NCHRP Project 15-68(01)

EFFECTIVE LOW-NOISE RUMBLE STRIPS

APPENDIX C:
MIDWEST SINUSOIDAL STRIPS TESTING

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

Paul Donavan and Carrie Janello

Illingworth & Rodkin, Inc.
Cotati, California

The National Cooperative Highway Research Program (NCHRP) is sponsored by the individual state departments of transportation of the American Association of State Highway and Transportation Officials. NCHRP is administered by the Transportation Research Board (TRB), part of the National Academies of Sciences, Engineering, and Medicine, under a cooperative agreement with the Federal Highway Administration (FHWA).

APPENDIX C

MIDWEST SINUSOIDAL STRIPS TESTING

TABLE OF CONTENTS

INTRODUCTION

This appendix contains the NCHRP Rumble Strip Project Midwest sinusoidal strips testing, completed in 2020 and 2021.

MEASUREMENT PROGRAM

The purpose of the second part of Task 8 of the project was to collect more data on the performance of exiting rumble strips of different designs than those measured in California. Previous work and the results of the Phase I literature review indicated that sinusoidal profiles can 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 beyond those constructed in California and evaluated in Phase I of this project. Sites in Indiana and Michigan provided sinusoidal strips with wavelengths of 12, 14, 18, and 24 inches within about a two-hour drive of each other. After contacting Indiana and Michigan DOTs, it was decided to measure these strips using the procedures developed in Phase I of this project.

Description of Rumble Strips

Indiana Sites

The sinusoidal strips in Indiana are located on Highway US 1, just northwest of Fort Wayne. This is a semi-rural two-lane highway with posted speeds of 50 and 55 mph. The wavelengths of the strips are 12, 18, 24 inches installed on the shoulders under the edge-of- lane stripe and on the centerline under the stripes. These strips had previously been evaluated by Purdue University and the Indiana DOT, as first reported in 2016[1] and published in 2018[2]. The measurements conducted in the current research were done at the same locations as two of the sites used in the previous study, with the third site just slightly northeast of the previous site. The previous measurements were conducted using an intrusion method, in which the test vehicle was briefly operated on the strips simulating a sudden lane departure and correction. The design dimensions of the three sinusoidal strips are shown in Figure C-1.[1]

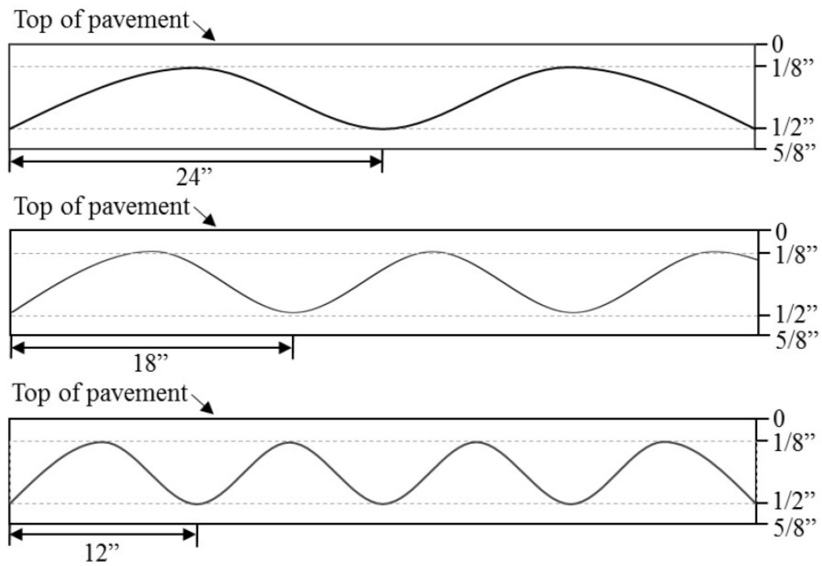


Figure C-1: Indiana sinusoidal rumble strips as designed

Upon initial visit to the sites, it was found that the pavement and 12- and 18-inch rumble strips had been overlaid with chip seal, while the 24-inch site appeared to be in its original as-milled condition. Photographs of the 12-inch rumble strips are shown in Figure C-2. The profiles of the strips were documented using a 20-inch contour gauge, producing the results shown in Figure C-3.

a) *Shoulder 12-inch strip*

b) *Centerline 12-inch strip*

c) *Shoulder 12-inch closeup*

Figure C-2: Photographs of the 12-inch sinusoidal rumble strips

From Figure C-2a and C-2b, the presence of the rumble strips is barely distinguishable from the coarse pavement. In the closer photograph (C-2c), the shape is more apparent, although not pronounced. In the measured profiles (Figure C-3), the green lines correspond to the nominal design wavelength, while the orange corresponds to the estimated, as installed wavelength. The measured wavelength appears to be less than the 12 inches specified; although, this is difficult to decipher given the regularity of the pavement surface. In comparison to the 10½ inch orange line shown at the top of Figure C-3, the wavelength appears to be in the range of 10½ to 11 inches. The light blue lines indicate the approximate peaks and valley of the rumble strip. For the shoulder strips in the longitudinal direction, the installed peak-to-peak dimension is about $^{7}/_{16}$ inches, which is slightly greater than the ⅜-inch specified. From the profile of the shoulder width taken at the trough of the sine wave, the overall depth of the rumble strip is also about $^{7}/_{16}$ inches instead of the ½ inches specified in Figure C-1.

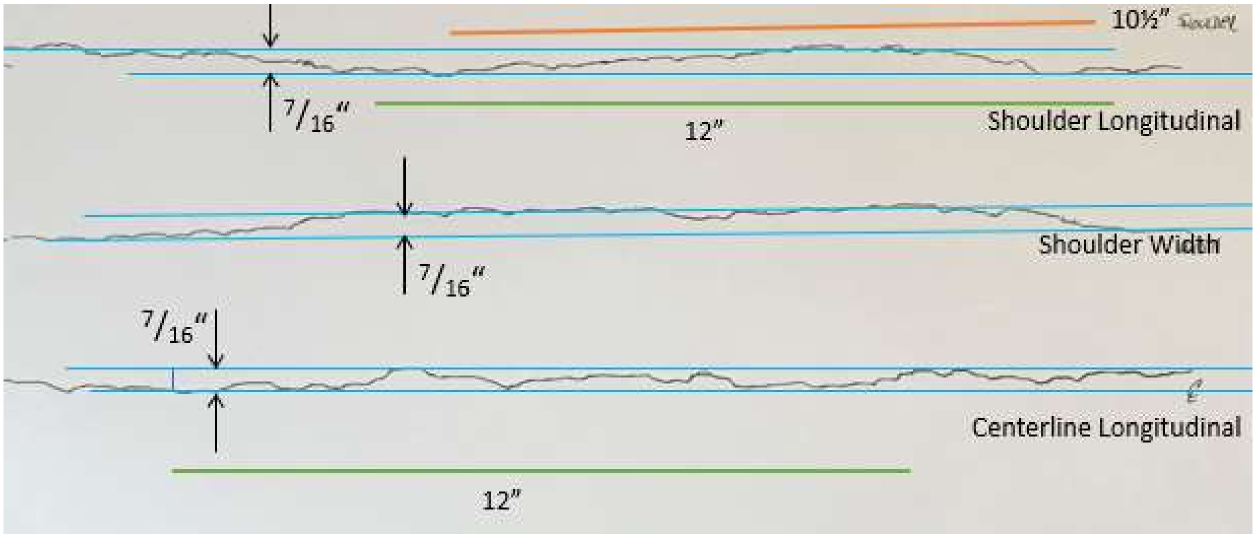


Figure C-3: Profiles of the 12-inch sinusoidal rumble strips as measured

Photographs of the 18-inch wavelength sinusoidal rumble strips are shown in Figure C-4. For these strips, the shape is even less obvious than it is for the 12-inch strips. The closeup of the shoulder strip in Figure C-4c indicates that the shape of the strip is all but lost relative to pronounced surface texture of the chip seal. This is borne out with the profiles shown in Figure C-5. In the first longitudinal profile of the shoulder strips (upper trace in Figure C-5), the shape is barely distinguishable, with a depth that appears to be less than $^{11}/_{32}$ inches, compared to the design depth of ⅜ inches. In the second trace, the shape is more distinguishable but indicates a peak-to-peak dimension of less than ⅜ inches on the right end of the trace. For the shoulder strip width, the depth varies across the trace, with a nominal depth of $^{5}/_{16}$ inches, compared to the design recess of ½ inch from the pavement surface for the trough of the sinusoidal shape. The loss of this recess may have been due to the application of the chip seal. For the centerline rumble strip, a sinusoidal shape is not distinguishable. The noted depth of $^{5}/_{32}$ inches is more between the local peaks and valleys, apparently produced by chip seal aggregate and raveling of the pavement. Across the centerline strips, a maximum depth of $^{9}/_{32}$ inches was determined; however, the shape of the recess is not apparent. From Figure C-1, a depth of ½ inch should have occurred.

a) Shoulder 18-inch strip

b) Centerline 18-inch strip

c) Shoulder 18-inch closeup

Figure C-4: Photographs of the 18-inch sinusoidal rumble strips

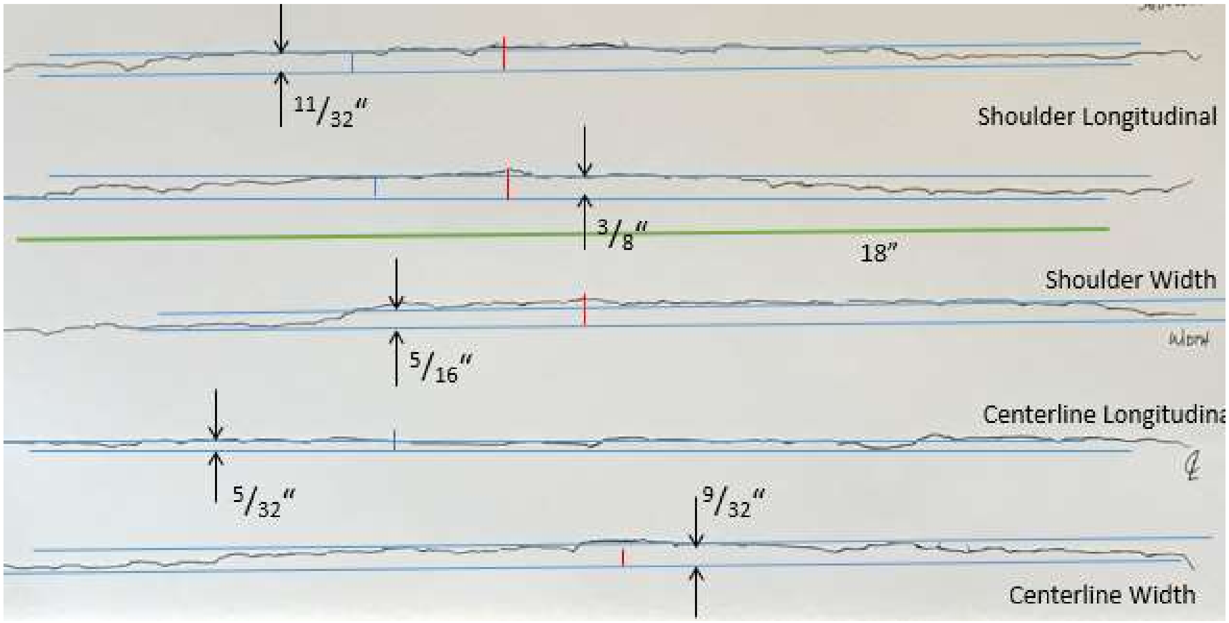


Figure C-5: Profiles of the 18-inch sinusoidal rumble strips as measured

Photographs of the 24-inch wavelength sinusoidal rumble strips are shown in Figure C-6. At this location, the pavement did not have a chip seal overlay like the 12- and 18-inch strips. As a result, the shape of the sinusoidal shape was better defined. The pavement had suffered some distress, and sealant had been applied at some time, particularly in the tire paths and the shoulder. The pavement was an older dense grade asphalt with less texture than the 12- and 18-inch sites. Visually from Figure 3-6c, the rumble strips did not appear to be as deeply recessed into the pavement as specified in Figure C-1. The profiles for these strips are shown in Figure C-7. Due to the 20-inch length of the contour gauge, a full 24-inch wavelength could not be documented; however, the peak to trough distance corresponding to half a wavelength could be captured, as shown in Figure C-7. As in Figure C-3, the green line in Figure C-7 corresponds to the designed half wavelength of 12 inches, and the orange line is the estimated half wavelength from the measured profile. Similar to the 12-inch strips, the wavelength of the 24-inch strips appears to be somewhat shorter than the specified dimension, with estimated length of 21 inches from the half wavelength measurement of 10½ inches. The peak-to-peak height for the upper two profiles in Figure C-7 corresponds to the specification of Figure C-1 of ⅜ inches, while the third profile is less at ¼ inches. The depth below the pavement surface is also less than the specification, varying from 7/16 to ⅜ inches compared to the depth of ½ inch in Figure C-1. For the rumble strips on the centerline, the peak-to-peak height corresponds to the ⅜ inches of Figure C-1, as does the 24-inch wavelength.

a) Shoulder 24-inch strip *b) Centerline 24-inch strip*

c) Shoulder 24-inch closeup

Figure C-6: Photographs of the 24-inch sinusoidal rumble strips

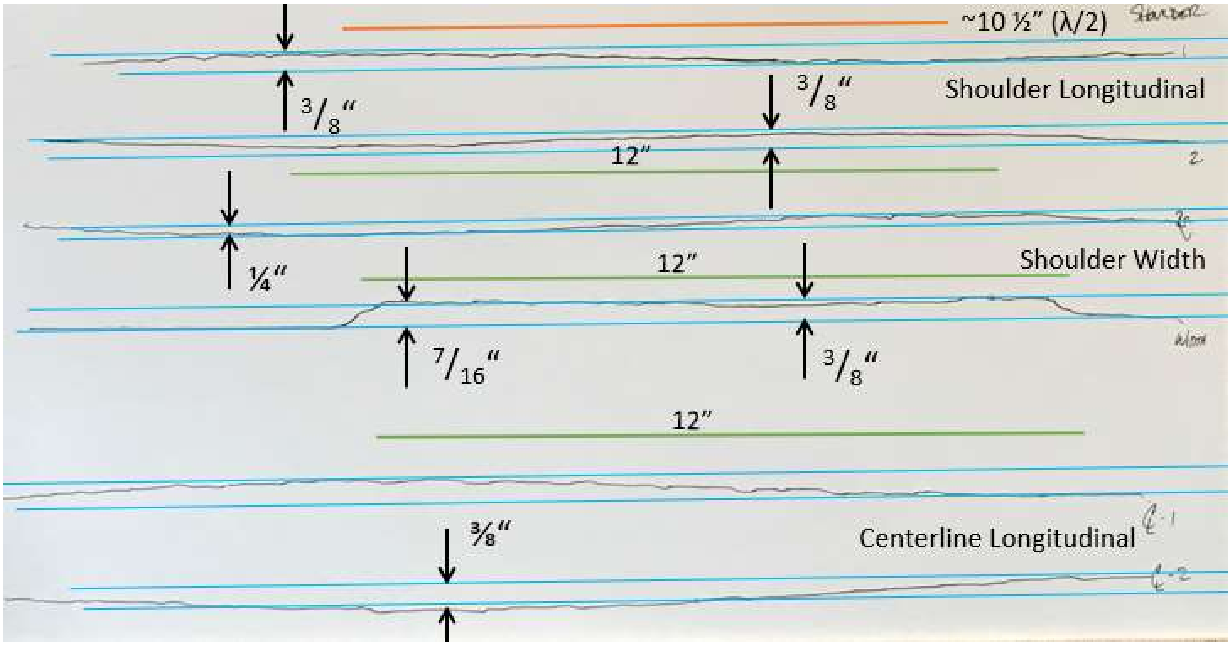


Figure C-7: Profiles of the 24-inch sinusoidal rumble strips as measured

Michigan Site

The site of the 14-inch wavelength sinusoidal rumble strips in Michigan was on State Route 124 just east of Brooklyn. SR 124 is also a two-lane highway in a semi-rural environment. The rumble strips were on the shoulders and centerline, and the posted speed limit was 55 mph. According to Michigan DOT, these strips were recently installed and had not yet been documented with noise or vibration measurements. The pavement appeared to be relatively new dense graded asphalt with fine aggregate. Photographs of the strips are shown in Figure C-8. For these strips, the recess is clearly visible from the photographs. The profile contours are shown in Figure C-9. For the installed shoulder strips, the wavelength appears to be somewhat longer than the nominal 14-inch, as shown in the upper two profiles, and is approximately 15⅛ inches. The centerline strips matched the nominal 14-inch design quite closely, as shown in the lower profile in Figure C-9. The peak-to- peak height of the strips was consistently $^{15}/_{32}$ inches for the shoulder and the centerline. The depth of the trough of the sine wave was $^{11}/_{16}$ inches, providing a recess of about $^{7}/_{32}$ inches. The shoulder strips were 16 inches wide and centerline strips 14 inches.

a) Shoulder 14-inch strip

b) Centerline 14-inch strip

c) Shoulder 14-inch closeup

Figure C-8: Photographs of the 14-inch sinusoidal rumble strips

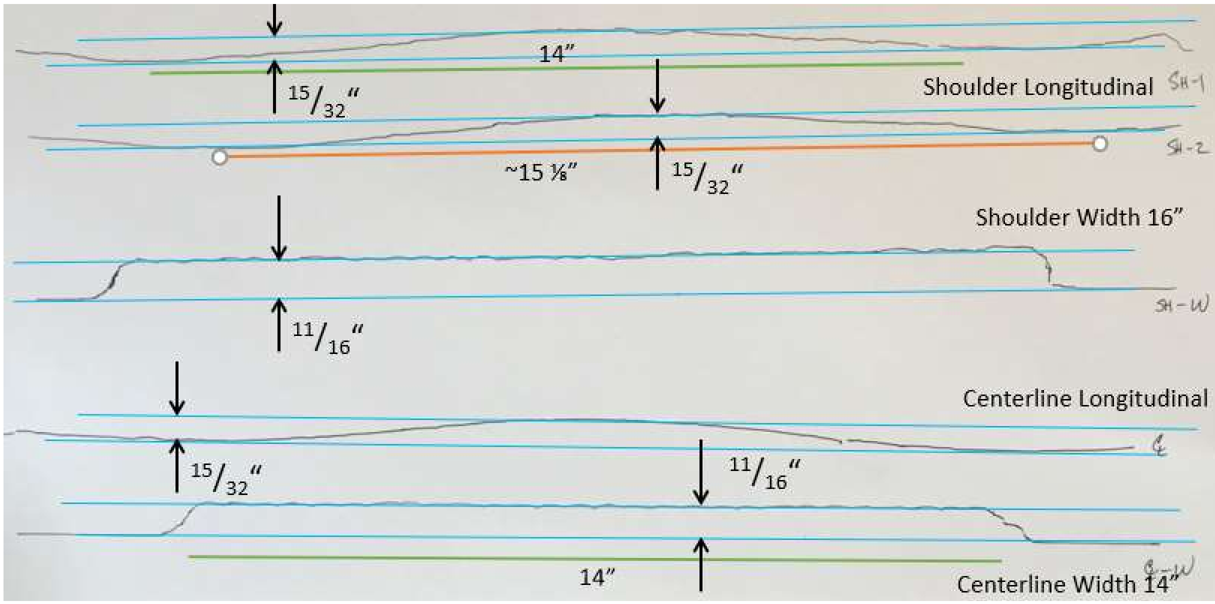


Figure 3-9: Profiles of the 14-inch sinusoidal rumble strips as measured

Test Vehicles

Following the recommended test procedure developed in Phase I, four vehicles were included in the measurements representing 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 Phase II testing, two sets of vehicles were used.

Figure C-10: Test vehicles used in the Midwest pass-by measurements

Figure C-11: Test vehicles used in the Midwest interior noise and vibration measurements

Except for Test Car C-4 and Test Car C-8, all other test vehicles were front wheel drive vehicles. Test Car C-4 and Test Car C-8 are 4-wheel drive capable, but tested in rear axle, 2-wheel drive. Table C-1 summarizes the vehicles' tire information and wheelbase.

Table C-1: Test vehicles with tire sizes and wheelbase dimensions

Test Car	Tire Size	Tire Dia. (in.)	Wheelbase (in.)	WB/λ 12 in.	WB/λ 14 in.	WB/λ 18 in.	WB/λ 24 in.
Test Car C-1	185/65R15	24	102	8.5	7.3	5.7	4.3
Test Car C-2	235/45R18	26	112	9.3	8.0	6.2	4.7
Test Car C-3	225/65R17	28	107	8.9	7.6	5.9	4.5
Test Car C-4	275/65R18	32	145	12.1	10.4	8.1	6.0
Test Car C-5	185/65R15	24	101.5	8.5	7.3	5.7	4.2
Test Car C-6	235/45R18	26	112	9.3	8.0	6.2	4.7
Test Car C-7	225/55R19	29	106.5	8.9	7.6	5.9	4.4
Test Car C-8	265/70R17	31	140.5	11.7	10.0	7.8	5.9

The metric wheelbase divided by the sinusoidal wavelength (WB/λ) defines the phase relationship of inputs to the vehicle. 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 eight test vehicles are reported in Table C-2. The corresponding interior cavity first and second modes are given in Table C-3 for the fore/aft, lateral, and vertical directions.

Table C-2: Test vehicle interior dimensions

Test Car	**Windshield/Backlite (Inches)**	**Door-to-Door (Inches)**	**Floor to Roof (Inches)**
Test Car C-1	115	54	47.5
Test Car C-2	122	61	46
Test Car C-3	130	60	49
Test Car C-4	101	71	48
Test Car C-5	105	56.5	46.5
Test Car C-6	113	61	46
Test Car C-7	121	60.5	48
Test Car C-8	96.5	71	48

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

Test Car	Frequency, Hz Fore/Aft		Frequency, Hz Lateral		Frequency, Hz Vertical	
	1st Mode	2nd Mode	1st Mode	2nd Mode	1st Mode	2nd Mode
Test Car C-1	59	118	125	251	143	285
Test Car C-2	56	111	111	222	147	295
Test Car C-3	52	104	113	226	138	276
Test Car C-4	67	134	95	191	141	282
Test Car C-5	64	129	120	239	145	290
Test Car C-6	60	120	111	221	147	294
Test Car C-7	56	112	112	223	141	281
Test Car C-8	70	140	95	190	141	281

Pass-by Noise Measurements

The shoulder rumble strips pass-by noise measurements were performed following the AASHTO TP-98 procedure,[2] modified for measurement of specific vehicles in a manner consistent the testing conducted in Phase I and the first set of measurements of Task 8 in Phase II. Two Larson Davis 831 sound level meters (SLM) were used. For pass-by off the rumble strips, one SLM was positioned 25 feet from the center of the 12-foot width lane of test vehicle travel. A second SLM was 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 25-foot SLM when on the rumble strip. For centerline rumble strips, a single Larson Davis LxT SLM was used six feet closer to the roadway, and the vehicle was operated in the opposite direction while on the centerline rumble strips. For the off-rumble strip measurements, the vehicle was 3 feet further away, 28 feet from the SLM, creating a 1 dB lower level relative to 25 feet, which was added back to the level for the off-strips case. The SLMs captured the one-third octave band pass-by noise using ⅛-second exponential averaging ("fast" response), sampled every 0.1 seconds for the duration of the pass-by. A typical SLM setup used for the pass-by measurements is shown in Figure C-12.

Figure C-12: Typical sound level meter arrangement for shoulder and centerline rumble strip pass-by noise measurements

Interior Noise Measurements

Following the recommended procedure from the conclusion of Phase I of the 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 bottom. The center center microphone was hung from the roof at the middle of the limits of the fore/aft seat adjustment and centered on the headrest, while the front center was hung from the roof at the foremost seat adjustment position and centered on the headrest.

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 location, as shown in Figure C-13, and at the secondary steering column position. All acceleration and interior noise data were acquired using National Instruments analog-to-digital converters and LabView software. These consisted of 0.1 second 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.

Figure C-13: Triaxial accelerometer installed at the seat track location

On-Board Sound Intensity Measurements

On-board sound intensity (OBSI) measurements were made at each of the Indiana and Michigan sites. These measurements were conducted according to the AASHTO Standard Method of Test T 360[3]. As described in the Task 8 Report completed for Phase II in California, OBSI data was collected at a vehicle speed of 60 mph. Test Car C-2 was the test vehicle used for the OBSI testing in Indiana on October 22, 2020, between 4:00 p.m. and 5:00 p.m. At the Michigan site, Test Car C-6 was used as the test vehicle on June 10, 2021, between 10:00 a.m. and 10:30 a.m. At all four sites, three runs were made, with a standard deviation of 0.2 dB or less. The same setup, hardware, and acquisition system described in the March 3, 2020, Task 8 Report were used here.

EXTERIOR NOISE MEASUREMENT RESULTS

Community response to the noise generated by lane departures can be a deterrent to the installation of rumble strips and be a source of complaint after they are installed. The primary concern is the increase in noise level when a vehicle "strikes" the strips. This increase is defined both by the pass-by noise off of the strips and the noise on the strips. The noise off of the strip is a function of the pavement type and age. As a result, measurements were performed both to evaluate the on/off performance of the strips and the performance of the pavement as the baseline level. Previous research has shown that the difference in pass-by noise level can vary as much as 13 dB depending on the pavement[4]. As a result, on/off performance of a given rumble design is determined by the geometry of the strip and the pavement on which it is installed.

On-Board Sound Intensity

Each of the sites in Indiana and Michigan were located along two-lane highways. Since the centerline measurements were made in the far lane, OBSI data was collected in both directions at the location where the pass-by measurements were made. Five-second averages were made continuously for the entire length of the test site. All data collected at each site was averaged for an overall level. Figure C-14 summarizes the overall OBSI results at each test site in both directions of travel. As previously mentioned, a chip seal overlay had been applied at the 12- and 18-inch sites, and the non-overlaid 24- and 14-inch sites were an older DGAC pavement.

The chip seal sites resulted in overall OBSI levels of 105.7 and 107.3 dB at the 12-inch site and 106.9 and 107.5 dB at the 18-inch site. The average of both lanes at each site was 106.5 and 107.2 dB for the 12-inch and 18-inch sites, respectively. The 24-inch DGAC site had levels of 103.5 and 103.6 dB, which averaged to be 103.6 dB. In Michigan, the 14-inch site had levels of 103.5 and 103.9 dB, which averaged to be 103.7 dB.

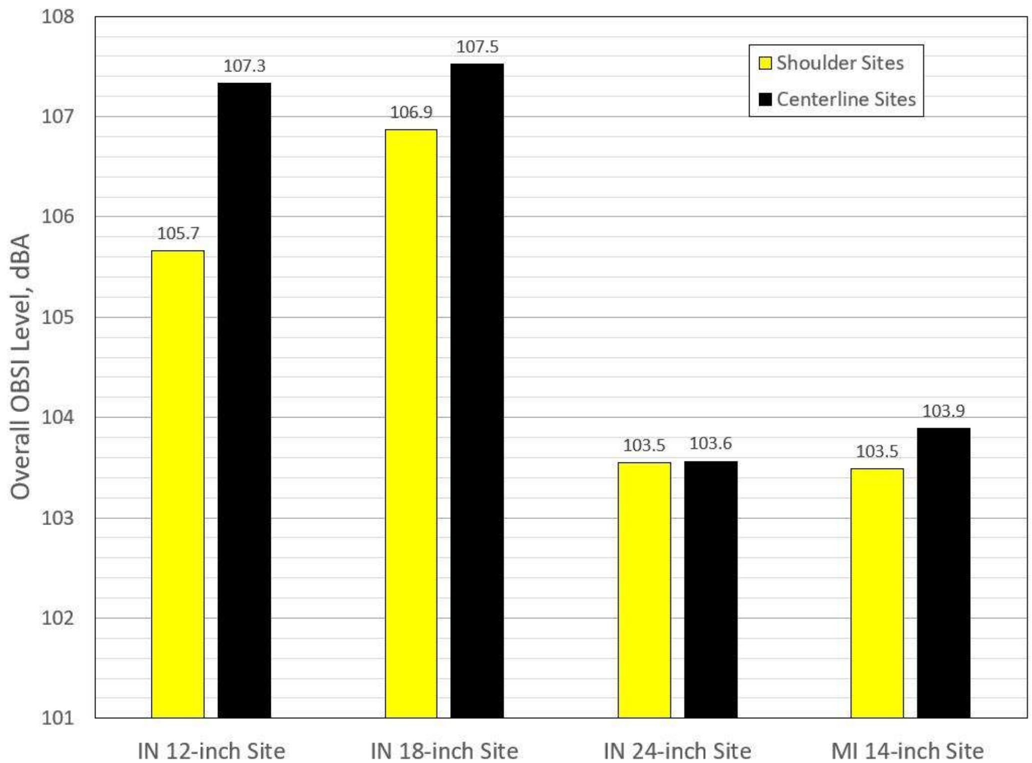


Figure C-14: Temperature-corrected overall OBSI levels at the Indiana and Michigan test sites, measured off strips

The average spectra measured at each test site and in both directions (shoulder side and centerline side) are shown in Figure C-15. Each spectra measured on the older DGAC pavement, which includes the 24-inch test site in Indiana and the 14-inch test site in Michigan, have peaks at 1,000 Hz. The peaks measured at the 14-inch Michigan site were about 102 dB, while the peak levels at the 24-inch Indiana site were about 100 dB. The chip seal overlay at the 12- and 18-inch test sites shifted the peak levels to 800 Hz and had a bit more variation between the shoulder and centerline lanes. The peak levels at the 12-inch site ranged from 101 dB at the shoulder to 103 dB at the centerline. The peak levels at the 18-inch site ranged from 103 to 104 dB. Based on the general spectral trends shown in Figure C-15, the higher overall levels for the chip seal sites are dominated by the levels below 800 Hz.

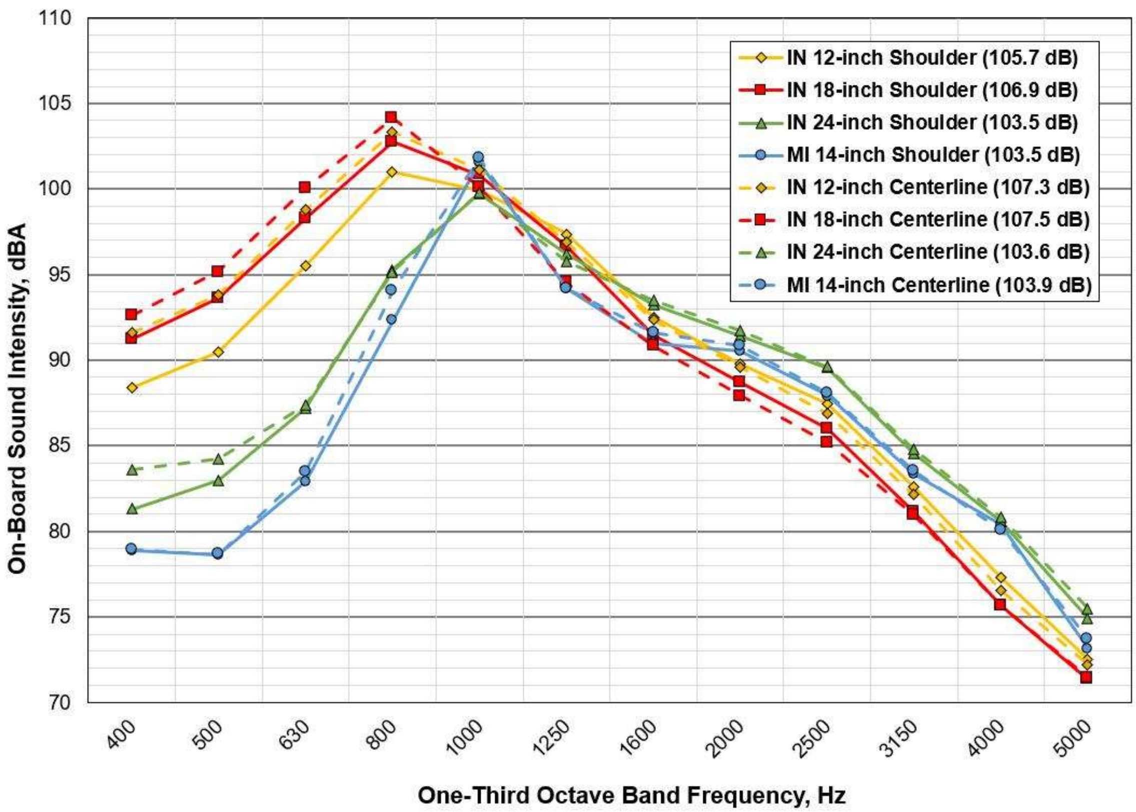


Figure C-15: Average one-third octave band spectra measured at the 12-, 18-, and 24-inch mumble strip test sites in Indiana and the 14-inch site in Michigan

The centerline and shoulder levels at each site were averaged together to estimate a single overall level and spectra. Figure C-16 compares the overall OBSI levels measured in Indiana and Michigan to the overall OBSI levels measured in California at the 14-inch mumble strip site and the California conventional rumble strip site. The fairly new DGAC pavement at the 14-inch California mumble strip resulted in the lowest overall level of 101.7 dB, which was about 2 dB lower than the older DGAC pavements at the 14- and 24-inch sites in the Midwest. However, the aged DGAC at the California conventional rumble strip site was 107.1 dB, which was over 3 dB higher than the older DGAC pavements in the Midwest. While the ages of each pavement are unknown, it would seem reasonable to assume that the DGAC pavements in the Midwest were considerably newer than the California conventional rumble strip site. Further, the aged DGAC pavement at the California conventional rumble strip site is comparable to the chip seal overlay located at the 12- and 18-inch sites in Indiana, which were 106.5 and 107.2 dB, respectively.

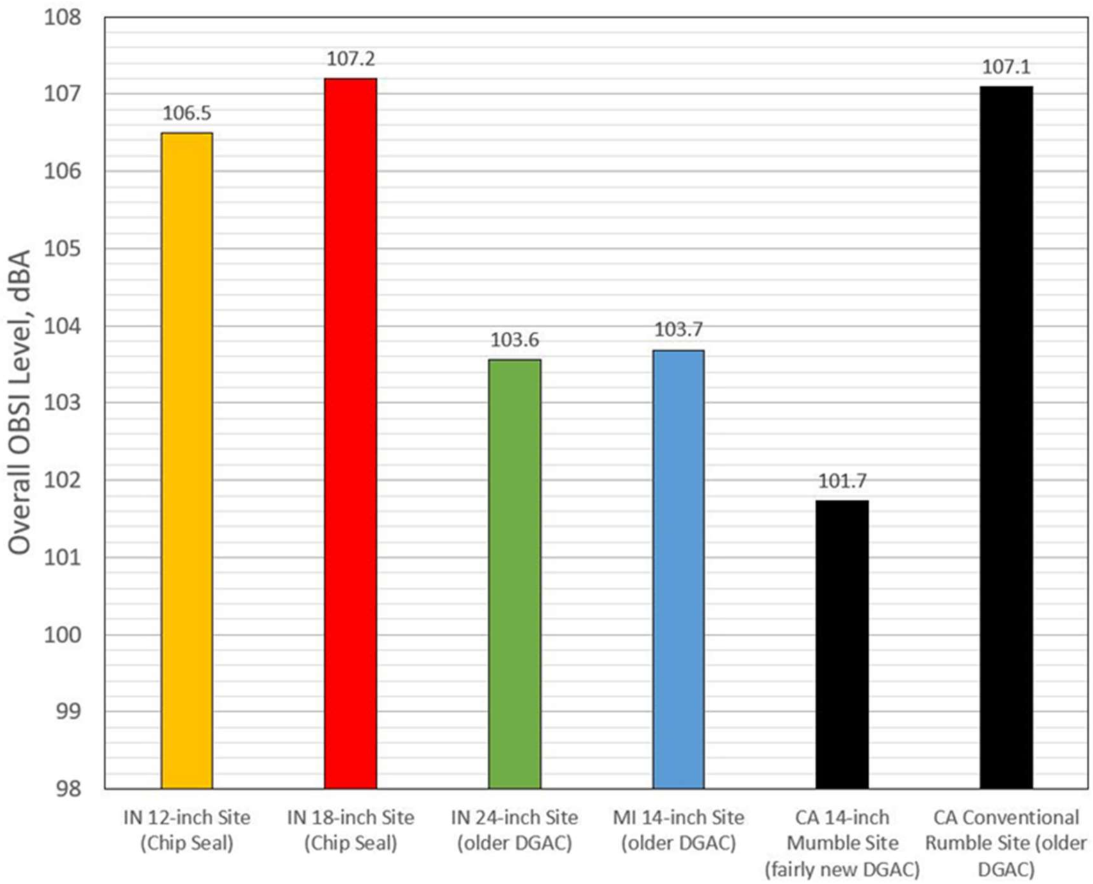


Figure C-16: Average overall OBSI levels at the Indiana and Michigan test sites compared to the California test sites

The average one-third octave band spectra for the shoulder and centerline sites in Indiana and Michigan were compared to the one-third octave band spectra measured at the California test sites (see Figure C-17). The peak level at both of the California test sites occurred at 800 Hz, similar to the chip seal sites in Indiana. The aged DGAC at the California conventional rumble strip site is nearly identical to the 18-inch chip seal site in Indiana at frequencies of 800 Hz and below. The aged DGAC pavement at the 14-inch site in Michigan had levels lower than all other spectra at frequencies of 800 Hz and below, while the newer DGAC pavement at California's 14-inch mumble strip site was lower than all other spectra above 800 Hz.

…

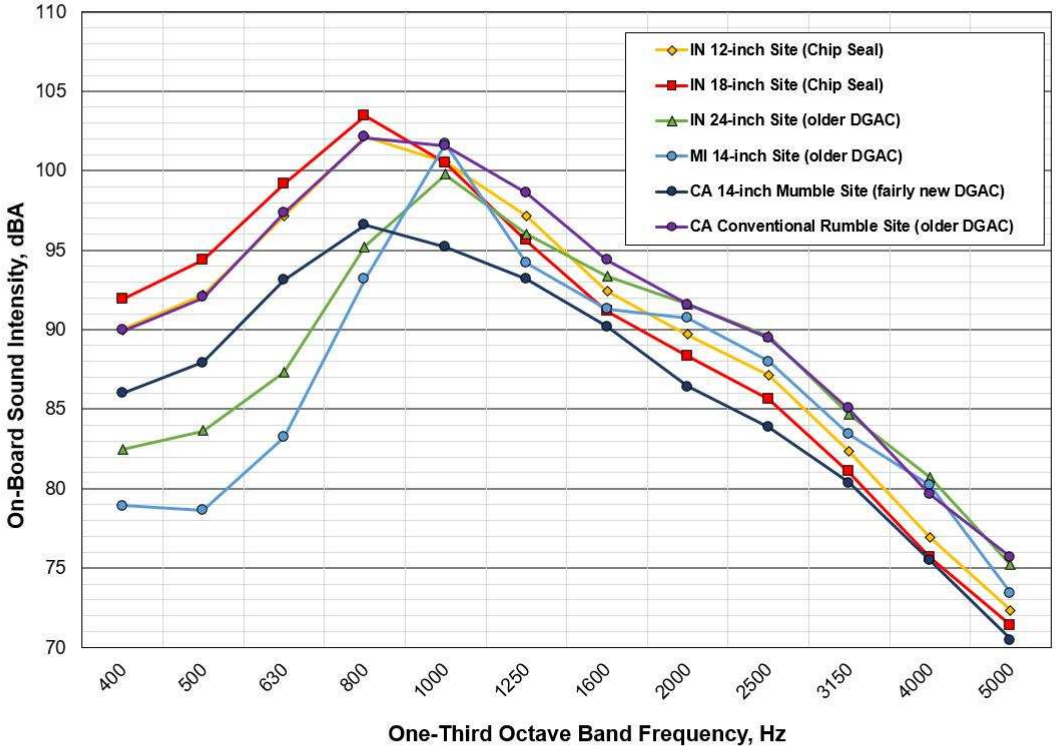
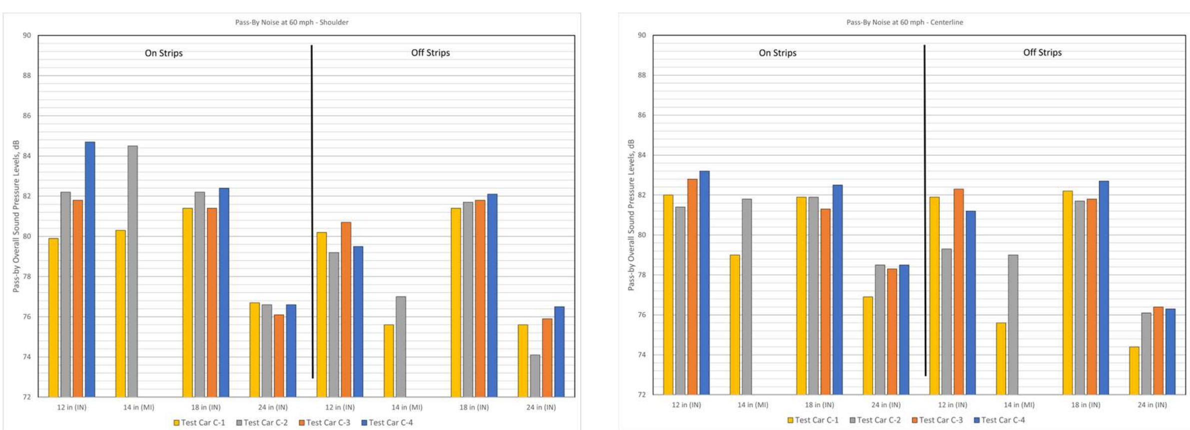


Figure C-17: Average one-third octave band spectra measured at the Indiana and Michigan test sites compared to the California test sites

60 mph Pass-by

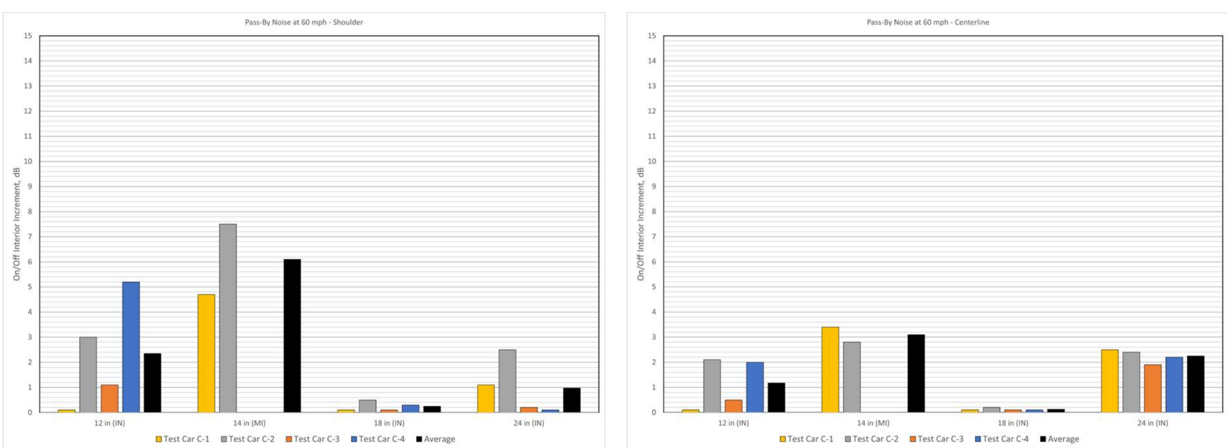
The overall pass-by results for each site, on and off the strips, are shown in Figure C-18 for the shoulder (a) and centerline (b) measurements, respectively, at 60 mph. The overall levels measured at the shoulder site ranged from about 76 to 85 dB on the strips and from 74 to 82 dB off the strips for all test vehicles. The off-strip measurements for both sites with the chip seal



a) Shoulder *b) Centerline*

Figure C-18: Average overall pass-by levels at the Indiana and Michigan test sites, measured on and off the shoulder (a) and centerline (b) strips at 60 mph overlay, which includes the 12- and 18-inch wavelength sinusoidal strips in Indiana, resulted in the highest levels. At the 12-inch site, the off-strip levels range from 79 to 82 dB with the average for the shoulder and centerline being 80 dB. The off-strip levels at the 18-inch site range from 81 to 83 dB with an average of 82 dB. On-strips, the 18-inch site resulted in levels of 81 to 83 dB, as well. The on-strips levels measured at the 12-inch site showed more variability from vehicle-to-vehicle, with levels ranging from 80 to 85 dB. Similarly, the 24-inch site showed some variability, as well, with on-strips levels ranging from 76 to 79 dB and off-strips levels ranging from 74 to 77 dB with an average of 76 dB. The 14-inch site was only tested with two vehicles: the sedan and the compact car. As shown in Figure C-18, there was variability in these two vehicles. The off-strips levels ranged from 76 to 79 dB with an average of 77 dB, while the on-strips levels ranged from 79 to 85 dB. Comparing the off-strip levels for each pavement to the overall OBSI levels above indicates good correlation between the two types of measurements with the OBSI being 26.7 dB higher than the pass-by levels with a range of +1.1 to -1.2 consistent with the standard deviation between OBSI and raw statistical pass-by levels of 1.2 dB reported in the NCHRP Report 630, Measuring Tire-Pavement Noise at the Source[4].

Figure C-19 shows the on/off increments for the shoulder (a) and centerline (b) sites at 60 mph. As discussed above, the on/off difference at the 18-inch site was essentially 0 dB. With a bit more variability, the on/off increments measured at the 12-inch site ranged from 0 to 5 dB. Both of these sites had chip seal surface overlays. Additionally, the profile for the 18-inch site shows the sinusoidal strip to be flattened (see Figure C-5), which may contribute to the lower increments at this site. The increments at the 24-inch site ranged from 0 to 2 dB. The highest on/off increments occurred at the 14-inch site in Michigan, which ranged from about 3 to 7 dB. The human ear can perceive a noise level increase of 3 dB or more for similar sounds. For dissimilar sounds, smaller differences can be detected, however, for vehicles traveling on the strips at the Indiana sites versus off the strips, the change in noise level would not be sufficient to create a significant difference for receptors located along the wayside.



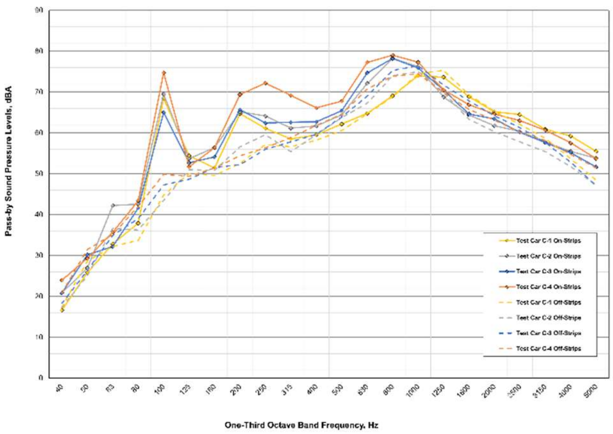
a) Shoulder *b) Centerline*

Figure C-19: On/off increments at the Indiana and Michigan test sites, measured along the shoulder (a) and centerline (b) strips at 60 mph

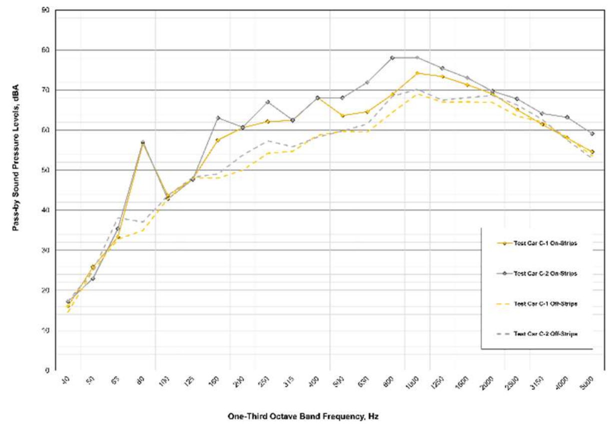
The goal of this NCHRP study is to design rumble strips to minimize noise projected along the wayside, and while these sites may indicate that the wayside noise from the rumble strips is negligible, it is difficult to determine whether the overall on/off differences calculated to be below 3 dB are due to the rumble strip design or due to the noisy off-strips measurements influenced by the pavement types, which were measured at the source to be about 104 to 108 dB (see OBSI data above). It should be noted that significant subjective complaints regarding the noisy chip seal overlay were made to the pass-by technician during data acquisition. Several neighbors living along the corridor of the 12- and 18-inch sinusoidal strips complained about the noisy pavement and not about noise from rumble strips.

Figure C-20 shows the one-third octave band spectra, on and off each site for every test vehicle at the shoulder site. The overall trends for each test site with varying wavelengths show peaks for all test vehicles at 100 Hz for the 12-inch strips, at 80 Hz for the 14-inch strips, at 63 Hz for the 18-inch strips, and at 50 Hz for the 24-inch strips. The spectra show a smaller peak at the second repetition rate for each test site.

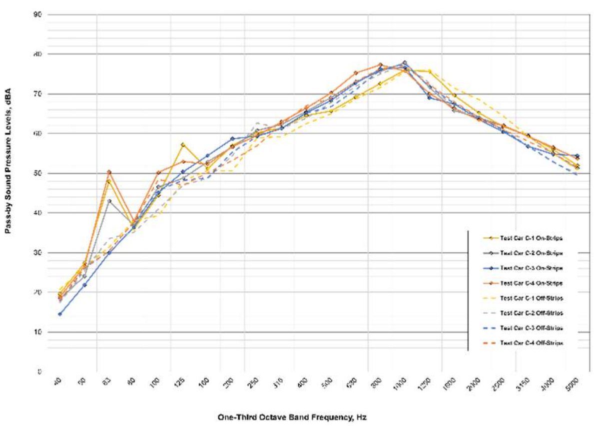
The spectra measured at the sites with 12- and 14-inch wavelengths showed the greatest difference between on and off strips at frequencies below 1,000 Hz. Of these two designs, the 12-inch strips produce the highest one-third octave band level at the frequency corresponding to the wavelength repetition rate (100 Hz). In the absence of the high noise levels produced by the chip seal, the higher amplitude produced by the 12-inch strip would be more detectible and possibly a source of complaints. In contrast, there is little to no difference between on and off strips at the 18- and 24-inch sites at frequency bands above 160 Hz for the 18-inch wavelength and above 125 Hz for the 24-inch wavelength. Results for the centerline strips are similar.



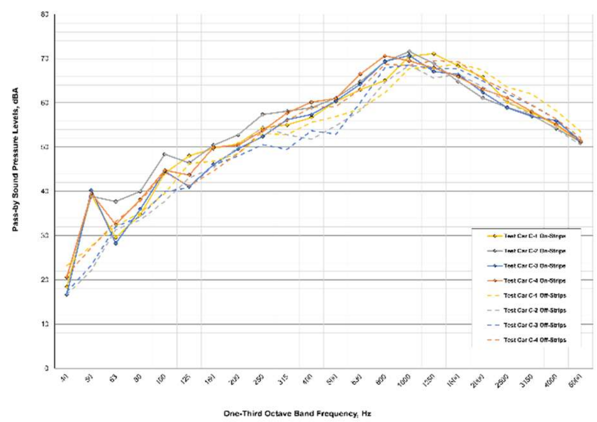
(a) 12-inch test site



b) 14-inch test site



c) 18-inch test site



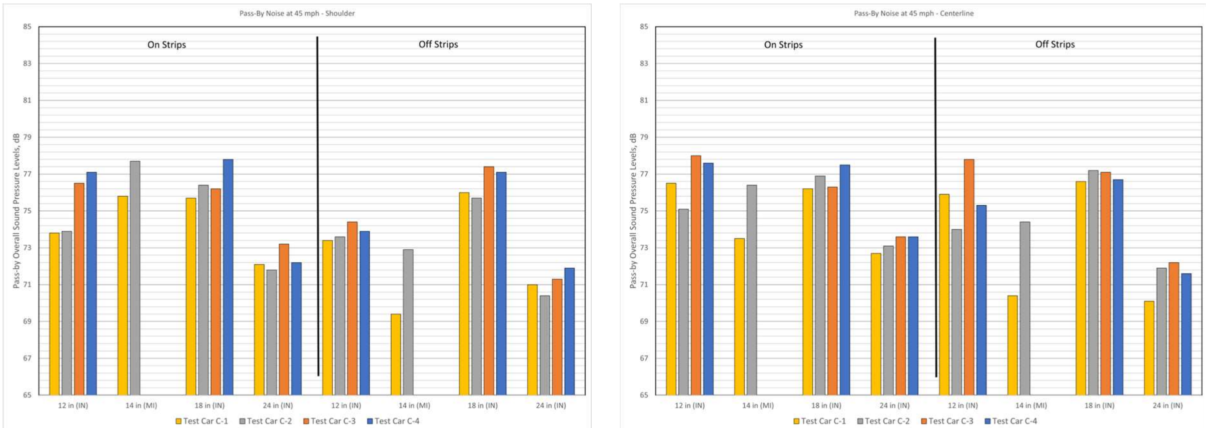
d) 24-inch test site

Figure C-20: One-third octave band spectra measured at each test site on the shoulder side, on and off strips at 60 mph

45 mph Pass-By

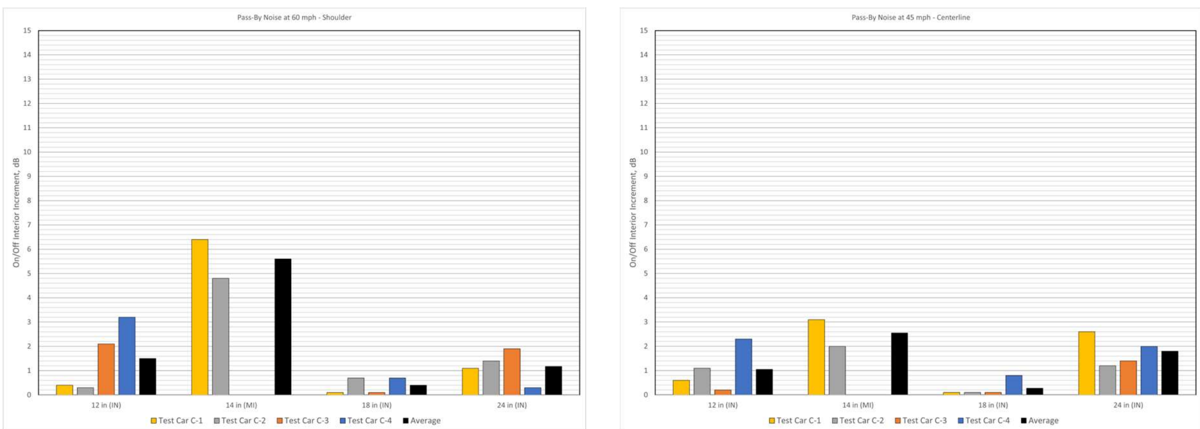
Runs were made at 45 mph, in addition to 60 mph, at each site. The overall levels, on and off the strips, are shown in Figure C-21 for both shoulder (a) and centerline (b) strips. The on/off increments are shown in Figure C-22. Similar to data collected at 60 mph, there is little difference between the on strips levels and the off strips levels at the 18-inch site, both at the shoulder and at the centerline. Additionally, overall levels on and off the strips were the lowest at the 24-inch site for measurements taken at both 45 and 60 mph. This, however, is likely due to the pavement at this site being the quietest (see OBSI data above).

While all three Indiana sites showed on/off increments of about 3 dB or below at shoulder and at the centerline, the increments at the 14-inch shoulder site were about 5 to 7 dB, with the centerline increments being about 3 dB lower than at the shoulder. The increments at the 14-inch site are similar to those measured at 60 mph. The average overall increments measured at the shoulder and at the centerline were within 1 dB of the average increments measured at 60 mph at each site.



a) Shoulder *b) Centerline*

Figure C-21: Average overall pass-by levels at the Indiana and Michigan test sites, measured on and off the shoulder (a) and centerline (b) strips at 45 mph



a) Shoulder *b) Centerline*

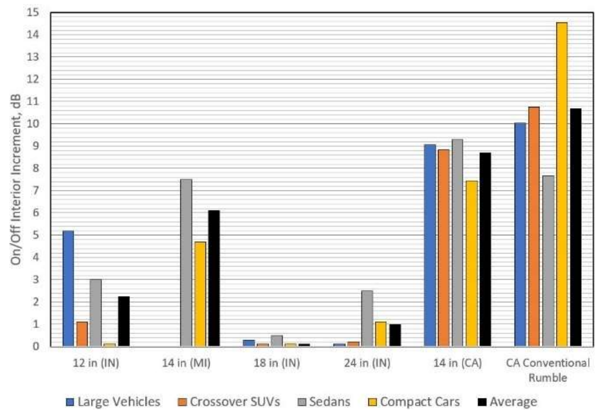
Figure C-22: On/off increments at the Indiana and Michigan test sites, measured along the shoulder (a) and centerline (b) strips at 45 mph

Comparison to California Pass-by Results

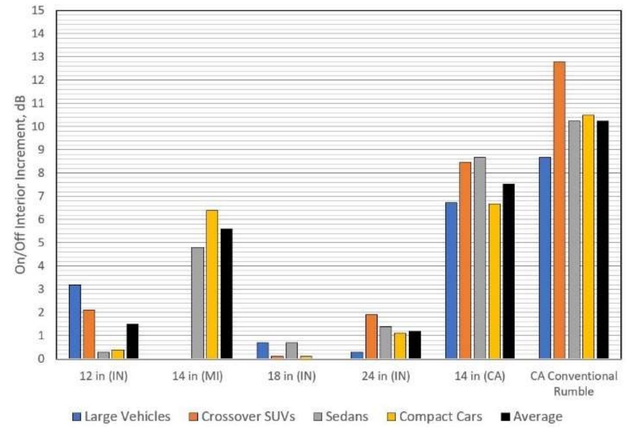
Task 8 measurements made in Indiana and Michigan were compared to the Task 4 measurements made in California. The four vehicle groupings introduced in Task 4 (large vehicles, crossover SUVs, sedans, and compact cars) were used to compare to Task 8 results. Figure C-23 shows the average on/off increments calculated at 60 mph (a) and 45 mph (b) for all test sites. Note, since the sites in California were located along a four-lane highway, there were no centerline strips; therefore, all data shown in Figure C-23 reflect shoulder data only.

The average overall on/off increments in Indiana and Michigan were lower than the California sites at both traveling speeds, with the 14-inch wavelength in Michigan producing on/off increments about 2 dB lower than the 14-inch wavelength site in California. The pavement at the

California site is about 2 dB quieter than at the Michigan site (see OBSI data above). While the wavelengths are supposed to be the same, the profile for the Michigan shoulder strips (Figure C-



a) 60 mph



b) 45 mph

Figure C-23: On/off increments for vehicle groupings at the Indiana and Michigan test sites, compared to the Task 4 measurements made in California, at 60 mph (a) and 45 mph (b)

9) indicate a wavelength of about 15⅛ inches. This may contribute to the 2 dB incremental differences between the two sites.

The average on/off incremental difference at the 18-inch site was 0 to 1 dB; however, based on the excessively loud off-strips pass-by data shown in Figures C-18 and C-21 for 60 and 45 mph, respectively, as well as the OBSI levels measured at the source (see OBSI data above), it is difficult to conclude if the 18-inch wavelength design effectively reduced pass-by on/off increments to imperceptible to the human ear or if the pavement is so loud that the shoulder strips are ineffective.

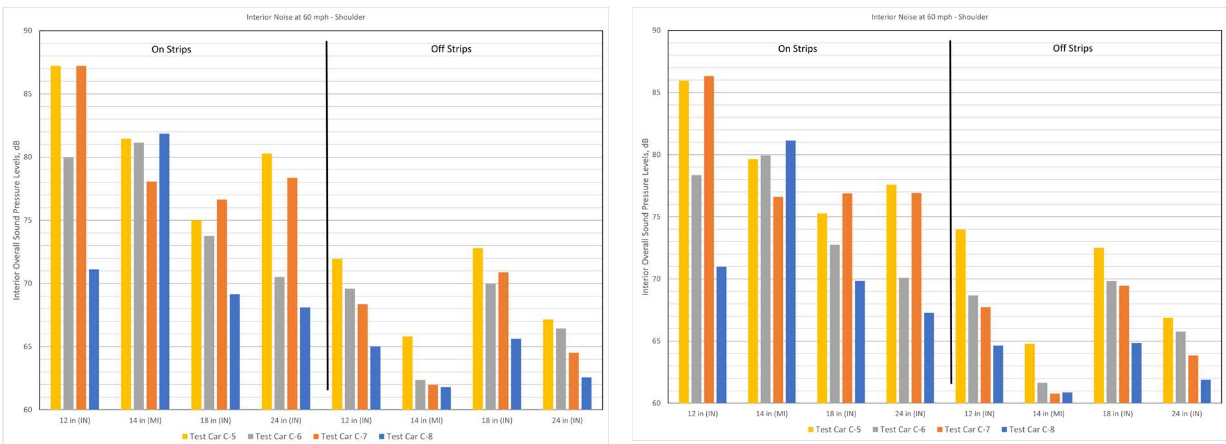
The average on/off difference at the 12- and 24-inch sites was less than 3 dB at both speeds. While the 12-inch site had the noisy chip seal, similar to the 18-inch site, the 24-inch site had an older DGAC pavement with similar OBSI levels to the California conventional rumble strip site and higher OBSI levels than the 14-inch sinusoidal strips in California. At this site, the imperceptible on/off increments would likely be due to the wavelength of the sinusoidal strips and the shallow depth of the ingress.

INTERIOR NOISE AND VIBRATION MEASUREMENT RESULTS

The ability of a rumble strip to alert a vehicle operator to an out-of-lane departure depends on the magnitude of the change in the audible and tactile input to the operator. This is considered to be the increase in interior noise and vibration produced by departing from the lane of travel and striking the rumble strip. Recommended increases in level on/off the strips is from 10 to 15 dB[5]. On/off strip measurements made on the vehicle interiors were completed in Indiana and Michigan from June 10 through 15, 2021. A representative vehicle from each vehicle grouping identified in Task 4 (large vehicles, crossover SUVs, sedans, and compact cars) were tested as part of Task 8. The results are presented in this section.

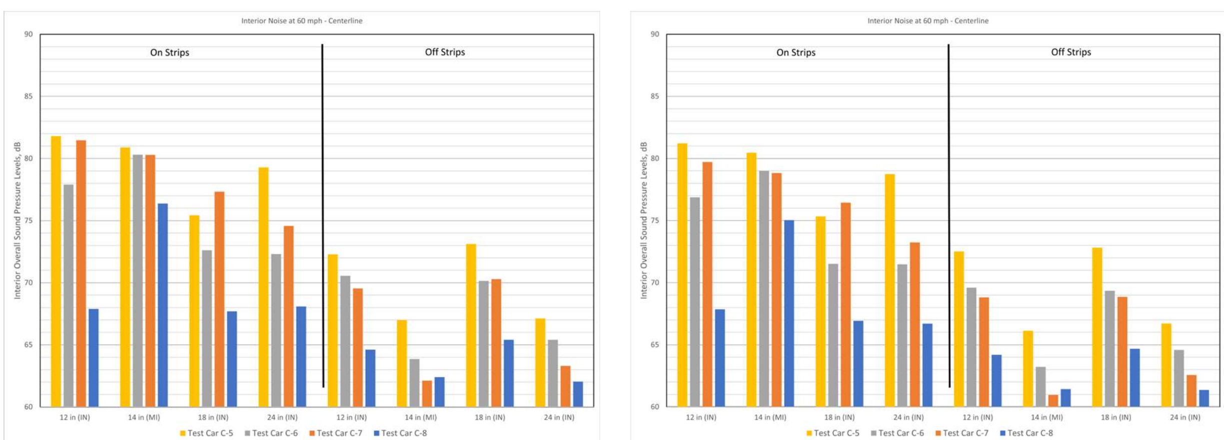
60 mph Interior Noise

The interior overall A-weighted sound pressure levels for test vehicles on and off the shoulder sinusoidal rumble strips in Indiana and Michigan are shown in Figure C-24 for the center center (CC) microphone position (a) and front center (FC) microphone position (b), as measured at 60 mph. Results measured at 60 mph along the centerline sinusoidal strips at both microphones are shown in Figure C-25. The microphones typically resulted in levels within 2 dB of each other, with the exception of the Accent at the 24-inch site where the center center microphone was 2.7 dB higher on the strips. On average, the microphones were within 1 dB of each other.



a) Center Center Microphone *b) Front Center Microphone*

Figure C-24: Overall A-weighted interior noise levels measured on and off the sinusoidal rumble strips located at the shoulder, measured at 60 mph at both microphone positions



a) Center Center Microphone *b) Front Center Microphone*

Figure C-25: Overall A-weighted interior noise levels measured on and off the sinusoidal rumble strips located at the centerline, measured at 60 mph at both microphone positions

As expected, the off strips data for the DGAC pavement at the 14-inch site in Michigan resulted in the lowest overall levels, with the older DGAC pavement at the 24-inch site in Indiana having the second lowest overall levels. Interestingly, at each of the sites, Test Car C-5 (compact car) had the highest overall levels, off strips, and Test Car C-6 (sedan) had the second highest levels. This was true along the shoulder and centerline off-strip lanes. At all of the Indiana sites, Test

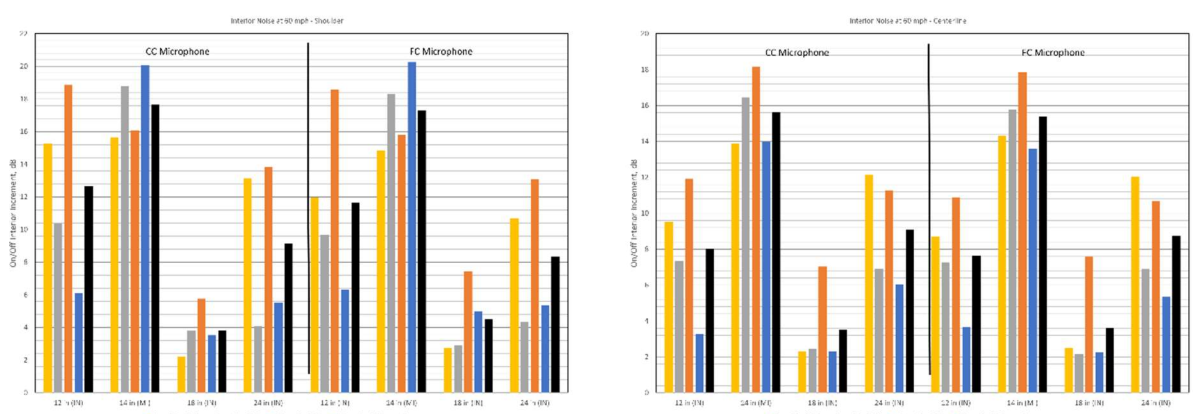
Car C-7 (crossover SUV) had the third highest overall levels, and Test Car C-8 had the quietest levels. At the 14-inch DGAC site in Michigan, however, Test Car C-7 and C-8 had overall levels within 1 dB of each other.

Overall, the levels measured on the strips were loudest on the 12- and 14-inch strips; however, the vehicle-to-vehicle variation at the Indiana sites was considerable. The most consistent overall levels, across all vehicle types occurred at the 14-inch site in Michigan. For all vehicles, interior noise levels at both microphones ranged from about 77 to 82 dB on the shoulder strips and from about 75 to 81 dB on the centerline strips. While a 4 to 6 dB scatter across all vehicles occurred on the newer DGAC in Michigan, the vehicle scatter across all vehicles on the 24-inch older DGAC was 10 to 12 dB, on strips. On the chip seal rumble strips, the scatter of overall levels was about 13 to 16 dB at the 12-inch site and 7 to 10 dB at the 18-inch site.

Figure C-26 shows the on/off increments calculated by subtracting the overall off strips levels from the on strips levels at the shoulder strips (a) and centerline strips (b). With louder off strips levels and quieter on strips levels, the chip seal site with an 18-inch wavelength had the lowest on/off increments, which were 2 to 8 dB on the shoulder and centerline strips and well-below the 10 to 15 dB requirement. The other chip seal site has considerable variation. The Ram pickup truck had on/off increments of 3 to 6 dB, while all other vehicles had increments of 7 to 19 dB. However, due to the vehicle-to-vehicle variability of the overall levels on and off the strips, it is difficult to draw conclusions regarding the effectiveness of the 12-inch wavelength in alerting the driver of lane departure with the chip seal overlay.

The 24-inch strips, which had aged DGAC pavement, had considerable vehicle-to-vehicle variation, as well. Test Car C-8 and Test Car C-6 had on/off increments of 4 to 7 dB, while the Mazda and Accent had 11 to 14 dB increments. It could be concluded that sinusoidal strips with a 24-inch wavelength would be ineffective at alerting the driver of all passenger vehicle types.

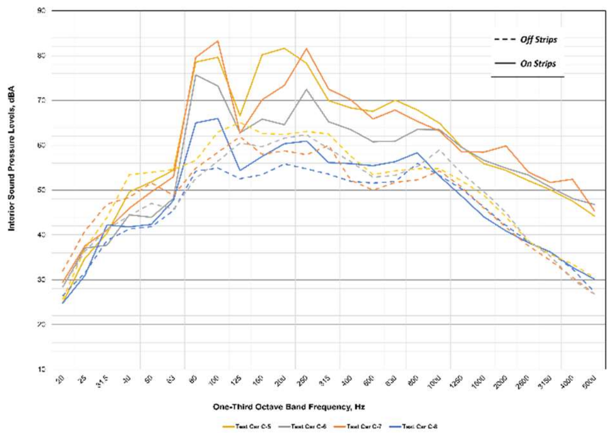
The 14-inch site in Michigan had on/off increments ranging from 14 to 20 dB across all vehicles. While there is some variability, the minimum range of noise level differences in alerting the driver would be satisfied across all vehicle types.



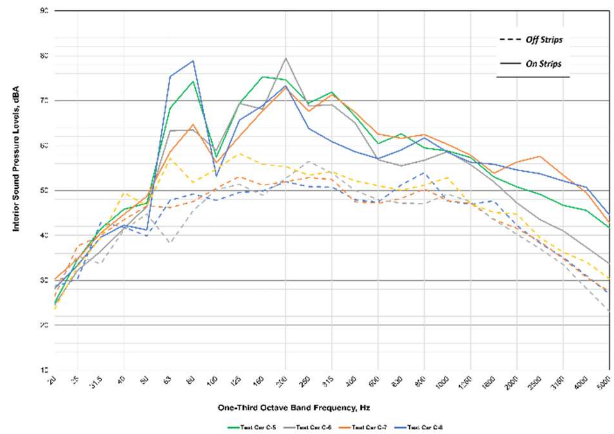
a) Shoulder strips *b) Centerline strips*

Figure C-26: Overall A-weighted sound level increments for on and off shoulder and centerline rumble strips at 60 mph

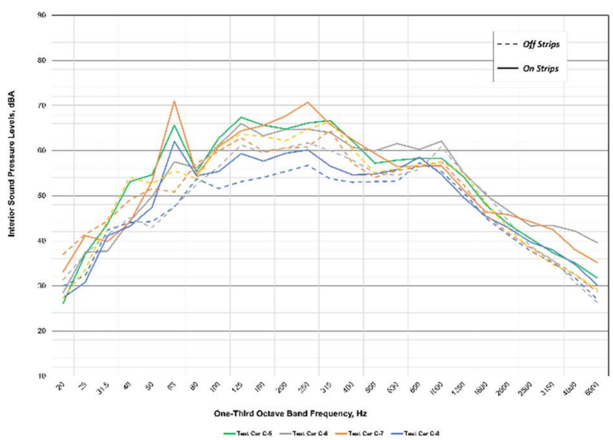
Figure C-27 shows the one-third octave band spectra measured at the center center microphone, on and off each site for every test vehicle at the shoulder sites. Spectra for the front center



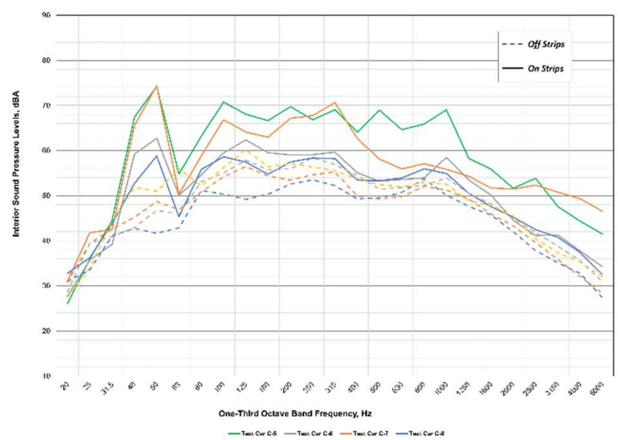
a) 12-inch Site



b) 14-inch Site



c) 18-inch Site



d) 24-inch Site

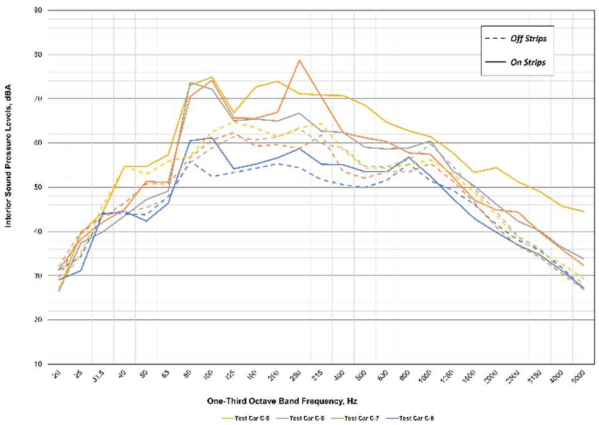
Figure C-27: ⅓ octave band sound pressures for on and off shoulder rumble strips at 60 mph, as measured at the center center microphone

microphone are provided at the end of this appendix. The spectra were similar to the center center microphone.

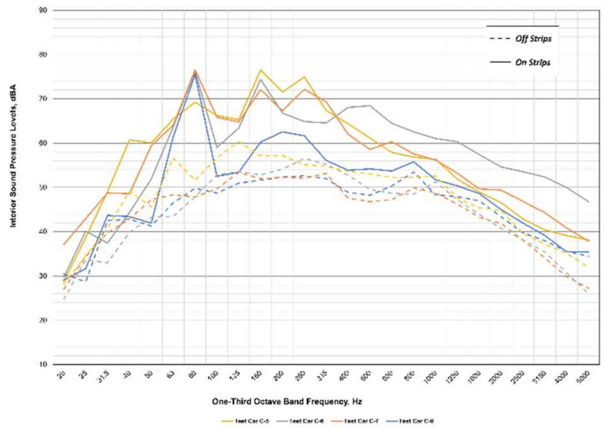
The split peaks generated on the rumble strips were 80 and 100 Hz on the 12-inch strips, 63 and 80 Hz on the 14-inch strips, and 40 and 50 Hz on the 24-inch strips, while the single peak on the 18-inch strips occurred at 63 Hz. All types of test vehicles did indicate a peak at these frequencies; however, the amplitudes varied. The peaks on the 18-inch strips were the least defined of all the sites, and the peak in Test Car C-6 was not as significant to the overall levels as the chip seal pavement trend, which is indicated in the range of 100 to 1,000 Hz. In this frequency range and at the higher frequencies, there is no difference between the on and off strip spectra.

As observed in the overall levels, the vehicle-to-vehicle variation showed Test Car C-8 generating the lowest amplitudes on the 12-inch and 24-inch strips throughout the frequency bands. While Test Car C-8 had higher levels at the 63-Hz-peak on the 18-inch strips than Test Car C-6, amplitudes at frequencies above 63 Hz were lower than all other vehicles.

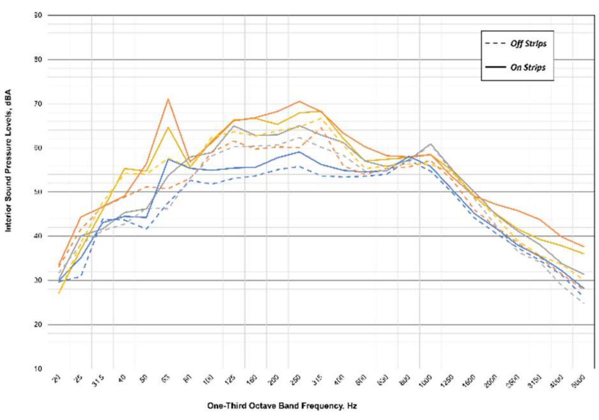
The spectra measured at all centerline strips are shown in Figure C-28. At 60 mph, the peaks occurred at the same frequency bands on each strip. Similar to the shoulder strips, Test Car C-8 had the highest peak levels at the bands excited by the strips at the 14-inch site, while having the lowest peak levels at the 12- and 24-inch sites. On the 18-inch strips, the only vehicle with lower peak levels at the excited frequency bands was Test Car C-6. The remaining frequency bands for Test Car C-8 are lower than the other vehicles.



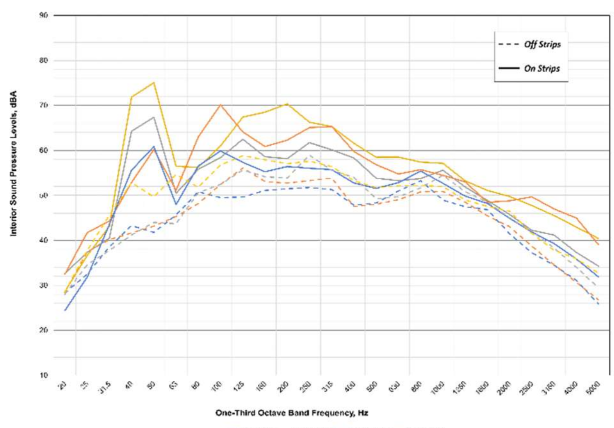
a) 12-inch Site



b) 14-inch Site



c) 18-inch Site



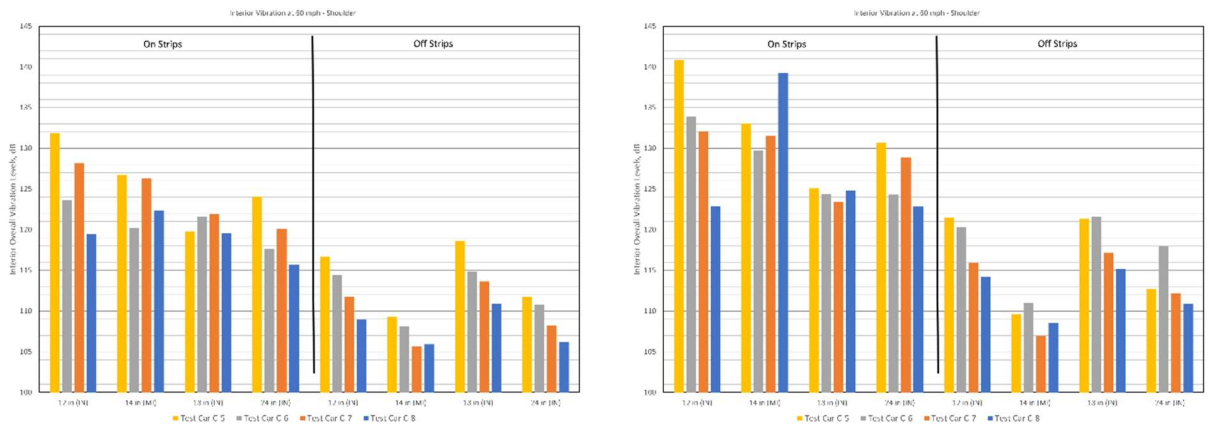
d) 24-inch Site

Figure C-28: ⅓ octave band sound pressures for on and off centerline rumble strips at 60 mph, as measured at the center center microphone

While the frequency spectra do indicate that each set of strips, at the shoulder and centerline locations, affectively excite sound pressure in the vehicle cabs of each type of vehicle, the elevated levels at the remaining bands, which is due to pavement type did reduce the effectiveness displayed in the overall levels on each set of strips.

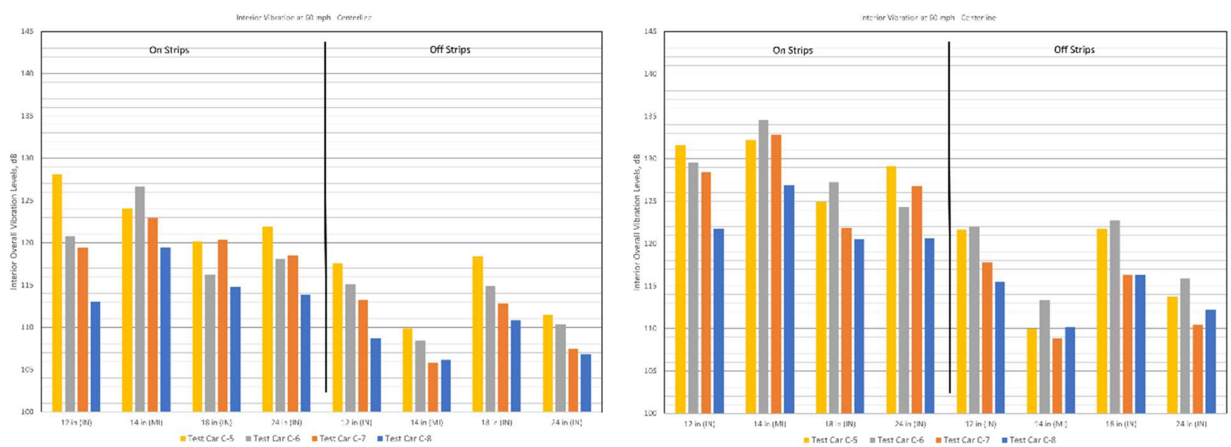
60 mph Interior Vibration

The overall vehicle vibration levels measured at the seat track and steering column for each test vehicle on and off the shoulder strips are shown in Figure C-29, as measured at 60 mph. Figure C-30 shows the same on the centerline strips at both accelerometers. While the sensors at each location in the vehicle were triaxial accelerometers, the data measured in all three directions were combined for an overall vibration metric. Reasons for this were discussed in the Task 4 report. All data presented in this section is the combined vibration measurement.



a) Seat Track Accelerometer *b) Steering Column Accelerometer*

Figure C-29: Overall vehicle vibration levels measured on and off the sinusoidal rumble strips located at the shoulder, measured at 60 mph at both accelerometer positions



a) Seat Track Accelerometer *b) Steering Column Accelerometer*

Figure C-30: Overall vehicle vibration levels measured on and off the sinusoidal rumble strips located at the centerline, measured at 60 mph at both accelerometer positions

As expected, the off-strips vibration levels at the 12- and 18-inch sites, which have the chip seal overlay, were the highest overall levels, which ranged from about 110 to 119 dB for all vehicles at the seat track (ST) and from 114 to 123 dB at the steering column (SC) for both the shoulder and centerline strips. The vehicle-to-vehicle variation ranges from about 8 to 9 dB off-strips at both chip seal sites for the ST, and the variation ranges from 6 to 7 dB off-strips at both sites for the SC.

The range of vehicle-to-vehicle variation on the strips at the chip seal sites was significantly greater than the off-strips. On the 12-inch strips, the variation ranged from 12 to 15 dB at the ST and from 10 to 18 dB at the SC for both the shoulder and centerline strips. On the 18-inch chip seal strips, however, the vehicle-to-vehicle variation ranged from 2 to 6 dB at the ST and from 2 to 7 dB at the SC.

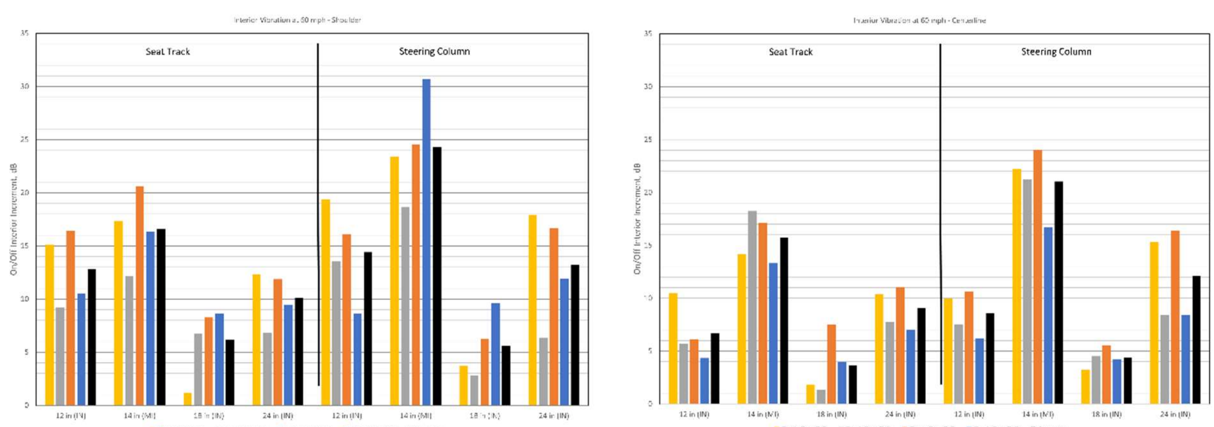
For the DGAC pavements, vehicle-to-vehicle variation ranged from 4 to 5 dB off the strips at the 14-inch site and from 5 to 7 dB off the strips at the 24-inch site for both sensors. On the strips at the 14-inch site, vehicle-to-vehicle variation ranged from 6 to 7 dB at the ST sensor and from 8 to 10 dB at the SC. On the 24-inch strips, vehicle-to-vehicle variation ranged from 8 to 9 dB at both sensors.

The levels measured on the strips at the seat track did not have a distant overall loudest at one site like the microphones did. From vehicle-to-vehicle, however, the steering wheel measured slightly higher vibration levels on the 12- and 14-inch strips.

Figure C-31 shows the on/off increments calculated by subtracting the overall off strips levels from the on strips levels at both the shoulder and centerline strips. At both the shoulder and centerline strips, the on/off increments were greatest at the 14-inch site at both sensors, with increments from 12 to 21 dB at the ST and from 17 to 31 dB at the SC. The increments at the 24-inch site ranged from 7 to 12 dB at the ST and from 6 to 18 dB at the SC.

The chip seal site with 12-inch wavelengths had increments ranging from 4 to 16 dB at the ST and from 6 to 19 dB at the SC. Increments at the 18-inch site ranged from 1 to 9 dB at the ST and from 3 to 10 dB at the SC.

The varying incremental results at the three Indiana sites, which did not meet the minimum 10 to 15 dB incremental requirement for all vehicles, further shows that the 24-inch wavelength is not adequate for alerting the driver consistently and that roadways with chip seal overlay is not ideal for alerting the driver to lane departure when equipped with shallow sinusoidal strips.

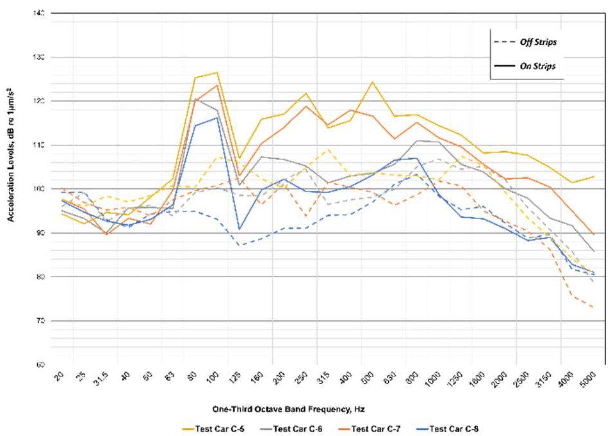


c) *Shoulder strips* d) *Centerline strips*

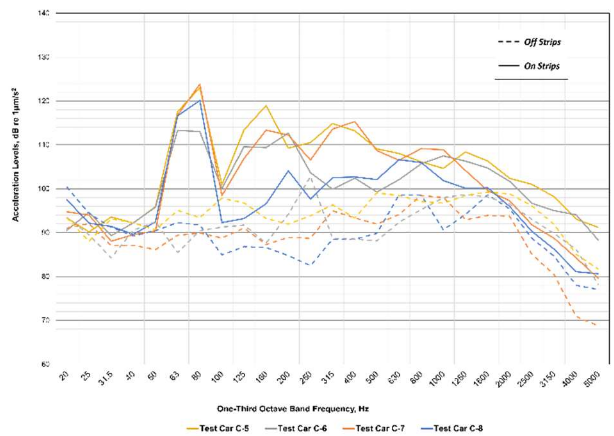
Figure C-31: Overall vibration increments for on and off shoulder and centerline rumble strips at 60 mph

Figure C-32 shows the one-third octave band spectra measured at the seat track accelerometer, on and off each site for every test vehicle at the shoulder sites. Figure C-33 shows the same at the centerline strips of each site. Spectra for the steering column accelerometer are provided at the end of this appendix.

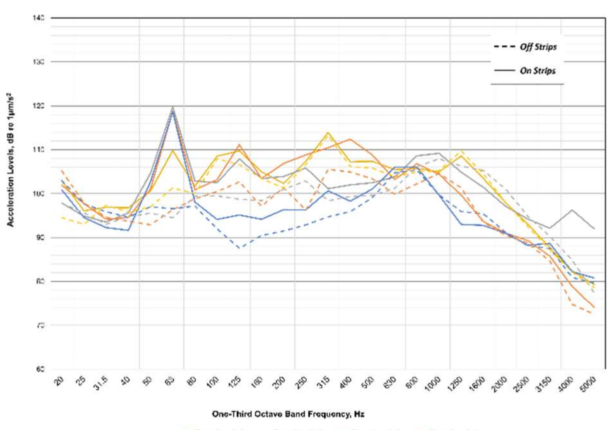
The split peaks generated on the rumble strips (at 80 and 100 Hz) from the 12-inch strips were distinct on the shoulder strips. Additionally, Test Car C-7 and Test Car C-5 had levels significantly higher between 160 to 800 Hz on the shoulder strips, while Test Car C-8 and Test Car C-6 were only slightly higher than the off-strips levels in this range. On the centerline strips, the peaks generated by the 12-inch strips were less distinct in Test Car C-8, and between 160 and 800 Hz, Test Car C-7, C-6, and C-5 all had elevated levels.



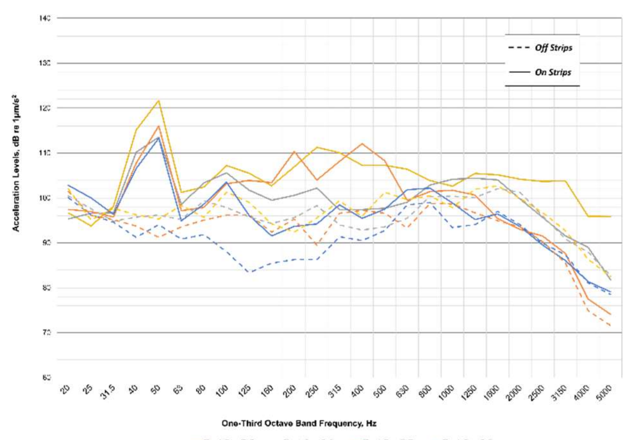
a) 12-inch Site



b) 14-inch Site



c) 18-inch Site



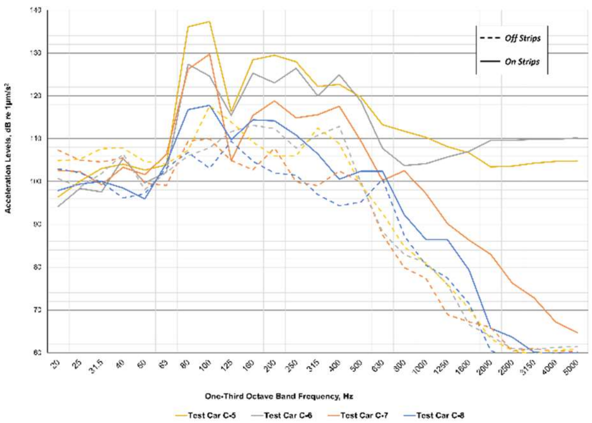
d) 24-inch Site

Figure C-32: ⅓ octave band vibration levels for on and off shoulder rumble strips at 60 mph, as measured at the seat track accelerometer

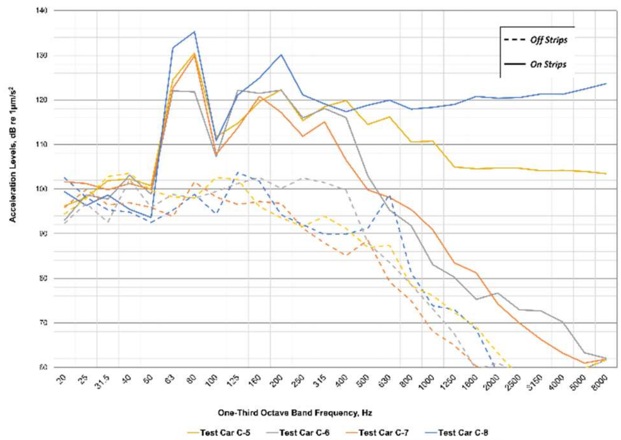
Similar to the peaks generated on the 12-inch strips, the split peaks (at 63 and 80 Hz) from the 14-inch shoulder strips were distinct for all vehicles. These split peaks on the 14-inch centerline strips are also distinct in each vehicle. Additionally, elevated levels are shown at 125 through 500 Hz for all vehicles. On the centerline strips, the spectra for the Ram stayed around 120 dB at frequencies above 400 Hz. The Accent also demonstrated elevated levels on the centerline strips at the higher frequencies.

The 63 Hz peak generated on the 18-inch shoulder strips is distinct for Test Car C-8, C-7, and C-6 (over 20 dB above the off-strips spectra). In Test Car C-5, the peak at 63 Hz is less than 10 dB higher than the off-strips spectra. The peaks were distinct for all vehicles on the centerline strips and were 12 to 19 dB higher than off-strips levels. On shoulder and centerline strips, the spectra are not significantly elevated over off strips levels.

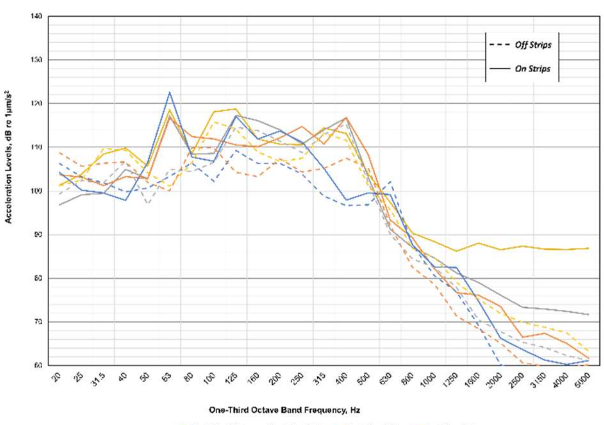
The split peaks at 40 and 50 Hz were distinct for all vehicles on the 24-inch shoulder strips, while the peaks on the centerline strips are less distinct in Test Car C-8 and C-6. Just like the other centerline strips, Test Car C-5 showed elevated levels in the higher frequency bands.



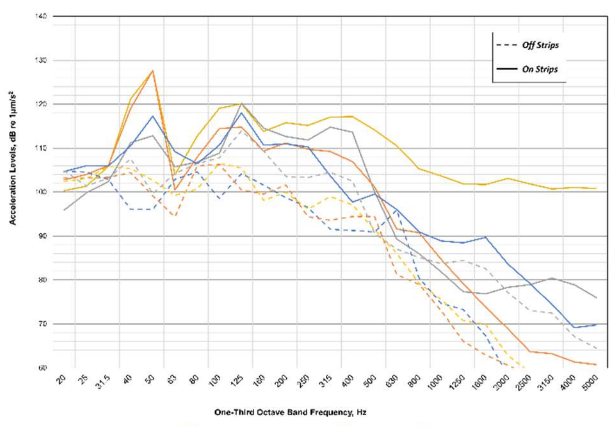
a) 12-inch Site



b) 14-inch Site



c) 18-inch Site

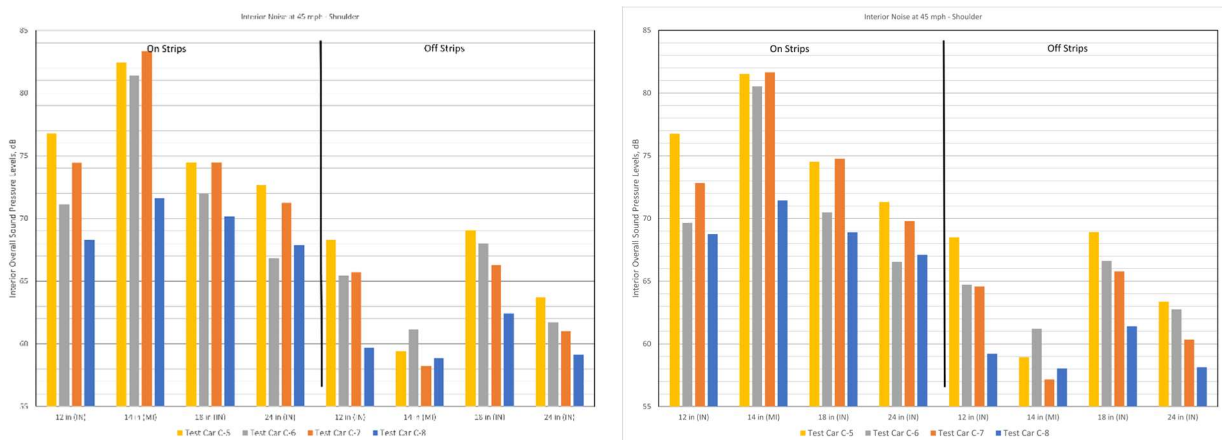


d) 24-inch Site

Figure C-33: ⅓ octave band vibration levels for on and off centerline rumble strips at 60 mph, as measured at the seat track accelerometer

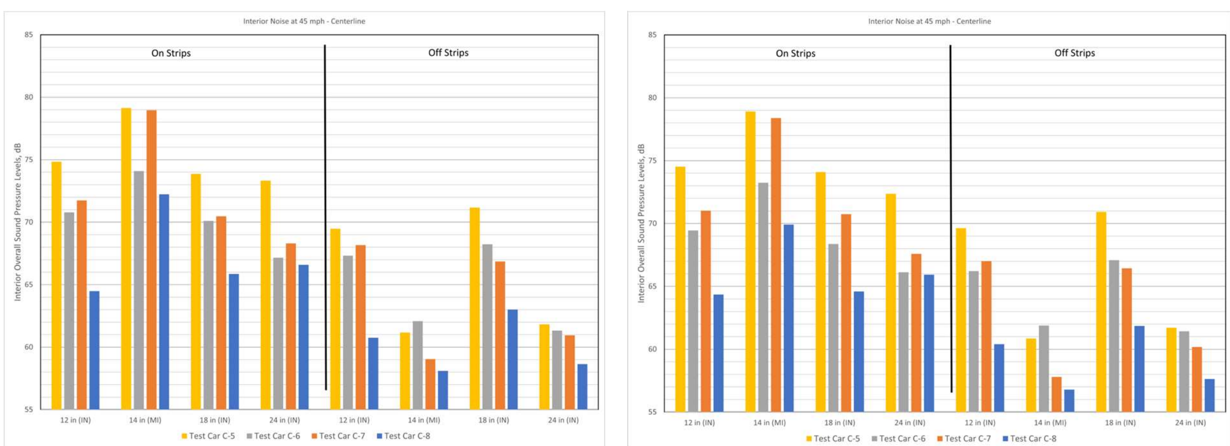
45 mph Interior Noise

The overall interior noise levels measured on and off the four rumble strip designs at 45 mph are shown in Figure C-34 for all test vehicles operating on the shoulder strips at the (a) center center microphone and (b) front center microphone. Figure C-35 shows the overall levels at 45 mph for both microphones on the centerline strips. With a few exceptions, the levels measured at 45 mph are lower than those at 60 mph, as would generally be expected. The most outstanding exception occurred for Test Car C-7 on the 14-inch strips, where the overall levels on the strips at 45 mph were about 5 dB higher than those at 60 mph on the shoulder at both microphones.



a) Center Center Microphone *b) Front Center Microphone*

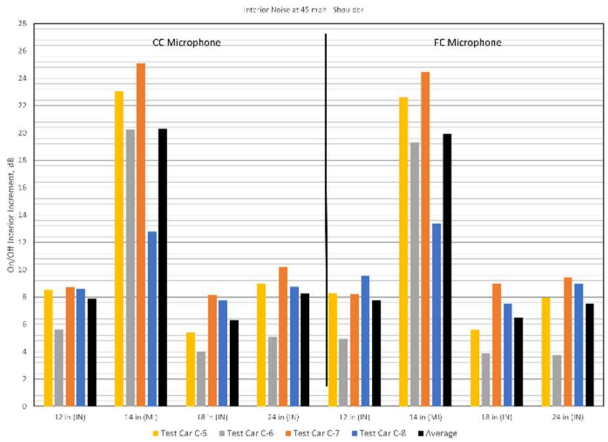
Figure C-34: Overall A-weighted interior noise levels measured on and off the sinusoidal rumble strips located at the shoulder, measured at 45 mph at both microphone positions



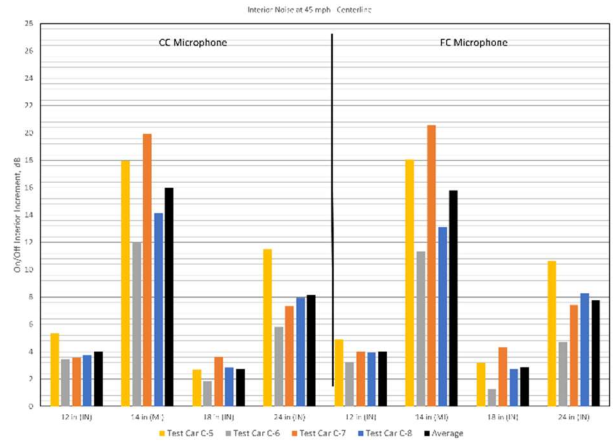
a) Center Center Microphone *b) Front Center Microphone*

Figure C-35: Overall A-weighted interior noise levels measured on and off the sinusoidal rumble strips located at the centerline, measured at 45 mph at both microphone positions

The on/off increments at 45 mph are shown in Figure C-36 for the shoulder and centerline strips at both microphone locations. On both the shoulder and centerline strips, the increments measured at the 14-inch strips were significantly more dominant than the other sites. While the increments on the 14-inch strips were 16 dB or higher than off strips levels, the increments on all other strips were below 10 dB. At 45 mph, only the 14-inch strips would meet the 10 dB criterion for alerting vehicle operators.



a) Shoulder strips

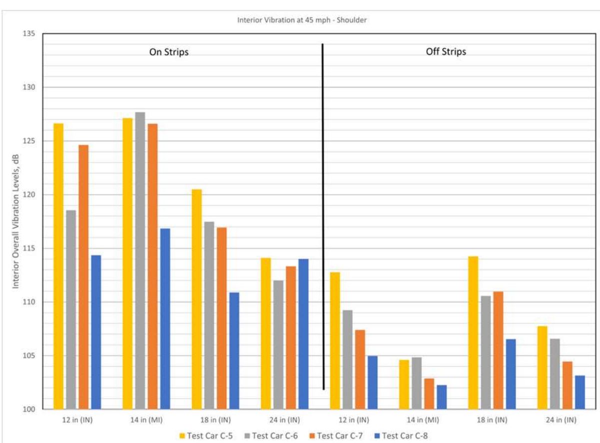


b) Centerline strips

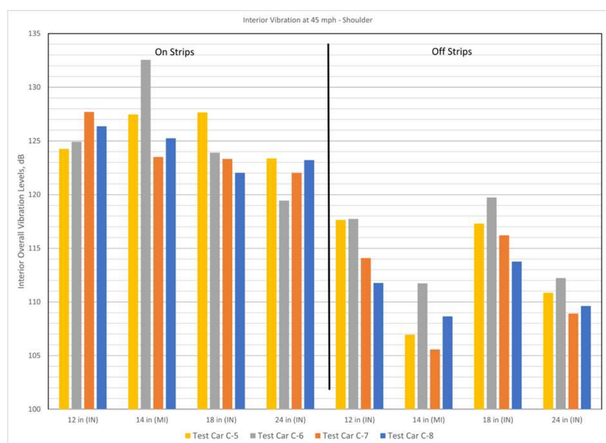
Figure C-36: Overall A-weighted sound level increments for on and off shoulder and centerline rumble strips at 45 mph

45 mph Interior Vibration

The overall seat track acceleration levels for test vehicles on and off the sinusoidal rumble strips in Indiana and Michigan are shown in Figure C-37 for the shoulder strips at the (a) seat track sensor and (b) the steering column sensor, as measured at 45 mph. Figure C-38 shows the same on the centerline strips. Similar to the 60 mph results, the vibration levels for the steering column were consistently higher than the seat track.

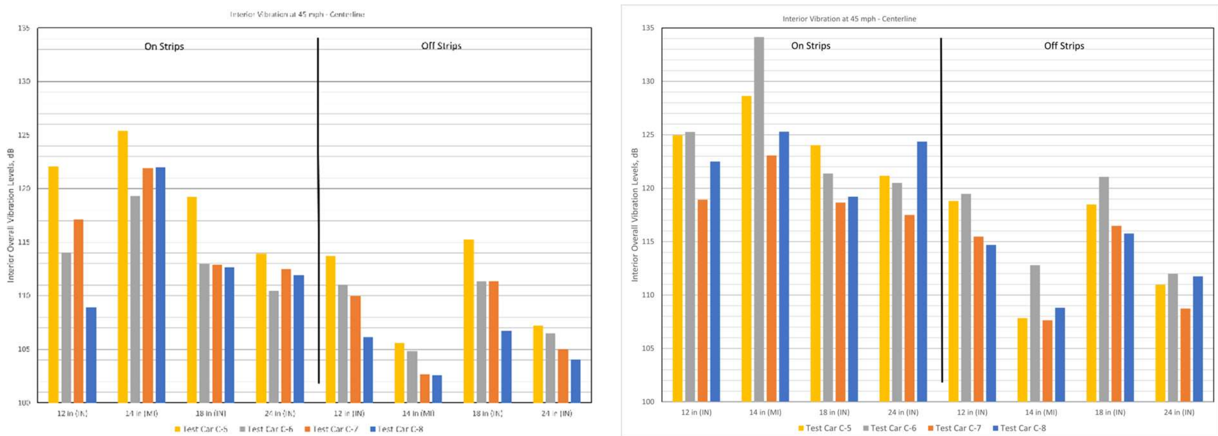


a) Seat Track Accelerometer



b) Steering Column Accelerometer

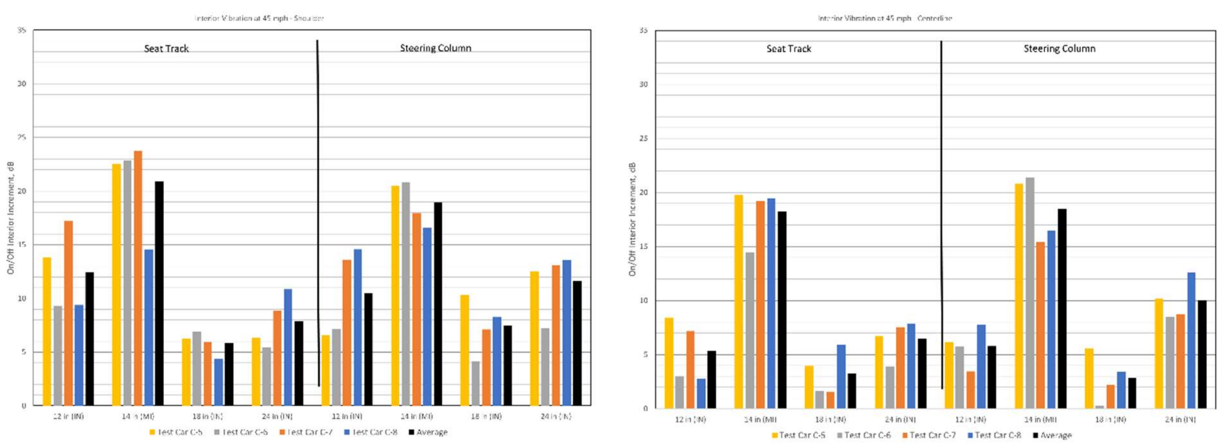
Figure C-37: Overall vehicle vibration levels measured on and off the sinusoidal rumble strips located at the shoulder, measured at 45 mph at both accelerometer positions



a) Seat Track Accelerometer *b) Steering Column Accelerometer*

Figure C-38: Overall vehicle vibration levels measured on and off the sinusoidal rumble strips located at the centerline, measured at 45 mph at both accelerometer positions

The on/off increments at 45 mph are shown in Figure C-39. Similar to the microphones, the increments measured at both accelerometers on the 14-inch strips resulted in the greatest on/off differences, which ranged from about 15 to 24 dB. The remaining sites showed significant variation in on/off increments, ranging from virtually no on/off difference to about 17 dB. This is similar to the results at 60 mph. Therefore, the only site that consistently results in the minimum 10 dB increase on the strips would be the 14-inch site. This is consistent with the results from the interior noise measurements.

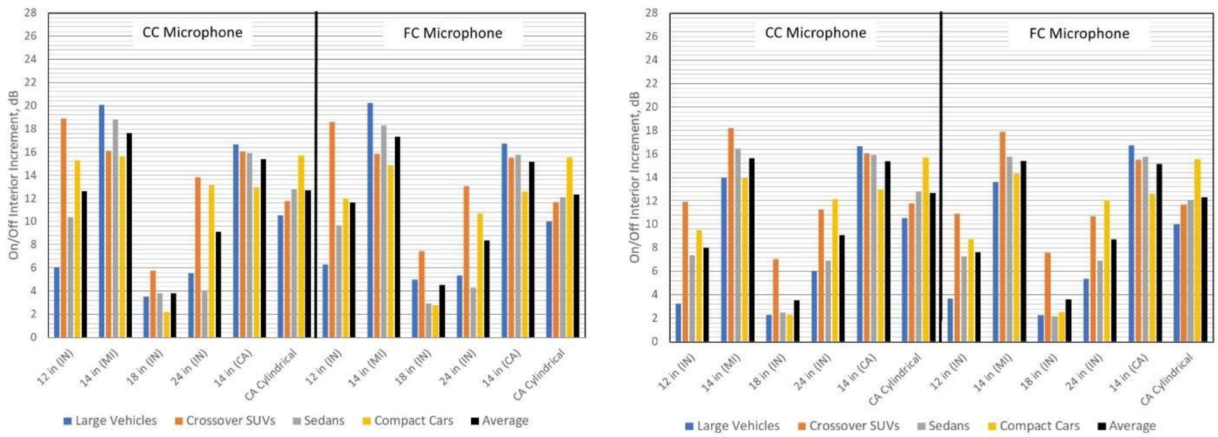


a) Shoulder strips *b) Centerline strips*

Figure C-39: Overall vibration increments for on and off shoulder and centerline rumble strips at 45 mph

Comparison to California Interior Noise and Vibration Results

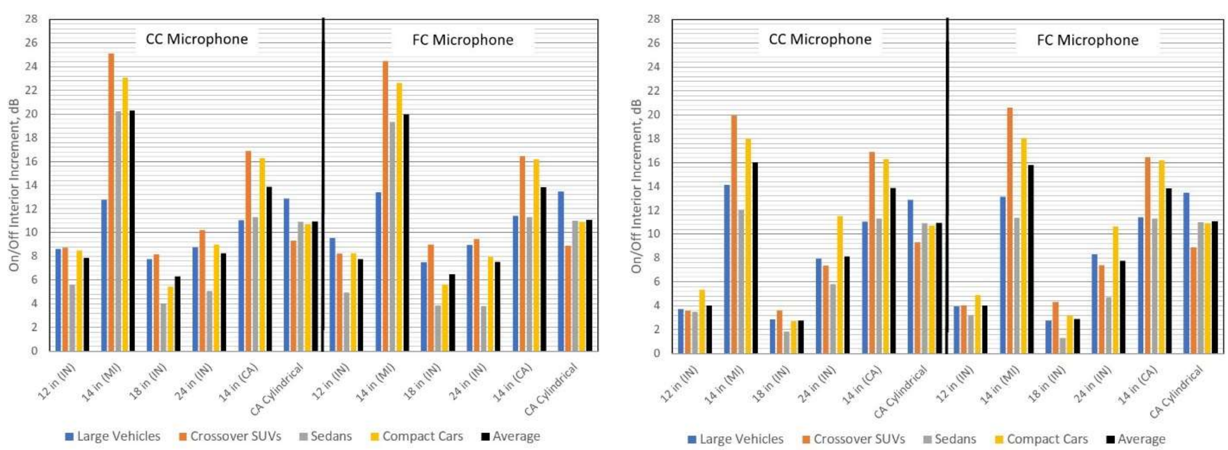
The on/off increments for the interior noise increments for the Michigan and Indiana sinusoidal strips are compared to the 14-inch sinusoidal strips and cylindrical ground strips in California as measured at 60 mph in Figure C-40. The shoulder California strips are compared to the Midwest shoulder strips in Figure C-40(a) and to the centerline strips in Figure C-40(b). These figures provide the average of all vehicles measured on each of the six rumble strip designs, as well as the maximum and minimum increments. The minimum increments are of interest as these values provide some indication of how low of an input that each design could generate for alerting operators of lane departures. Ideally, the minimum values would be 10 dB or greater. Across all vehicle types, the sites that achieve this are the 14-inch sinusoidal strips in Michigan and California, as well as the cylindrical strips in California. Further, there is more consistency across all vehicle types on these strips.



a) Midwest shoulder strips & CA strips *b) Midwest centerline strips & CA strips*

Figure C-40: Comparison of interior noise increments for the Midwest shoulder and centerline strips to the California shoulder strips at 60 mph

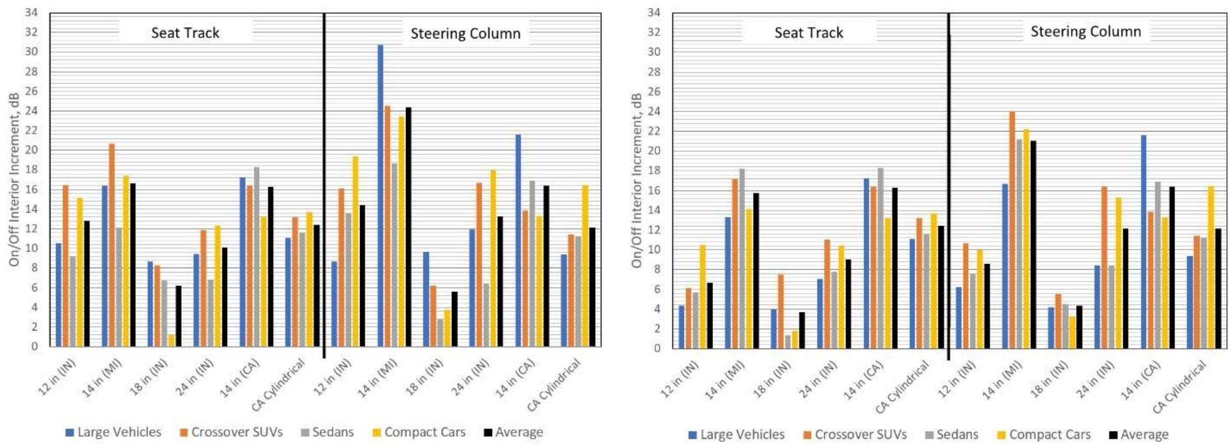
The 45 mph interior noise increments for the Midwest and California strips are presented in Figure C-41. At this speed, only the 14-inch sinusoidal strips in Michigan and California achieve a minimum of 10 dB on/off difference across all vehicle types, with the Michigan strips performing better than the California strips in terms of average, minimum, and maximum increments. The other Midwest strips with wavelengths of 12-, 18-, and 24-inches all have lower averages than 14-inch strips.



a) Midwest shoulder strips & CA strips *b) Midwest centerline strips & CA strips*

Figure C-41: Comparison of interior noise increments for the Midwest shoulder and centerline strips to the California shoulder strips at 45 mph

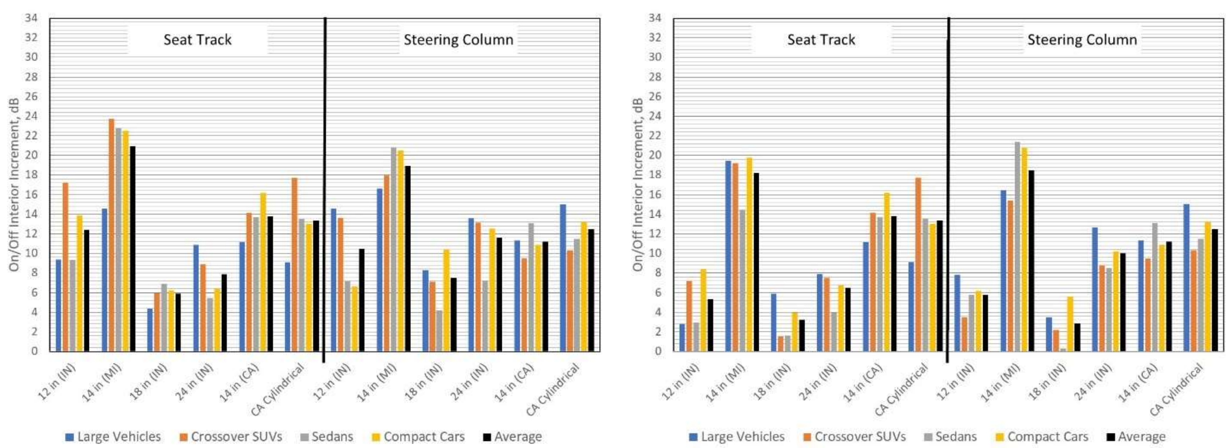
The comparison of on/off increments for vibration sensors at 60 mph are shown in Figure C-42 for the average of all vehicles measured on the Midwest shoulder (a) and centerline (b) strips relative to the California shoulder strips. Similar to the interior noise results, the increments for 14-inch Michigan shoulder and centerline strips and the 14-inch strips in California meet the minimum 10 dB increment requirement, while none of the other sites show this performance across all vehicles.



a) Midwest shoulder strips & CA strips *b) Midwest centerline strips & CA strips*

Figure C-42: Comparison of interior vibration increments for the Midwest shoulder and centerline strips to the California shoulder strips at 60 mph

The vibration sensor increments for 45 mph are shown in Figure C-43 for the Midwest shoulder and centerline strips compared to the California strips. The increments for the Midwest strips at 45 mph are similar to those at 60 mph, except that the 14-inch strips in California did not result in 10 dB on/off difference across all vehicles at the steering column. At 45 mph, the only set of strips that consistently achieved the minimum 10 dB requirement was the 14-inch sinusoidal strips in Michigan.



a) Midwest shoulder strips & CA strips *b) Midwest centerline strips & CA strips*

Figure C-43: Comparison of interior vibration increments for the Midwest shoulder and centerline strips to the California shoulder strips at 45 mph

SUMMARY AND CONCLUSIONS

The purpose of Phase I of the Task 1 measurements was to evaluate various sinusoidal rumble strip designs of different wavelength to assess their performance relative to the 14-inch design executed by Caltrans in California. This was done using the four different categories of vehicles and the testing parameters established in NCHRP Project 15-68.

The Indiana sites were designed for nominal wavelengths of 12, 18, and 24 inches. All three were specified for peak-to-peak depth of ⅜ inches with a recess of ⅛-inch below the surface of the pavement. It was found upon arrival that the 12- and 18-inch strips had apparently been overlaid with chip seal since the time of installation and evaluation by Indiana DOT.[1,2] As a result, the actual dimensions of these were somewhat ambiguous due to the roughness of the chip seal. For the 24-inch strips, the estimated wavelength for the shoulder strips was about 21 inches or 3 inches less than specified, while the centerline strips met the specified dimensions. At the Michigan site, the measured wavelength of the shoulder strips was 15⅛ inches compared to the 14-inch specification. The centerline strips were installed to specification.

The evaluation of the 12- and 18-inch strips were muddied by the presence of the chip seal overlay compared to the other strips. During pass-by measurements at the 12- and 18-inch test sites in Indiana and at the 14-inch test site in Michigan, neighbors in the area provided subjective critiques of the pavements and rumble strips. The chip seal overlay at the Indiana sites were extremely unpopular. Most neighbors were hoping this testing would lead to removing the overlay. When asked about the rumble strips, the neighbors did not complain about the noise increase from the rumble strips with the chip seal overlay and prior to the overlay. The neighbors in Michigan were not bothered in the least by the rumble strips. They did complain about noise from a nearby bridge pavement, but the newly installed 14-inch sinusoidal rumble strips were not even disturbing to the residents in the middle of the night.

In order to get direction regarding the specification of quiet, effective rumble strip designs for evaluation in Task 3 of the project, from the literature search and data from California, it was apparent that sinusoidal designs were the most promising as they were typically quieter for pass-by and produced equal or better warning to the vehicle operator of a lane departure. Comparison of pass-by on/off from the measurements in Indiana, Michigan, and California are compared in Figure C-44. For this figure, the results of shoulder and centerline strips at each site from the Midwest testing were averaged together. Although on the Indiana strips, the 12-inch and 18-inch provided the lowest on/off difference, these results were strongly influenced by the chip seal as the tire/pavement noise was elevated relative to the other pavements as indicated in Figure C-16. In Figure C-45, the on/off increments produced by the interior noise measurements are shown. Based on the literature, it is expected that the 12-inch would produce the highest increments, however, this is not the case. From Figures C-24 and C-25, the levels are actually higher than the other strips on the strips as well as off of the strips. In Figure C-46, the vibration increments are also shown which mimic the results for interior noise. The 18-inch strips indicate a similar influence of the chip seal as do the 12-inch results. In Figure C-44, the pass-by increments for the 24-inch strips are also small compared to the 14-inch strips. This is also seen in the interior

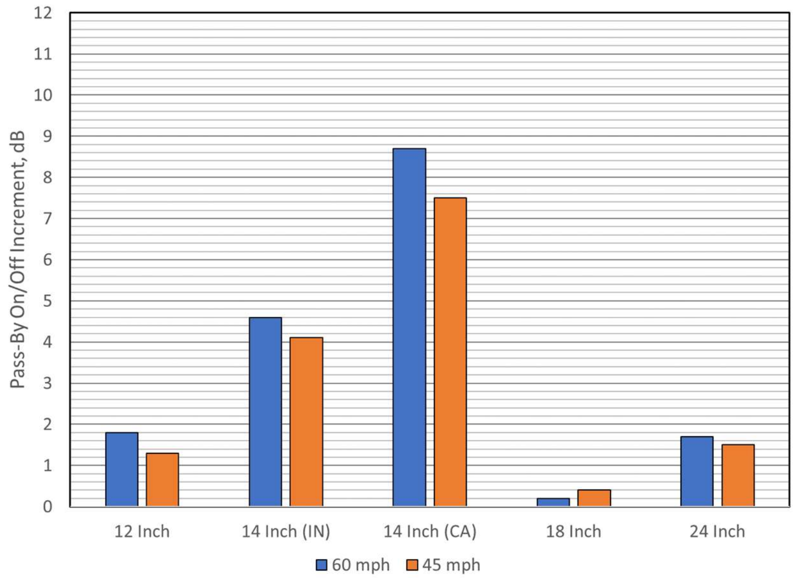


Figure C-44: Summary of pass-by on/off increments measured in NCHRP15-68 and 15-68(01)

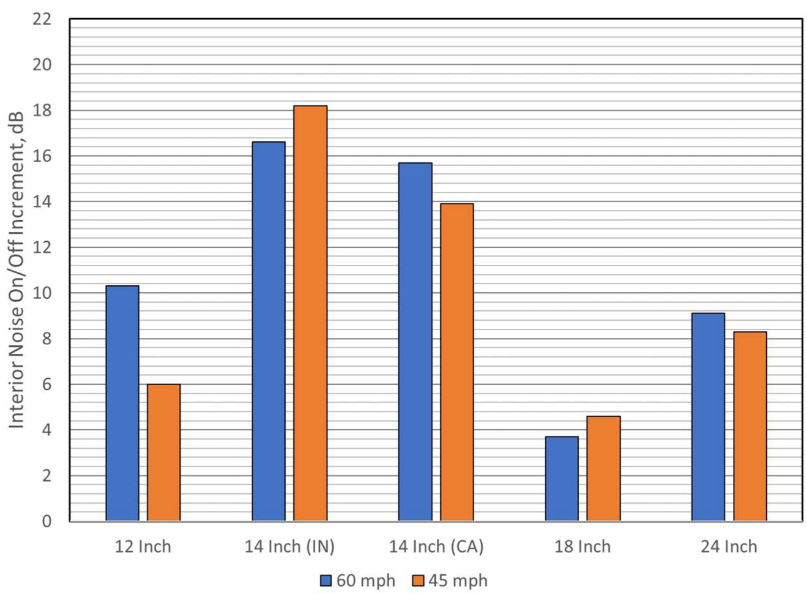


Figure C-45: Summary of interior noise on/off increments measured in NCHRP 15-68 and 15-68(01)

noise and vibration results (Figure C-45 and C-46, respectively). This behavior has also been reported in the literature and is not unexpected. Of the five sets of strips, only the two 14-inch designs consistently achieve the 10 dB on/off performance target for alerting the operator. Based on these findings, the search for an optimized sinusoidal design will be centered around a 14-inch design.

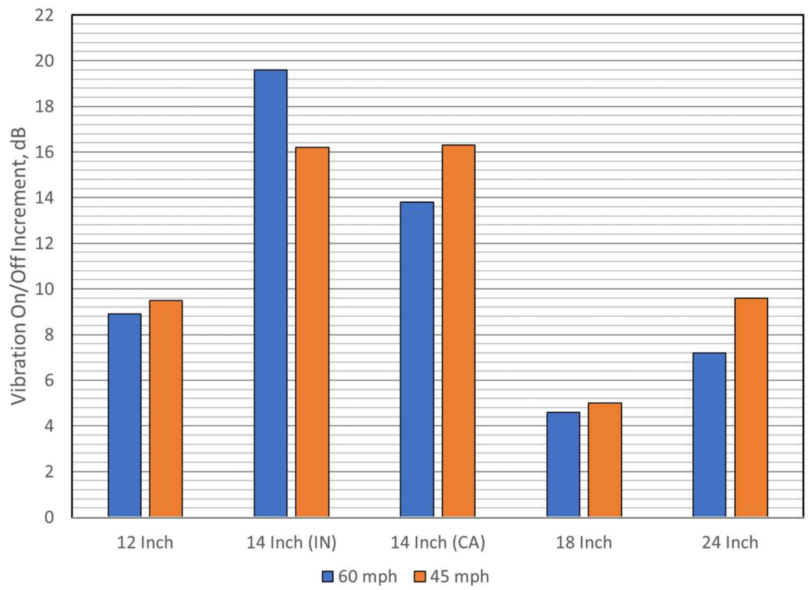


Figure C-46: Summary of interior noise on/off increments measured in NCHRP 15-68 and 15-68(01)

In Task 3 of this NCHRP project, the Project Team will be working with the Washington Department of Transportation to install up to 16 sinusoidal designs along a stretch of State Route 105 near Aberdeen, Washington. Table C-4 summarizes the proposed design configurations.

Table C-4: Proposed Test Site Designs for Task 9 Testing in Washington

Case #	Wavelength, in.	Peak-to-Peak, in.	Recess, in.
1	13	3/8	1/8
2	14	3/8	1/8
3	15	3/8	1/8
4	16	3/8	1/8
5	17	3/8	1/8
6	14	5/16	1/8
7	14	7/16	1/8
8	14	½	1/8
9	14	5/16	0
10	14	3/8	0
11	14	7/16	0
12	14	½	0
13	16	3/8	0
14	12	3/8	1/8
15	18	3/8	1/8
16	24	3/8	1/8

These tests will use the methods developed in Task 4 of NCHRP 15-68, with the goal of creating interior noise and vibration on/off increments of 10 to 15 dB while reducing pass-by on/off levels to 5 dB or below. In conducting tests in the Midwest, it was found that unlike the

California design, most designs in Midwest region use recessed sinusoidal designs. As a result, iterations in recess versus no recess will be evaluated along with wavelength and peak-to-peak sine wave amplitude. Due to the ambiguity created by the chip seal in Indiana sites, these designs will be replicated for the Task 3 testing. These are scheduled for installation beginning September 27, 2021.

REFERENCES

1. Balmos, A. D., J. K. Mathew, D. Plattner, J. V. Krogmeier, and D. M. Bullock, Evaluation of Sinusoidal Rumble Strip Noise Levels, Proceedings of the Transportation Research Board, Washington, D.C., January 2017.

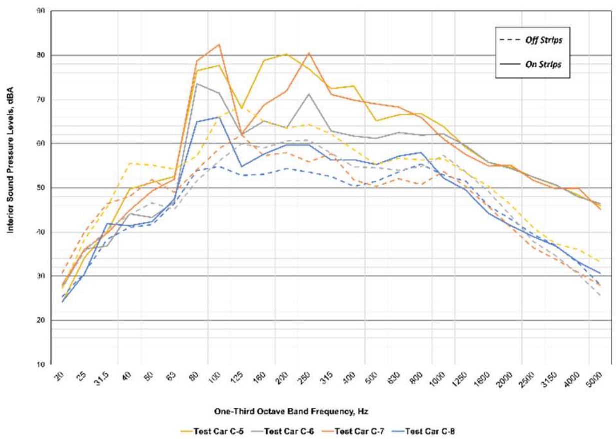
2. Mathew, J. K., Balmos, A. D., Plattner, D., Wells, T., Krogmeier, J. V., & Bullock, D. M. (2018). Assessment of Alternative Sinusoidal Rumble Stripe Construction (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/05). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316648

3. Standard Practice 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 2016. Washington, D.C. 20001.

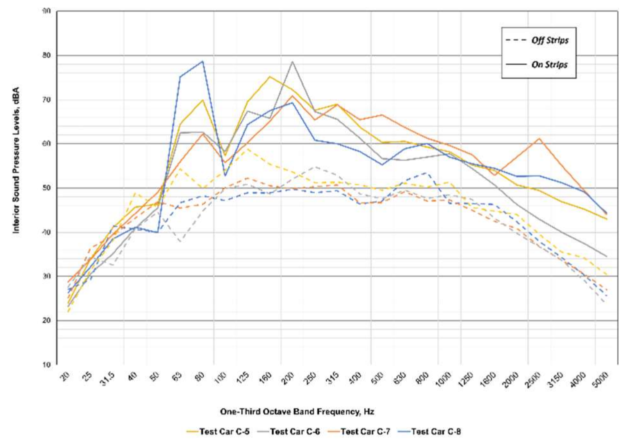
4. Donavan, P. and D. Lodico, "Measuring Tire-Pavement Noise at the Source", NCHRP Report 630, Transportation Research Board, Washington, D.C., 2009.

5. Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, Guidance for the Design and Application of Shoulder and Centerline Rumble Strips, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

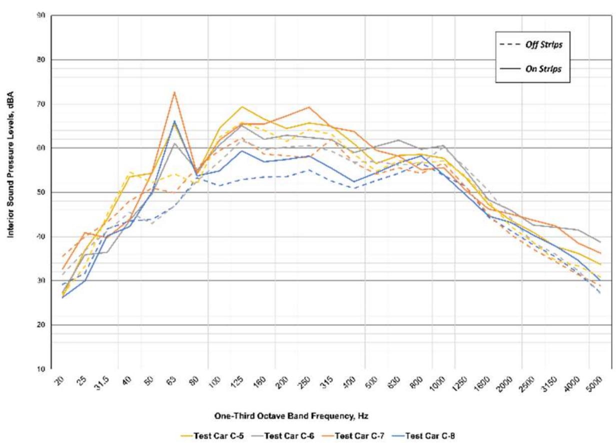
ADDITIONAL INTERIOR NOISE SPECTRA FOR FRONT-CENTER MICROPHONE LOCATION



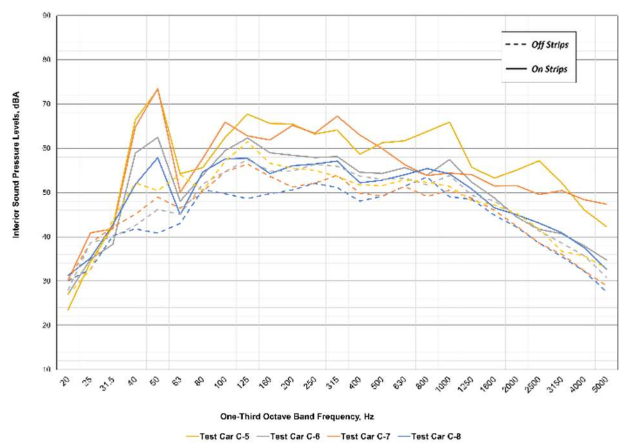
e) 12-inch Site



f) 14-inch Site

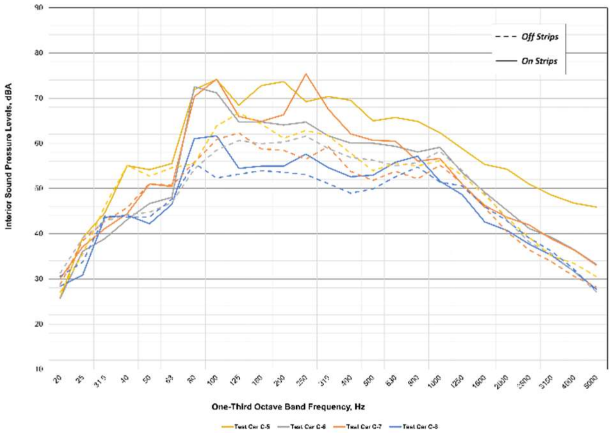


g) 18-inch Site

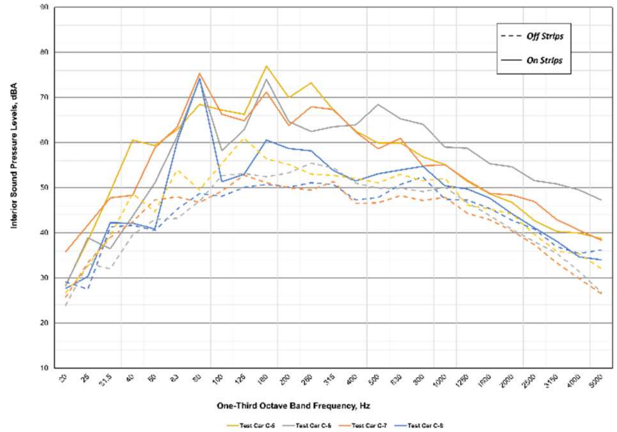


h) 24-inch Site

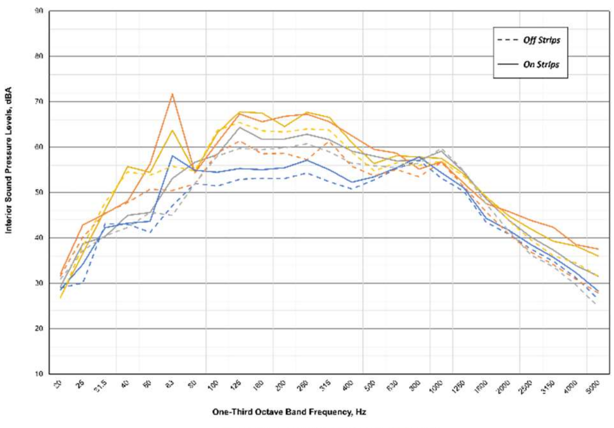
Figure C-47: ⅓ octave band sound pressures for on and off shoulder rumble strips at 60 mph, as measured at the front center microphone



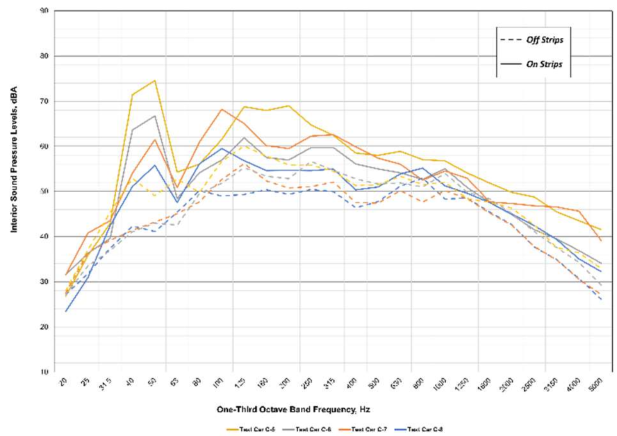
e) 12-inch Site



f) 14-inch Site



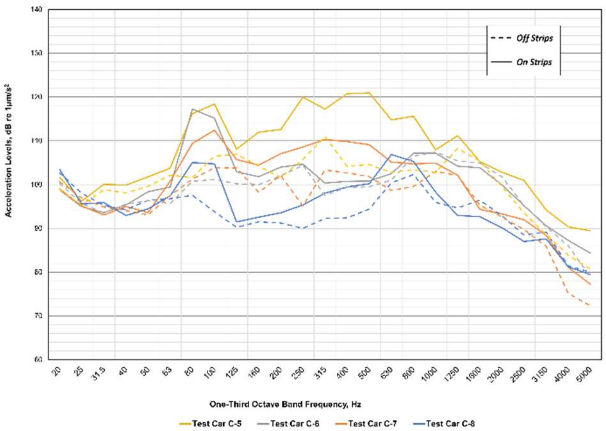
g) 18-inch Site



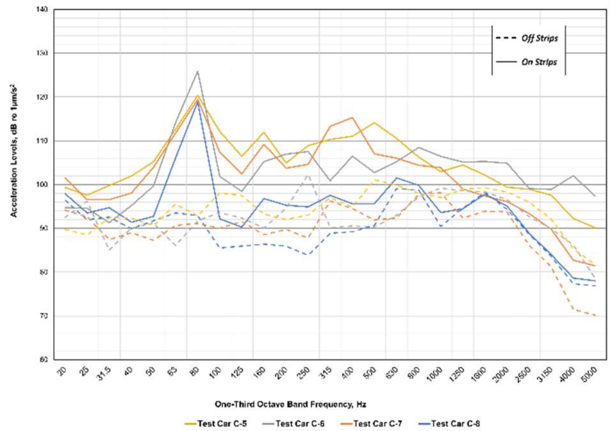
h) 24-inch Site

Figure C-48: ⅓ octave band sound pressures for on and off centerline rumble strips at 60 mph, as measured at the front center microphone

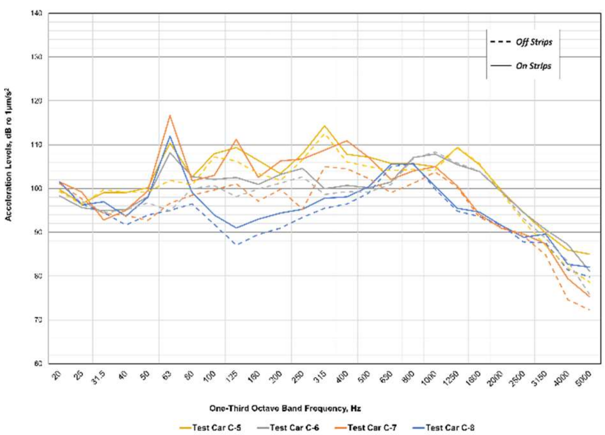
Additional Vibration Spectra for Steering Column



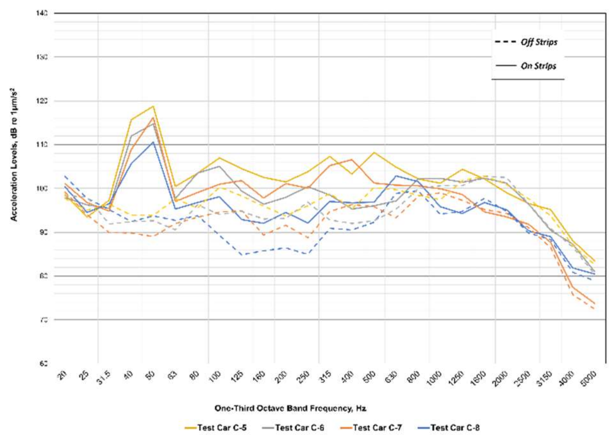
e) 12-inch Site



f) 14-inch Site

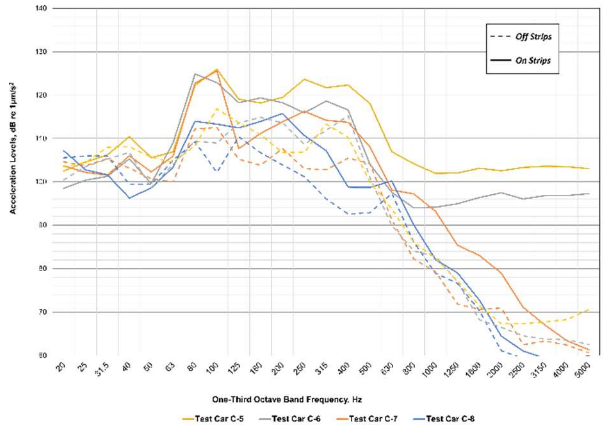


g) 18-inch Site

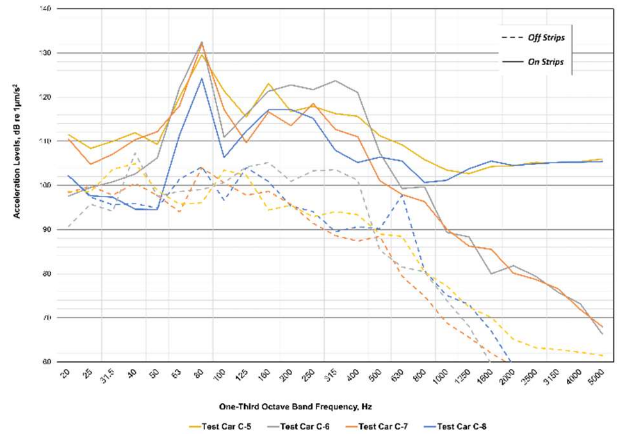


h) 24-inch Site

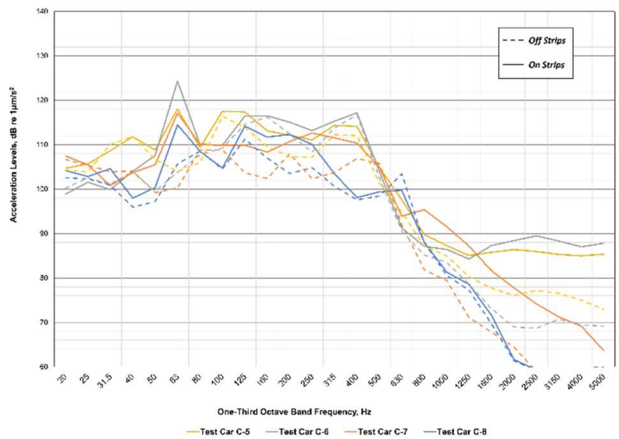
Figure C-49: ⅓ octave band vibration levels for on and off shoulder rumble strips at 60 mph, as measured at the steering column accelerometer location



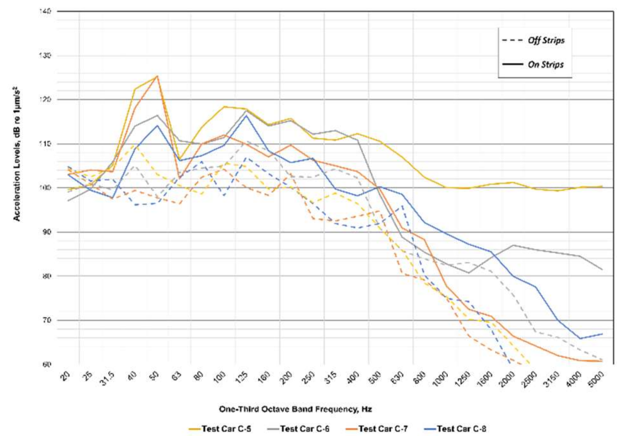
e) 12-inch Site



f) 14-inch Site



g) 18-inch Site



h) 24-inch Site

Figure C-50: ⅓ octave band vibration levels for on and off centerline rumble strips at 60 mph, as measured at the steering column accelerometer location