8	6.8	13.6	3.0

Site	Measured Dimensions			On/Off Increments		
	Wavelength, in.	Amplitude, in.	Recess, in.	CC Mic.	ST Accel.	Pass-by Mic.
EB1	14	5/16	0	8.2	14.5	3.7
EB2	14	5/16	0	6.9	14.5	1.8
EB3	14	1/2	0	9.9	17.0	1.3
EB4	16	3/8	0	6.4	12.5	1.7
EB5	14	7/16	1/8	5.2	12.0	0
EB6	24	3/8	0	2.7	8.5	0
EB7	14	5/16	0	2.5	8.2	1.3
EB8	17	3/8	0	8.0	9.7	0
EB9	13	5/16	0	7.1	10.7	2.1
EB10	15	7/16	0	9.3	13.8	0.7
EB11	15	5/16	1/8	6.8	10.6	0.5

SUMMARY AND CONCLUSIONS

While all the sinusoidal wavelength designs would reduce on/off increments at the exterior pass-by measurement locations from the conventional rectangular rumble strips, the wavelengths which resulted in consistent 10 dB or more increments on the vehicle interior at both the noise and vibration sensors were 13 to 16 inches.

Peak-to-peak amplitudes of 5/16, 3/8, 7/16, and 1/2 inches were tested, with 1/2 inches resulting in the highest on/off increments on the vehicle interiors. The amplitudes that resulted in the lowest on/off increments on the wayside was 3/8 inches.

Recesses from 0 to 1/8 inches were tested, with no direct correlation found on the vehicle interiors or at the exterior pass-by locations. However, the sites with 0-inch recesses had on/off increments slightly higher on the interior and slightly lower on the exterior than 1/8-inch recesses.

The average on/off increments across all four test vehicle categories were compared, and one site resulted in 10 dB or more increments with both interior noise and vibration sensors and also had pass-by increments of 5 dB or less at 60 mph. Additionally, one site resulted in about 10 dB or more increments with both interior noise and vibration sensors and also had pass-by increments of 5 dB or less at 45 mph. These sites include the following dimensions: 14- or 15-inch wavelengths, 7/16- or ½-inch peak-to-peak amplitudes, and 0-inch recesses.

- Sinusoidal wavelengths ranging from 14 to 15 inches. Considering potential issues with installation consistency, providing a nominal recommended wavelength of 14½inches with a safety tolerance of ±1/2 inch would be reasonable. Although this wavelength was not actually included in the matrix, both 14- and 15-inches generally provided better performance.

- Recess of 0 inches is recommended. In addition to providing the optimal interior and exterior noise and vibration results, installation of a 0-inch recess would likely be easier and repeatable. Further, it is expected that a 0-inch recess would be safer for bicyclists.

- Peak-to-peak amplitudes of 7/16 to 1/2 inches is recommended. Amplitudes of ½ inches consistently provided the highest interior on/off increments for interior noise and vibration. For pass-by measurements, both 7/16- and ½- inch amplitudes had similar results, which were not the lowest increments but reasonably low to reduce wayside disruption.