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INDIANA DEPARTMENT OF TRANSPORTATION  
AND PURDUE UNIVERSITY



## Assessment of Alternative Sinusoidal Rumble Stripe Construction



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## JOINT TRANSPORTATION RESEARCH PROGRAM

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<b>16. Abstract</b> <p>Studies have shown that rumble strips installed on a roadway significantly reduce the number of accidents caused by lane departures. However, when a vehicle engages the strips, a loud exterior noise is generated in addition to the alerting in-cabin noise. The extraneous exterior noise can travel at least several hundred feet at a volume which is considered a nuisance by nearby residents. In the recent years, a new rumble strip design in the form of a sine wave has been reported to produce low exterior noise, while still providing adequate warnings for drivers.</p> <p>This study evaluated three sinusoidal rumble strips of different wavelengths—12, 18, and 24 inch. The rumble strips were quantitatively compared by measuring the noise inside and outside of the vehicle as well as the vibration of the front seat frame. Results showed that the sound responses varied across the vehicles. From the exterior, all three sinusoidal rumble strips were quieter than the traditional rumble strips, with a reduction in sound power by 5 to 11 dBA. Interior cabin sound level was similar to standard rumble strips, with some cases increasing between 2 and 9 dBA. The retro reflectivity tests also exceed the minimum threshold set by INDOT specifications.</p> <p>Sinusoidal rumbles strips are a promising technology that is well suited for lane departure warning in residential areas. The results from this study suggest that the 12 in wavelength has a desirable decrease in exterior noise while still maintaining adequate lane departure warning to the driver.</p>			
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## EXECUTIVE SUMMARY

### ASSESSMENT OF ALTERNATIVE SINUSOIDAL RUMBLE STRIPE CONSTRUCTION

#### Motivation

Studies have shown that rumble strips installed on a roadway significantly reduce the number of crashes caused by lane departures. However, when a vehicle engages the strips, a loud exterior noise is generated in addition to the alerting in-cabin noise. The extraneous exterior noise can travel at least several hundred feet at a volume that is considered a nuisance by nearby residents. To limit exterior noise, the National Cooperative Highway Research Program (NCHRP) Report 641 on the Guidance for Design and Application of Rumble Strips considers noise levels of 6 to 12 dBA above the roadway noise as acceptable. In recent years, a new rumble strip design in the form of a sine wave has been reported to produce low exterior noise, while still providing adequate warnings for drivers.

#### Study

Although studies on sinusoidal rumble strips are limited, the results have shown that they can significantly reduce exterior noise compared to traditional square designs. However, there are still questions regarding the impact of the waveform parameters (wavelength, depth, and amplitude on noise volume) and the alerting of drivers departing from their lane. This study evaluated three sinusoidal rumble strips of different wavelengths: 12", 18", and 24". The sinusoidal rumble strips have fixed amplitude (3/16") and depth (5/16"). The test bed was constructed on IN1, near Fort Wayne, Indiana, with each wavelength being approximately 4 miles long. Data was collected from six vehicles, ranging from a passenger car to a semi-truck at a speed of 50 mph. The rumble strips were quantitatively compared by measuring the noise inside and outside of the vehicle (50' from edge line) as well as the vibration of the front seat frame. To exclusively capture the noise

generated from the rumble strips, and for safety reasons, the tests were conducted using short-term flagging operations to temporarily restrict traffic. For comparison purposes, sound and vibration measurements were made on standard Indiana Department of Transportation (INDOT) rumble strips.

#### Results

Results showed that the sound responses varied across vehicles. For heavy vehicles, engine noise and vibrations were found to dominate from inside the vehicle. From the exterior, all three sinusoidal rumble strips were quieter than the traditional rumble strips, with a reduction in sound power by anywhere between 5 and 11 dBA. Interior cabin sound level was similar to standard rumble strips, with some selected cases increasing between 2 and 9 dBA.

Retro reflectivity tests were performed on the three sinusoidal patterns, a year after their installation, to evaluate the visibility during night and inclement weather conditions. The retro reflectivity tests on all three sinusoidal patterns, on both the edge and center lines, were found to exceed the minimum threshold set by INDOT specifications.

#### Recommendations

The 12" sinusoidal rumble strip was the only pattern found to routinely satisfy the recommendations for in-cabin and exterior sound levels proposed by NCHRP Report 641. The width of the rumble strips did not play a major role in the noise, as the sound levels produced from the edge line and center line were equally loud in the interior. The retro reflectivity tests on all three sinusoidal patterns, on both the edge and center lines, were found to exceed the minimum threshold set by INDOT specifications.

Sinusoidal rumbles strips are a promising technology that is well suited for lane departure warning in residential areas. The results from this study suggest that the 12" wavelength has a desirable decrease in exterior noise while still maintaining reasonable or even, at times, superior (than the standard milled rumbles) lane departure warning to the driver.

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## LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
CFD	Cumulative Frequency Diagram
INDOT	Indiana Department of Transportation
NCHRP	National Cooperative Highway Research Program
RMS	Root Mean Square
RPM	Raised Pavement Marker
SPL	Sound Power Level
SUV	Sports Utility Vehicle
USB	Universal Serial Bus



## 1. INTRODUCTION

Rumble strips have been suggested as an alternative to raised pavement markers (RPM's), particularly during periods of decreased visibility and/or adverse weather conditions (Brennan, Mitkey, & Bullock, 2014). Studies have also established that rumble strips reduce vehicle crashes by 35% to 45% (Bucko, 2001; Brennan et al., 2014). However, when a vehicle engages the strips a loud exterior noise is generated in addition to the alerting in-cabin noise. The extraneous exterior noise is capable of traveling at least several hundred feet at a volume which is considered a nuisance by nearby residents. The National Cooperative Highway Research Program (NCHRP) Report 641 on the Guidance for Design and Application of Rumble Strips recommends that rumble strips should be designed to produce an in-cabin sound level increase of 10 to 15 dBA over the travel lane on freeways. To limit exterior noise near residential land uses, an increase of 6 to 12 dBA is considered acceptable (Torbic et al., 2009). Studies have found that traditional milled and rolled rumble strips increase the exterior noise levels from 100' to 150' away from the center line of the roadway (DelDOT, 2012; Finley & Miles, 2007; Karkle, 2011). Sound propagation was also found to vary depending on the installation method (Bucko, 2001), width and spacing (Finley & Miles, 2007; Sexton, 2014), speed, type of vehicle (Bucko, 2001; Karkle, 2011), and environmental conditions such as air temperature, humidity and wind speed (Lamancusa, 2009).

In the recent years, a new rumble strip design, in form of a sine wave has been reported to produce low exterior noise, while still providing adequate warnings for drivers (Kragh & Andersen, 2008; Terhaar & Braslau, 2015). This work studies the sound and vibration of six different vehicles at a speed of 50mph on sinusoidal rumble strip incursions of three different wavelengths (12", 18", and 24"). For comparison purposes, sound and vibration measurements were made on traditional (standard) rumble strips. Retro reflectivity tests were also performed on the sinusoidal rumble strips.

## 2. LITERATURE REVIEW

Rumble strips are safety countermeasures that uses tactile vibration and audible rumbling to alert inattentive drivers of a potential danger. Rumble strips are typically laid in two different formats – longitudinal and transverse. Longitudinal rumble strips are effective in providing lane-departure warnings when a vehicle drifts off a lane, whereas transverse rumble strips are more useful in providing advance warnings such as in the case of a slow-down or of an approaching construction zone (Srinivasan, Baek, & Council, 2010). Longitudinal rumble strips are usually placed along the center line and edge line. Center line rumble strips are effective in reducing head-on collisions and opposite-direction sideswipes, especially in the case of drivers crossing center lines of two-lane roads (FHWA, 2011a). Shoulder or edge line rumble

strips are commonly used in narrow roads to warn drivers when they drift off from their lanes. They are primarily effective in reducing run-off-the-road crashes (FHWA, 2011c).

Rumble strips can be rolled, formed, milled and raised (FHWA, 2011b). Rolled rumble strips are rounded or V-shaped grooves pressed into the asphalt pavements during construction. Formed rumble strips are similar to rolled, except they are made by pressing forms into concrete shoulders. Milled rumble strips are grooves (typically 5" to 7" wide with a 12" spacing and 0.5" depth) cut into the pavement by a machine with a rotary cutting head. Raised rumble strips are round or rectangular markers or thermoplastic strips (typically 2" to 12" wide and 0.25" to 0.5" high) which adhere to new or existing pavements. The application of raised rumble strips are limited in areas where snowplow operations are predominant during winter (FHWA, 2015a). Milled rumble strips are more common due to their ease of constructability, durability and cost. Studies have also found that milled rumble strips produce more noise than rolled and formed (Bucko, 2001).

In the recent years, longitudinal rumble strips based on a new sinusoidal design, have been reported to provide effective lane departure warnings to a driver with lower exterior noise. A pilot study conducted by the Danish Road Institute found that the sinusoidal pattern led to an exterior increase of only 0.5 to 1 decibels (dB) over regular road noise (Kragh & Andersen, 2008). The Minnesota Department of Transportation (Terhaar & Braslau, 2015) evaluated the noise on three different rumble strip types:

1. *California design*: sinusoidal shaped with a flat crest (14" center to center, 1/32–5/8" depth and 8" width)
2. *Pennsylvania design*: sinusoidal (24" center to center, 1/8–1/2" depth and 8" width)
3. *Minnesota design*: traditional milled rumble strips (12" center to center, 3/8–1/2" depth and 16" width)

Three different vehicle types were tested at speeds of 30, 45, and 60 mph. The in-cabin noise levels for the Pennsylvania design (sinusoidal) were found to be 3 to 5 dBA higher than the Minnesota design (standard milled) in the test car and 14 to 19 dBA higher in the test pick-up truck.

Rumble strips are painted with a retroreflective coating to increase the visibility of the pavement edges and centerline, at night and during adverse weather conditions. These rumble strips are known as rumble stripes (FHWA, 2015b). Various studies have been conducted in the past to evaluate the performance of rumble stripes. Researchers from Indiana Department of Transportation (INDOT) and Purdue University conducted a study to compare the retroreflective characteristic of rumble strips and standard painted lines (Mitkey et al., 2012). The study also evaluated the durability of both after a season of winter snowplowing operations. The results showed that rumble stripes were effective in providing increased night time visibility in dry and wet conditions, as well as

increased durability after snowplow operations. However, recent deployments have exhibited low retro-reflectivity characteristics, perhaps due to new fog seal treatment procedures.

A study conducted by Virginia DOT compared the durability of six different pavement marking technologies over a period of 23 months and found that the markings installed on grooves or rumble strips retained more reflectivity and received less damage than those on the surface of the roadway (Gibbons & Williams, 2012). A recent study by the Minnesota Department of Transportation evaluated the retroreflectivity of the rumble stripes on 14 different roadways, 12 months after their installation. The results showed that more than half of the sites had 90% of their retroreflective readings in excess of the arbitrary benchmark set for performance (Hawkins, Smadi, Kinckerbocker, & Carlson, 2016).

A comprehensive study on the various designs of sinusoidal patterns that affect the noise and vibrations on vehicles are yet to be performed. Although studies have established rumble stripes to be effective in providing increased visibility during night time, as well as improved durability after snow plow operations,

their performance on sinusoidal rumble strips have not been evaluated.

### 3. MOTIVATION AND SCOPE

Prior work (Kragh & Andersen, 2008; Terhaar & Braslau, 2015) has shown sinusoidal rumble strips can significantly reduce exterior noise compared to traditional square designs. However, there are still open questions regarding the impact of the waveform parameters: wavelength, depth, and amplitude on noise volume and alerting of drivers departing from their lane. This study evaluated a standard Indiana Department of Transportation (INDOT) rumble strip (Figure 3.1 (a)) and three sinusoidal rumble strips (Figure 3.1 (b)) of different wavelengths (12", 18", and 24"). The geometric construction details of these are shown in Figure 3.2. The sinusoidal rumble strips have fixed amplitude (3/16") and depth (5/16"). The rumble strips were quantitatively compared by measuring the noise inside and outside of the vehicle as well as the vibration of the front seat frame. Retroreflectivity tests were also performed on the three sinusoidal patterns, a year after installation, to compare and evaluate the retro reflectivity and durability.

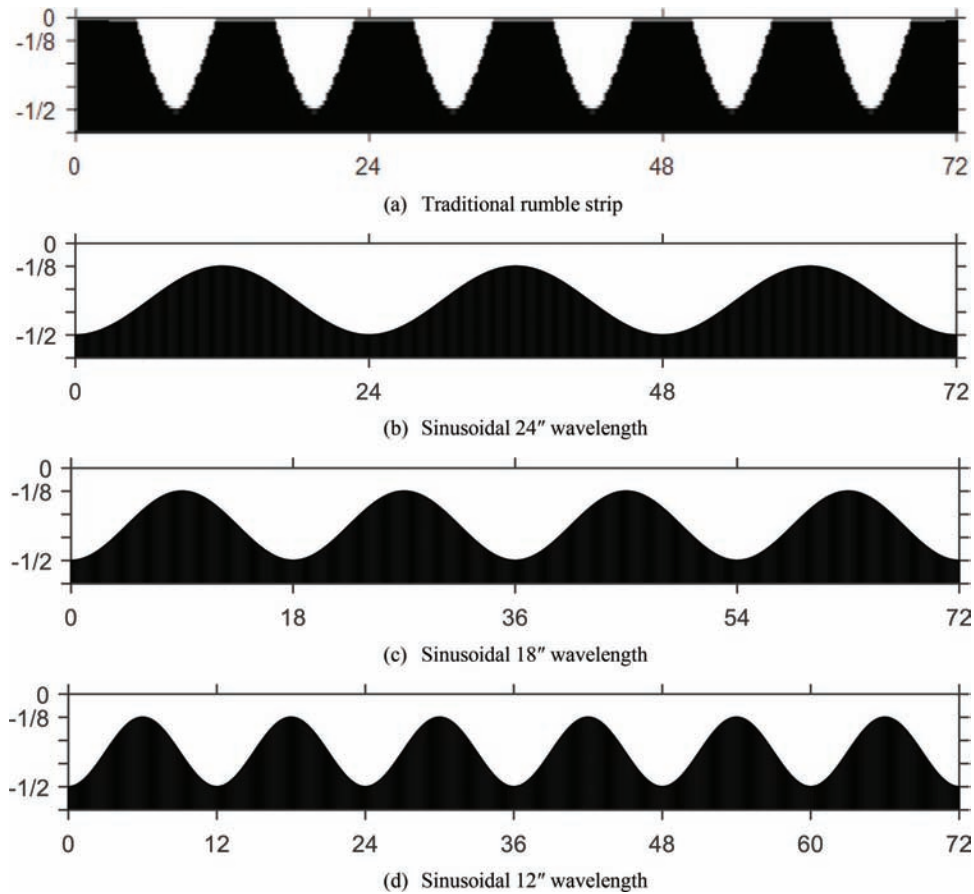


(a) Traditional rumble strip



(b) Sinusoidal rumble strip

**Figure 3.1** Traditional and sinusoidal rumble strip.



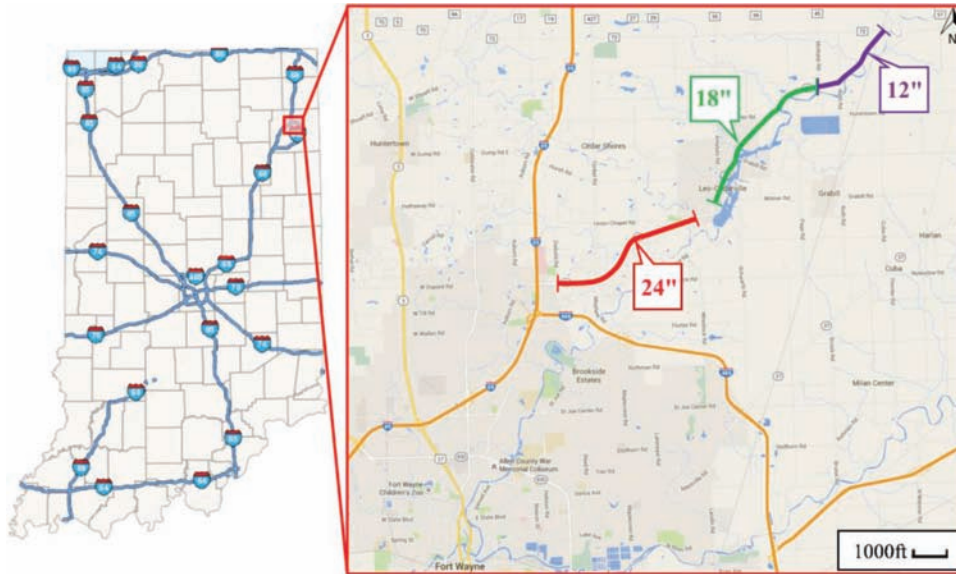
**Figure 3.2** Profile of alternative rumble strip configurations (not to scale). The y-axis represents the depth of the rumble strips with zero being the top of the pavement.

#### 4. FIELD TEST LOCATION AND CONSTRUCTION ACTIVITIES

The three sinusoidal rumble strip configurations were constructed by INDOT at a test site on IN 1, near Fort Wayne, Indiana, as shown in Figure 4.1. The 24" and 18" rumble strips were constructed for a length of approximately 4 miles. The 12" wavelength rumble

strips is approximately 2.4 miles long. For comparison purposes standard milled rumble strips along SR 25, near Shadeland, Indiana, were also studied.

The construction process has been video documented (<https://doi.org/10.4231/R76H4FPJ>). Figure 4.2 shows pictures of the milling process, the milling head, sweeping process and the finished product from the construction.



**Figure 4.1** Location of sinusoidal rumble strip test bed on IN 1, Fort Wayne, IN.



**Figure 4.2** Sinusoidal rumble strip construction on June 8, 2016.

## 5. DATA COLLECTION

Data was collected at three sites along IN 1, Fort Wayne, IN one for each sinusoidal configuration, and one site along SR 25, Shadeland, IN for the standard milled configuration. Data collection on the standard milled rumble strips were only performed for the smaller vehicles (Minivan, Suburban and Impala). Locations and pictures of the test sites are shown in Figure 5.1.

### 5.1 Test Vehicles

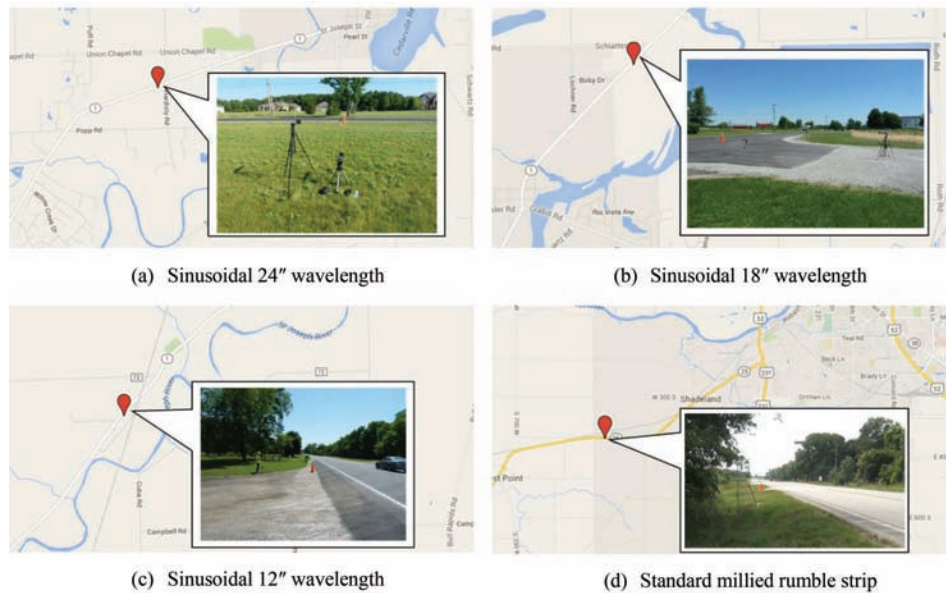
Data collection was carried out on a wide spectrum of vehicles, ranging from a passenger car to a semi truck. The six vehicles tested were: semi-trailer truck,

single axle truck, tandem axle truck, Ford E-150 (Minivan), Chevrolet Suburban (SUV) and Chevrolet Impala (sedan) (Figure 5.2).

### 5.2 Test Sensors and Data Processing

The sensors consisted of a 3-axis accelerometer and class 1 sound level meters. In particular, a GCDC X2-2 tri-axial USB accelerometer (Gulf Coast Data Concepts, n.d.), with sampling frequency of 512 Hz, was mounted on the driver side seat frame (Figure 5.3). The data was stored as plain text comma separated files and imported in MATLAB for processing. The sound level meters were Larson-Davis Model 831 Type 1 units (Figure 5.4 (b)), with audio recording functionality. The data was stored





**Figure 5.1** Test site locations.



**Figure 5.2** Test vehicles: (a) tandem axle, (b) single axle, (c) semi-trailer, (d) Chevrolet Suburban, (e) Chevrolet Impala, and (f) Ford E-150 Minivan.

as raw wav files and imported in MATLAB for processing. Additionally, a camcorder was used to record each test event. All the sound meters and accelerometers were calibrated and time synchronized.

### 5.3 Sound Level Measurement

Figure 5.4 shows the placement of the exterior and in-cabin sound level meters. The exterior sound meters were placed at a distance of 50' from the closest edge line rumble strip and at a height of 4' from ground level (Figure 5.4 (a)). This layout was adopted after testing out various configurations during the preliminary analysis

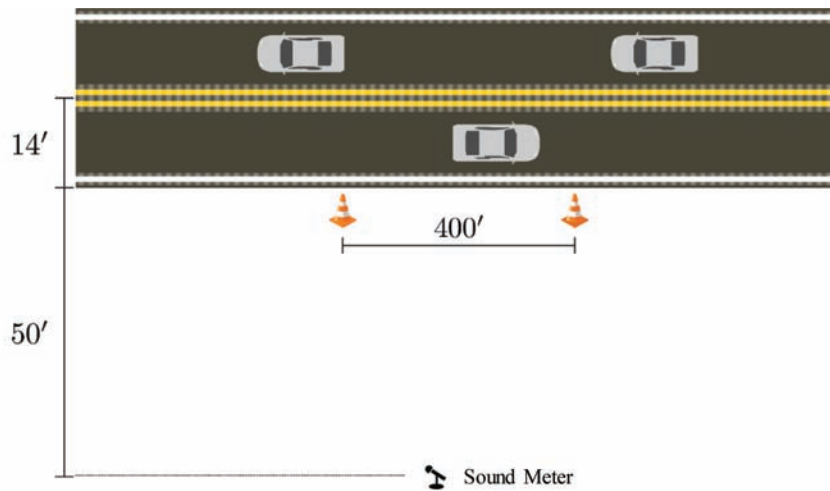
(Appendix A). The in-cabin sound meter was mounted inside the vehicle near the driver's ear as seen in Figure 5.4 (d) and (e). Traffic cones were placed at a distance of 200' on either side of outside sound meter to provide reference locations for the driver and video logs.

### 5.4 Test Scenarios

Road noise is generated by passing vehicles under a variety of conditions that include rumble strip incursions as well as pass-by traffic with no rumble strip incursions. Five test scenarios were evaluated during the preliminary tests (Appendix A).



Figure 5.3 Accelerometer installation.



(a) Layout of the exterior sound meter at test site



(b) Larson-Davis Model 831 Type 1 sound meter



(c) Sound meter at distance of 50' off the edge line and at a height of 4' above ground level



(d) In-cabin sound meter in heavy vehicles



(e) In-cabin sound meter in smaller vehicles

Figure 5.4 Deployment of sound meters during data collection.

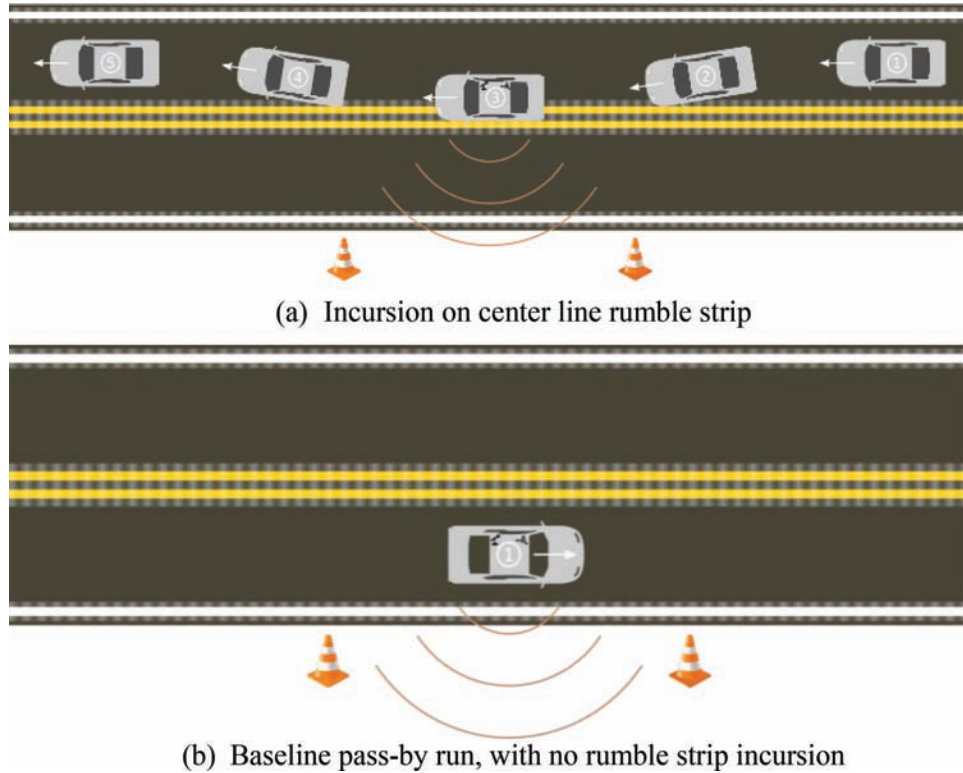


Figure 5.5 Test scenarios.

To effectively characterize various noise levels, the road was closed to avoid the interference from regular traffic. Due to time constraints and road closure, only the following test scenarios were evaluated:

1. *Center line:* Incursion on the far side center line rumble strip (Figure 5.5 (a))
2. *No incursion or baseline pass-by run:* Normal pass-by of the vehicle without any incursion on the rumble strips (Figure 5.5 (b))

## 6. RESULTS AND ANALYSIS

### 6.1 Accelerometer Analysis

The accelerometer measures acceleration in the sensor’s three-dimensional frame using units of gravity (g). This study is predominantly interested in acceleration caused by vibration; therefore, the constant acceleration of Earth’s gravity must be accounted for. However, that is not easily accomplished because the coordinate frame of the sensor is not precisely known. Instead, for each incursion the constant acceleration is subtracted from each of the sensor’s 3-axis. A time-series “dynamic magnitude” trace,  $a_d[n]$  is computed from the result, as shown in Equation 6.1.

$$a_d^N[n] = \sqrt{(a_x[n] - \mu_x)^2 + (a_y[n] - \mu_y)^2 + (a_z[n] - \mu_z)^2} \quad (6.1)$$

where  $a_\alpha[n]$  is the acceleration,  $\mu_\alpha$  is the mean acceleration in the  $\alpha$  direction during the N-th trial, and  $n$  is the discrete-time index with a sample rate of 512 Hz (data was collected at a frequency of 512 Hz).

The design of the experiment requires that the test vehicle travel at a constant speed during a rumble strip incursion. Therefore, the only constant acceleration present during the data collection is gravity. In this fact, the gravity components are estimated by averaging all data collected during a particular trail. By subtracting this average from the original signal, the dynamic portion of the total vibration is estimated.

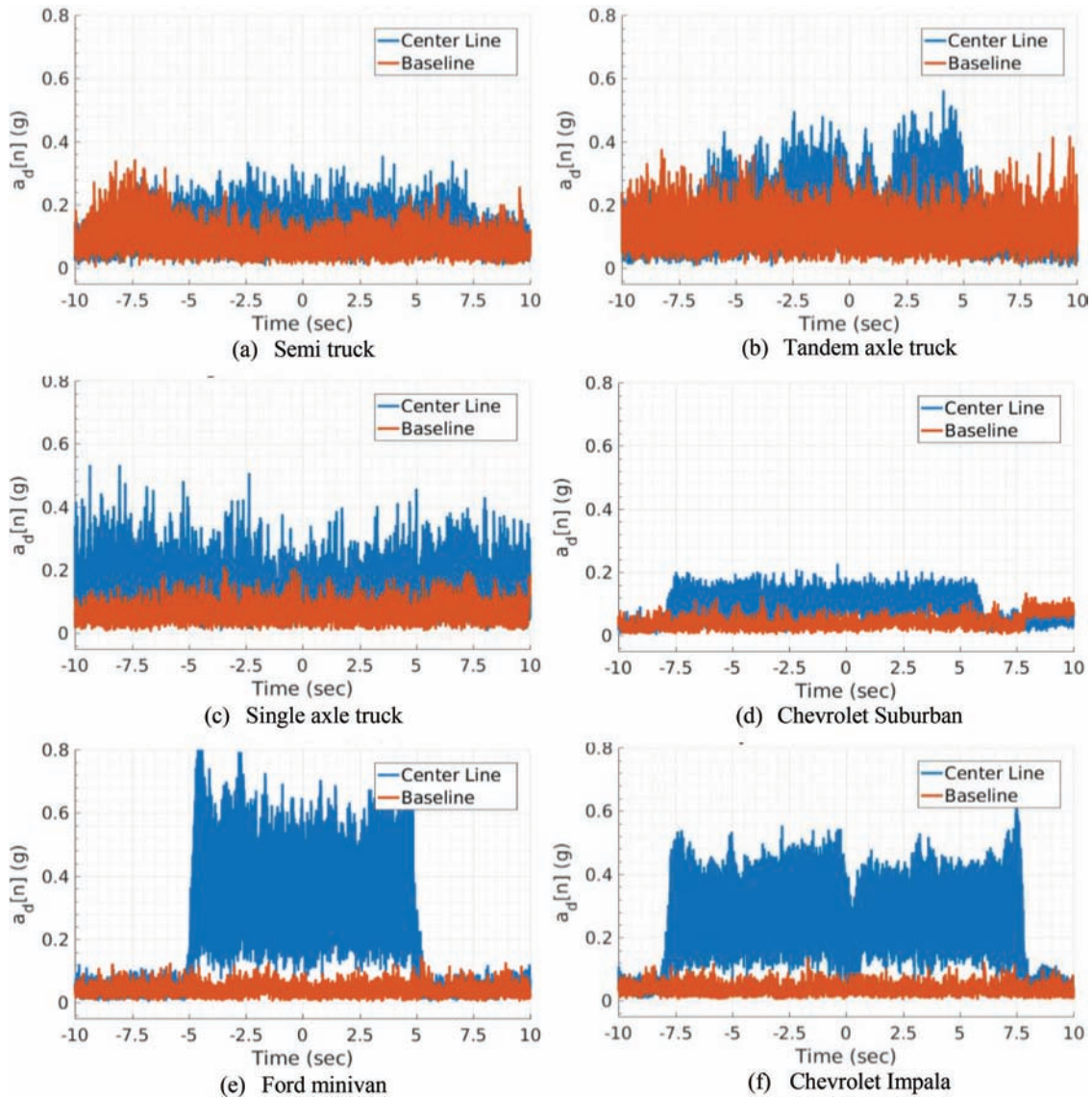
#### 6.1.1 Acceleration Magnitude Traces

Figure 6.1 features some example dynamic magnitude traces collected on the 12” wavelength rumble strips for all the test vehicles at 50 mph. As seen, the engine vibrations are dominant across the heavy vehicles and it is very difficult to separate the rumble strips from the baseline traces (Figure 6.1 (a) – (c)). As for the smaller vehicles (Figure 6.1 (d) – (f)), there is a clear distinction between the acceleration traces from the rumble strips and the baseline (no rumble). Acceleration traces on the 18” and 24” rumble strips can be found in Appendix B.

#### 6.1.2 Comparison of Acceleration Levels across the Three Wavelengths

Vibration is an important aspect of alerting a driver to an impending lane departure. Therefore, it is important to consider the level of vibration induced on the vehicle by the rumble strips. Figure 6.2 compares the average maximum of observed root-mean-squared (RMS) dynamic acceleration across the experiment runs.





**Figure 6.1** Acceleration traces for test vehicles on 12" sinusoidal rumble strips at 50 mph.

The RMS is computed using a 125 millisecond (ms) long moving window. The baseline marks the average maximum RMS of the dynamic acceleration during the baseline pass-by run, driving only on the road and not the rumble strip. The induced vibration is a function of the vehicle's suspension and therefore no clear pattern emerges. However, the vibration does tend to decrease in the seat frame with increasing wavelength. Somewhat surprisingly, the suburban was most effective at suppressing the induced sinusoidal vibrations. This may be explained by the suburban suspension design accounting for washboard, or corrugated, dirt roads given its off-road nature. Whereas the van and impala design likely focused on paved road conditions.

## 6.2 Sound Level Analysis

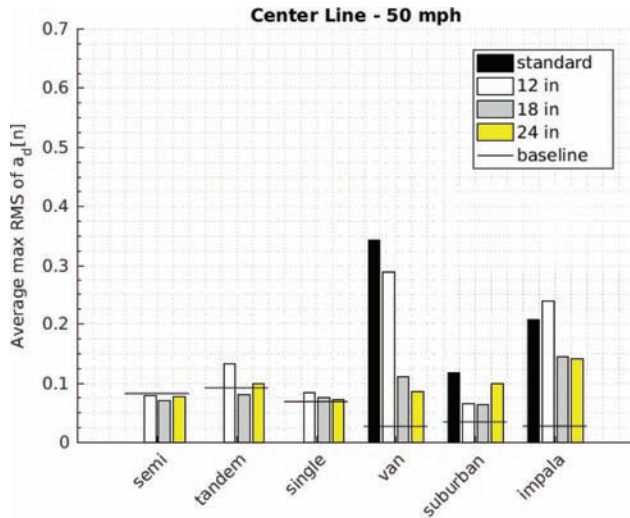
Developing a metric for the perception of a sound is difficult (Hudspeth, 1989; Smith, 1999) and is still somewhat

of an open problem today. The human ear and the auditory processing center in the brain<sup>1</sup> is a very complex organ with many individual parts that each sense its own portion of the sound spectrum. As a result, sound perception is not only dependent on frequency but also other characteristics of the pressure wave, such as the length of time a particular component is present and the overall complexity of the pressure waveform, e.g., a single tone vs. a composition of tones.

In practice, the solution to this problem is to compute the sound power level (SPL) after filtering the waveform by a weighting function that approximates the human ear's response, as shown in Equation 6.2. However, because no linear, time-invariant filter can completely capture the processing done by the ear,

<sup>1</sup>For the remainder of this report, by ear we refer to the human ear and the auditory processing center in the brain.





**Figure 6.2** Average maximum RMS of accelerometer dynamic magnitude for all test vehicles at 50 mph.

many different weightings functions have been proposed, each useful within its own criteria.

$$L_w[n] = 20 \log_{10} \left( \frac{s[n] * h_w[n]}{20 \mu Pa} \right) \text{ dB} \quad (6.2)$$

where  $L_p[n]$  is the signal power, weighted by the  $w$  weighting function,  $s[n]$  is the sound waveform in Pascals,  $h_w[n]$  is the  $w$  weighting filter's impulse response, and  $20 \mu Pa$  is the standard reference for SPL (often considered the threshold of human hearing).

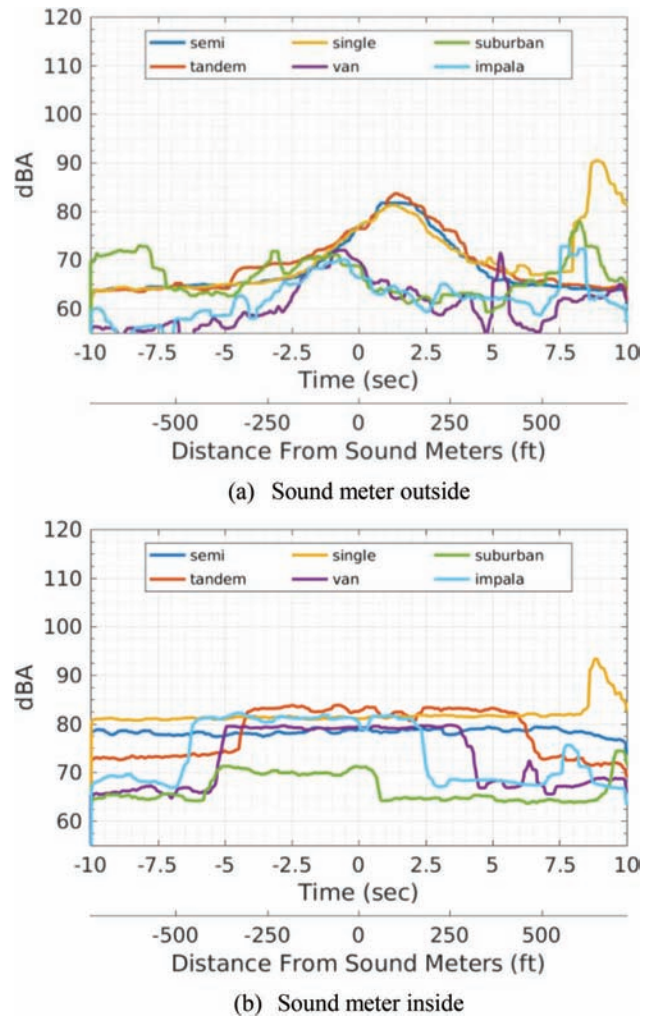
Three weighting functions, defined as frequency responses with acceptable tolerances were evaluated during the preliminary stage of this research – A-weighting, ITU-R 468-4 weighting, and C-weighting (Appendix A). Based on the preliminary results, it was decided to adopt the A-weighting for further tests.

The A-weighting is a commonly used filter in the United States of America and is defined by IEC 61672-1: 2013 (2013). Low frequencies are devalued by the A-weighting function because it was originally designed for measuring low volume sounds where the Fletcher-Munson (1993; ISO, 2003) equal loudness curves predicated severe attenuation by the ear (approximately 40 phon<sup>2</sup> curve (Fletcher & Munson, 1933)). Regardless, nowadays it is often used as the required weighting function for many safety and environmental noise standards.

### 6.2.1 Sound Power Traces

Figure 6.3 compares sound power traces measured by each sound meter on the 50 mph center line incursion for all the test vehicles. The signals are averaged with a 125 millisecond moving window, defined by the IEC as the “fast” average (14). The vehicles attempt to drive on the rumble strip for approximately 200' before

<sup>2</sup> 1 phon is the perceived loudness of a 1dB SPL1kHz sine wave.



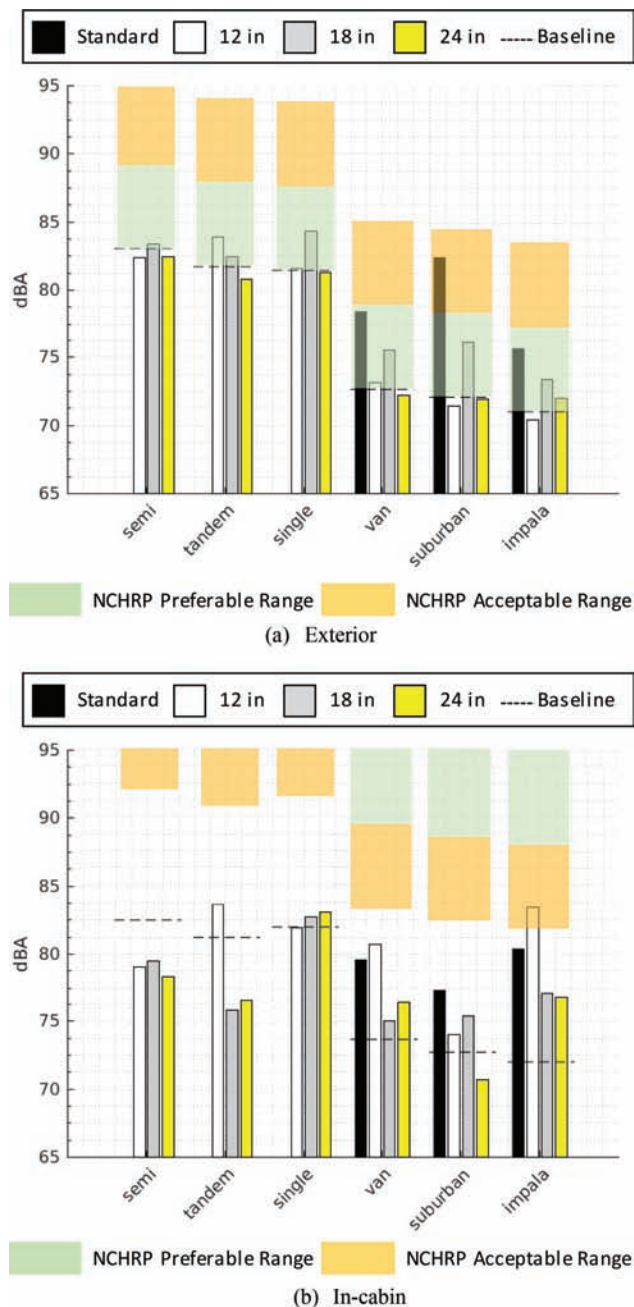
**Figure 6.3** Sound power traces on center line incursion for 12” sinusoidal rumble strip at 50 mph.

and after the location of the exterior sound meter, as shown in Figure 5.4. Some of the traces indicate loud periods before and after the trial. For exterior measurements this is accounted for by other vehicles on the road. Additionally, for both exterior and interior measurements, the researcher’s wireless radio use was sometimes captured immediately before and after the test.

From testing done that included 40 mph incursions, the sound level traces were consistent in shape. As expected, the 50 mph tests are louder than the 40 mph. However, relative increase in loudness when comparing wavelength to wavelength at one speed is similar. Example 40 mph traces can be found in Figure A.7.

### 6.2.2 Sound Levels

To reduce the time-series traces (Figure 6.3) to a single metric, the maximum observed power values for each vehicle encounter of a rumble strip, given a particular configuration, was averaged. For the baseline pass-by measurements, which do not include a rumble incursion, the maximum observed power level within a  $\pm 4$  second



**Figure 6.4** Sound level comparison for all vehicles on center line rumble at 50 mph.

**TABLE 6.1**  
Sound level comparisons with NCHRP recommendations

NCHRP recommendations	Exterior sound levels	In-cabin sound levels
	To limit exterior noise near residential land uses, sound should not increase by more than 12 dBA and preferably by less than 6 dBA	In-cabin (inside) sound level should increase by 10 dBA and preferably over 15 dBA
12"	✔ 0 to 1 dBA above baseline	⚠ 4 to 12 dBA above baseline
18"	✔ 3 to 5 dBA above baseline	✘ 1 to 5 dBA above baseline
24"	✔ 0 to 1 dBA above baseline	✘ 0 to 4 dBA above baseline
Standard	⚠ 5 to 11 dBA above baseline	✘ 5 to 8 dBA above baseline

window surrounding the time the vehicle passes the sound meter was averaged. All of the configurations have at least three averaged repetitions. Figure 6.4 compares the measured sound level on center line incursions across the experiment's runs. The dotted line shown on the sound level plots is the average sound level during baseline (no incursion) runs.

Overall, the in-cabin and exterior sound responses varied across the vehicles. In general, from the exterior, the sinusoidal rumble strips are less loud than the traditional rumble strips, with a reduction in sound power by anywhere between 5 dBA and 11 dBA (Figure 6.4 (a)). From the interior of the vehicle, the sinusoidal rumble strips are almost as loud as the standard rumbles, but still increase the in-cabin sound level by between 2 and 9 dBA (Figure 6.4 (b)) as compared to baseline (or no incursion) case. Some of the data suggests that the 24" wavelength is actually quieter than the baseline, however, this is a result of stochastic variation. During the experiment, the researchers observed some difficulties in detecting the difference between a 24" wavelength incursion and a baseline pass-by run from outside of the vehicle. There is also a large drop-off of interior noise for the heavy vehicles, which is likely due to their dominant engine noise and superior vehicle suspensions.

Interestingly, the 12" wavelength seems to strike a balance between a reduced exterior noise and an increased interior noise. From outside, the 12" sinusoidal rumble strips were found to be 5 to 11 dBA quieter than standard rumbles, and from inside, they were found to produce a sound level increase of 4 to 12 dBA compared to baseline road noise. The 12" was also found to routinely satisfy the recommendations for in-cabin and exterior sound levels proposed by the NCHRP Report 641 on Guidance for Design and Application of Rumble Strips (Torbic et al., 2009) (see Table 6.1). The light orange and light green bands in Figure 6.4 display the acceptable and preferable increase in sound level ranges, respectively, from the NCHRP report.

### 6.3 Comparison of Edge Line and Center Line Rumble Strip Sound Levels

In order to utilize maximum right of way, the edge line rumble strips were constructed with a 12" width

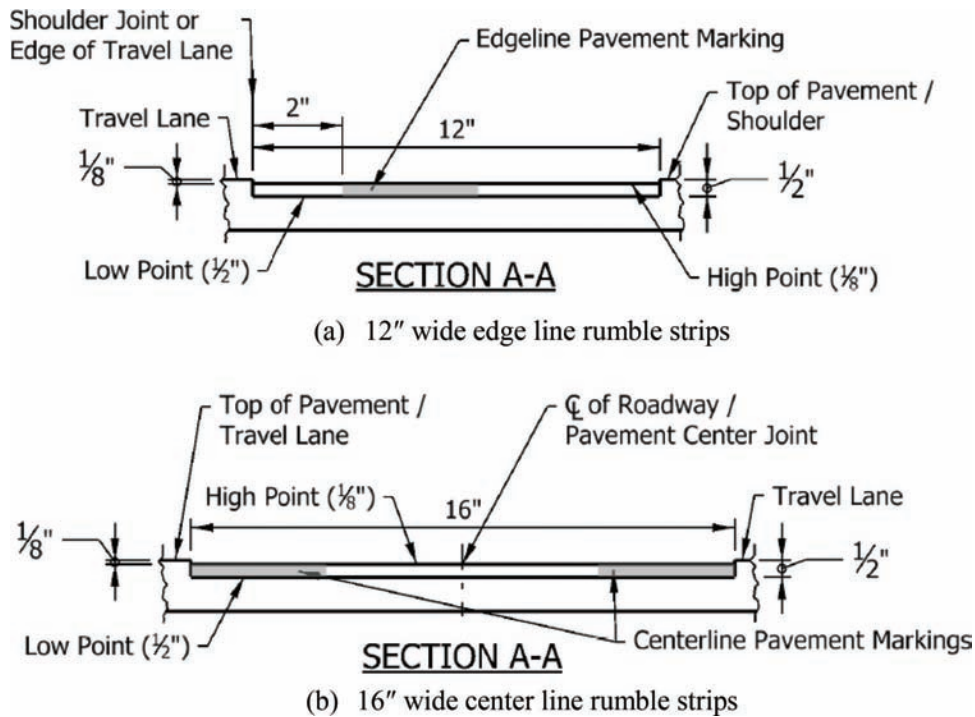


Figure 6.5 Section details of edge line and center line rumble strips.

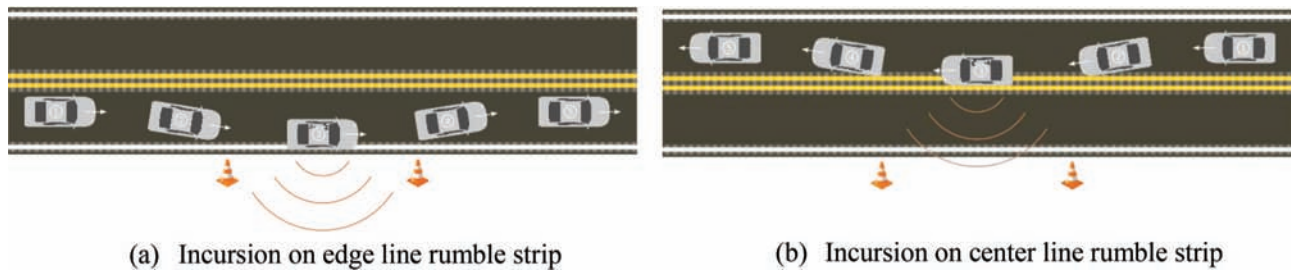


Figure 6.6 Edge line and center line incursion.

and the center line rumble strips with a 16" width. Figure 6.5 (a) and (b) shows the section details of the edge line and center line rumble strips, respectively. As a result, it was decided to evaluate whether the width of the rumble strips had an effect on the exterior sound level.

Due to time constraints, data collection on the edge line rumble strips was only carried out on the 24" sinusoidal rumble strip at 50 mph. The edge line incursions were performed on the edge line closest to the sound meter. Figure 6.6 compares the edge line and center line incursions.

The sound level comparison of edge line and center line sinusoidal rumble strips (24" wavelength) from the exterior sound meter is shown in Figure 6.7. As seen, the sound levels are equally effective on both the configurations. The sound level from the edge lines are slightly higher, probably due to their close proximity from the sound meter.

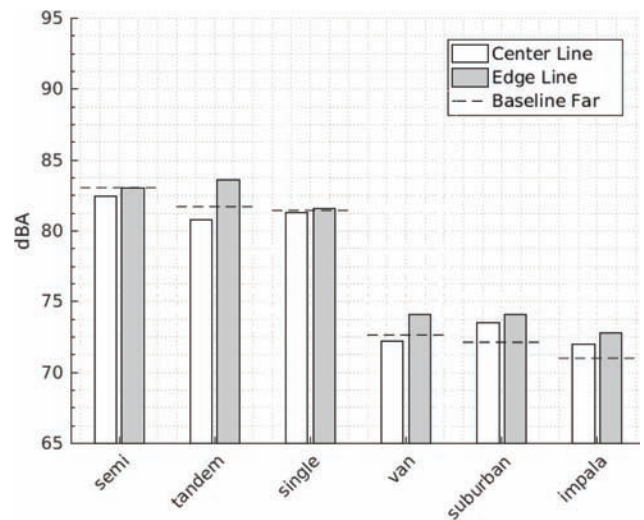


Figure 6.7 Comparison of exterior edge line and center line incursion sound levels on 24" sinusoidal rumble.

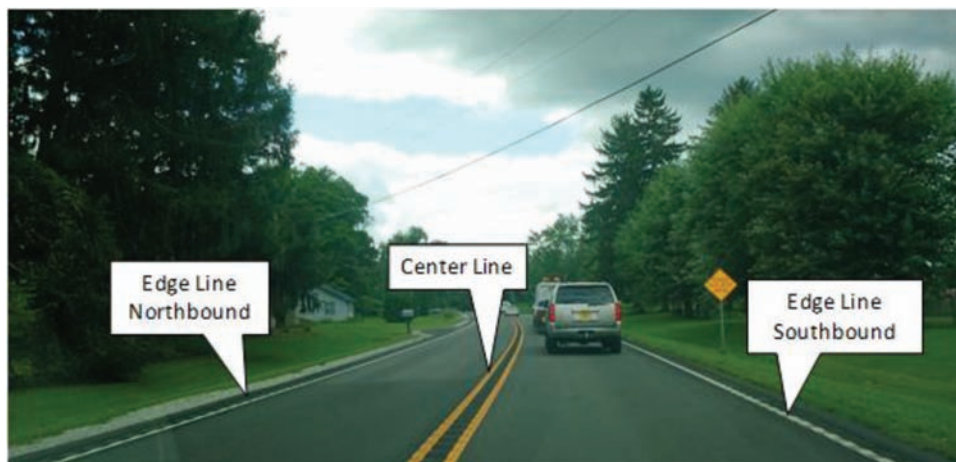


## 7. RETRO REFLECTIVITY TESTS

Retro reflectivity tests were performed on the three sinusoidal rumble strip patterns, a year after their installation. The Delta LTL-M mobile road unit (DELTA, 2018) was used to collect the retro reflectivity data. The equipment, mounted on an INDOT vehicle, collected readings every 0.1 mi along the edge lines and center lines (Figure 7.1). The mobile equipment also logged the GPS coordinates of the data points. Figure 7.2 shows a close-up view of an 18" sinusoidal rumble stripe with thermoplastic marking.

A cumulative frequency diagram (CFD) of the retroreflective data on the three sinusoidal patterns

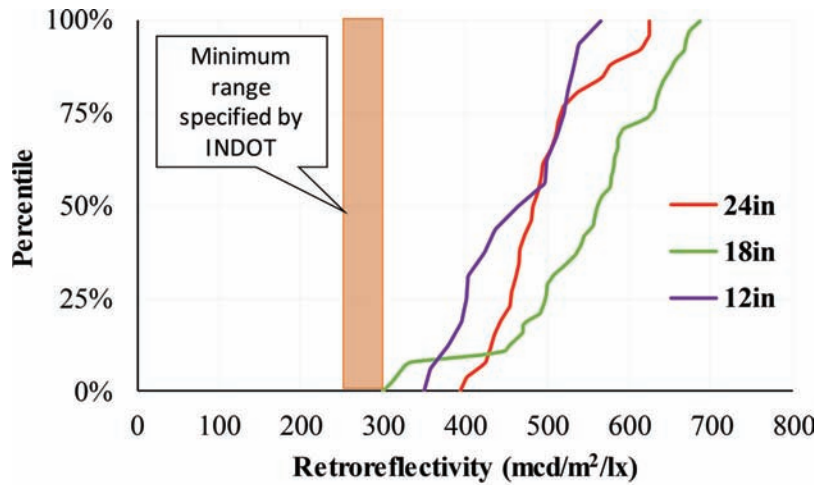
for edge line and center line are shown in Figure 7.3 and Figure 7.4, respectively. The orange colored ranges in these figures denote the minimum retro reflectivity values specified by INDOT (2018). INDOT specifies a minimum range of 250 to 299 mcd/m<sup>2</sup>/lx for the white thermoplastic (edge lines) and 150 to 199 mcd/m<sup>2</sup>/lx for the yellow thermoplastic (center line) material. For the northbound edge line (Figure 7.3 (a)) and the center line rumble stripes (Figure 7.4), all the three sinusoidal patterns surpass the minimum retro reflectivity readings. In case of the southbound edge lines, almost all of the readings exceeded the minimum threshold.



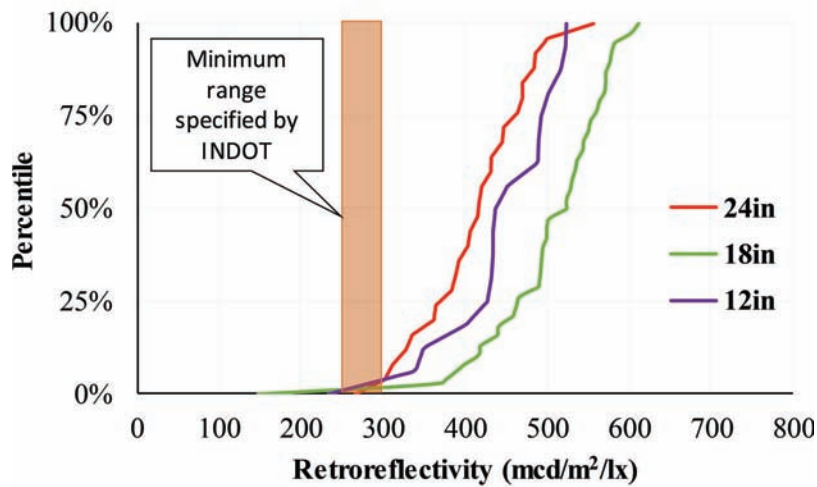
**Figure 7.1** Retro reflectivity data collection on edge and center line.



**Figure 7.2** Close-up view of thermoplastic marking on sinusoidal rumble strips.



(a) Northbound (NB)



(b) Southbound (SB)

Figure 7.3 CFDs of retro reflectivity readings on edge line rumble strips.

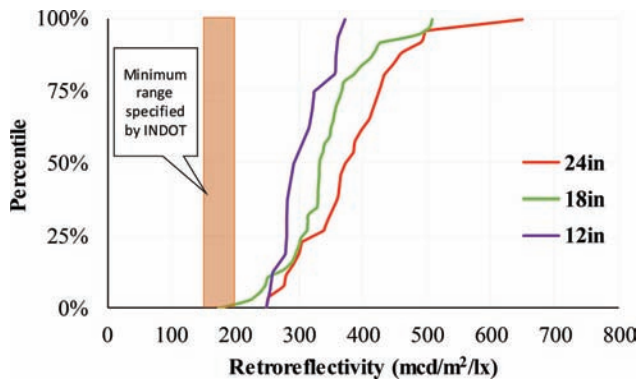


Figure 7.4 CFDs of retro reflectivity readings on center line rumble strips.

## 8. SUMMARY AND RECOMMENDATIONS

This study performs a preliminary analysis and comparison of the noise generated by sinusoidal rumble strip patterns and traditional milled rumble strips.

Sinusoidal rumble strips with three different wavelengths were analyzed: 12", 18", and 24". Data was collected from six test vehicles, ranging from a passenger car to a semi truck at a speed of 50 mph. In addition to the acceleration data collected to measure the vibrations in the vehicle, sound level meters were also used to collect acoustic data, both inside and outside the test vehicle (50' from the edge line). Additionally, the sound responses from the 16" wide centerline and 12" wide edge lines were compared. Finally, retro reflectivity tests were performed (after a period of 1 year) to evaluate the visibility and durability of the rumble strips.

The study discovered some promising results:

1. Sound responses varied across the vehicles.
2. For heavy vehicles, engine noise and vibrations were found to dominate from inside the vehicle.
3. From the exterior, all three sinusoidal rumble strips were less loud than the traditional rumble strips, with a reduction in sound power by anywhere between 5 and 11 dBA.

4. From the interior of the vehicle, they are almost as loud as the standard rumbles, but with some selected cases increasing between 2 and 9 dBA.
5. Sound levels from center and edge line (16" and 12" width, respectively) rumble strips were found to be equally loud in the interior.
6. The retro reflectivity tests on all the three sinusoidal patterns, on both the edge and center lines, were found to exceed the minimum threshold set by INDOT specifications one year later.

Interestingly, the 12" wavelength seemed to strike a balance between a reduced exterior noise and an increased interior noise. From outside, the 12" sinusoidal rumble strips were found to be 5 to 11 dBA quieter than standard rumbles, and from inside, they were found to produce a sound level increase of 4 to 12 dBA compared to baseline road noise. The 12" was also the only pattern found to routinely satisfy the recommendations for in-cabin and exterior sound levels proposed by the NCHRP Report 641 on Guidance for Design and Application of Rumble Strips (Torbic et al., 2009) (see Table 6.1).

Sinusoidal rumble strips are effective given the correct choice of wavelength. At a high level, the results from this study suggest that the 12" wavelength has a desirable decrease in exterior noise while still maintaining reasonable or even, at times, superior (than the standard milled rumbles) lane departure warning to the driver.

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## APPENDIX A. PRELIMINARY SETUP AND RESULTS

### Data Collection

A preliminary data collection was carried out to study the impact of various sound level weightings and to finalize the most optimum test scenario. The test vehicle used in the preliminary data collection was a 2014 Chevrolet Suburban (Figure A.1 (a)).

The data was collected at speeds of 50 mph (speed limit) and 40 mph on the sinusoidal rumble strips and 55 mph (speed limit) and 40 mph on the standard milled rumble strip. Only experiment runs where the test vehicle was the dominant sound source and isolated from other traffic noise were processed.

### Sound Level Measurement

The sound level meters were placed as shown in Figure A.2 (a) and (b). The notation  $S_{d,h}$  represents a sound meter setup  $d$  feet from the closest edge line rumble strip at a height of  $h$  feet from ground level. The  $S_v$  sound meter was mounted inside the vehicle near the driver's ear as seen in Figure A.2 (c). Traffic cones were placed at a distance of 200' on either side of  $S_{20,2}$  to provide reference locations for the driver and video logs.

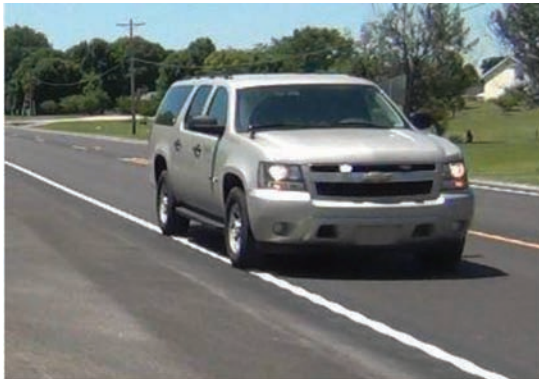
### Test Scenarios

Road noise is generated by passing vehicles under a variety of conditions that include rumble strip incursions as well as pass-by traffic with no rumble strip incursions. To effectively characterize various noise levels, five test scenarios (Figure A.3) were defined:

1. *Near edge line*: Incursion on the edge line rumble strips closest to the sound meters (Figure A.3 (a))
2. *Far edge line (occluded)*: Incursion on the edge line rumble strips furthest from the sound meters. The test vehicle is in between the rumble strips and the sound meters, and hence occludes the test (Figure A.3(b))
3. *Center line*: Incursion on the far side center line rumble strip (Figure A.3 (c))
4. *Center line (occluded)*: Incursion on the near side center line rumble strip (Figure A.3 (d))
5. *Baseline pass-by run*: Normal pass-by of the vehicle without any incursion on the rumble strips (Figure A.3 (e))

### Results and Analysis

The experiment consisted of three independent variables and four dependent variables (Table A.1). In total 82 trials were conducted, resulting in, at a minimum, two successful runs for each combination of the independent variables.



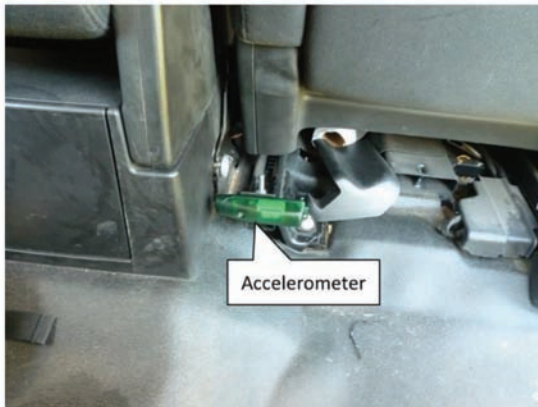
(a) Test vehicle, 2014 Chevrolet Suburban



(b) Sound meter mounted on a tripod



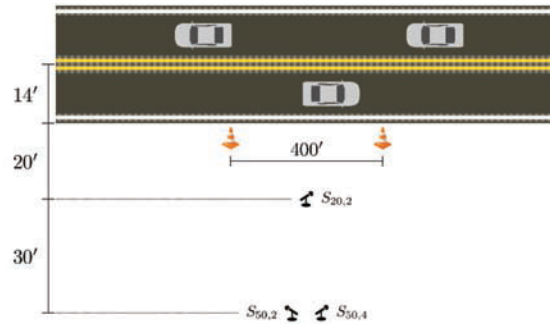
(c) Accelerometer on passenger seat frame



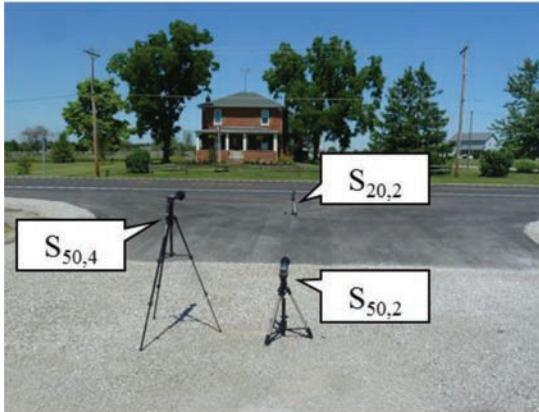
(d) Close up of (c)

Figure A.1 Test vehicle and sensors.

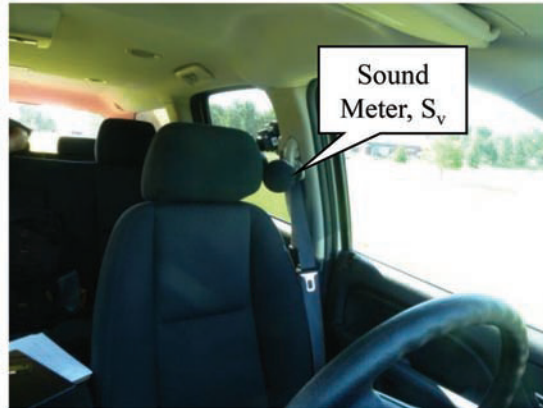




(a) Layout of the sound meters at test site



(b) Sound meter setup at 18" wavelength site



(c) Sound meter inside the vehicle

**Figure A.2** Sound meters deployed during data collection.

To efficiently organize and rank the dependent variables across the many different combinations of independent variables, the raw sensor data was reduced to representative metrics.

#### *Accelerometer Analysis*

Figure A.4 features some example dynamic magnitude traces collected during 40 mph edge line not occluded (Figure A.4 (a)) and center line not occluded (Figure A.4 (b)) rumble strip incursions. For safety reasons on seat positioning, the passenger side seat frame was used to mount the accelerometer (Figure A.1 (d)). For that reason, vibrations from rumble strip incursions on the passenger side of the vehicle (Figure A.4 (a), edge line) will measure larger than incursions on the driver side (Figure A.4 (b), center line) because the sensor is closer to the vibration source for passenger side encounters.

Figure A.5 compares the average maximum of observed root-mean-squared (RMS) dynamic acceleration across the experiment runs. The RMS is computed using a 125 millisecond (ms) long moving window. As mentioned earlier, the induced vibration is a function of the vehicle's suspension and therefore no clear pattern emerges. The initial results also shows that the vibration does tend to decrease in the seat frame with increasing wavelength.

#### *Sound Level Metrics*

Three weighting functions were evaluated in this research: A-weighting, ITU-R 468-4 weighting, and C-weighting, are defined as frequency responses with acceptable tolerances. The frequency response of the actual filter realizations used in this work can be seen in Figure A.6.

The A-weighting is a commonly used filter in the United States of America and is defined by IEC 61672:2003 ("Electroacoustics Sound Level Meters Part 1: Specifications," 2013). Low frequencies are devalued by the A-weighting function because it was originally designed for measuring low volume sounds where the Fletcher-Munson (ISO, 2003) (Fletcher & Munson, 1933) equal loudness curves predicated severe attenuation by the ear (approximately 40 phon curve (Fletcher & Munson, 1933)). Regardless, nowadays it is often used as the required weighting function for many safety and environmental noise standards.

The ITU-R 468-4 noise weighting function (BS.468-4, n.d.) was developed with the perspective that human ears respond differently to random noise than they do to pure and constant tones. The standard filter requires the use of quasi-peak detector; however, in this work we did not include one. The omission of the quasi-peak detector is in line with other standards such as the ISO 21727 (ISO, 2016) that measures the loudness and/or annoyance of audio tracks.

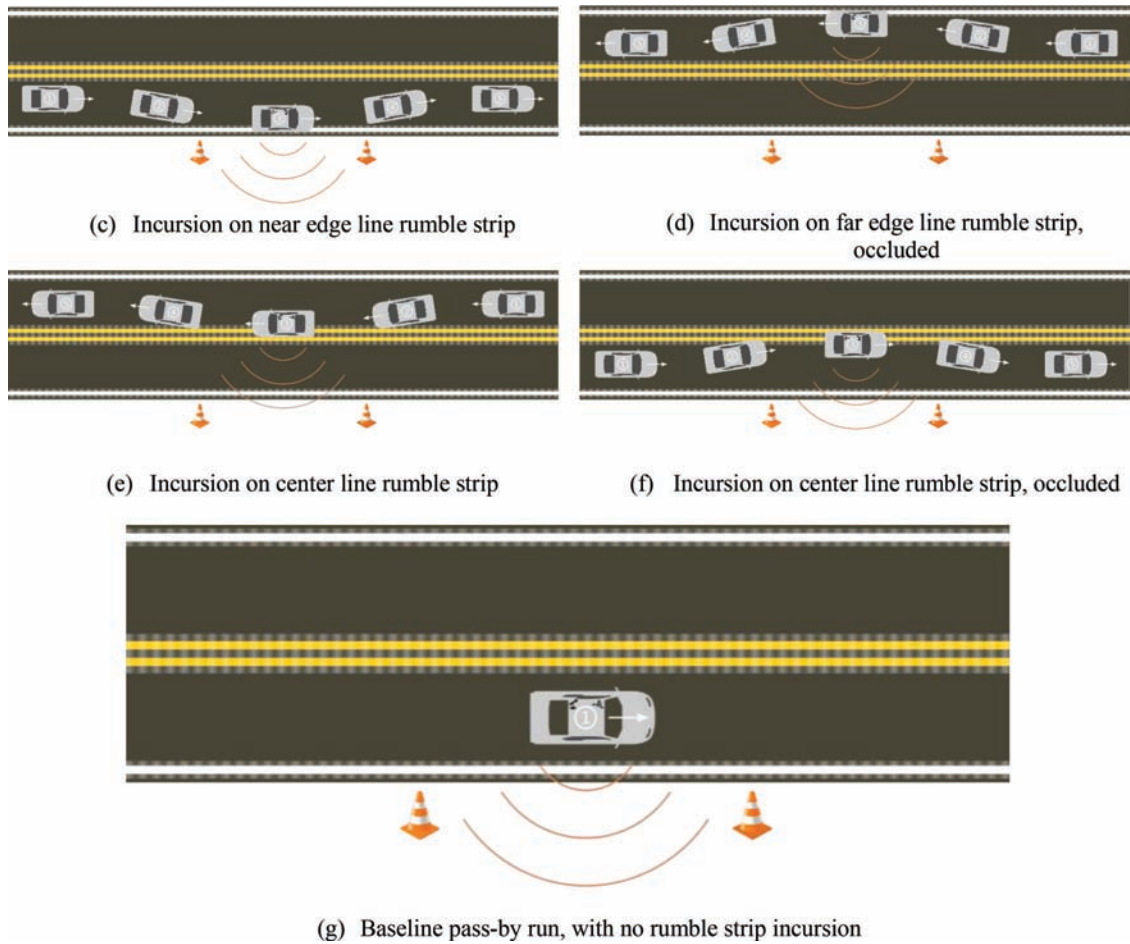


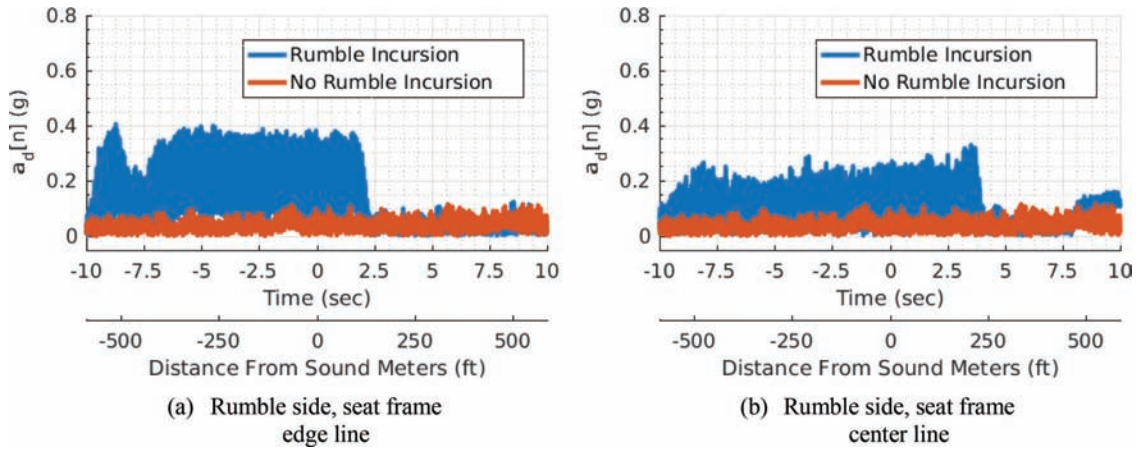
Figure A.3 Test scenarios.

TABLE A.1  
Experiment variables

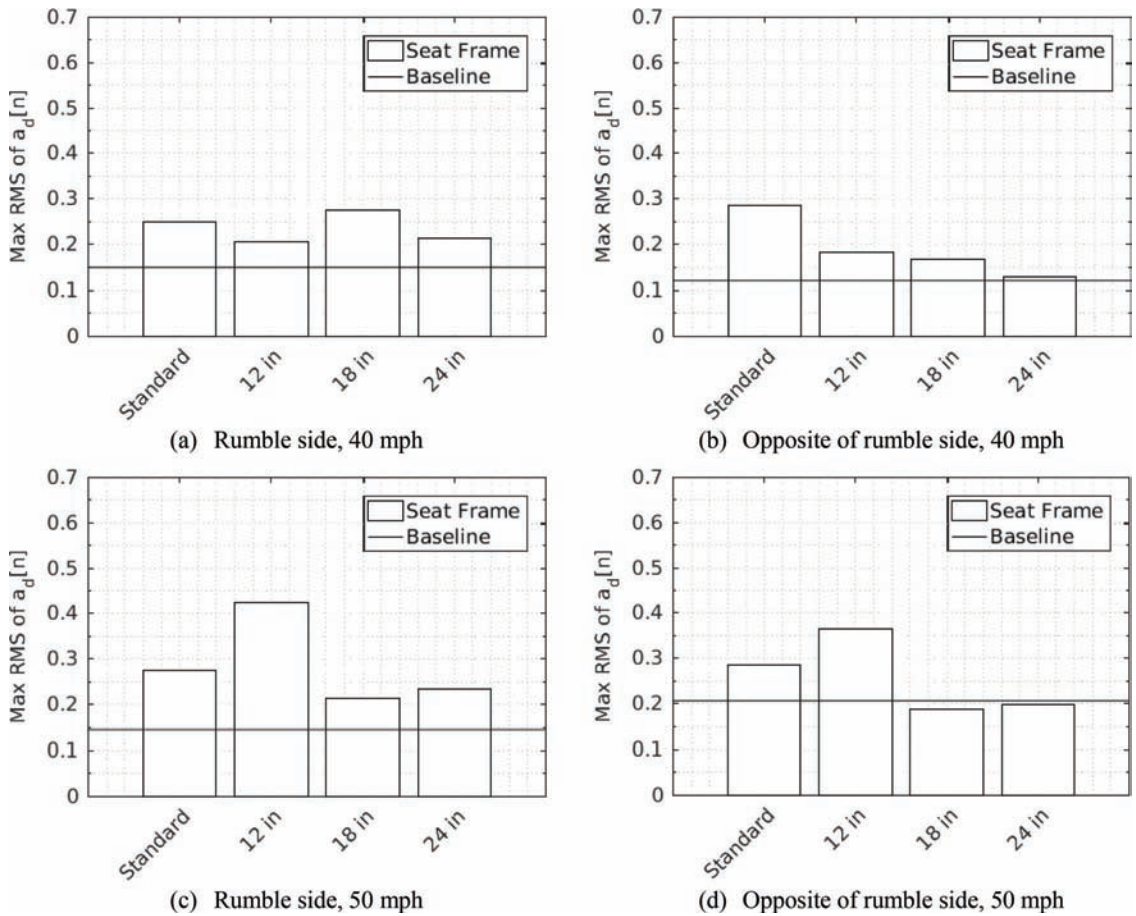
Independent Variables	
Wavelength	12" 18" 24"
Incursion type	Center line Center line occluded Edge line Edge line occluded Pass by
Speed	40 mph 50 mph (55 mph for standard rumble strips)
Dependent Variables	
Acceleration	Seat frame (passenger side)
Sound level	In-vehicle (near drivers left ear) Out-of-vehicle (50' away from the side of the road)

Finally, the C-weighting function, also defined by the IEC 61672:2003 standard (“Electroacoustics Sound Level Meters Part 1: Specifications,” 2013), is typically

used with very loud sounds, near 100 dBSPL, where human perception of low frequencies is improved (approximately the 100 phon curve (Fletcher & Munson, 1933)).



**Figure A.4** Accelerometer dynamic magnitude traces representative of rumble strip incursion at 40 mph.



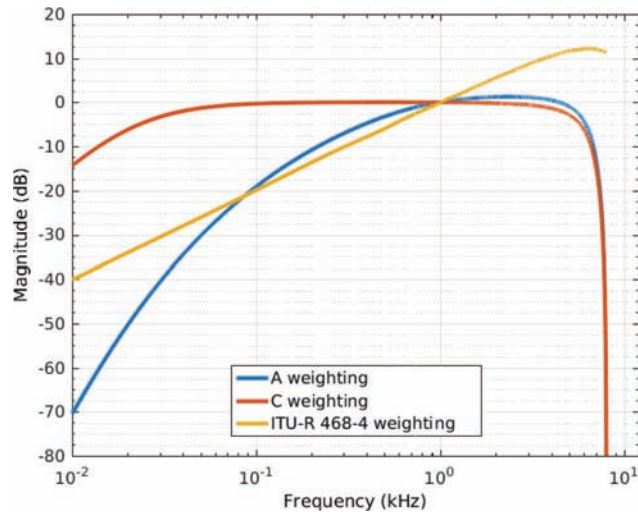
**Figure A.5** Average maximum RMS of accelerometer dynamic magnitude during 40 and 50 mph (55 mph for the standard rumble strip) incursions.

As a result, low frequencies are not nearly as devalued as they are with the A or ITU-R 468-4 weighting functions.

All three weighting functions have merit. For example, baseline pass-by and long wavelength sinusoidal incursions have SPL low enough to warrant A-weighting. Short wavelength and traditional rumble strips have SPL high enough that C-weighting is appropriate. Finally,

the rattling of the vehicle's interior and external noise during a baseline pass-by seems to be mostly stochastic in nature and therefore well matches the ITU-R 468-4 weighting. As a result, this study considers all three weightings simultaneously.

Figure A.7 compares sound power traces measured by each sound meter during 40 mph incursions and the



**Figure A.6** Audio filter responses for A, C and ITU-R 468-4 weighting.

baseline pass-by for all three weighting functions. The signals are averaged with a 125 ms moving window, defined by the IEC as the “fast” average (14).

#### *Comparison of Three Alternative Sound Level Weightings*

Figure A.8 and Figure A.9 compare the measured sound level across the experiment’s runs. Only edge line and center line incursions are considered because they were found to be very similar to the edge line occluded and center line occluded results. To reduce the time-series traces to a single metric the maximum observed power values for each vehicle encounter of a rumble strip, given a particular configuration, was averaged. For the baseline pass-by measurements, the maximum observed power level within a  $\pm 4$  second window surrounding the time the vehicle passes the  $S_{50,4}$  meter was averaged. All of the configurations have at least two averaged repetitions.

The baselines shown on the sound level plots of Figure A.8 and Figure A.9 are the noise level during the baseline pass-by runs. The alert lines, shown only on the dBA interior plots (Figure A.8 (a), (b) and Figure A.9 (a), (b)), are 6 dBA higher than the associated baseline. This sound level increase is the threshold defined by NCHRP Report 641 (Torbic et al., 2009) as the acceptable interior noise for warning a driver to an impending lane departure in residential areas.

In general, irrespective of the weighting function, the sinusoidal rumble strips are less loud than the traditional rumble strips. This is particularly true for the

exterior noise level where the sound power is reduced by anywhere between 13 dBA and 28 dBA. The interior noise vehicle is reduced by 2 to 21 dBA but is often within approximately 5 dBA. Interestingly, the 18” wavelength seems to strike a balance between a reduced exterior noise and limited reduction to interior noise within the vehicle for 40 mph incursions. However, there is large drop-off of interior noise for the 50 mph cases, which is likely due to the characteristic of the vehicle suspension. Some of the data suggests that the 24” wavelength is actually quieter than the baseline, however, this is a result of stochastic variation. During the experiment, the researchers observed some difficulties in detecting the difference between a 24” wavelength incursion and a baseline pass-by run from outside of the vehicle.

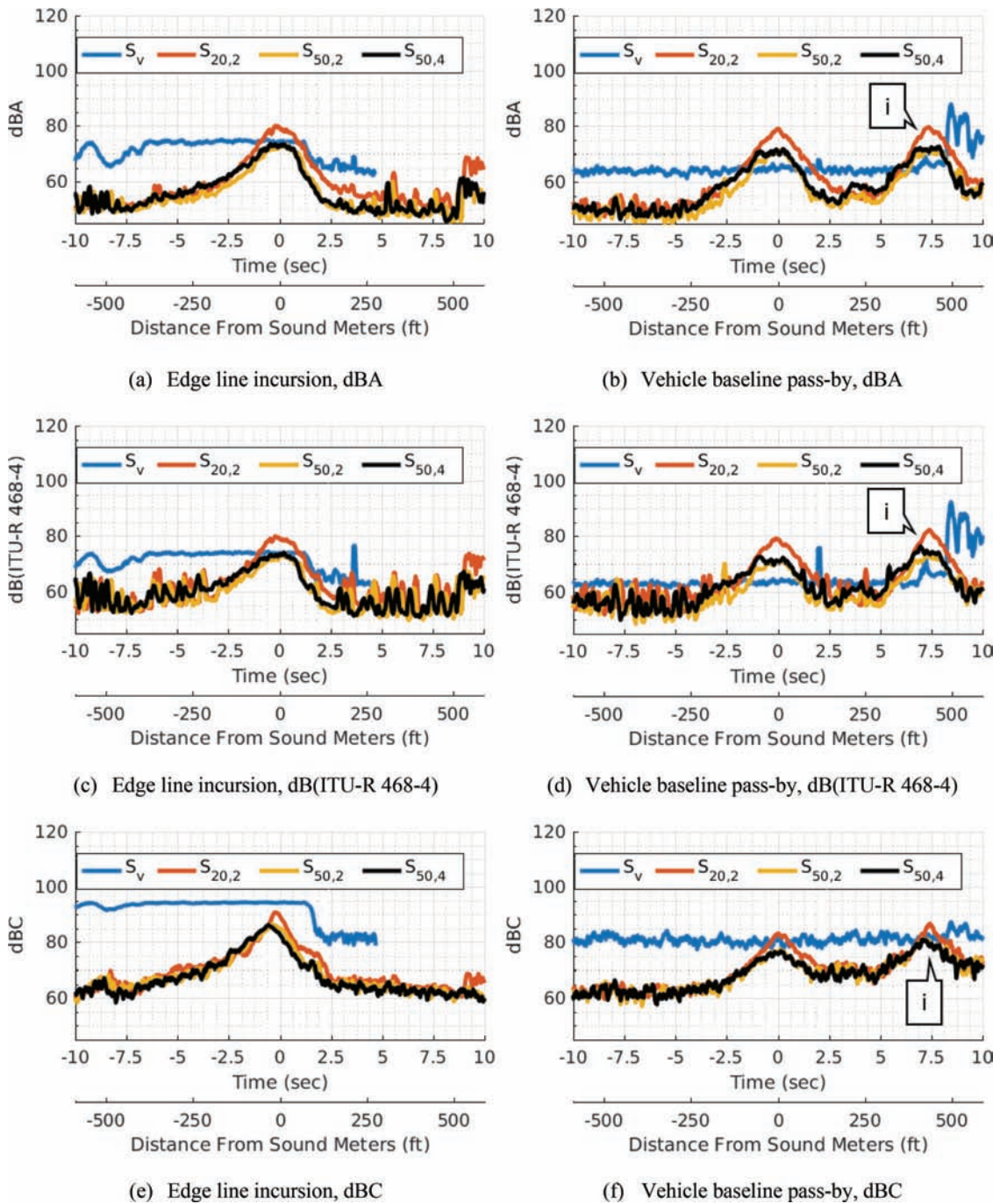
It is clear that much of the sound energy is of low frequency because of the significantly higher values of dBC as compared to the other two weightings. This is expected because of the fundamental vibration induced by the rumble strips wavelength and vehicle speed is quite low, between and 29.3 and 73.3 Hz. The slowest frequency results from the longest wavelength (25”) and the slowest speed 40 mph and is given by:

$$\frac{40 \text{ mph}}{25''} = 29.3 \text{ Hz} \quad (\text{A.1})$$

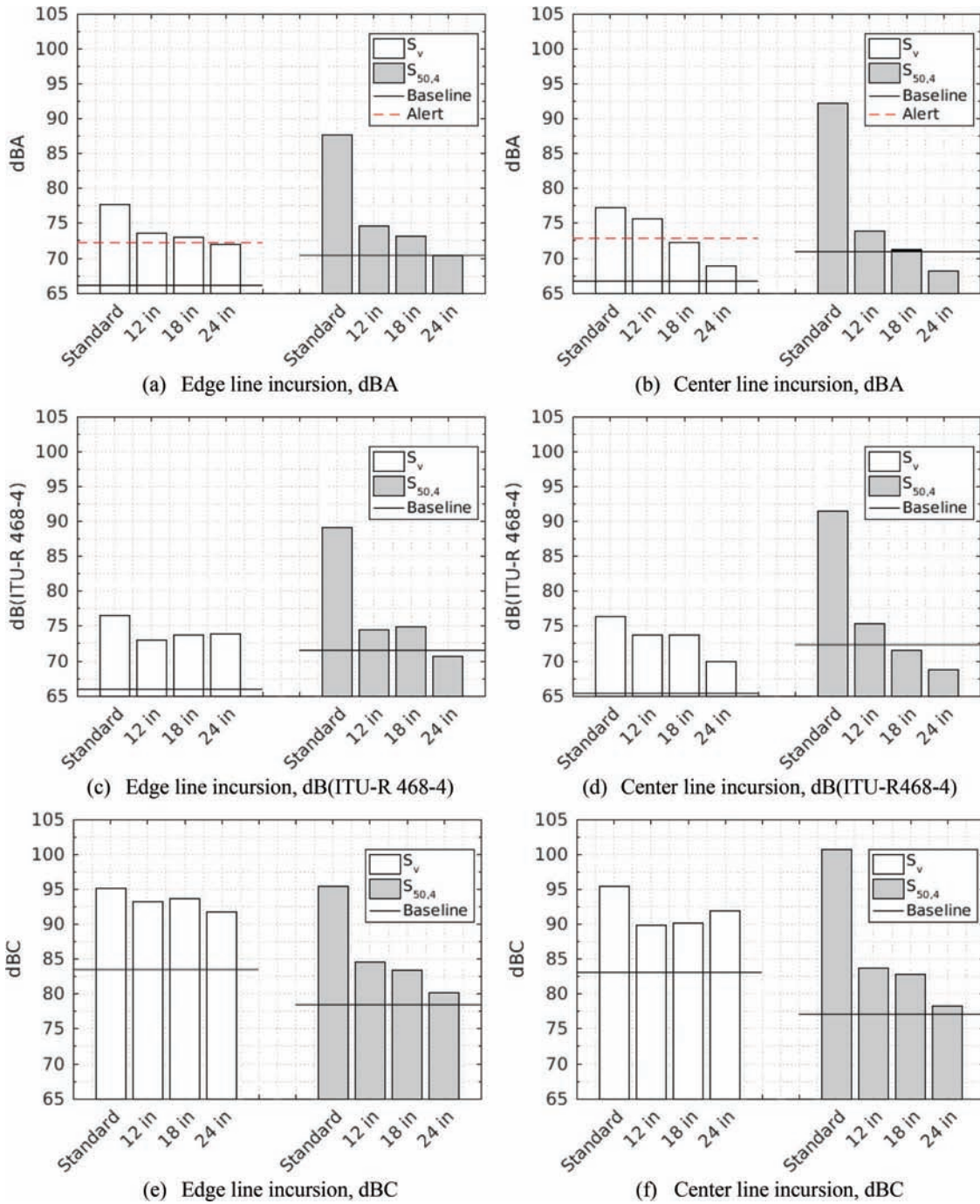
Similarly, Equation A.2 shows the highest frequency results from the shortest wavelength and (12”) the fastest speed 50 mph.

$$\frac{50 \text{ mph}}{12''} = 73.3 \text{ Hz} \quad (\text{A.2})$$





**Figure A.7** Sound meter traces representative of edge line rumble strip incursion at 40 mph. Callout (i) indicates noise measured from other traffic from directly behind the test vehicle.



**Figure A.8** Average maximum sound power for  $S_v$  and  $S_{50,4}$  during 40 mph incursions.

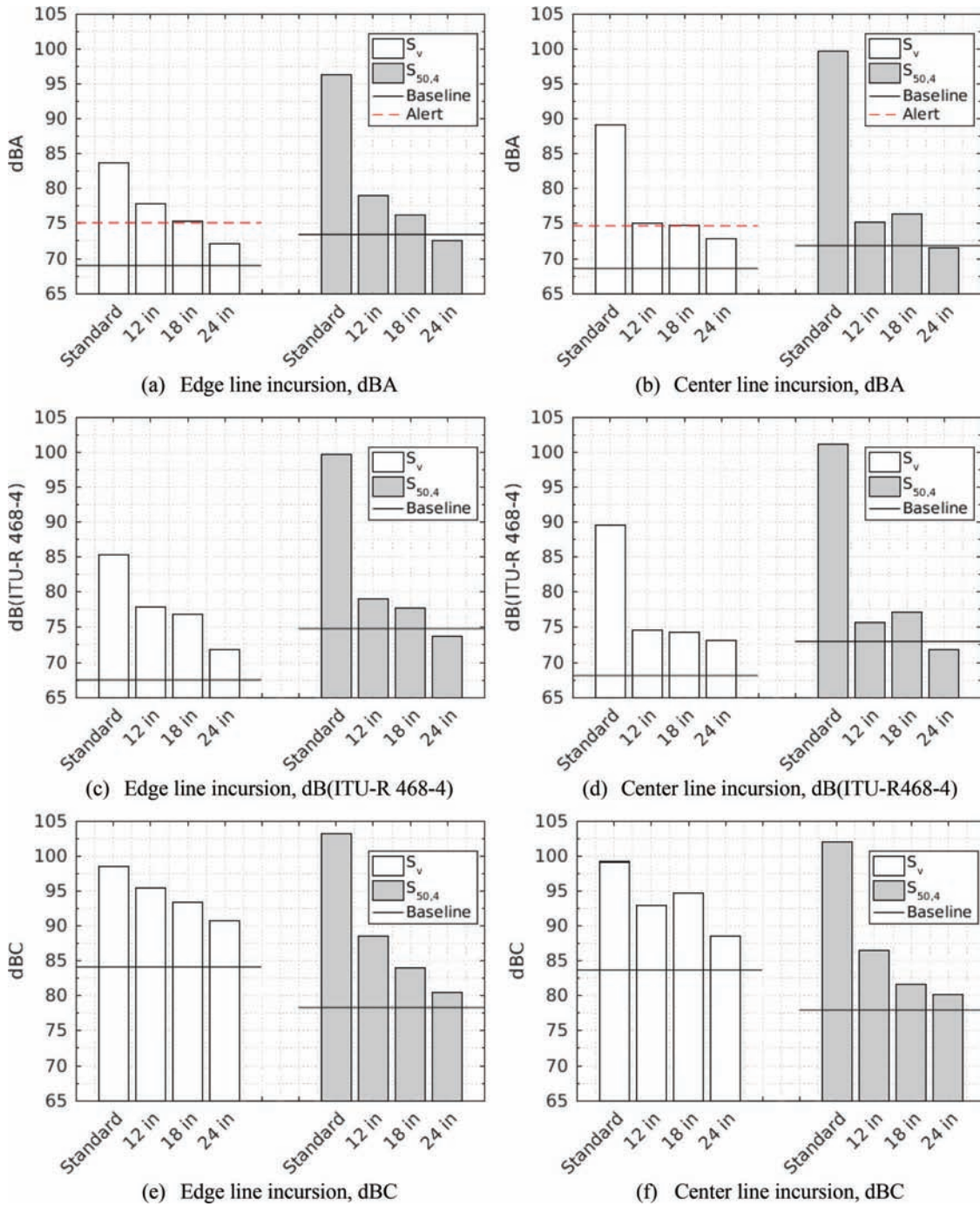


Figure A.9 Average maximum sound power for  $S_v$  and  $S_{50,4}$  during 50 mph incursions (55 mph for the standard rumble strip).



APPENDIX B. ACCELERATION TRACES

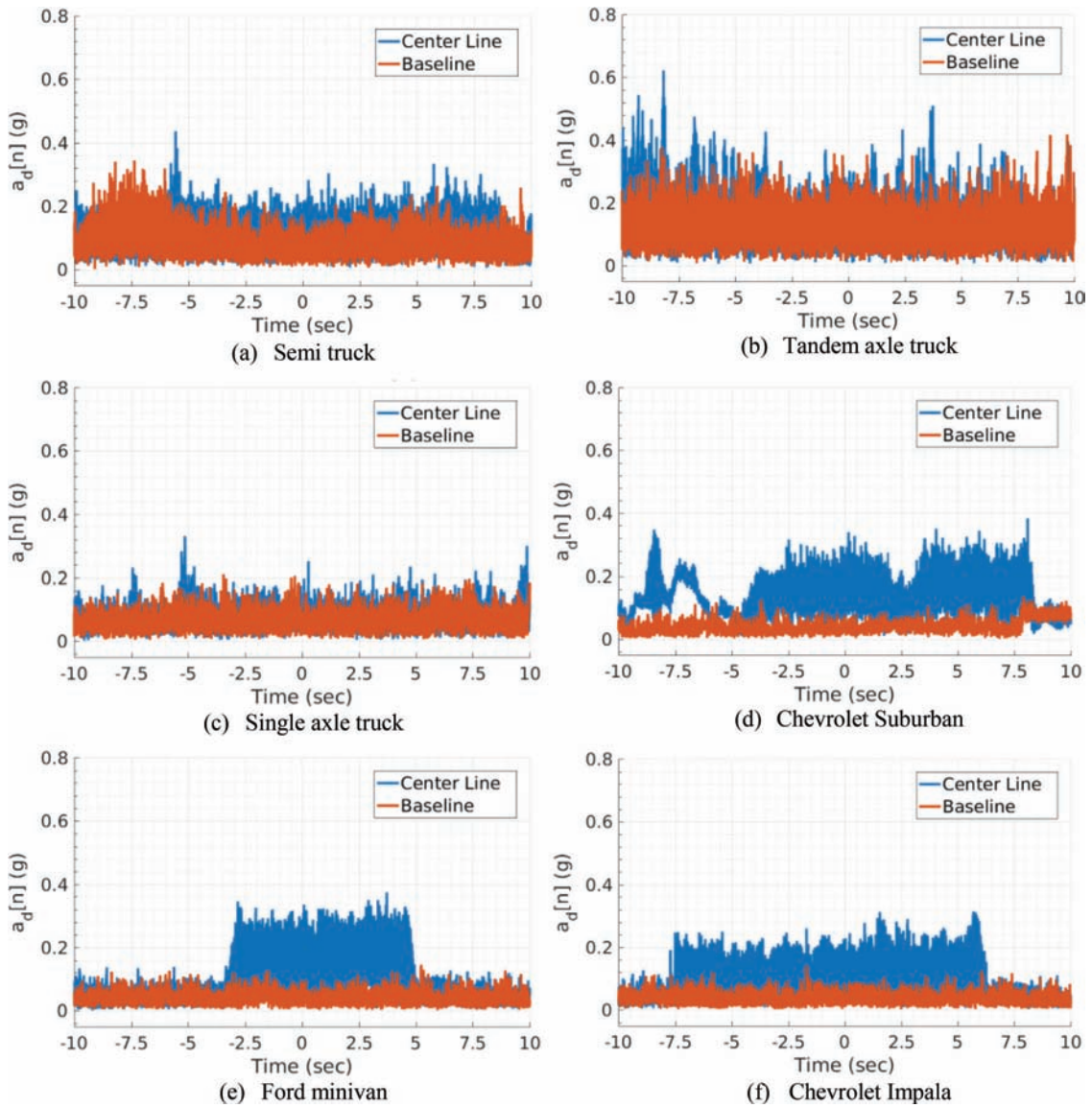
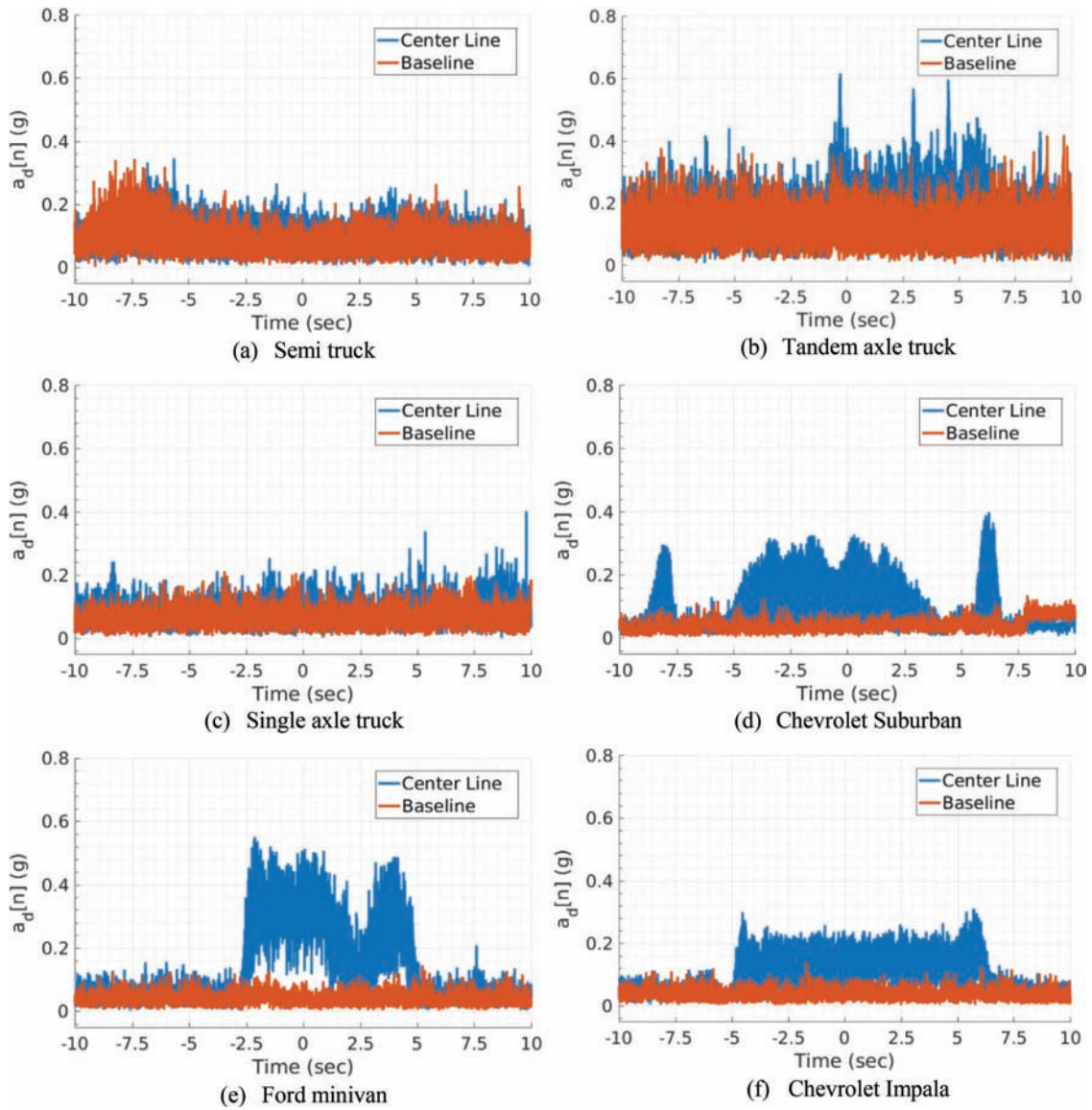


Figure B.1 Acceleration traces for test vehicles on 18" sinusoidal rumble strips.





**Figure B.2** Acceleration traces for test vehicles on 24" sinusoidal rumble strips.

## APPENDIX C. VIDEO DOCUMENTATION

- Sinusoidal rumble strips construction: <https://doi.org/10.4231/R76H4FPJ>
- Noise levels from the Chevrolet Suburban test: <https://doi.org/10.4231/R7B856CT>
- Sound and acceleration traces from all test vehicles on 12" rumble: <https://doi.org/10.4231/R72R3PXC>

## About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: <http://docs.lib.purdue.edu/jtrp>

Further information about JTRP and its current research program is available at: <http://www.purdue.edu/jtrp>

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