Evaluation of Noise Levels due to Controlled Vehicle Pass-bys on Rumble Strips across New Hampshire

Final Noise Analysis Technical Report

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- Patrol Shed 203 - Rumney
- Patrol Shed 301 - Conway
- Patrol Shed 315 - Alton
- Patrol Shed 405 - Westmoreland
- Patrol Shed 504 - Henniker
- Patrol Shed 611 - Kingston

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Executive Summary

The Federal Highway Administration and state departments of transportation across the country are currently looking into new methods to install rumble strips so as to minimize noise impacts upon affected communities, while at the same time maintaining safety for users of the road. [1] The study described in this report represents the New Hampshire Department of Transportation's efforts to understand the noise emissions produced by vehicle incursions onto rumble strips. The study involved measuring the noise emissions from different rumble strip designs in various parts of the state. The results of this study and other research will be used to inform the Department about the noise emitted by different rumble strips for the ultimate purpose of identifying a design that minimizes noise emissions while meeting all of the Department's safety requirements. The focus of this study was on the exterior noise from a test vehicle on rumble strips – measured along the side of the road (i.e. at the wayside) – interior measurements were not included in the scope of this study.

The principal findings and conclusions are as follows:

- The noise emissions of pass-bys on rumble strips increase with increasing speed. Further, the noise emissions of rumble strips increase with speed at a greater rate than do the noise emissions of vehicles on smooth pavement (for the range of speeds examined in this study).
- The rumble strips along NH Route 25 in Plymouth and along NH Route 28 in Alton produced the highest noise levels. Both rumble strips are still relatively new, having been installed in 2016.
  - Along NH Route 28 in Alton, the pass-by level on the rumble strip was more than 20 decibels higher than the pass-by level on smooth pavement at a speed of 60 mph.
- The rumble strip at Site 4 (Alton) is clearly audible at the pickle ball court on the grounds of the Roberts Knoll Campground. The measured maximum sound levels of pass-bys on rumble strips was more than 10 decibels above nighttime background sound levels at the campground, and so is considered very noticeable.
- The rumble strip along NH Route 9 in Chesterfield produced levels that were lower than the rumble strip in Alton, even though the cut depths appeared to be similar at both sites.
- Along NH Route 111 in Danville, the sinusoidal profile of the shoulder rumble strip on the westbound lane was approximately 4 to 7 decibels lower than the milled profile centerline rumble strip.
- The two sinusoidal rumble strips installed on the eastbound and westbound shoulders at Site 1A in Danville are reportedly different. However, the measurements show that the two rumble strips produce noise levels that are within approximately +/- 1 decibel of one another. The shoulder rumble strips were installed at slightly different depths – the eastbound strip was 3/8" with a 2-foot cycle and the westbound strip was ½" with a 2-foot cycle.
- At 40 and 50 mph, the LAF_{max} for automobiles on the rumble strip in Danville were the same as, or slightly lower than, the LAF_{max} for a motorcycle and heavy truck pass-by on smooth pavement.

[1] Webinar hosted by the Transportation Research Board on March 28, 2017, available at: http://www.trb.org/Main/Blurbs/175712.aspx (accessed 8/15/2017).

- At 60 mph, the LAF_{max} for automobiles on the rumble strip in Danville were higher than the LAF_{max} for a motorcycle and heavy truck pass-by on smooth pavement.
- The spectra for the milled rumble strips generally exhibit peaks in the 1/3 octave bands from 50 to 160 Hz, whereas the spectra for the sinusoidal rumble strips exhibit a peak band centered at 31.5 Hz.

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1 Introduction

Harris Miller Miller & Hanson Inc. (HMMH) was retained by the New Hampshire Department of Transportation (NHDOT) to evaluate the measured noise levels from controlled vehicle pass-bys on rumble strips and smooth pavement at six locations across the state. The study included a limited review of the current technical literature, wayside noise measurements of controlled vehicle pass-bys on rumble strips and on smooth pavement, and subsequent analysis of the measured data. The objectives of this study were to document and compare noise levels for different rumble strip installations across the state, and if possible, make comparisons to the results published by other researchers. The results of this study and other research will be used to inform the Department about the noise emitted by different rumble strips for the ultimate purpose of identifying a design that minimizes noise emissions while meeting all of the Department's requirements for safety.[i]

1.1 What are rumble strips?

For the purpose of this study, a rumble strip is a roadway safety feature consisting of a series of milled or raised elements in the pavement intended to alert an inattentive driver (through vibration and sound) that the vehicle has left the lane of travel. There are generally two types of rumble strips that serve this purpose – a centerline rumble strip[ii] and a shoulder rumble strip.[iii] In both cases, the rumble strip serves to assist drivers who may unintentionally drift over the centerline or the edge line of the roadway. When pavement markings are placed over a rumble strip, the rumble strip is sometimes referred to as a rumble "stripe." Both types of rumble strips were evaluated in this study.

1.2 Study Area and Project Description

At the outset of the study, NHDOT identified six noise measurement sites along two-lane state-owned highways with rumble strip installations. As shown in Figure 1, the sites were located across the state in six of the state's different counties. Table 1 provides details about the measurement sites, including the highway facility, the town, whether the highway had passing zones, the location of the rumble strip, the type of rumble strip (milled or sinusoidal), and the physical dimensions of each rumble strip.

The installation dates and rumble strip depths shown in Table 1 were provided by NHDOT. At Sites 1, 5, and 6, the tabulated depths are the specified milled depths of the rumble strips. At Sites 3 and 4, NHDOT took actual samples of the rumble strip depth using a custom depth gage (see Appendix D). During the noise testing, HMMH personnel conducted spot measurements of the rumble strip depth in the vicinity of each microphone location; hence, the columns labeled "(HMMH) ~Depth (in.)" and "(HMMH) ~Length (in.)" in Table 1. The lengths and depths of the rumble strips as measured by HMMH are considered approximate since we obtained a limited number of samples. In addition, the depth of the rumble strip at Sites 5 & 6 was measured on the first day of testing. Because we refined our measurement technique after the first day, we expect that there is more uncertainty in our measured depths at these two sites than there is at the other sites we measured.

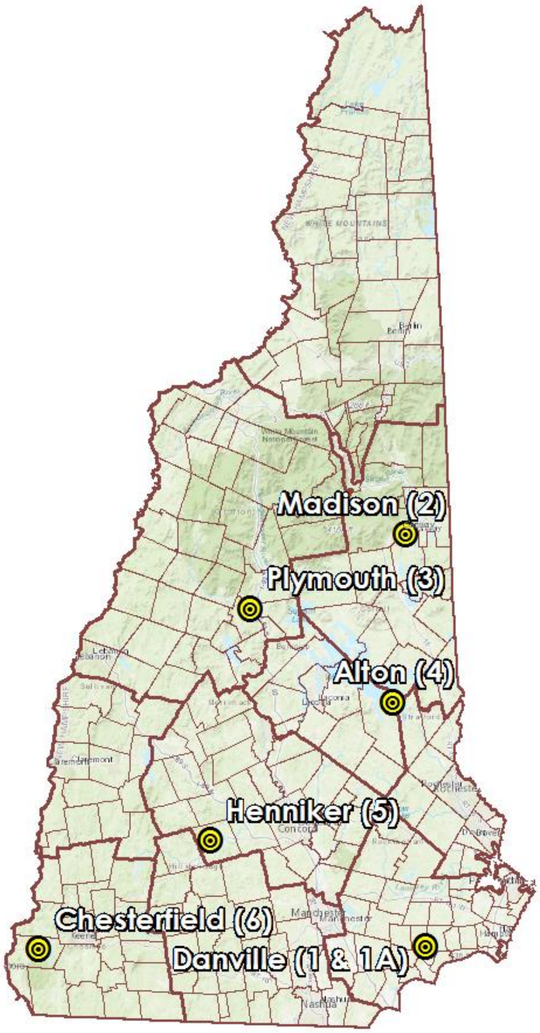


Figure 1 Overview of Wayside Noise Measurement Site Locations

Table 1 Summary of Wayside Noise Measurement Sites

Site	Road	Town	Passing Zone (Direction)	Rumble Strip Data					
				Location	Type	Install Date	Depth (in.)	(HMMH) ~Depth (in.)	(HMMH) ~Length (in.)
1	NH Rte. 111	Danville	EB & WB	Centerline	Milled	2013	½ to 5/8	3/8	11
1A	NH Rte. 111	Danville	EB & WB	Shoulder (EB)	Sinusoidal	2013	3/8”	n/a	22
				Shoulder (WB)	Sinusoidal	2013	1/2”	n/a	22
2	NH Rte. 16	Madison	None	Centerline	Milled	2015	¼	¼	13
3	NH Rte. 25/Tenney Mountain Hwy	Plymouth	WB only/Both	Centerline	Milled	2016	½ to 3/8*	n/a	12
4	NH Rte. 28	Alton	NB & SB	Centerline	Milled	2016	½ to 5/8*	3/4	12
5	US Rte. 202/NH Rte. 9	Henniker	EB & WB	Centerline	Milled	2008	½ to 5/8	¼ to 5/8**	11.5
6	NH Rte. 9	Chesterfield	EB & WB	Centerline	Milled	2016	½ to 5/8	3/4	12

* The depth of the rumble strips at Site 3 (MM 40.3) & Site 4 (MM 70.0) were measured by NHDOT. Refer to Appendix D for detailed depth measurement data.

** The depths of the rumble strips at Sites 5 & 6 were measured on the first day. HMMH refined the measurement technique after the first day. So, there is likely to be more uncertainty in the measured depths at these two sites than there is at the other sites measured by HMMH.

Source: HMMH, 2017.

1.3 Report Contents

Section 2 summarizes the results of a literature review that was limited to two recent studies that were sponsored by the Minnesota and Washington State Departments of Transportation. Section 3 describes the measurement procedures and methods used by HMMH. Section 4 presents an overview of the noise measurement data that was collected, processed and analyzed. Section 5 presents our findings and conclusions. The appendices provide supporting details about the measurement program. Appendix A provides an overview of the noise level metrics used in this report. Appendix B provides a table of measured A-weighted maximum noise levels (fast response) for each controlled pass-by at all six sites. Appendix C provides photographs of the measurement sites and graphs showing the pass-by spectra at the time of the A-weighted maximum noise level for each pass-by at all sites, as well as sample spectrograms from a long-term monitor installed at the Roberts Knoll Campground. Appendix D provides a table of measured rumble strip depths by mile-marker that was supplied by the Department. Appendix E lists the contents of a companion DVD and Appendix F contains references and end notes.

The companion DVD includes audio recordings of each controlled vehicle pass-by at the 25-foot microphone position at each wayside noise measurement location, as well as pass-bys from a long-term noise monitor that had been installed overnight at the Robert Knoll campground in Alton. The companion DVD also contains sound level spectrograms from the long-term site and additional charts that graph the difference between rumble strip pass-bys and smooth pavement in 1/3 octave bands.

2 Literature Review

HMMH reviewed of two recently-completed studies of rumble strip noise that were sponsored by the Minnesota and Washington State Departments of Transportation. These studies were chosen for their completeness and the quality of the data collection and analysis. The objectives of the literature review were to examine the measurement methods and procedures used by other DOTs and to use their findings as a basis of comparison for the results found as a result of this study.

2.1 Minnesota Department of Transportation 2015

In 2015, the Minnesota Department of Transportation (MNDOT) released a report that presented the results of sound level monitoring for three different types of rumble strips installed along the edge of two-lane rural roads in Polk County.[iv] The study was undertaken in response to landowner objections to unwanted noise from vehicles traveling over the rumble strips when they drift over the edge or centerline of the road. The overall objective was to identify the design that would maximize noise levels within the vehicle while minimizing the exterior noise levels generated by the vehicles on the rumble strips. The three types of rumble strips were identified as follows:

- California: 14” center-to-center; 1/32" to 5/8" depth; and 8" width
- Pennsylvania: 24" center-to-center; 1/8" to ½" depth; and 8" width
- Minnesota: 12" center-to-center; 3/8" to ½" depth; and 16" width

Figure 2 is reproduced from Figure 3.1 of the MNDOT report. It shows longitudinal profiles for each of the rumble strips that were evaluated by Terhaar and Braslau. The Pennsylvania design has a sinusoidal shape, while the Minnesota design has a square profile. The California design also has a sinusoidal shape, although the high points or peaks appear to be flattened out (or “clipped”). With respect to the Pennsylvania design, the sinusoidal shape of the California rumble strip is deeper (larger amplitude) with a smaller distance between peaks (shorter period).

The MNDOT study evaluated rumble strip noise levels for three vehicles (automobile, pickup truck, and semi-trailer truck) and three speeds (30, 45, and 60 mph). Terhaar and Braslau measured pass-by levels along the wayside and inside each vehicle. Wayside noise measurements were made at distances of 50 and 100 feet. Rumble strip noise levels were described in terms of the maximum A-weighted sound level and in 1/3-octave band sound levels. In-vehicle noise measurements were described in terms of overall A-weighted and C-weighted noise levels.

Terhaar and Braslau also evaluated the distance from the roadway at which the rumble strips under evaluation could be detected by a person. The approach was based on earlier research performed by Fidell and Bishop in 1974.[v] The detectability of a noise source depends upon the ambient sound level spectrum and the spectrum of the intruding source, such as a vehicle pass-by on a rumble strip. They used detectability factor of 7 dB to determine the distance(s) at which rumble strip noise would be “just detectable.”

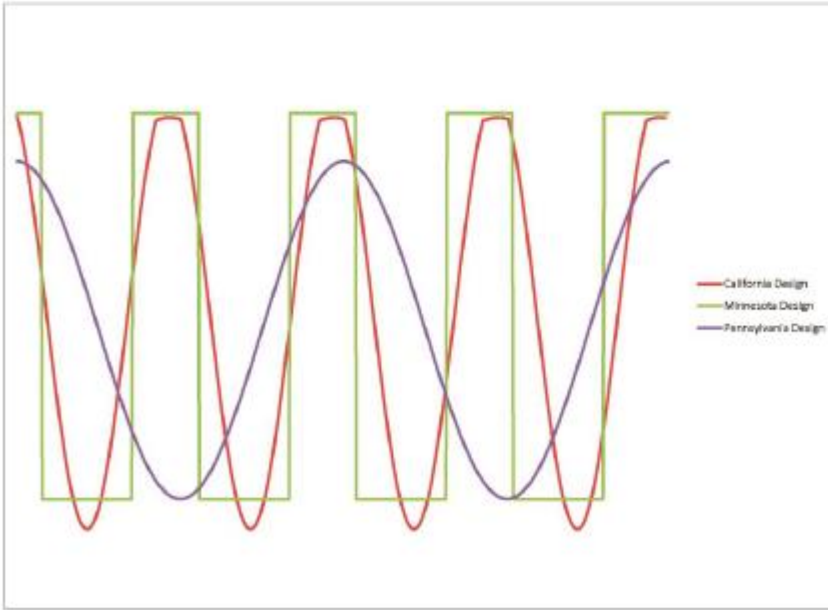


Figure 2 Longitudinal profiles of the rumble strips evaluated by Terhaar and Breslau for MNDOT in 2015

Source: Reproduced from Figure 3.1 of Terhaar, Edward and David Braslau, "Rumble Strip Noise Evaluation," Minnesota Department of Transportation, Report No. MN/RC 2015-07, February 2015.

Terhaar and Braslau found that overall A-weighted noise levels increased proportionately with increasing speed and vehicle weight. Other findings suggest that exterior levels with the Pennsylvania design were lower than the levels for both the California and the Minnesota design. Based on the detectability analysis with a car traveling at 60 mph, the Pennsylvania design would be detectable at a distance of 1,000 feet, the California design at 3,000 feet, and the Minnesota design at well over 3,000 feet.

Terhaar and Braslau concluded that the California strip provided adequate driver feedback, while providing lower exterior sound levels than the Minnesota design. While the Pennsylvania design provided the lowest exterior noise levels, it did not provide much driver feedback.

2.2 Washington State Department of Transportation, 2014

In 2014, the Washington State Department of Transportation (WSDOT) released a report authored by Timothy Sexton that evaluated wayside noise levels at nine centerline rumble strip locations across the state.[vi] The study focused on exterior rumble strip noise and sought to identify the quietest design currently in use. Additional analysis also estimated interior rumble strip noise from the rumble strip geometry at each site, as per NCHRP 641.[vii]

The WSDOT study evaluated rumble strip noise levels at 60 mph for each site, using a 2010 Ford Escape Hybrid. Three to ten pass-by events were measured at each of the nine sites, both for near and far pass-by conditions. Wayside measurements were taken for these events at distances of 25 and 50 feet, measuring from the center of the near lane. A-weighted broadband and 1/3 octave band levels (400 Hz to 5,000 Hz) were captured for all events.

Sexton found that levels were consistently lower during near pass-by events, due to car body shielding in the propagation path. Site variance was also large, ranging from 12 to 14 dB depending on the pass-by condition. Notably, two locations with the exact same design specifications differed by more than 7 dB. Table X is reproduced from Table 3 in the WSDOT report, illustrating the variation in values of the A-weighted L_{max} and the dimensions of the various rumble strip designs.

Table 2 Dimensions of measured rumble strip designs and average maximum sound levels (1 = Quiet)

SR	Design Dimensions (in.)				Vehicle Passing in Near Lane (L_{max} dBA)		Vehicle Passing in Far Lane (L_{max} dBA)		Rank Order: Quiet to Loud (25' far lane)
	Depth	Width	Length	Spacing	25'	50'	25'	50'	
SR 6	0.5	6.9	8	12	80	76	84	80	2
US 12	0.5	6.9	12	24	86	80	88	81	5
SR 14	0.5	6.9	10	12	89	81	93	91	8
SR 28	0.375	6.0	12	12	88	84	88	83	6
SR 97	0.375	6.0	8	18	86	82	86	80	4
SR 202	0.5	6.0	12	12	84	82	84	83	3
SR 203	0.5	6.0	12	12	88	90	89	93	7
SR 410	0.375	6.0	8	12	81	76	82	77	1
SR 507	0.375	6.0	12	12	92	86	96	90	9

Note: SR 202 and SR 203 were based on WSDOT Standard Plans that allow a depth of 1/2-5/8.

Source: Reproduced from Table 3 of Sexton, Timothy V., "Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety," Washington State Department of Transportation, Report No. WA-RD 835.1, September 2014.

The quietest designs were found to have energy relatively evenly distributed across the 1/3 octave bands measured, with the most dominant being 800 Hz. The final recommended design dimensions were a depth of 0.375 to 0.5 inches, a width between 6 and 6.9 inches, a length of 8 inches, and a spacing of 12 inches. However, Sexton found that independent effects of each of these dimensions on the sound levels were inconclusive. The relationship between the measured exterior levels and the estimated interior levels was also found to be inconclusive.

HMMH notes that the WSDOT study does not analyze 1/3 octave band data below 400 Hz, omitting potentially significant bands, such as those in which the fundamental frequency of the rumble strip noise would likely be present. In addition, it only considers rumble strip pass-by events, with no comparison to equivalent pass-by events on smooth pavement, meaning that the results reflect both the rumble strip sound levels and the site-specific topography.

3 Measurement Procedures

HMMH conducted wayside noise measurements of vehicle pass-bys on June 1-2 and June 8-9, 2017. All of the measurement sites were located on two-lane state highways and so required full lane closures in both directions during a controlled vehicle pass-by or set of vehicle pass-bys. In each case, the closest NHDOT District Patrol shed provided personnel that performed the required traffic control duties. The goal at each site was to collect as much noise data as possible, in a safe manner, while minimizing impacts and disruptions to commuters and other highway users.

All sound level measurements were performed with HMMH-owned Bruel & Kjaer model 2250 sound level meters that meet the requirements of American National Standard S1.4 for Type 1 precision sound measurement instruments. The sound measurement system (comprised of a microphone, preamplifier, and sound level meter) was calibrated at the beginning and end of the measurement period using an acoustic calibrator; all instruments have calibrations that are traceable to the National Institute of Standards and Technology (NIST). Sound level data were recorded onto a flash card, which was removed from the sound level meter and downloaded to a personal computer for subsequent analysis.

Data collection procedures and microphone locations followed industry best practices, based in part on AASHTO TP 98-13, *Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-By (SIP) Method,* and the Minnesota and Washington State rumble strip noise studies.

The noise monitors collected and stored continuous time histories of 0.1-second sound level data in one-third octave bands and as broadband levels. The monitors also captured high-resolution monaural (single channel) audio recordings, which were used during the analysis to assist with source identification. In addition, a portable solid state recorder with special in-ear microphones also was used to make binaural (two channel) recordings of vehicle pass-bys at Sites 1 and 1A. The binaural recordings were not used in any of the analyses, but are available either for playback or for other future analyses, as needed. Video of the controlled vehicle pass-bys also were made using a digital camera.

HMMH personnel also took periodic instantaneous measurements of on-site wind speeds and air temperature using a hand-held anemometer and pavement temperature using a hand-held infrared temperature meter. Table 3 lists the noise measurement instrumentation.

Table 3 Noise Measurement Instrumentation

Instrument	Make & Model	Serial No.
Sound Level Meter #4	Bruel & Kjaer 2250	2579777
Microphone #4	Bruel & Kjaer 4189	2589635
Preamplifier #4	Bruel & Kjaer ZC0032	7764
Calibrator #4	Bruel & Kjaer 4231	2579293
Sound Level Meter #5	Bruel & Kjaer 2250	2619791
Microphone #5	Bruel & Kjaer 4189	2616506
Preamplifier #5	Bruel & Kjaer ZC0032	11159
Calibrator #5	Bruel & Kjaer 4231	2579294
Sound Level Meter #6	Bruel & Kjaer 2250	2579776
Microphone #6	Bruel & Kjaer 4189	2616507
Preamplifier #6	Bruel & Kjaer ZC0032	18967
Calibrator #6	Bruel & Kjaer 4231	2579295

Table 4 provides a summary of the controlled vehicle pass-bys that were performed at each measurement site. The table shows the road surface, the test vehicle, the type of pass-by, the lane in which the test vehicle was traveling, the nominal speed, and the microphone distances from the roadway centerline. The wayside noise measurements included a number of default variables, which were tested at each site. These default variables included:

- One test vehicle: 2017 Nissan Altima
- Two microphone positions: 17 feet & 25 feet from the roadway centerline (adjacent to the near lane)
- Two pass-by directions: near lane & far lane
- Two road surfaces: smooth pavement & centerline rumble strips
- "Continuous" vehicle pass-bys
- At least one vehicle speed: 50 or 55 mph

The measurements also included several additional variables that were included at some of the sites. Decisions about what additional variables to include in the testing were based on the physical constraints at the site, the schedule, the availability of traffic control personnel, and the availability of HMMH staff and equipment.

- Two additional test vehicles: 2014 Masda3 & a NHDOT dump truck
- Three additional microphone positions: 50 feet from the roadway centerline, 25 feet from the roadway centerline (on the opposite side of the road, adjacent to the far lane) & 250 feet from the roadway centerline (on the grounds of the Roberts Knoll campground)
- One additional road surface: shoulder rumble strips
- Vehicle pass-by with a "maneuver"
- Two additional vehicle speeds: 40 & 60 mph

Table 4 Summary of Controlled Vehicle Pass-by Tests

Site	Road Surface	Vehicle	Pass-by Type	Lane(s)	Nominal Speed (mph)	Distances to Road Centerline (feet)
1	Centerline RS	Nissan Altima	Continuous	Near/Far	40/50/60	17/25/50
	Centerline RS	Mazda3	Continuous	Near/Far	40/50/60	17/25/50
	Smooth	Nissan Altima	Continuous	Near/Far	40/50/60	17/25/50
	Smooth	Mazda3	Continuous	Near/Far	40/50/60	17/25/50
	Centerline RS	Nissan Altima	Partial Maneuver	Near/Far	40/50/60	17/25/50
	Centerline RS	Mazda3	Partial Maneuver	Near/Far	40/50/60	17/25/50
1A	Shoulder RS	Nissan Altima	Continuous	Near/Far	40/50/60	25/50 & 25
	Centerline RS	NHDOT Truck	Continuous	Near/Far	40/50/60	25/50 & 25
	Smooth	Nissan Altima	Continuous	Near/Far	40/50/60	25/50 &25
	Smooth	NHDOT Truck	Continuous	Near/Far	40/50/60	25/50 &25
2	Centerline RS	Nissan Altima	Continuous	Near/Far	40/50	17/25 & 25
	Smooth	Nissan Altima	Continuous	Near/Far	40/50	17/25 & 25
	Centerline RS	Nissan Altima	Partial Maneuver	Near/Far	40/50	17/25 & 25
3	Centerline RS	Nissan Altima	Continuous	Near/Far	40/50	17/25
	Smooth	Nissan Altima	Continuous	Near/Far	40/50	17/25
	Centerline RS	Nissan Altima	Partial Maneuver	Near/Far	40/50	17/25
4	Centerline RS	Nissan Altima	Continuous	Near/Far	40/50/60	17/25 & 250
	Smooth	Nissan Altima	Continuous	Near/Far	40/50/60	17/25 & 250
	Centerline RS	Nissan Altima	Full Maneuver	Near/Far	40/50/60	17/25 & 250
	Centerline RS	NHDOT Truck	Continuous	Near/Far	40/50/60	17/25 & 250
	Smooth	NHDOT Truck	Continuous	Near/Far	40/50/60	17/25 & 250
	Centerline RS	NHDOT Truck	Full Maneuver	Near/Far	40/50/60	17/25 & 250
5	Centerline RS	Nissan Altima	Continuous	Near/Far	55	17/25
	Smooth	Nissan Altima	Continuous	Near/Far	55	17/25
6	Centerline RS	Nissan Altima	Continuous	Near/Far	50	17/25
	Smooth	Nissan Altima	Continuous	Near/Far	50	17/25

Source: HMMH, 2017.

Figure 3 shows a generalized cross-section of a measurement site that depicts the possible microphone positions that were used for the pass-by measurements (except the 250-foot microphone position at the Roberts Knoll Campground). Microphones were installed at 17 feet, 25 feet, and 50 feet from the centerline of the roadway, adjacent to the near lane, at heights of 3 feet, 5 feet, and 12 feet above ground level (AGL), respectively. At each site, the reference ground level was the ground elevation at the 17-foot microphone. At Sites 1A and 2, a microphone was installed at a distance of 25 feet from the roadway adjacent to the far lane, i.e. “25-foot opposite” in Figure 3.

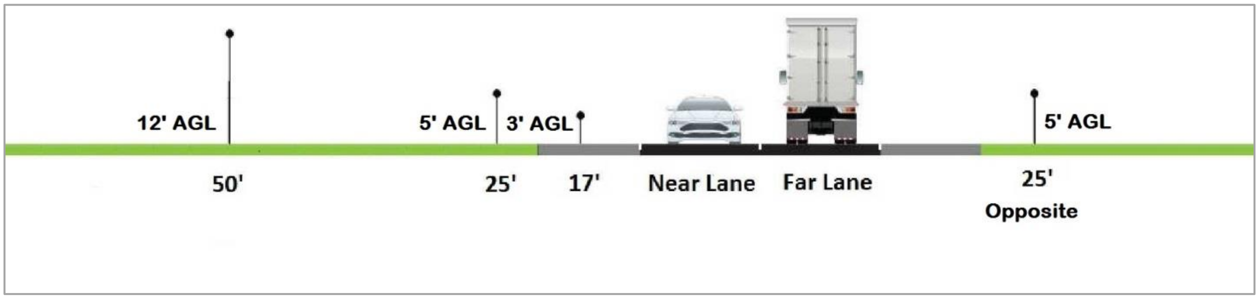


Figure 3 Generalized cross-section of a measurement site

Orange traffic cones were installed 200 feet “upstream” and “downstream” of the microphone locations creating a 400-foot long “target zone” for the driver(s) of the test vehicle(s). For a “continuous” pass-by (refer to Table 4), the test vehicle was in contact with the rumble strip over the entire 400-foot length of the target zone. For a partial maneuver, one set of tires on the test vehicle drifted onto the rumble strips for a very brief period of time before returning to the original lane of travel. The partial maneuver was intended to replicate a lane departure and recovery. For a full maneuver, the entire test vehicle crossed over the rumble strip into the opposing lane of travel before returning to the original lane of travel. The full maneuver was intended to replicate a passing movement. Both the partial and the full maneuver occurred within the limits of the 400-foot target zone.

Figure 4 is a photograph at Site 4 (Alton) that shows a continuous pass-by on the center rumble strip traveling in the near lane. Note the locations/heights of the microphones (17 feet/3 feet and 25 feet/5 feet) adjacent to the near lane in the foreground. Orange traffic cones on either side of the road mark the end of the target zone (in the middle ground of the photograph). In the background of the photograph, the traffic queue in the northbound direction can be seen.

Figure 4 Continuous Vehicle Pass-by on the Center Rumble Strip (Near Lane) at Site 4 (Alton)

4 Measurement Results

This section provides an overview of the wayside noise measurements. Initially, Section 4.1 compares the measured overall A-weighted maximum noise levels across all six sites. Then, Section 4.2 provides spectral noise level data from Site 1 in 1/3 octave bands. Finally, Section **Error! Reference source not found.** presents the results of unattended noise monitoring that was performed at the Roberts Knoll Campground in Alton in the vicinity of Site 4. The presentation of the results at the campground also includes an analysis and brief discussion about the audibility or noticeability of rumble strip noise.

Additional measurement data are provided in the appendices. Appendix B provides a table of the overall A-weighted maximum noise level for each controlled vehicle pass-by. Appendix C provides site photographs and graphs of pass-by spectra in 1/3 octave bands obtained at the time of the overall A-weighted maximum noise level.

4.1 Wayside Noise Measurements – Overall Sound Levels

Figure 5 presents the measured noise levels from controlled vehicle pass-bys traveling in the far lane for all seven sites. The figure includes results for pass-bys on smooth pavement, on different types of rumble strips (centerline and shoulder/edge line), for different types of pass-bys on the rumble strips (continuous and maneuver), and for different pass-by speeds. In Figure 5, pass-by noise levels are given for the 2017 Nissan Altima in terms of the A-weighted maximum sound level, fast response, (LAF_{max}) at the 25-foot microphone position (see Appendix A for more details about the noise level metrics used in this report). Rather than having to refer to Table 1, Table 5 provides a brief summary of the rumble strip locations and types of installation to aid the reader in reviewing this section.

Table 5 Summary of Rumble Strip Locations and Types Evaluated in this Study

Site	Road	Town	Passing Zone (Direction)	Rumble Strip Location	Rumble Strip Type
1	NH Rte. 111	Danville	EB & WB	Centerline	Milled
1A	NH Rte. 111	Danville	EB & WB	Shoulder (EB)	Sinusoidal
				Shoulder (WB)	Sinusoidal
2	NH Rte. 16	Madison	None	Centerline	Milled
3	NH Rte. 25/Tenney Mountain Hwy	Plymouth	WB only/Both	Centerline	Milled
4	NH Rte. 28	Alton	NB & SB	Centerline	Milled
5	US Rte. 202/NH Rte. 9	Henniker	EB & WB	Centerline	Milled
6	NH Rte. 9	Chesterfield	EB & WB	Centerline	Milled

Source: HMMH, 2017.

HMMH offers the following observations about the graph in Figure 5:

- The rumble-strip pass-bys at Site 3 (Plymouth) and at Site 4 (Alton) produced the highest noise levels:
  - At Site 3, the rumble strips were installed in 2016; NHDOT's measured depth was ½" to 3/8"; HMMH did not measure the depth

  - At Site 4, the rumble strips were installed in 2016; NHDOT's measured depth was ½" to 5/8"; HMMH's measured depth was approximately 3/4"
- At Site 6 (Chesterfield), rumble-strip pass-bys were lower than the pass-bys at Site 4 – even though HMMH measured similar depths at both sites[viii]
- Pass-by noise levels are generally dependent on speed, i.e. noise levels generally increase with increasing speed for vehicles on smooth pavement and on the rumble strips – with two exceptions:[ix]
  - At Site 3, the pass-by noise level on the centerline rumble strip decreases from 40 to 50 mph
  - At Site 4, the pass-by noise level on the centerline rumble strip also decreases from 40 to 50 mph, but then increases again from 50 to 60 mph
- At Sites 1 (Danville), 2 (Madison), 3, and 4, the pass-bys that performed a maneuver on the rumble strips produced *higher* noise levels than pass-bys on smooth pavement and *lower* noise levels than the pass-bys that were continuously on the rumble strip for the full length of the 400-foot target zone.

Figure 6 shows the corresponding results for vehicles traveling in the near lane. Many of the same trends are observed when these near-lane results are compared to the results of Figure 5 (pass-bys in the far lane).

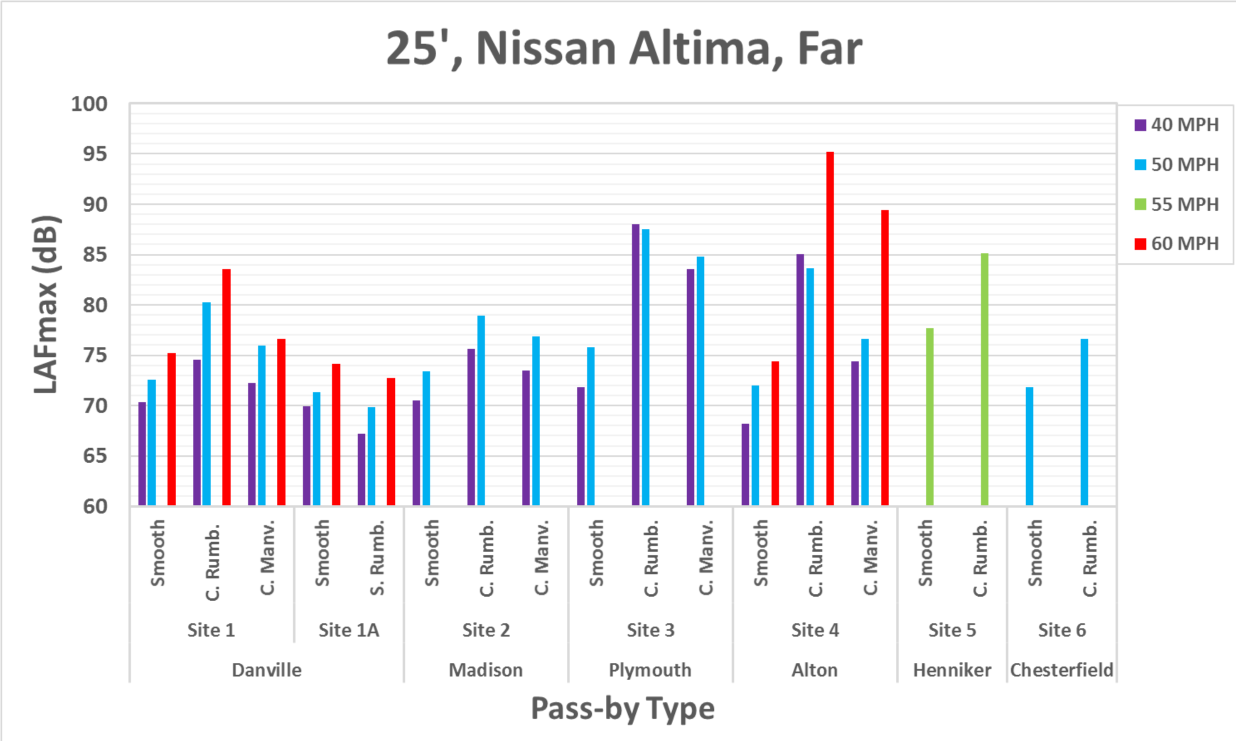


Figure 5 Measured LAF_{max} at 25 feet for the Nissan Altima in the Far Lane at All Six Sites

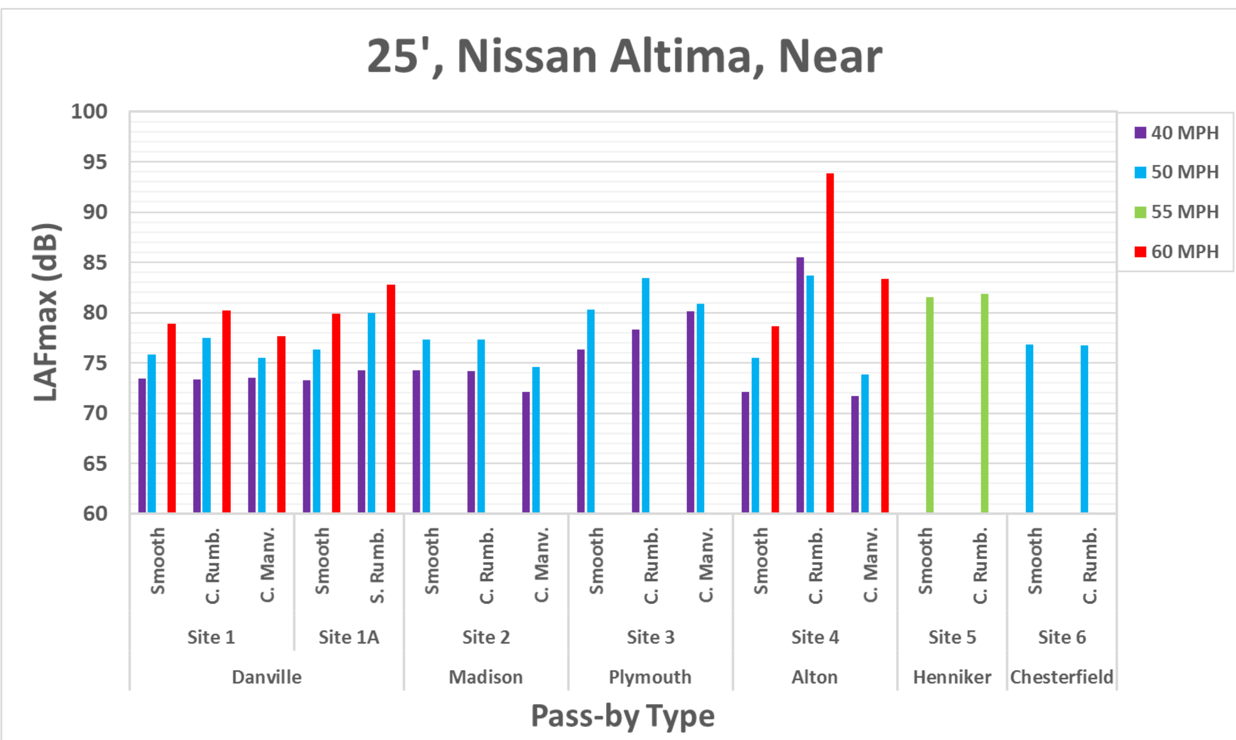


Figure 6 Measured LAF_{max} at 25 feet for the Nissan Altima in the Near Lane at All Six Sites

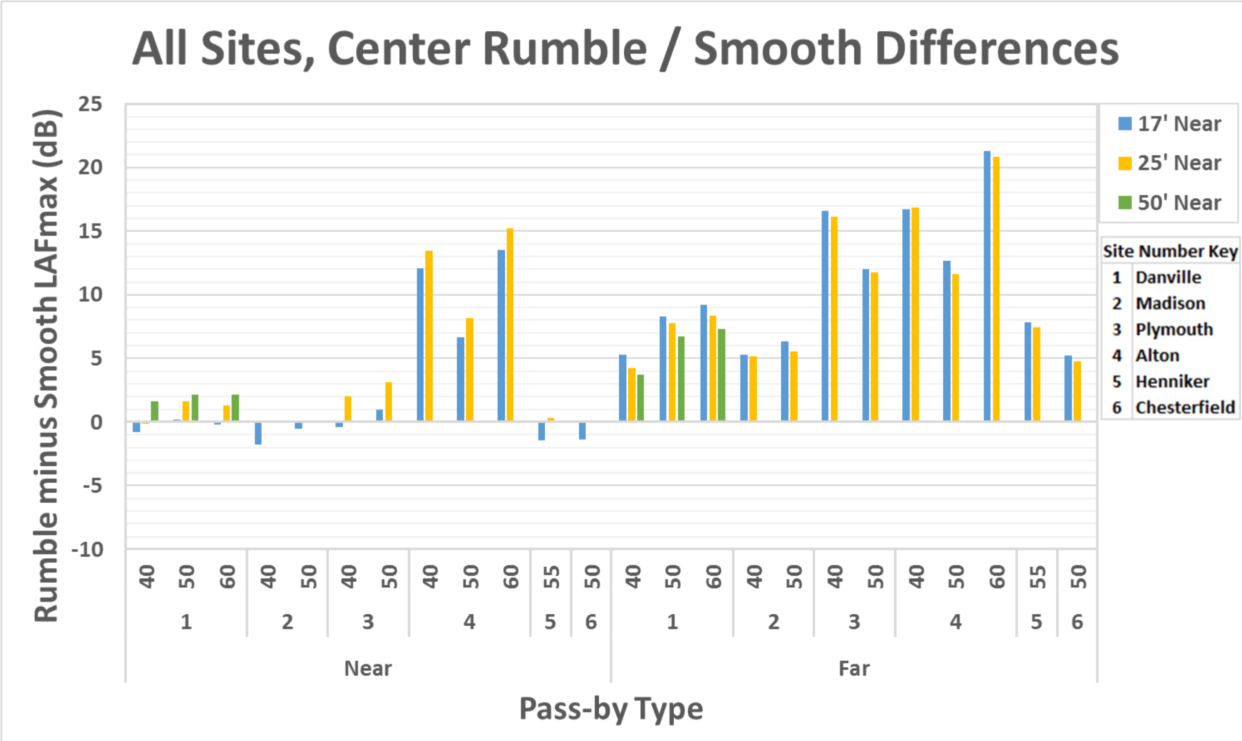


Figure 7 Pass-by LAF_{max} on Rumble Strips Relative to Pass-by on Smooth Pavement

Figure 6 shows another phenomenon related to rumble strip noise. The measured LAF_{max} for the centerline rumble-strip pass-bys in the *near* lane (Figure 6) are all lower than the corresponding measured LAF_{max} for pass-bys in the *far* lane (Figure 5). The lower levels for the near lane pass-bys are attributed to the shielding between the tires on the rumble strips and the microphone position that is provided by the car body. For a vehicle pass-by in the far lane, the propagation path between the tire/rumble-strip interface is unshielded. These findings are generally consistent with those of Sexton in the WSDOT study – with one exception. At 40 and 50 mph, the near lane pass-bys on centerline rumble strips are the same as, or slightly higher than, the far lane pass-bys at Site 4 (see Events 102 to 107 in the table in Appendix B).[x]

Figure 7 provides a graph of the differences between pass-by noise levels on rumble strips and on smooth pavement – for both the near lane (on the left side of the graph) and the far lane (on the right side). The difference chart shows:

- The rumble strips at Site 3 (Plymouth) and Site 4 (Alton) produced the highest sound levels relative to smooth pavement.
- The rumble strips at Site 2 (Madison) and Site 6 (Chesterfield) produced the lowest sound levels relative to smooth pavement.
- At Site 4, the pass-by level on the rumble strip was more than 20 decibels higher than the pass-by level on smooth pavement at a speed of 60 mph.
- The car body provides significant amounts of shielding between the tire/rumble strip interface for pass-bys in the near lane at all sites except Site 4.
- The relative LAF_{max} at Sites 3 and 4 are very similar for pass-bys in the far lane; however, the relative LAF_{max} at Site 3 is noticeably lower than the relative level at Site 4.
- The noise level "dip" at 50 mph is present in the data at Sites 3 and 4.

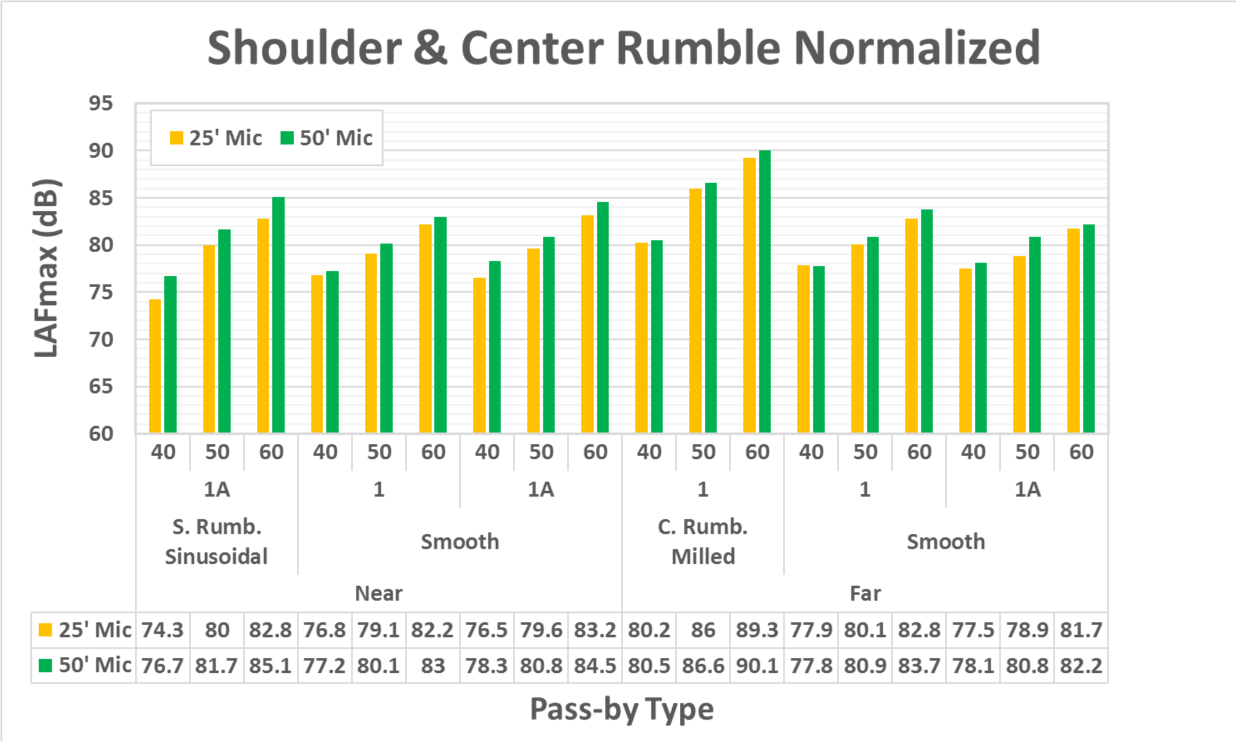


Figure 8 Pass-by Levels on Milled Rumble Strips and Sinusoidal Rumble Strips at Sites 1 and 1A

4.1.1 A comparison of milled and sinusoidal rumble strips

Figure 8 compares the LAF_{max} for pass-bys on different rumble strip profiles at Sites 1 and 1A. In effect, this figure provides a comparison of the noise emissions for the milled and sinusoidal rumble strips. In this chart, the sound level data are based on the unshielded pass-by levels (near lane for the sinusoidal profile on the shoulder and far lane for the milled profile on the centerline) normalized for distance. This chart suggests that the sinusoidal profile (shoulder rumble strip) on the southbound lane at Site 1A was approximately 4 to 7 decibels lower than the milled profile (centerline rumble strip) at Site 1. Differences between the normalized results at the 25-foot and 50-foot microphone positions can be attributed to different ground effects along the respective propagation paths.

The measured pass-by levels at Site 1A also offer a comparison of the two sinusoidal rumble strips installed along the shoulder in Danville. In the table of Appendix B, Events 31 to 36 are the pass-bys on smooth pavement, while Events 37 to 42 are the pass-bys on the shoulder rumble strips. The measured LAF_{max} at the 25-foot microphone in the near lane (southbound travel lane) is directly comparable and equivalent to the 25-foot “opposite” microphone position in the far lane (northbound travel lane). In both of these scenarios, the 25-foot microphone is directly exposed to the tires on the rumble strip when the test vehicle is in the lane closest to the respective microphone. Table 6 summarizes these data and computes the differences in the last column, showing that the sinusoidal rumble strip noise levels are within approximately +/- 1 dB of one another.

Table 6 Comparison of Measured LAF_{max} on the Shoulder Rumble Strips at Site 1A (Danville)

NH Route 111 SB Shoulder Rumble Strip				NH Route 111 NB Shoulder Rumble Strip				LAF_{max} NB minus LAF_{max} SB (dB)
Event	Lane	Speed (mph)	LAF_{max} (dBA) at 25'	Event	Lane	Speed (mph)	LAF_{max} (dBA) at 25' Opposite	
37	Near	40	74.3	38	Far	40	75.5	1.2
39	Near	50	80.0	40	Far	50	79.2	-0.8
41	Near	60	82.8	42	Far	60	82.1	-0.6

Source: HMMH, 2017.

Appendix B provides a table of the measured LAF_{max} for each controlled vehicle pass-by on the rumble strips and on smooth pavement. Appendix B also provides charts that graph the measured LAF_{max} against vehicle speed.

4.1.2 Comparisons of LAF_{max} for controlled pass-bys on rumble strips and random pass-bys on smooth pavement

Table 7 and Table 8 provide comparisons of measured LAF_{max} for pass-bys on rumble strips and smooth pavement. Table 7 provides measured sound level data from Sites 1 and 1A along NH Route 111 in Danville and Table 8 provides data from Site 3 along NH Route 25/Tenney Mountain Highway in Plymouth. The motorcycle and heavy truck levels were obtained from the traffic that passed each site between the shutdown periods for the controlled vehicle pass-bys. That is, the motorcycle and heavy truck LAF_{max} were sampled directly from the fleet of vehicles using New Hampshire roads.

As shown in Table 7, at speeds of 40 and 50 mph, the measured LAF_{max} for automobiles on the rumble strip were the same as, or slightly lower than the LAF_{max} for a motorcycle and a heavy truck on smooth pavement. However, at 60 mph, automobiles on the rumble strip produced higher noise levels than either the motorcycle or the heavy truck on smooth pavement. Note that the speeds of the motorcycle and the heavy truck were not documented at the time of the measurement.

Table 7 Comparisons of LAF_{max} for Pass-bys on Rumble Strips and Smooth Pavement at the Danville Site

Pavement	Site	Vehicle	Lane	Speed (mph)	LAF_{max} at 25' (dBA)
Smooth pavement	**1A**	**Motorcycle**	**Near**	**n/a**	**80**
	1	**Heavy truck**	**Far**	**n/a**	**82**
Centerline rumble strip (milled)	1	Altima	Far	40	75
				50	80
				60	84
	1	Mazda3	Far	40	75
				50	79
				60	85
	1A	NHDOT truck	Far	40	83
				50	89

Source: HMMH, 2017.

As shown in Table 8, at Site 3 (Plymouth) the Altima on the rumble strips produced higher noise levels than either the motorcycle or the heavy truck on smooth pavement. Again, note that the speeds of the motorcycle and the heavy truck were not documented. Section 0 provides the corresponding spectra for each of the pass-bys in Table 7 and Table 8.

Table 8 Comparisons of LAF_{max} for Pass-bys on Rumble Strips and Smooth Pavement at the Plymouth Site

<table>
<tr><th>Pavement</th><th>Site</th><th>Vehicle</th><th>Lane</th><th>Speed (mph)</th><th>LAF_{max} at 25' (dBA)</th></tr>
<tr><td rowspan="2">Smooth pavement</td><td rowspan="2">3</td><td>Motorcycle</td><td>Near</td><td>n/a</td><td>80</td></tr>
<tr><td>Heavy truck</td><td>Far</td><td>n/a</td><td>82</td></tr>
<tr><td rowspan="2">Centerline rumble strip (milled)</td><td rowspan="2">3</td><td rowspan="2">Altima</td><td rowspan="2">Far</td><td>40</td><td>88</td></tr>
<tr><td>50</td><td>88</td></tr>
</table>

Source: HMMH, 2017.

4.2 Wayside Noise Measurements – 1/3 Octave Band Sound Levels

Figure 9 shows the difference spectra for the 2017 Nissan Altima at a speed of 40 mph. The top two charts show the difference between the milled profile (centerline rumble strip) and smooth pavement at Site 1 (Danville), while the bottom charts show the difference between the sinusoidal profile (shoulder rumble strip) and smooth pavement.

The top charts show peaks in the spectra in the 1/3 octave bands centered at 63 and 125 Hz for the milled profile. The peaks are more pronounced for the vehicle pass-bys in the far lane (chart on the right). As the speed of the automobile increases, these peaks tend to shift to higher bands. The bottom charts show that the spectral peak for the sinusoidal profile is located in the band centered at 31.5 Hz.

Also of note on the Site 1 milled rumble strip is the significant increase in sound level in the middle frequencies, particularly for the far-lane pass-bys. The Site 1A sinusoidal strips show less increase in the middle frequencies. It is the increase in the middle and high frequencies that correlates strongest with the change in overall A-weighted sound level as well as human audibility.

The two bottom charts also offer a comparison of the two sinusoidal rumble strips installed along the shoulder at Site 1A (Danville). Compare the 25-foot curve in the bottom chart on the left (near lane – westbound) to the 25-foot *opposite* curve in the bottom chart on the right (far lane – eastbound). Both rumble strips show a peak in the 31.5 Hz band – the relative level for the westbound rumble strip in this band is slightly higher than +20 dB, while the relative level for the eastbound strip is just about +20 dB. Note that the eastbound rumble strip shows more noise in the 1/3 octave bands above 125 Hz at a speed of 40 mph. The shoulder rumble strips were installed at slightly different depths – the eastbound strip was 3/8" with a 2-foot cycle and the westbound strip was ½" with a 2-foot cycle.

Appendix C provides charts of the individual spectra at each site for all of the controlled vehicle pass-bys at all of the sites. Appendix C also provides representative photographs of the microphone positions at each site. The companion DVD provides additional spectral difference curves for each pass-by at the other sites.

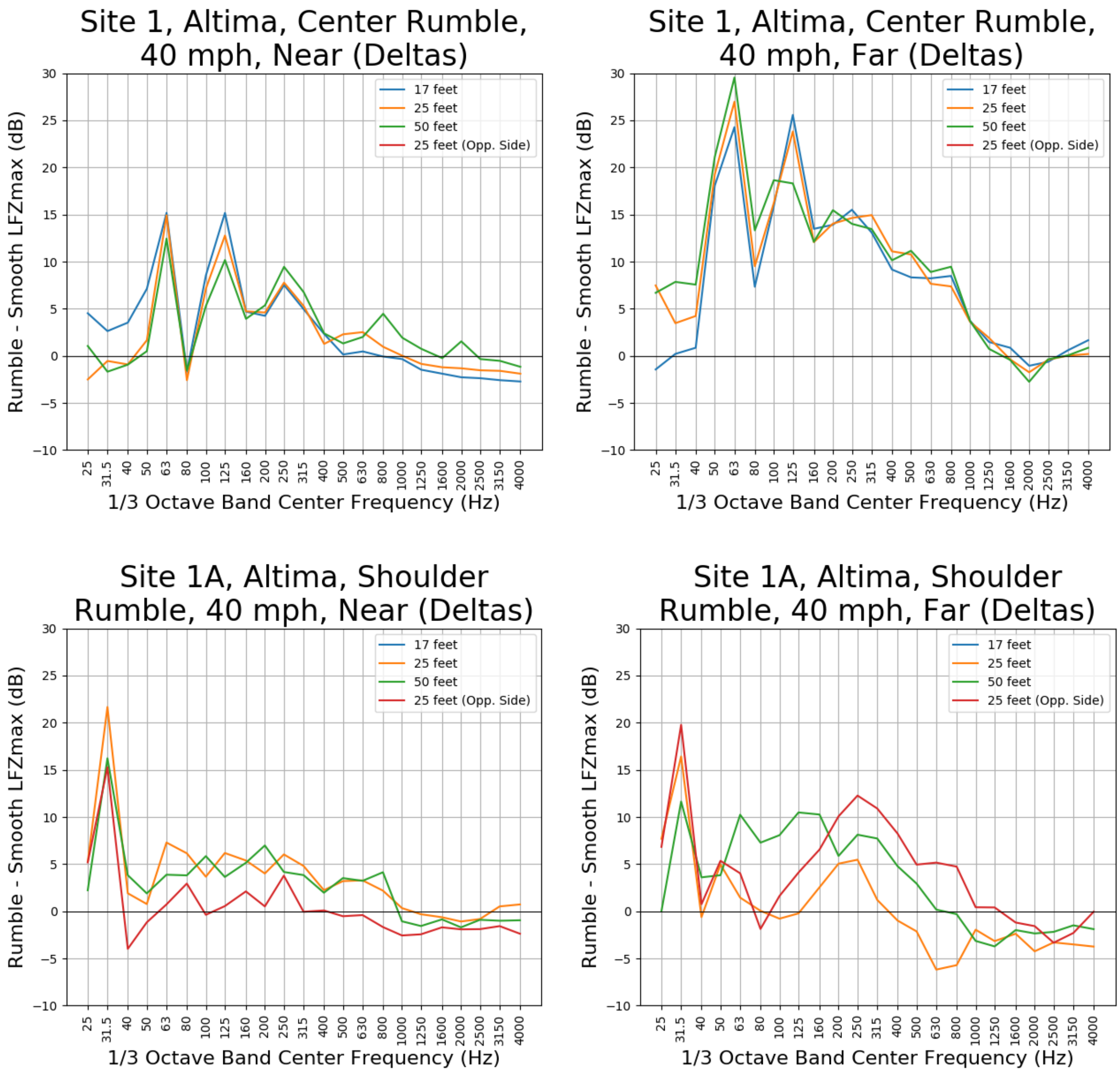


Figure 9 Difference Spectra for Pass-bys at 40 mph at Sites 1 and 1A

The fundamental frequencies of the rumble strip pass-bys are dependent upon the speed of the test vehicle and the on-center spacing of the rumble strip (i.e. the peak-to-peak distance). Table 9 provides a summary of the 1/3 octave bands that contain the fundamental frequency for a range of typical vehicle speeds and a range of spacing values. As the rumble strip spacing increases, the fundamental frequency decreases. A doubling of the rumble strip spacing, halves the fundamental frequency.

Table 9 1/3 Octave Bands Containing Fundamental Frequencies based on Rumble Strip Spacing and Vehicle Speed

Spacing (in.)	1/3 Octave Band Center Frequecny (Hz) Containing the Fundamental Frequency			
	40 mph	50 mph	55 mph	60 mph
10	63	80	100	100
10.5	63	80	100	100
11	63	80	80	100
11.5	63	80	80	100
12	63	80	80	80
12.5	63	63	80	80
13	50	63	80	80
13.5	50	63	80	80
14	50	63	63	80
14.5	50	63	63	80
15	50	63	63	63
15.5	50	63	63	63
21	31.5	40	50	50
21.5	31.5	40	50	50
22	31.5	40	40	50
22.5	31.5	40	40	50
23	31.5	40	40	50
23.5	31.5	40	40	50
24	31.5	40	40	40
24.5	31.5	40	40	40
25	25	31.5	40	40

Source: HMMH, 2017.

4.2.1 Comparisons of spectra for controlled pass-bys on rumble strips and random pass-bys on smooth pavement

Figure 10 compares the spectra for selected automobile pass-bys on rumble strips to both a motorcycle pass-by and a heavy truck pass-by on smooth pavement. The motorcycle and heavy truck spectra were obtained from the traffic that passed each site between the shutdown periods for the controlled vehicle pass-bys. That is, the motorcycle and heavy truck spectra were randomly sampled from the fleet of vehicles using New Hampshire roads. These spectra correspond to the LAF_{max} values in Table 7 and Table 8 in Section 4.1.2.

In the top left graph of Figure 10, the spectra for the Altima on the milled rumble strips at Site 1 (Danville) are compared to a motorcycle and heavy truck spectra obtained on the same stretch of road. The graph in the top right corner shows similar comparisons for observed pass-bys at Site 3 (Plymouth). The following trends are observed in the top two graphs:

- The motorcycle pass-by on smooth pavement generally produced higher sound levels than the Altima (at 50 and 60 mph) in the bands below 63 Hz; while the Altima on the milled rumble strips produced higher levels in the bands from 125 to 400 Hz.
- The heavy truck pass-by on smooth pavement produced sound levels that were similar to the Altima (at 50 and 60 mph) in the bands from 125 to 400 Hz; while the Altima on the milled rumble strips produced higher levels in the bands below 63 Hz (at both 40 and 50 mph).
- At 40 mph, the pass-by levels for the Altima were lower than the levels for the motorcycle and the truck at Site 1 (Danville).

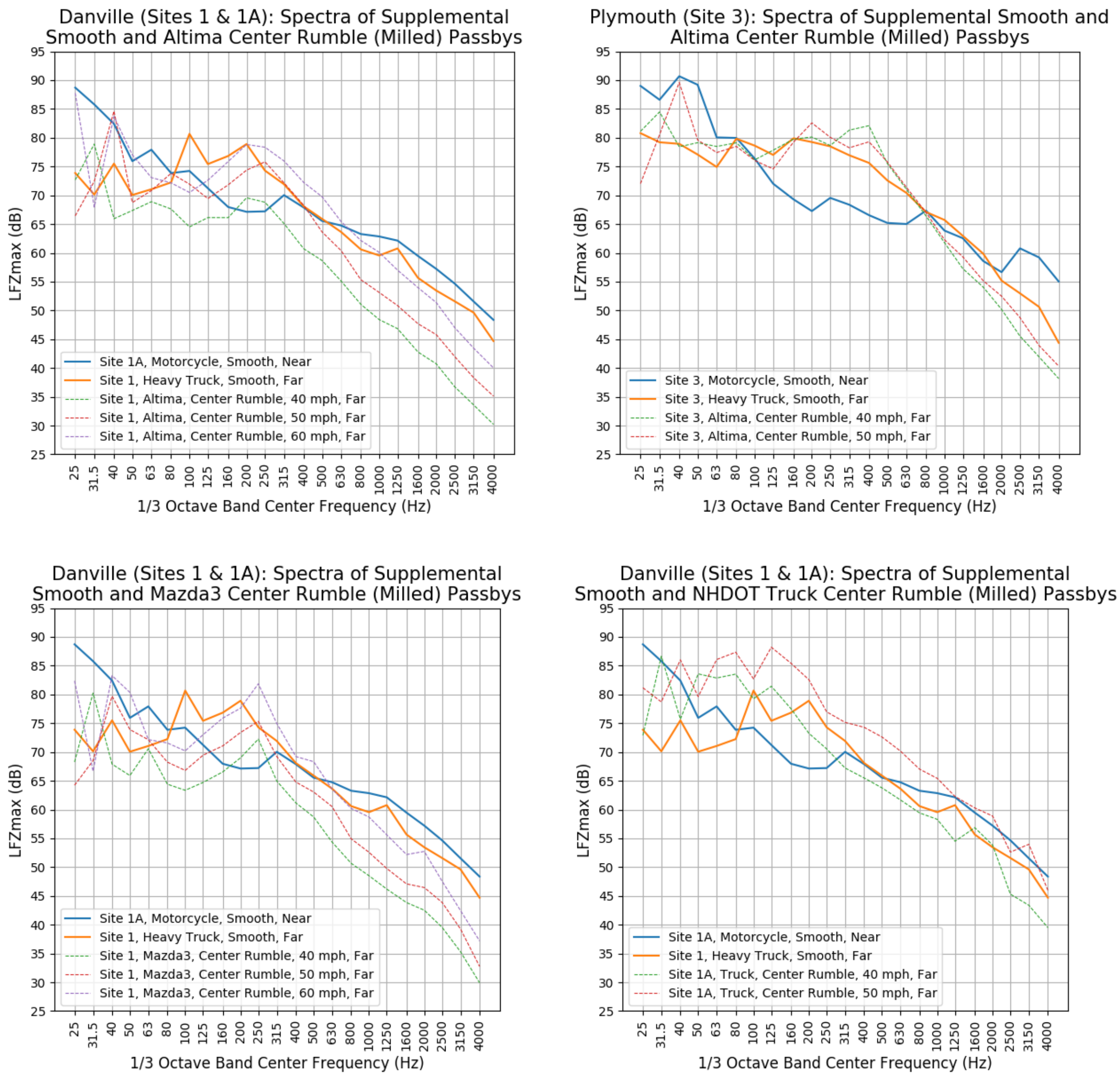


Figure 10 Comparisons of Automobile Spectra on Rumble Strips and Motorcycle & Truck Spectra on Smooth Pavement

In the bottom left graph of Figure 10, the spectra for the Mazda3 on the milled rumble strips at Site 1 (Danville) are compared to a motorcycle and heavy truck spectra obtained on the same stretch of road. The graph in the bottom right corner compares NHDOT truck pass-bys on the milled rumble strips to the motorcycle and heavy truck spectra on smooth pavement. The following trends are observed in the bottom two graphs:

- In general, the Mazda3 spectra display similar trends as the Altima spectra. That is, in the bands below 63 Hz, the Mazda3 produced levels that are higher than the truck and lower than the motorcycle. In the bands from 125 to 400 Hz, the Mazda3 produced levels that are similar to, or slightly less than the levels from the truck, and levels that are higher than the motorcycle.
- The NHDOT truck on rumble strips produced higher levels than the heavy truck on smooth pavement in the bands below 160 Hz. At 50 mph, the NHDOT truck produced higher levels than the truck on

smooth pavement. At 40 mph, the NHDOT truck produced levels that were the same as, or slightly lower than the truck on smooth pavement in the bands above 200 Hz.

4.3 Unattended Noise Measurements at the Roberts Knoll Campground

In the late afternoon on June 8, 2017, HMMH personnel installed a long-term noise monitor on the grounds of the Roberts Knoll campground in Alton for unattended monitoring. The monitor was located approximately 1,475 feet north of Site 4 and 250 feet from the centerline of NH Route 28. The long-term monitor was used to continuously sample and store various A-weighted noise metrics for the overnight period from June 8 to June 9, including the period on the morning of June 9 during which HMMH personnel measured controlled vehicle pass-bys on the rumble strips at Site 4. The monitor also was programed to sample and store sound levels in 1/3 octave bands and to make continuous audio recordings. Figure 11 shows the location of the microphone on the right side of the photograph – in the middle ground near the southwest corner of the pickle ball court.

Figure 11 Unattended Noise Monitoring near the Pickle Ball Court at Roberts Knoll Campground

The long-term monitor provided an opportunity to measure pass-by noise levels at a noise-sensitive land use in proximity to the rumble strip installation in Alton. The objectives of the long-term monitor were to:

- Evaluate the noticeability or audibility of rumble strip noise in the campground
- Compare the LAF_{max} of pass-bys on the rumble strip to pass-bys on smooth pavement
- Document overall A-weighted and 1/3 octave band sound levels from pass-bys on smooth pavement and on the rumble strip at the campground
- Document ambient sound levels at the campground for a nighttime period

Table 10 compares the average LAF_{max} of pass-bys on smooth pavement and on the rumble strips as measured in the campground. As a general rule, a human with normal hearing sensitivity would characterize a 3-decibel change in sound level as "barely perceptible," a 5-decibel change as "readily perceptible," and a 10-dB change very noticeable, since that change would be perceived as either twice as loud (for an increase in sound level) or half as loud (for a decrease in sound level).[xi] As shown in Table 10, the average LAF_{max} for all vehicle types on the rumble strip was 59 dBA, while the average LAF_{max} for selected automobiles on smooth pavement was 54 dBA. So, this change in sound level due to pass-bys on rumble strips would be readily perceptible at the campground.

Table 10 Comparison of Measured Average LAF_{max} for Overnight Pass-bys on Rumble Strip and Smooth Pavement at the Campground

Road Surface / Pass-by Type	Statistical Descriptor	Measured LAF_{max} (dBA)
Rumble Strip (All Vehicles)	Maximum	76
	10^{th} Percentile	68
	Average	59
	Minimum	36
Smooth Pavement (Automobile)	Average	54
Smooth Pavement (Truck)	Average	63

Source: HMMH, 2017.

Community reaction to noise is influenced by the presence of distinguishing characteristics of the sound emitted by a source, such as the presence of pure tones or impulsive noise. If a pure tone is present, it is customary practice to make an upward decibel adjustment to the sound level emitted by the source to account for increased sensitivity to and noticeability of tonal sounds.[xii] In the case of a pure tone, a 5-decibel adjustment may be added to the sound level of the source when attempting to predict community response or compare to noise impact criteria.

HMMH evaluated the sound level spectra of 87 overnight rumble strip events for the presence of pure tones following the methods of ANSI Standard 12.9.[xiii] Of the 87 events, 18-percent exhibited the presence of a pure tone. Since pure tones are present in some of the rumble strip pass-bys, a 5-decibel upward adjustment may be applied to the sound level of the events containing a pure tone. The average LAF_{max} with a 5-decibel adjustment applied would be 65 dBA – effectively representing an 11-decibel increase relative to an automobile passby on smooth pavement. An increase of this magnitude is readily perceptible. Most occurrences of pure tones according to this method were in the 1/3 octave bands centered from 80 to 250 Hz.

Figure 12 provides a graph of measured spectra for several selected pass-by events over the nighttime period from 5:00 PM on June 8 to 10:00 AM on June 9 as well as for a period of quiet background with no traffic passing. The dashed lines show the measured spectra for an automobile pass-by and a truck pass-by on smooth pavement. The solid lines show the spectra for pass-bys on the rumble strip.[xiv] The rumble strip spectra show characteristic peaks at 80, 100, and 125 Hz. Note that the spectra for the pass-bys on smooth pavement were obtained at the LAF_{max} of the pass-by, which is likely to have occurred on the part of the roadway nearest the campground. The spectra for the rumble strip events do not necessarily emanate from the part of the roadway nearest the campground and might have occurred at distances greater than 250 feet from the long-term noise monitor.

Figure 12 also includes an ambient spectrum for a quiet period of the night that incorporates the threshold of audibility according to ISO 389-7:2005(E),[xv] since the measured ambient sound levels were very low in certain 1/3 octave bands.

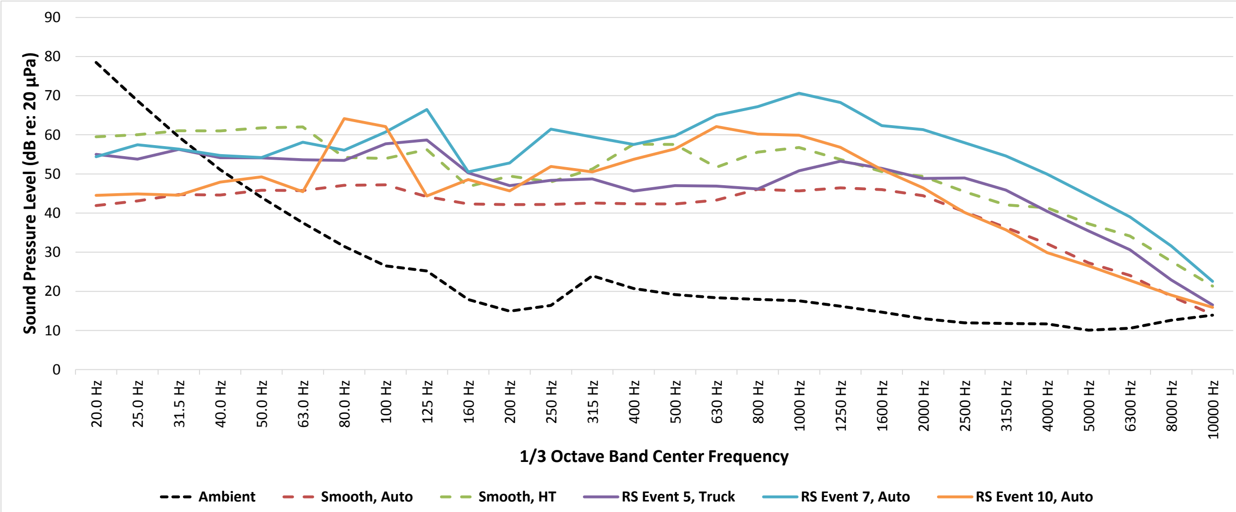


Figure 12 Comparisons of Measured Sound Level Spectra at the Roberts Knoll Campground

Table 11 provides a summary of the measured LAF_{max} of overnight rumble strip noise events at the Roberts Knoll Campground for the period that started at 5:00 PM on June 8 and ended at 10:00 AM on June 9. The third column contains the maximum LAF_{max} as measured at the long-term monitor over each one hour period, and the fourth column contains the maximum LAF_{max} of those events identified as a pass-by on a rumble strip. Note that other sources of sound in the environment produce maximum noise levels that are sometimes greater than the maximum noise levels from the rumble strip.

Table 11 Measured LAF_{max} of Overnight Rumble Strip Events at the Roberts Knoll Campground

Hour Starting	Hourly LA_{eq} (dBA)	Maximum LAF_{max} (dBA) During the Hour	Maximum LAF_{max} (dBA) due to Rumble Strip	Measured Ambient as LA_{90} (dBA)	Maximum LAF_{max} from Rumble Strip minus LA_{90} (dB)	Total Number of Rumble Strip Events	Total Number of Rumble Strip "Peaks" or "Incursions"
5:00 PM	55.8	70.1	64.2	44.2	20.0	2	3
6:00 PM	54.1	69.2	61.3	40.0	21.4	2	8
7:00 PM	53.0	74.5	74.5	38.3	36.2	8	21
8:00 PM	52.6	72.7	72.0	37.8	34.2	8	37
9:00 PM	48.9	75.5	75.5	36.8	38.6	7	23
10:00 PM	46.8	65.8	57.2	30.3	26.9	4	8
11:00 PM	43.9	60.2	59.9	28.8	31.1	4	8
12:00 AM	42.2	65.7	54.6	27.2	27.4	2	2
1:00 AM	40.7	65.3	65.3	27.2	38.1	4	6
2:00 AM	40.0	64.4	--	27.3	--	0	0
3:00 AM	44.9	67.6	66.0	27.7	38.3	2	3
4:00 AM	44.1	67.7	67.7	28.3	39.4	2	5
5:00 AM	52.1	74.7	67.2	35.5	31.7	9	25
6:00 AM	54.9	70.5	68.0	39.3	28.7	10	21
7:00 AM	53.9	67.1	63.8	39.6	24.1	8	19
8:00 AM	55.8	73.0	73.0	42.8	30.3	7	16
9:00 AM	-	75.6	75.6	48.5	27.1	8	24

Source: HMMH, 2017.

A comparison of rumble strip noise levels to ambient sound levels provides some measure of the noticeability of the sound source. Within the industry, the ambient sound level is typically defined as the background A-weighted sound level that is exceeded 90% of the time (i.e. the LA_{90}).[xvi] HMMH's experience is that a 10-dBA threshold above ambient has proven to be a reasonable measure of the noticeability of a sound source. The LAF_{max} of pass-bys on rumble strips are clearly well above the 10-decibel threshold and so may be considered very noticeable.

The seventh column shows the number of rumble strip events that were identified from the long-term sound level data and the audio recordings. HMMH identified a total of 87 rumble strip events over the nighttime period. Each event contained at least one "peak," but in some cases multiple "peaks," if for example a car crossed the rumble strip and then returned to its original lane of travel, there would be four peaks (also refer to the spectrograms in Appendix C.8).

The second column shows the hourly A-weighted equivalent sound level (abbreviated $L_{eq,1-hr}$ or LA_{eq}). The LA_{eq} is the value or level of a steady, non-fluctuating sound that represents the same sound energy as the actual time-varying sound evaluated over the same time period. For highway traffic noise assessments, LA_{eq} is the sound level metric used to identify noise impact following Federal Highway Administration (FHWA) regulations[xvii] and NHDOT policies and guidance.[xviii] For residential land use and campgrounds, noise impact occurs when predicted exterior noise levels *approach or exceed* 67 dBA in terms of hourly LA_{eq} during the worst noise hour. NHDOT defines the word "approach" in "approach or exceed" as within 1 decibel. Therefore, the threshold for noise impact for residences and campgrounds is where exterior hourly noise levels are within 1 decibel of 67 dBA, LA_{eq}, or 66 dBA. As shown in Table 11, the values of the measured hourly LA_{eq}, which include contributions from all pass-by events over the nighttime period, are well below FHWA's threshold for noise impact.

5 Findings and Conclusions

As previously stated, HMMH was retained by NHDOT to evaluate the measured noise levels from controlled vehicle pass-bys on rumble strips and smooth pavement at six locations across the state. The study included a limited review of the current technical literature, wayside noise measurements of controlled vehicle pass-bys on rumble strips and on smooth pavement, and subsequent analysis of the measured data. The objectives of this study were to document and compare noise levels for different rumble strip installations across the state, and if possible, make comparisons to the results published by other researchers. We trust that the results of this study and other research will be used to inform the Department about the noise emitted by different rumble strips for the ultimate purpose of identifying a design that minimizes noise emissions while meeting all of the Department's requirements for safety.

Our principal findings and conclusions are as follows:

- The noise emissions of pass-bys on rumble strips increase with increasing speed. Further, the noise emissions of rumble strips increase with speed at a greater rate than do the noise emissions of vehicles on smooth pavement (for the range of speeds examined in this study).
- The rumble strips along NH Route 25 in Plymouth and along NH Route 28 in Alton produced the highest noise levels. Both rumble strips are still relatively new, having been installed in 2016.
  - Along NH Route 28 in Alton, the pass-by level on the rumble strip was more than 20 decibels higher than the pass-by level on smooth pavement at a speed of 60 mph.
- The rumble strip at Site 4 (Alton) is clearly audible at the pickle ball court on the grounds of the Roberts Knoll Campground. The measured maximum sound levels of pass-bys on rumble strips was more than 10 decibels above nighttime background sound levels at the campground, and so is considered very noticeable.
- The rumble strip along NH Route 9 in Chesterfield produced levels that were lower than the rumble strip in Alton, even though the cut depths appeared to be similar at both sites.
- Along NH Route 111 in Danville, the sinusoidal profile of the shoulder rumble strip on the westbound lane was approximately was approximately 4 to 7 decibels lower than the milled profile centerline rumble strip.
- The two sinusoidal rumble strips installed on the eastbound and westbound shoulders at Site 1A in Danville are reportedly different. However, the measurements show that the two rumble strips produce noise levels are within approximately +/- 1 decibel of one another. The shoulder rumble strips were installed at slightly different depths – the eastbound strip was 3/8" with a 2-foot cycle and the westbound strip was ½" with a 2-foot cycle.
- At 40 and 50 mph, the LAF_{max} for automobiles on the rumble strip in Danville were the same as, or slightly lower than, the LAF_{max} for a motorcycle and heavy truck pass-by on smooth pavement.
- At 60 mph, the LAF_{max} for automobiles on the rumble strip in Danville were higher than the LAF_{max} for a motorcycle and heavy truck pass-by on smooth pavement.
- The spectra for the milled rumble strips generally exhibit peaks in the 1/3 octave bands from 50 to 160 Hz, whereas the spectra for the sinusoidal rumble strips exhibit a peak band centered at 31.5 Hz.

Appendix A Overview of Sound Level Metrics

This Appendix describes the terminology and sound metrics used in this report.

A.1 Decibels (dB), Frequency and Sound Level Weightings

Loudness is a subjective quantity that enables a listener to order the magnitude of different sounds on a scale from quiet to loud. Although the perceived loudness of a sound is based somewhat on its frequency and duration, chiefly it depends upon the sound pressure level. This is a measure of the sound pressure at a point relative to a standard reference value; sound pressure level is always expressed in decibels (dB).

Decibels are logarithmic quantities, so combining decibels is unlike common arithmetic. For example, if two sound sources each produce 100 dB operating individually and they are then operated together, they produce 103 dB. Each doubling of the number of sources produces another three decibels of sound. A tenfold increase in the number of sources makes the sound pressure level go up 10 dB, and a hundredfold increase makes the level go up 20 dB. If two sources differ in sound pressure level by more than 10 decibels, then operating together, the total level will approximately equal the level of the louder source as the quieter source doesn't contribute significantly to the total.

People hear changes in sound level according to the following rules of thumb: 1) a change of 1 decibel or less in a given sound's level is generally not readily perceptible except in a laboratory setting; 2) a 5-dB change in a sound is considered to be generally noticeable in a community setting; and 3) it takes approximately a 10-dB change to be heard as a doubling or halving of a sound's loudness.

Another important characteristic of sound is its frequency, or "pitch." This is the rate of repetition of sound pressure oscillations as they reach our ears. Frequency is expressed in units known as Hertz (abbreviated "Hz" and equivalent to one cycle per second). Sounds heard in the environment usually consist of a range of frequencies. The distribution of sound energy as a function of frequency is termed the "frequency spectrum."

The human ear does not respond equally to identical sound levels at different frequencies. Although the normal frequency range of hearing for most people extends from a low of approximately 20 Hz to a high of around 10,000 Hz to 20,000 Hz, people are generally most sensitive to sounds in the voice range, between about 500 Hz to 2,000 Hz. Therefore, to correlate the amplitude of a sound with its level as perceived by people, the sound energy spectrum is adjusted, or "weighted."

A.1.1 A-weighting Network

The weighting system most commonly used to correlate with human response to sound is "A weighting" (or the "A-filter") and the resultant sound level is called the "A-weighted sound level" (dBA). A weighting significantly de-emphasizes those parts of the frequency spectrum from a sound source that occurs both at lower frequencies (those below about 500 Hz) and at very high frequencies (above 10,000 Hz) where we do not hear as well. The filter has very little effect, or is nearly “flat,” in the middle range of frequencies between 500 and 10,000 Hz. In addition to representing human hearing sensitivity, A weighted sound levels have been found to correlate better than other weighting networks with human perception of “noisiness.” One of the primary reasons for this is that the A weighting network emphasizes the frequency range where human speech occurs, and sound in this range interferes with speech communication. Another reason is that the increased hearing sensitivity makes sound more annoying in this frequency range.

A.1.2 Other Broadband Sound Level Weightings

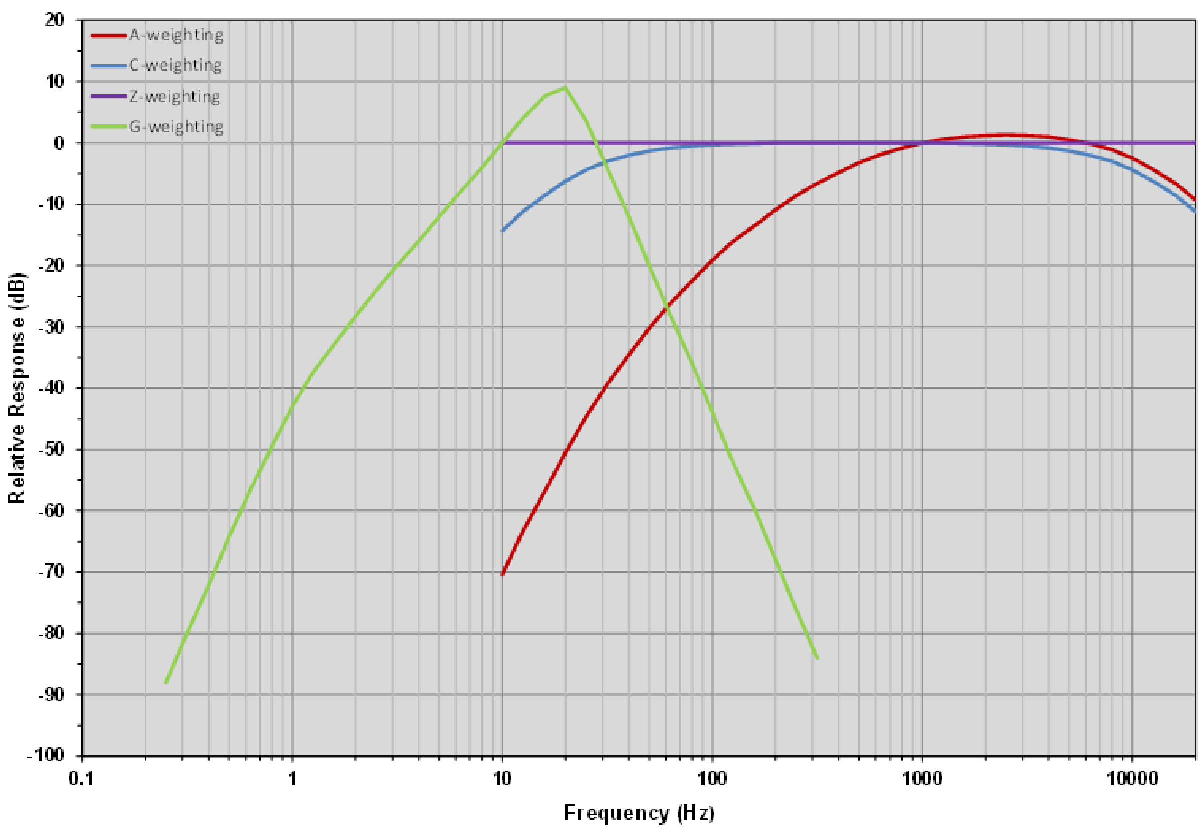
Another commonly-used weighting network is “C-weighting,” originally developed to mimic the human ear’s frequency response at a level of approximately 100 dB. C-weighting is flat (has no weighting) throughout most of the audible range, but tapers with small amounts of attenuation at the very highest and lowest frequency regions (above about 8000 Hz and below about 32 Hz). In recent years, C-weighted sound levels have sometimes been used for comparison with the A-weighted sound levels measured during the same time period as an indicator of the prominence of low frequency sound. The A- and C-weightings are similar at the highest frequencies, but A-weighting filters out much more of the low frequency sound below about 500 Hz.

G-weighting is a more recently-developed weighting network that is intended to isolate and measure only very low frequency sound, including sounds below the lower limit of human audibility (approximately 20 Hz) commonly known as infrasound. G-weighting actually incorporates 9 dB of amplification (gain) in the sound level signal at 20 Hz, with a steep taper at higher and lower frequencies, such that the weighting is 20 dB lower at approximately 5 Hz and 40 Hz.

An unweighted sound level is commonly called “Z-weighted,” although technically there is no weighting.

Figure A-1 presents a graph comparing the various broadband sound level weighting networks. As shown in this figure, the A-weighting, C-weighting, and Z-weighting networks comprise the frequency range from 10 Hz to 20,000 Hz, while the G-weighting network includes the frequency range from 0.25 Hz to 315 Hz.

Figure A-1. Broadband Sound Level Weighting Networks



A.1.3 Octave Band and 1/3-Octave Band Sound Levels

For analysis purposes, sound is also often broken down into different frequency divisions, or bands. The most common division is the standard octave band. An octave is a band of frequencies whose lower frequency limit is half of the upper frequency limit. An octave band is identified by its center frequency. For example the 1000 Hz octave band contains all the frequencies between 720 Hz and 1440 Hz. The next octave band higher would have values twice these, and the next octave lower would have values half of these. The range of human hearing is commonly divided into 10 standard octave bands that encompass the range from 20 Hz to 20,000 Hz: 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, and 16 kHz. For analyses that require even further frequency detail, each octave-band is often broken down into parts, such as 1/3 octave-bands.

A.2 Metrics that Describe Sound Levels over Time

Figure A-2 illustrates the different sound metrics that are calculated from a sound level that varies by several decibels over a period of time. A description of each metric is provided in the subsections below.

A.2.1 Maximum Sound Level (L_{max})

The variation in sound level over time often makes it convenient to describe a particular sound "event" by its maximum sound level, abbreviated as L_{max}. The maximum level describes only one dimension of an event; it provides no information on the cumulative sound exposure. In fact, two events with identical maxima may produce very different total exposures. One may be of very short duration, while the other may continue for an extended period and be judged more annoying.

A.2.2 Minimum Sound Level (L_{min})

The lowest sound level measured over a period of time is called the minimum sound level, and is abbreviated L_{min}.

A.2.3 Equivalent Sound Level (L_{eq})

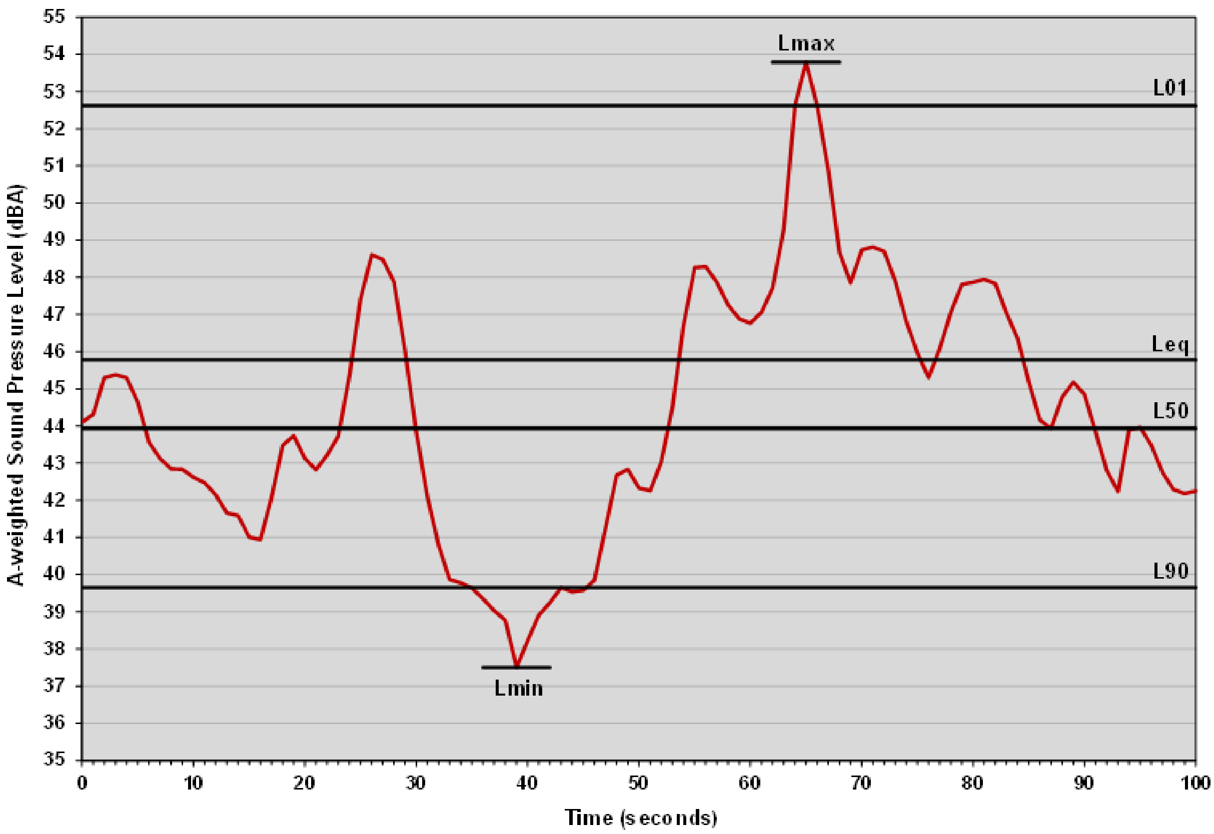
The Equivalent Sound Level, abbreviated L_{eq}, is a measure of the total exposure resulting from the accumulation of A-weighted sound levels over a particular period of interest – for example, an hour, an 8-hour school day, nighttime, or a full 24-hour day. However, because the length of the period can be different depending on the time frame of interest, the applicable period should always be identified or clearly understood when discussing the metric.

L_{eq} may be thought of as a constant sound level over the period of interest that contains as much sound energy as (is "equivalent" to) the actual time-varying sound level with its normal peaks and valleys. It is important to recognize, however, that the two signals (the constant one and the time-varying one) would sound very different from each other. Also, the "average" sound level suggested by L_{eq} is not an arithmetic value, but a logarithmic, or "energy-averaged" sound level. Thus, the loudest events may dominate the sound environment described by the metric, depending on the relative loudness of the events.

A.2.4 Statistical Sound Level Descriptors

Statistical descriptors of the time-varying sound level are often used to provide more information about how the sound level varied during the time period of interest. The descriptor includes a subscript that indicates the percentage of time the sound level is exceeded during the period. The L_{50} is an example, which represents the sound level exceeded 50 percent of the time, and equals the median sound level. Another commonly used descriptor is the L_{01}, which represents the sound level exceeded 1 percent of the measurement period and describes the sound level during the loudest portions of the period. The L_{90} is often used to describe the quieter background sound levels that occurred, since it represents the level exceeded 90 percent of the period. In Massachusetts, the Department of Environmental Protection's noise policy specifies the L_{90} metric as the appropriate sound level metric to describe the "ambient" background sound level.

Figure A-2. Sound Metric Calculations for an A-weighted Sound Level Time History



A.3 Sound Level Meter Response Time

Sound level meters have a few response times available to measure rapidly-varying sound levels, so that one can read the meter and determine sound levels reliably. The electronic response networks use "exponential" time averaging of the sound signal to provide the readings. "Slow" response is most commonly used for measurements of environmental sound, and has an averaging time of one second. "Fast" response is also commonly used; its response time is comparable to that of the human ear, and has an averaging time of 1/8 second (125 milliseconds). The sound metrics for a time-varying sound level can be quite different depending on whether a slow or fast meter response is used to establish the values.

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Appendix B Table of LAF_{max} for Each Controlled Pass-by and Graphs of LAF_{max} Vs Speed

This appendix includes a table of measured LAF_{max} values for each controlled vehicle pass-by on smooth pavement and on the rumble strips for all six sites. The end of this appendix contains several graphs that plot measured noise levels against vehicle speed.

B.1 A Note on Vehicle Speeds

During each pass-by, the test vehicle started from rest and accelerated to the nominal (target) speed. Once the nominal speed was achieved, the driver of the test vehicle engaged the cruise control to maintain (as close as possible) a constant speed while passing through the 400-foot target zone. At several sites, the speed of the vehicle also was measured by test personnel located along the wayside using a radar gun. In some cases, a single speed measurement was taken with the radar gun – usually when the test vehicle was approaching the target zone. In other cases, two speed measurements were taken with the radar gun – to capture the speed of the test vehicle throughout the 400-foot target zone. In these latter cases, an average measured speed was obtained.

The following table includes columns for the nominal speed, the measured speed (if available), and the average measured speed (if available).

Table xx Measured A-weighted maximum noise level for pass-bys on smooth pavement and on rumble strips

						Nominal		Speed Meas.	Avg Speed		LAFmax (dBA)				
Event	Start Datetime	End Datetime	Site	Vehicle	Pavement	Speed (mph)	Lane	(mph)	Meas. (mph)	Wind (mph)	17'	25'	50'	25' (Opp.)	LT-Camp
1	6/2/2017 09:20:35	6/2/2017 09:21:07	1	Altima	Smooth	40	Near				78.0	73.5	66.6	--	--
2	6/2/2017 09:21:09	6/2/2017 09:21:43	1	Altima	Smooth	40	Far			4	72.5	70.3	65.1	--	--
3	6/2/2017 09:21:56	6/2/2017 09:22:33	1	Altima	Smooth	50	Near				80.3	75.8	69.5	--	--
4	6/2/2017 09:22:34	6/2/2017 09:23:12	1	Altima	Smooth	50	Far				74.9	72.5	68.2	--	--
5	6/2/2017 09:23:19	6/2/2017 09:23:52	1	Altima	Smooth	60	Near				83.7	78.9	72.4	--	--
6	6/2/2017 09:23:55	6/2/2017 09:24:35	1	Altima	Smooth	60	Far				77.4	75.2	71.0	--	--
7	6/2/2017 09:38:09	6/2/2017 09:38:39	1	Altima	Center Rumble	40	Near				77.2	73.3	68.3	--	--
8	6/2/2017 09:38:50	6/2/2017 09:39:30	1	Altima	Center Rumble	40	Far				77.8	74.6	68.8	--	--
9	6/2/2017 09:39:39	6/2/2017 09:40:19	1	Altima	Center Rumble	50	Near			3	80.6	77.5	71.7	--	--
10	6/2/2017 09:40:24	6/2/2017 09:40:56	1	Altima	Center Rumble	50	Far				83.1	80.3	74.9	--	--
11	6/2/2017 09:41:05	6/2/2017 09:41:42	1	Altima	Center Rumble	60	Near			5-7	83.5	80.2	74.5	--	--
12	6/2/2017 09:41:46	6/2/2017 09:42:18	1	Altima	Center Rumble	60	Far				86.7	83.6	78.4	--	--
13	6/2/2017 10:07:46	6/2/2017 10:08:24	1	Altima	Center Rumble Maneuver	40	Near	41	41		76.8	73.6	67.1	--	--
14	6/2/2017 10:08:29	6/2/2017 10:09:04	1	Altima	Center Rumble Maneuver	40	Far	39	39	5	74.4	72.3	68.9	--	--
15	6/2/2017 10:09:28	6/2/2017 10:10:01	1	Altima	Center Rumble Maneuver	50	Near	50	50	8	79.1	75.5	69.9	--	--
16	6/2/2017 10:10:05	6/2/2017 10:10:41	1	Altima	Center Rumble Maneuver	50	Far	48	48	6	78.5	76.0	71.8	--	--
17	6/2/2017 10:11:02	6/2/2017 10:11:35	1	Altima	Center Rumble Maneuver	60	Near	58	58	9	80.5	77.7	73.3	--	--
18	6/2/2017 10:11:38	6/2/2017 10:12:12	1	Altima	Center Rumble Maneuver	60	Far	59	59	5	79.8	76.6	75.5	--	--
19	6/2/2017 10:35:09	6/2/2017 10:35:41	1	Mazda3	Smooth	40	Near	40	40		77.2	72.5	66.1	--	--
20	6/2/2017 10:35:43	6/2/2017 10:36:19	1	Mazda3	Smooth	40	Far	40	40		71.0	69.2	64.8	--	--
21	6/2/2017 10:36:35	6/2/2017 10:37:05	1	Mazda3	Smooth	50	Near	50	50	7	80.1	76.2	69.8	--	--
22	6/2/2017 10:37:17	6/2/2017 10:37:47	1	Mazda3	Smooth	50	Far	51	51		74.9	72.7	68.4	--	--
23	6/2/2017 10:38:08	6/2/2017 10:38:39	1	Mazda3	Smooth	60	Near	61	61	6	83.3	78.9	71.9	--	--
24	6/2/2017 10:38:46	6/2/2017 10:39:17	1	Mazda3	Smooth	60	Far	61	61		77.2	75.6	71.3	--	--
25	6/2/2017 10:51:12	6/2/2017 10:51:47	1	Mazda3	Center Rumble	40	Near	40	40	3	77.0	73.9	69.6	--	--
26	6/2/2017 10:51:59	6/2/2017 10:52:27	1	Mazda3	Center Rumble	40	Far	40	40	4	78.2	75.3	70.2	--	--
27	6/2/2017 10:52:49	6/2/2017 10:53:22	1	Mazda3	Center Rumble	50	Near	50	50	3	80.6	76.8	71.3	--	--
28	6/2/2017 10:53:36	6/2/2017 10:54:02	1	Mazda3	Center Rumble	50	Far	50	50		82.1	78.9	74.4	--	--
29	6/2/2017 10:54:20	6/2/2017 10:54:53	1	Mazda3	Center Rumble	60	Near	60	60	6	83.4	79.7	74.4	--	--
30	6/2/2017 10:55:00	6/2/2017 10:55:27	1	Mazda3	Center Rumble	60	Far	60	60	3	86.8	84.6	78.9	--	--
31	6/2/2017 12:52:35	6/2/2017 12:53:10	1.5	Altima	Smooth	40	Near	39	39		--	73.3	67.7	69.3	--
32	6/2/2017 12:53:14	6/2/2017 12:53:39	1.5	Altima	Smooth	40	Far	40	40		--	70.0	65.5	73.8	--
33	6/2/2017 12:54:07	6/2/2017 12:54:36	1.5	Altima	Smooth	50	Near	48	48	6	--	76.3	70.2	72.6	--
34	6/2/2017 12:54:46	6/2/2017 12:55:14	1.5	Altima	Smooth	50	Far	48	48		--	71.3	68.2	76.4	--
35	6/2/2017 12:55:33	6/2/2017 12:56:04	1.5	Altima	Smooth	60	Near	61	61		--	79.9	73.9	74.6	--
36	6/2/2017 12:56:11	6/2/2017 12:56:39	1.5	Altima	Smooth	60	Far	59	59		--	74.2	69.5	78.4	--
37	6/2/2017 13:10:17	6/2/2017 13:10:48	1.5	Altima	Shoulder Rumble	40	Near	40	40	4	--	74.3	67.4	67.5	--
38	6/2/2017 13:10:53	6/2/2017 13:11:34	1.5	Altima	Shoulder Rumble	40	Far	40	40		--	67.2	63.4	75.5	--
39	6/2/2017 13:11:51	6/2/2017 13:12:16	1.5	Altima	Shoulder Rumble	50	Near	50	50		--	80.0	72.3	71.4	--
40	6/2/2017 13:12:26	6/2/2017 13:12:52	1.5	Altima	Shoulder Rumble	50	Far	49	49		--	69.8	67.3	79.2	--
41	6/2/2017 13:13:16	6/2/2017 13:13:42	1.5	Altima	Shoulder Rumble	60	Near	59	59		--	82.8	75.8	74.1	--
42	6/2/2017 13:13:52	6/2/2017 13:14:23	1.5	Altima	Shoulder Rumble	60	Far	59	59		--	73.0	69.8	82.1	--
43	6/2/2017 13:25:54	6/2/2017 13:26:28	1.5	Truck	Center Rumble	40	Near	42	42		--	88.6	82.7	90.8	--
44	6/2/2017 13:26:31	6/2/2017 13:26:55	1.5	Altima	Shoulder Rumble	60	Far				--	72.7	69.1	80.1	--
45	6/2/2017 13:27:01	6/2/2017 13:27:35	1.5	Truck	Center Rumble	40	Far	42	42		--	83.4	80.3	84.0	--
46	6/2/2017 13:28:01	6/2/2017 13:28:42	1.5	Truck	Center Rumble	50	Near	52	52		--	88.3	82.3	88.4	--
47	6/2/2017 13:28:52	6/2/2017 13:29:31	1.5	Truck	Center Rumble	50	Far	52	52		--	89.2	84.1	90.1	--

Table xx Measured A-weighted maximum noise level for pass-bys on smooth pavement and on rumble strips

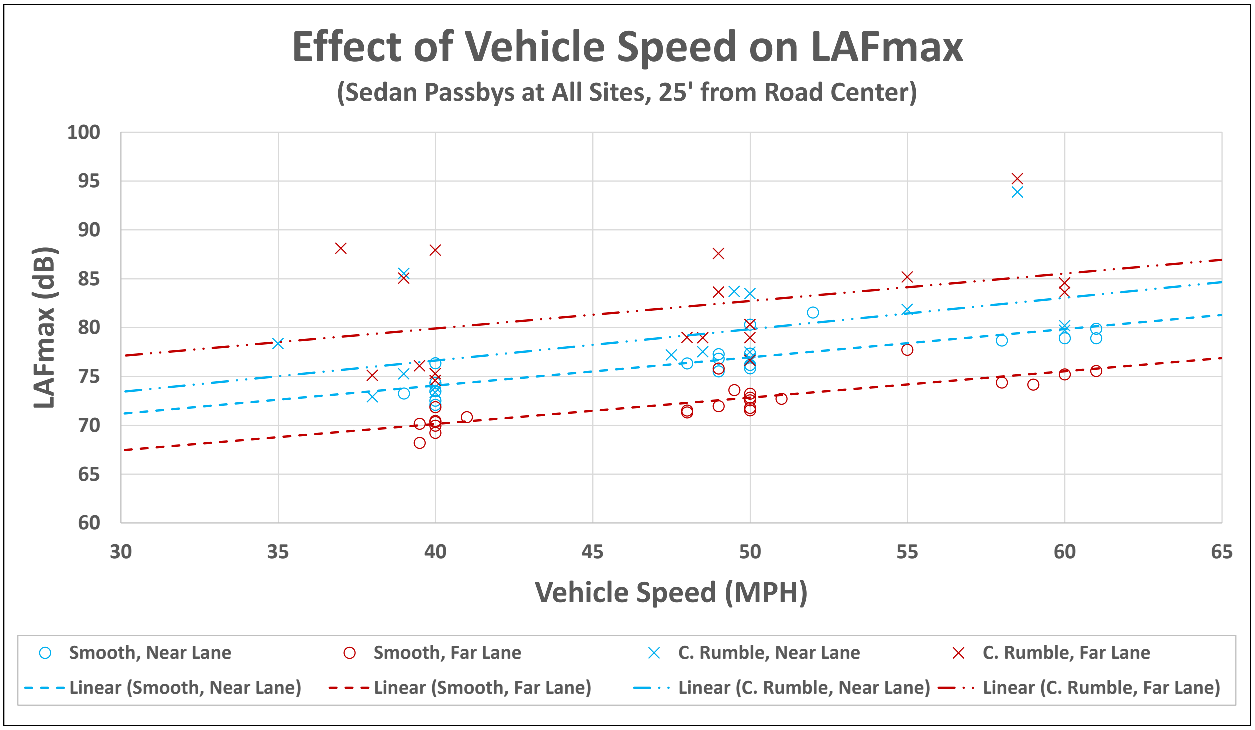
Event	Start Datetime	End Datetime	Site	Vehicle	Pavement	Nominal Speed (mph)	Lane	Speed Meas. (mph)	Avg Speed Meas. (mph)	Wind (mph)	LAFmax (dBA)				
											17'	25'	50'	25' (Opp.)	LT-Camp
48	6/2/2017 13:39:38	6/2/2017 13:40:10	1.5	Truck	Smooth	40	Near	41	41		--	82.9	76.9	79.0	--
49	6/2/2017 13:40:20	6/2/2017 13:41:01	1.5	Truck	Smooth	40	Far	43	43		--	79.7	76.1	83.8	--
50	6/2/2017 13:41:32	6/2/2017 13:42:07	1.5	Truck	Smooth	50	Near	50	50	5	--	86.0	79.1	80.6	--
51	6/2/2017 13:42:14	6/2/2017 13:42:58	1.5	Truck	Smooth	50	Far	53	53		--	82.5	78.1	87.3	--
52	6/8/2017 10:33:35	6/8/2017 10:34:03	2	Altima	Smooth	40	Near	40	40		77.8	73.3	--	69.7	--
53	6/8/2017 10:34:25	6/8/2017 10:34:57	2	Altima	Smooth	40	Far	41	41		73.4	70.8	--	74.9	--
54	6/8/2017 10:35:02	6/8/2017 10:35:31	2	Altima	Smooth	50	Near	50	50		82.4	77.3	--	73.4	--
55	6/8/2017 10:35:47	6/8/2017 10:36:16	2	Altima	Smooth	50	Far	50	50		76.1	73.2	--	77.4	--
56	6/8/2017 10:42:24	6/8/2017 10:42:50	2	Altima	Center Rumble	40	Near	40/36	38		75.9	72.9	--	73.5	--
57	6/8/2017 10:43:17	6/8/2017 10:43:44	2	Altima	Center Rumble	40	Far	40/39	39.5		78.9	76.1	--	73.9	--
58	6/8/2017 10:43:52	6/8/2017 10:44:18	2	Altima	Center Rumble	50	Near	50/47	48.5		81.8	77.5	--	80.3	--
59	6/8/2017 10:44:38	6/8/2017 10:45:03	2	Altima	Center Rumble	50	Far	50/47	48.5		82.2	78.9	--	77.4	--
60	6/8/2017 10:52:12	6/8/2017 10:52:38	2	Altima	Smooth	40	Near	40/36	38		77.9	72.9	--	69.5	--
61	6/8/2017 10:53:09	6/8/2017 10:53:36	2	Altima	Smooth	40	Far	40/39	39.5		72.8	70.1	--	74.4	--
62	6/8/2017 10:54:28	6/8/2017 10:54:52	2	Altima	Smooth	50	Near	50/48	49		75.7	73.6	--	78.6	--
63	6/8/2017 10:54:28	6/8/2017 10:54:52	2	Altima	Smooth	50	Far	50/49	49.5		75.7	73.6	--	78.6	--
64	6/8/2017 10:55:06	6/8/2017 10:55:31	2	Altima	Smooth	40	Near	40/40	40		79.0	74.3	--	70.2	--
65	6/8/2017 10:55:53	6/8/2017 10:56:22	2	Altima	Smooth	40	Far	40/40	40		72.9	70.4	--	74.9	--
66	6/8/2017 11:00:47	6/8/2017 11:01:16	2	Altima	Center Rumble	40	Near	40/38	39		78.3	75.2	--	77.8	--
67	6/8/2017 11:01:36	6/8/2017 11:02:03	2	Altima	Center Rumble	40	Far	39/37	38		77.8	75.1	--	74.2	--
68	6/8/2017 11:02:13	6/8/2017 11:02:40	2	Altima	Center Rumble	50	Near	49/45	47		78.6	75.0	--	75.7	--
69	6/8/2017 11:02:58	6/8/2017 11:03:23	2	Altima	Center Rumble	50	Far	49/47	48		82.3	79.0	--	77.3	--
70	6/8/2017 11:09:04	6/8/2017 11:09:32	2	Altima	Center Rumble Maneuver	40	Near	41/40/41	41		75.8	72.1	--	73.2	--
71	6/8/2017 11:10:04	6/8/2017 11:10:30	2	Altima	Center Rumble Maneuver	40	Far	40/37/39	39.5		76.6	73.5	--	73.1	--
72	6/8/2017 11:10:36	6/8/2017 11:11:03	2	Altima	Center Rumble Maneuver	50	Near	50/47/46	48		77.8	74.3	--	74.3	--
73	6/8/2017 11:11:23	6/8/2017 11:11:47	2	Altima	Center Rumble Maneuver	50	Far	49/46	47.5		79.0	77.3	--	76.2	--
74	6/8/2017 11:11:56	6/8/2017 11:12:21	2	Altima	Center Rumble	50	Near	50/45	47.5		81.2	77.2	--	79.5	--
75	6/8/2017 11:12:51	6/8/2017 11:13:20	2	Altima	Center Rumble Maneuver	50	Far	50/48/46	48		79.0	76.7	--	77.0	--
76	6/8/2017 11:20:23	6/8/2017 11:20:51	2	Altima	Center Rumble Maneuver	50	Near	49/48	48.5		78.3	74.9	--	76.3	--
77	6/8/2017 11:21:10	6/8/2017 11:21:38	2	Altima	Center Rumble Maneuver	50	Far	49/48	48.5		79.3	76.5	--	76.8	--
78	6/8/2017 06:42:02	6/8/2017 06:42:33	3	Altima	Smooth	40	Near				81.4	76.3	--	--	--
79	6/8/2017 06:42:52	6/8/2017 06:43:21	3	Altima	Smooth	40	Far	40	40		74.6	71.9	--	--	--
80	6/8/2017 06:43:49	6/8/2017 06:44:19	3	Altima	Smooth	50	Near	50	50		85.2	80.3	--	--	--
81	6/8/2017 06:44:39	6/8/2017 06:45:10	3	Altima	Smooth	50	Far	49	49		79.0	75.8	--	--	--
82	6/8/2017 06:54:36	6/8/2017 06:55:08	3	Altima	Center Rumble	40	Near	35	35		81.0	78.3	--	--	--
83	6/8/2017 06:55:42	6/8/2017 06:56:13	3	Altima	Center Rumble	40	Far	37	37		91.2	88.1	--	--	--
84	6/8/2017 06:56:43	6/8/2017 06:57:15	3	Altima	Center Rumble	50	Near	50	50		86.2	83.5	--	--	--
85	6/8/2017 06:57:34	6/8/2017 06:58:05	3	Altima	Center Rumble	50	Far	49	49		91.0	87.6	--	--	--
86	6/8/2017 06:58:37	6/8/2017 06:59:07	3	Altima	Center Rumble	40	Near	39	39		82.9	78.8	--	--	--
87	6/8/2017 06:59:19	6/8/2017 06:59:46	3	Altima	Center Rumble	40	Far	40	40		91.0	87.9	--	--	--
88	6/8/2017 07:07:10	6/8/2017 07:07:39	3	Altima	Center Rumble Maneuver	40	Near	41	41		84.7	80.2	--	--	--
89	6/8/2017 07:07:58	6/8/2017 07:08:26	3	Altima	Center Rumble Maneuver	40	Far	39	39		86.4	83.6	--	--	--
90	6/8/2017 07:09:43	6/8/2017 07:10:11	3	Altima	Center Rumble Maneuver	50	Near	50	50		86.4	84.8	--	--	--
91	6/8/2017 07:10:47	6/8/2017 07:11:06	3	Altima	Center Rumble Maneuver	50	Far	49	49		69.9	66.1	--	--	--
92	6/9/2017 07:01:18	6/9/2017 07:01:42	4	Altima	Smooth	40	Near	40/40	40		76.6	72.1	--	--	47.7
93	6/9/2017 07:01:48	6/9/2017 07:02:18	4	Altima	Smooth	40	Far	41/38	39.5		70.6	68.2	--	--	46.3
94	6/9/2017 07:02:28	6/9/2017 07:02:53	4	Altima	Smooth	50	Near	49/49	49		80.4	75.5	--	--	44.2

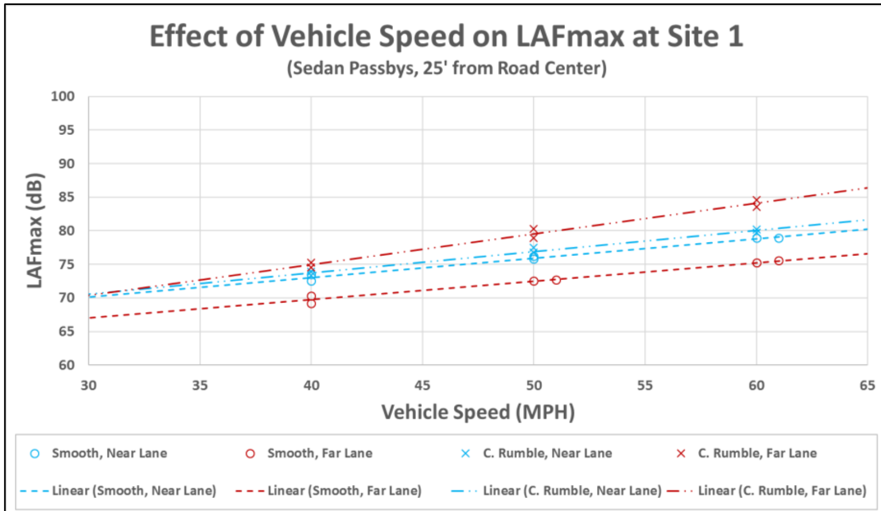
Table xx Measured A-weighted maximum noise level for pass-bys on smooth pavement and on rumble strips

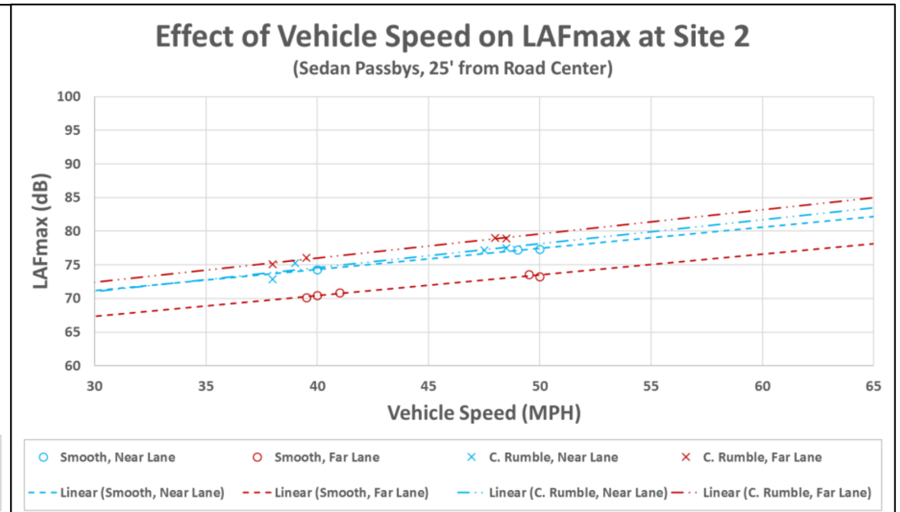
Event	Start Datetime	End Datetime	Site	Vehicle	Pavement	Nominal Speed (mph)	Lane	Speed Meas. (mph)	Avg Speed Meas. (mph)	Wind (mph)	LAFmax (dBA) 17'	25'	50'	25' (Opp.)	LT-Camp
95	6/9/2017 07:02:58	6/9/2017 07:03:27	4	Altima	Smooth	50	Far	48/48	48		74.0	71.5	--	--	46.1
96	6/9/2017 07:03:36	6/9/2017 07:04:05	4	Altima	Smooth	60	Near	56/56	56		81.2	76.4	--	--	42.1
97	6/9/2017 07:04:15	6/9/2017 07:04:45	4	Altima	Smooth	60	Far	58/58	58		76.8	74.4	--	--	46.4
98	6/9/2017 07:04:57	6/9/2017 07:05:26	4	Altima	Smooth	60	Near	57/58	57.5		81.9	76.9	--	--	43.4
99	6/9/2017 07:05:57	6/9/2017 07:06:23	4	Altima	Smooth	50	Far	50/50	50		74.7	72.8	--	--	42.3
100	6/9/2017 07:10:04	6/9/2017 07:10:32	4	Altima	Smooth	60	Near	57/59	58		83.3	78.7	--	--	54.2
101	6/9/2017 07:10:59	6/9/2017 07:11:24	4	Altima	Smooth	50	Far	50/50	50		74.0	71.5	--	--	46.4
102	6/9/2017 07:11:44	6/9/2017 07:12:09	4	Altima	Center Rumble	40	Near	39/39	39		88.7	85.5	--	--	47.7
103	6/9/2017 07:12:20	6/9/2017 07:12:46	4	Altima	Center Rumble	40	Far	40/38	39		87.3	85.1	--	--	46.1
104	6/9/2017 07:12:53	6/9/2017 07:13:21	4	Altima	Center Rumble	50	Near	50/49	49.5		87.1	83.7	--	--	47.8
105	6/9/2017 07:13:38	6/9/2017 07:14:06	4	Altima	Center Rumble	50	Far	**80/48**	64		86.9	83.6	--	--	48.2
106	6/9/2017 07:14:22	6/9/2017 07:14:48	4	Altima	Center Rumble	60	Near	59/58	58.5		96.9	93.9	--	--	52.8
107	6/9/2017 07:14:56	6/9/2017 07:15:30	4	Altima	Center Rumble	60	Far	59/58	58.5		98.1	95.2	--	--	49.6
108	6/9/2017 07:20:26	6/9/2017 07:20:52	4	Altima	Center Rumble Maneuver	40	Near	40/39	39.5		72.6	71.7	--	--	50.8
109	6/9/2017 07:20:58	6/9/2017 07:21:31	4	Altima	Center Rumble Maneuver	40	Far	40/41	40.5		79.5	74.4	--	--	45.8
110	6/9/2017 07:21:46	6/9/2017 07:22:15	4	Altima	Center Rumble Maneuver	50	Near	49/48	48.5		75.4	73.9	--	--	45.1
111	6/9/2017 07:22:23	6/9/2017 07:23:00	4	Altima	Center Rumble Maneuver	50	Far	50/49	49.5		80.7	76.6	--	--	48.5
112	6/9/2017 07:23:09	6/9/2017 07:23:43	4	Altima	Center Rumble Maneuver	60	Near	59/58	58.5		83.2	83.3	--	--	53.3
113	6/9/2017 07:23:51	6/9/2017 07:24:28	4	Altima	Center Rumble Maneuver	60	Far	59/58	58.5		92.7	89.5	--	--	50.2
114	6/9/2017 07:38:19	6/9/2017 07:38:58	4	Truck	Smooth	40	Near	40/39	39.5		90.3	86.0	--	--	50.5
115	6/9/2017 07:39:09	6/9/2017 07:40:03	4	Truck	Smooth	40	Far	41/40	40.5		83.4	81.9	--	--	57.1
116	6/9/2017 07:40:44	6/9/2017 07:41:40	4	Truck	Smooth	50	Near	49/50	49.5		95.1	90.1	--	--	59.4
117	6/9/2017 07:41:55	6/9/2017 07:42:53	4	Truck	Smooth	50	Far	50/49	49.5		88.4	85.5	--	--	53.2
118	6/9/2017 07:43:36	6/9/2017 07:44:28	4	Truck	Smooth	60	Near	52/56	54		96.4	91.4	--	--	60.1
119	6/9/2017 07:44:40	6/9/2017 07:45:37	4	Truck	Smooth	60	Far	60/60	60		89.4	87.2	--	--	55.2
120	6/9/2017 07:46:25	6/9/2017 07:47:04	4	Truck	Smooth	60	Near	53/57	55		95.0	90.3	--	--	56.9
121	6/9/2017 07:49:04	6/9/2017 07:50:05	4	Truck	Smooth	60	Near	55/58	56.5		95.8	91.2	--	--	63.0
122	6/9/2017 07:57:43	6/9/2017 07:58:28	4	Truck	Center Rumble	40	Far	41/41	41		91.6	89.0	--	--	54.2
123	6/9/2017 07:59:12	6/9/2017 08:00:03	4	Truck	Center Rumble	40	Near	40/41	40.5		92.7	89.2	--	--	49.2
124	6/9/2017 08:00:17	6/9/2017 08:01:14	4	Truck	Center Rumble	50	Far	49/49	49		95.0	92.0	--	--	54.9
125	6/9/2017 08:01:50	6/9/2017 08:02:48	4	Truck	Center Rumble	50	Near	49/49	49		93.5	90.1	--	--	59.9
126	6/9/2017 08:03:02	6/9/2017 08:03:51	4	Truck	Center Rumble	60	Far	58/57	57.5		97.8	95.2	--	--	55.2
127	6/9/2017 08:05:41	6/9/2017 08:06:27	4	Truck	Center Rumble	55	Near	54/57	55.5		96.4	91.8	--	--	56.7
128	6/9/2017 08:11:17	6/9/2017 08:12:24	4	Truck	Center Rumble Maneuver	40	Far	40/41	40.5		93.7	89.9	--	--	53.9
129	6/9/2017 08:13:05	6/9/2017 08:14:01	4	Truck	Center Rumble Maneuver	40	Near	39/38	38.5		82.5	79.7	--	--	56.7
130	6/9/2017 08:14:15	6/9/2017 08:15:11	4	Truck	Center Rumble Maneuver	50	Far	49/47	48		91.0	87.8	--	--	55.4
131	6/9/2017 08:15:55	6/9/2017 08:16:51	4	Truck	Center Rumble Maneuver	50	Near	49/47	48		87.9	85.8	--	--	61.1
132	6/9/2017 08:17:09	6/9/2017 08:17:57	4	Truck	Center Rumble Maneuver	60	Far	60/60	60		96.3	91.9	--	--	55.8
133	6/9/2017 08:18:53	6/9/2017 08:19:47	4	Truck	Center Rumble Maneuver	55	Near	55/58	56.5		90.3	87.5	--	--	64.9
134	6/1/2017 09:28:19	6/1/2017 09:28:49	5	Altima	Smooth	55	Far				80.8	77.7	--	--	--
135	6/1/2017 09:29:35	6/1/2017 09:30:15	5	Altima	Smooth	55	Near	52	52		87.2	81.5	--	--	--
136	6/1/2017 09:34:22	6/1/2017 09:34:56	5	Altima	Center Rumble	55	Far				88.6	85.2	--	--	--
137	6/1/2017 09:35:34	6/1/2017 09:36:11	5	Altima	Center Rumble	55	Near	55	55		85.7	81.9	--	--	--
138	6/1/2017 09:39:20	6/1/2017 09:39:53	5	Altima	Smooth	55	Far				87.1	82.9	--	--	--
139	6/1/2017 13:47:00	6/1/2017 13:47:34	6	Altima	Smooth	50	Far				74.2	71.8	--	--	--
140	6/1/2017 13:47:51	6/1/2017 13:48:32	6	Altima	Smooth	50	Near	49	49	7	81.3	76.8	--	--	--
141	6/1/2017 13:48:31	6/1/2017 13:49:03	6	Altima	Center Rumble	50	Far			7	79.4	76.6	--	--	--

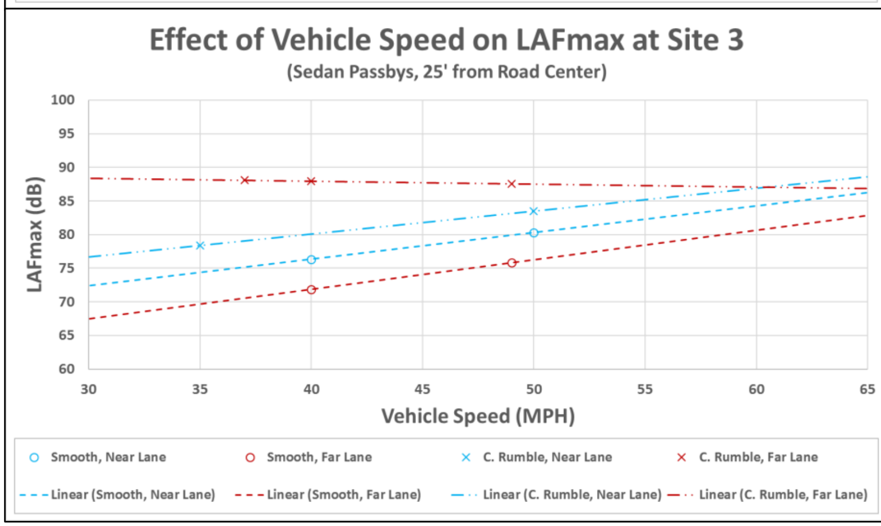
Table xx Measured A-weighted maximum noise level for pass-bys on smooth pavement and on rumble strips

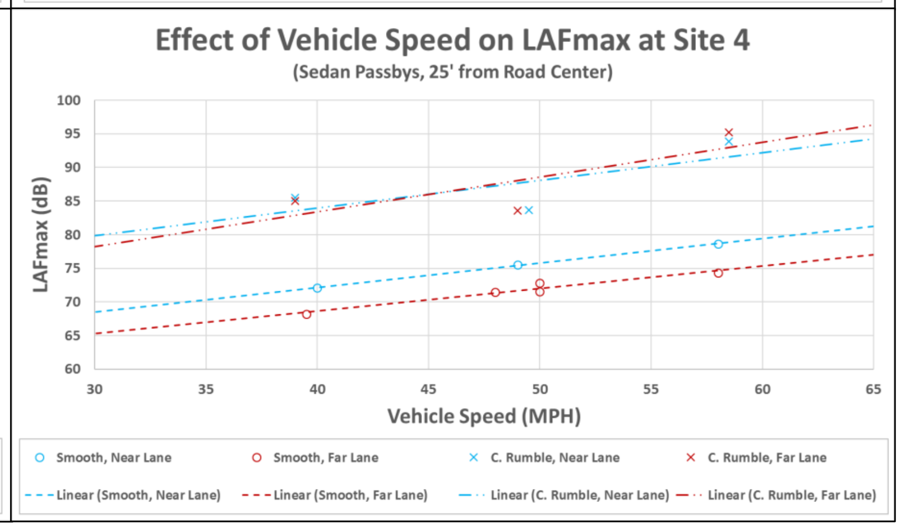
Event	Start Datetime	End Datetime	Site	Vehicle	Pavement	Nominal Speed (mph)	Lane	Speed Meas. (mph)	Avg Speed Meas. (mph)	Wind (mph)	LAFmax (dBA) 17'	25'	50'	25' (Opp.)	LT-Camp
142	6/1/2017 13:49:30	6/1/2017 13:49:56	6	Altima	Center Rumble	50	Near	50	50		79.9	76.8	--	--	--
143	6/1/2017 14:00:31	6/1/2017 14:01:01	6	Altima	Center Rumble	50	Near	50	50		79.9	76.6	--	--	--
144	6/1/2017 14:01:12	6/1/2017 14:01:37	6	Altima	Smooth	50	Far	49	49		74.1	71.9	--	--	--


Effect of Vehicle Speed on LAFmax
(Sedan Passbys at All Sites, 25' from Road Center)
LAFmax (dB)
100
95
90
85
80
75
70
65
60
30
35
40
45
50
55
60
65
Vehicle Speed (MPH)
Smooth, Near Lane
Smooth, Far Lane
C. Rumble, Near Lane
C. Rumble, Far Lane
Linear (Smooth, Near Lane)
Linear (Smooth, Far Lane)
Linear (C. Rumble, Near Lane)
Linear (C. Rumble, Far Lane)


Effect of Vehicle Speed on LAFmax at Site 1
(Sedan Passbys, 25' from Road Center)
LAFmax (dB)
Vehicle Speed (MPH)
Smooth, Near Lane
Smooth, Far Lane
C. Rumble, Near Lane
C. Rumble, Far Lane
Linear (Smooth, Near Lane)
Linear (Smooth, Far Lane)
Linear (C. Rumble, Near Lane)
Linear (C. Rumble, Far Lane)


Effect of Vehicle Speed on LAFmax at Site 2
(Sedan Passbys, 25' from Road Center)
LAFmax (dB)
Vehicle Speed (MPH)
Smooth, Near Lane
Smooth, Far Lane
C. Rumble, Near Lane
C. Rumble, Far Lane
Linear (Smooth, Near Lane)
Linear (Smooth, Far Lane)
Linear (C. Rumble, Near Lane)
Linear (C. Rumble, Far Lane)


Effect of Vehicle Speed on LAFmax at Site 3
(Sedan Passbys, 25' from Road Center)
LAFmax (dB)
Vehicle Speed (MPH)
Smooth, Near Lane
Smooth, Far Lane
C. Rumble, Near Lane
C. Rumble, Far Lane
Linear (Smooth, Near Lane)
Linear (Smooth, Far Lane)
Linear (C. Rumble, Near Lane)
Linear (C. Rumble, Far Lane)


Effect of Vehicle Speed on LAFmax at Site 4
(Sedan Passbys, 25' from Road Center)
LAFmax (dB)
Vehicle Speed (MPH)
Smooth, Near Lane
Smooth, Far Lane
C. Rumble, Near Lane
C. Rumble, Far Lane
Linear (Smooth, Near Lane)
Linear (Smooth, Far Lane)
Linear (C. Rumble, Near Lane)
Linear (C. Rumble, Far Lane)

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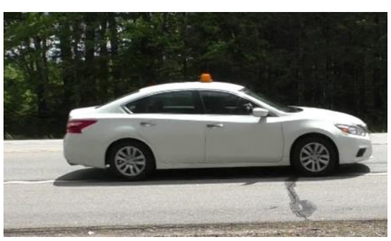
Appendix C Site Photographs, Pass-by Spectra and Spectrograms

This appendix provides photographs taken at each measurements site, as well as graphs of noise level spectra in 1/3 octave bands for the controlled vehicle pass-bys on both smooth pavement and the rumble strips. The spectra were obtained at the time of the A-weighted maximum noise level (fast response), or LAF_{max}, of the pass-by. Note that the legend of each chart includes symbols for all of the possible wayside microphone positions that were used in this study. In most cases, a certain microphone might not have been used. For example, at Site 1 wayside noise measurements were made at distances of 17 feet, 25 feet, and 50 feet from the centerline of the roadway. There was no 25-foot microphone on the opposite side of the roadway at Site 1 – even though the chart legend includes that label.

To assist the reader, a cross section of the measurement site appears below each set of charts to show the locations of the wayside microphones that were used. The cross section also shows the height above grade level (AGL) for each microphone, where the reference grade level is the elevation of the roadway. Note that the cross sections are not an accurate portrayal of the topographic features of the measurement sites.

In the following charts, “Auto” is a 2017 Nissan Altima and “Auto (CSN)” is a 2014 Mazda3. The following table provides some physical characteristics of the vehicles used for the controlled pass-bys. This table is provided for informational purposes.

Vehicle	Curb weight (lbs)	Wheel Base (in.)	Track Width (in.)
2017 Nissan Altima	3,197 to 3,462	109.3	62.4
2014 Mazda3	2,781	106.3	57.3 (rear) 61.2 (front)
NHDOT Dump Truck			


2017 Nissan Altima

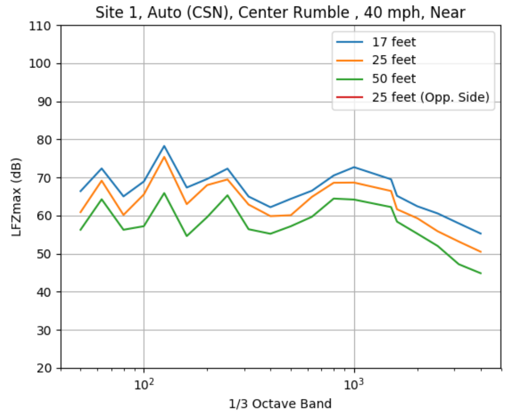

2014 Mazda3

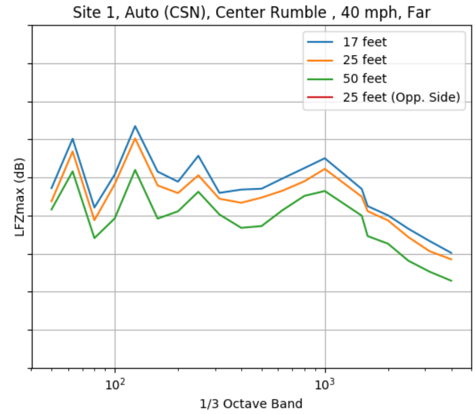

NHDOT truck

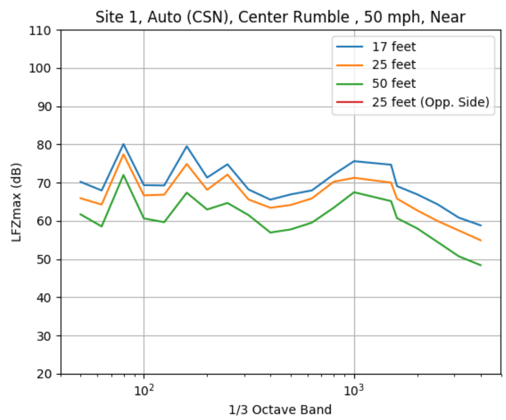
C.1 Site 1: NH Route 111, Danville (Centerline Rumble Strips)

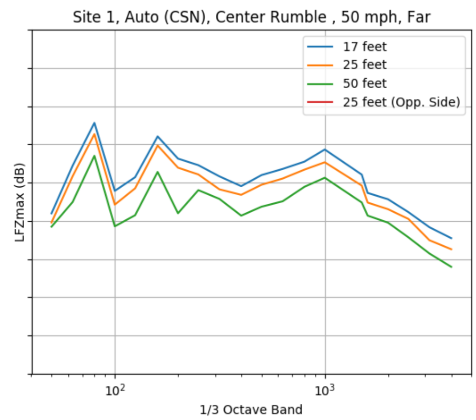
Site 1 – Microphone locations along southbound lane (near lane)

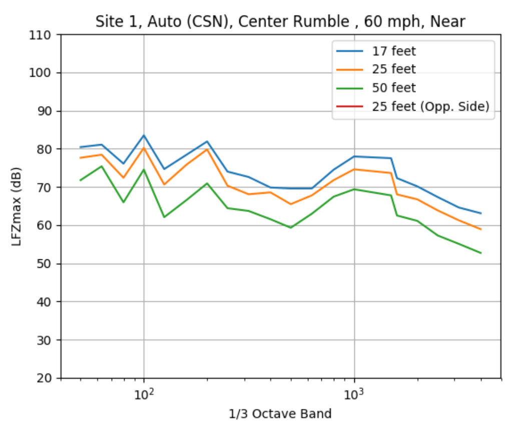
Site 1 – centerline rumble strip

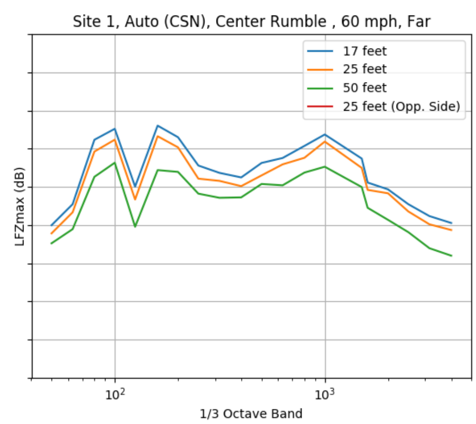

Site 1, Auto (CSN), Center Rumble , 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

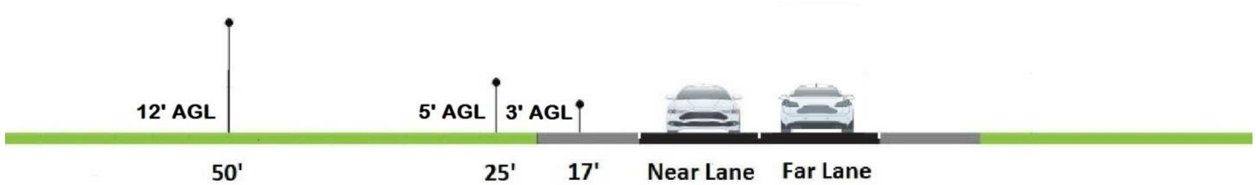

Site 1, Auto (CSN), Center Rumble , 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

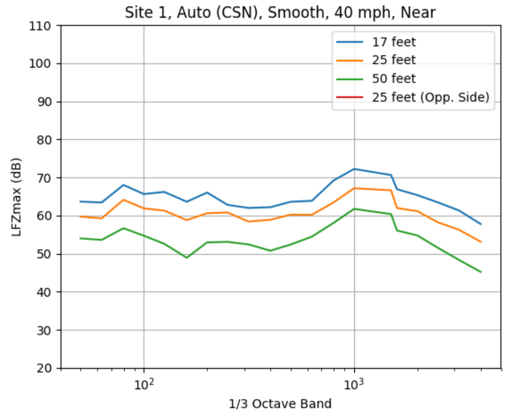

Site 1, Auto (CSN), Center Rumble , 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

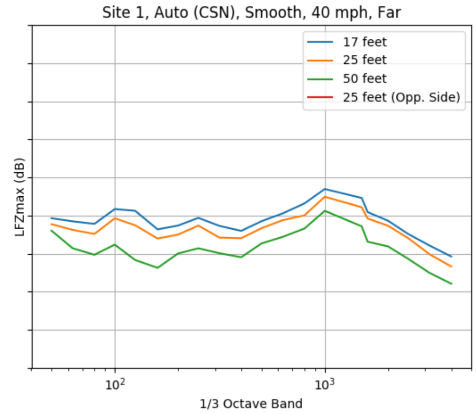

Site 1, Auto (CSN), Center Rumble , 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

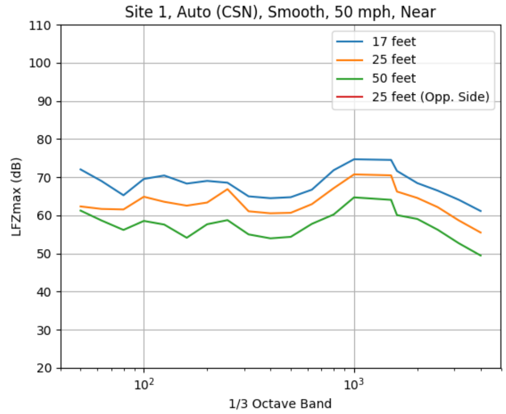

Site 1, Auto (CSN), Center Rumble , 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

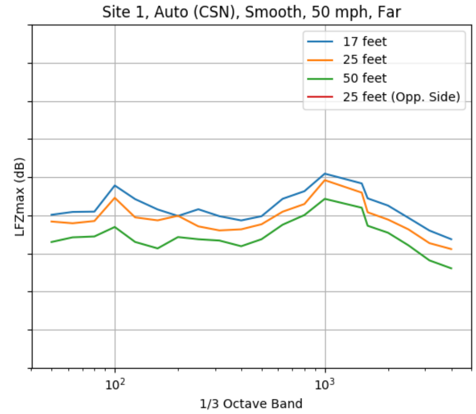

Site 1, Auto (CSN), Center Rumble , 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

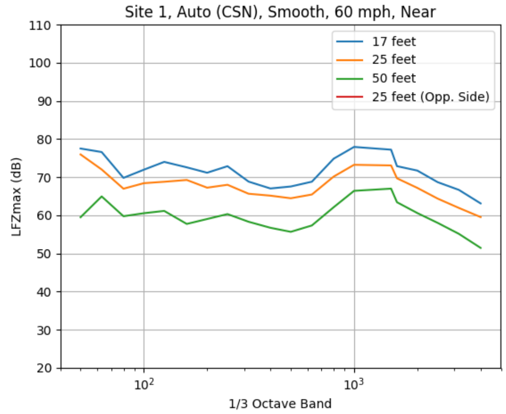

12' AGL
5' AGL
3' AGL
50'
25'
17'
Near Lane
Far Lane

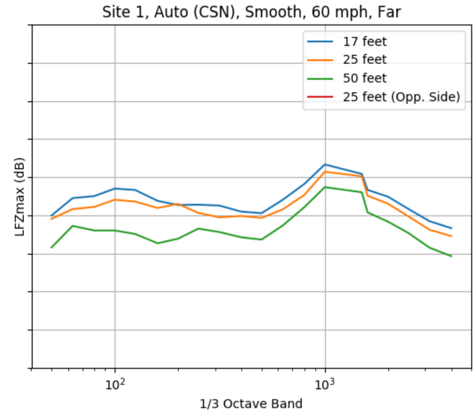

Site 1, Auto (CSN), Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

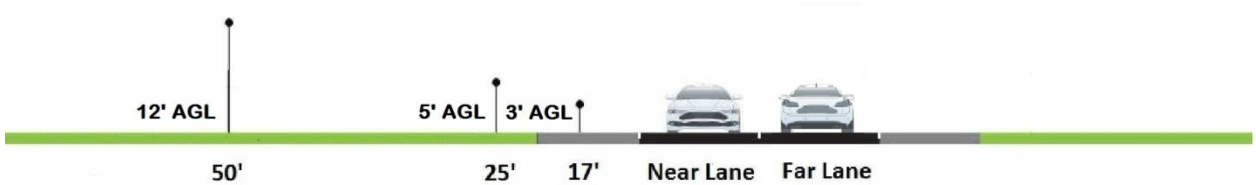

Site 1, Auto (CSN), Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

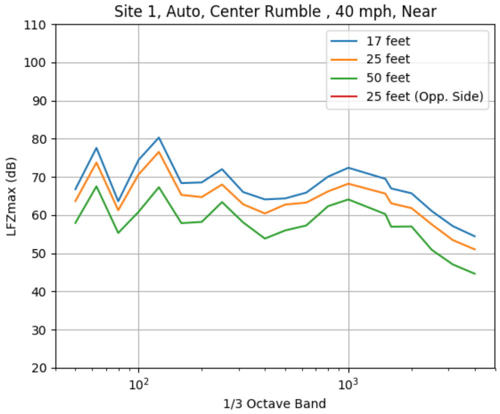

Site 1, Auto (CSN), Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

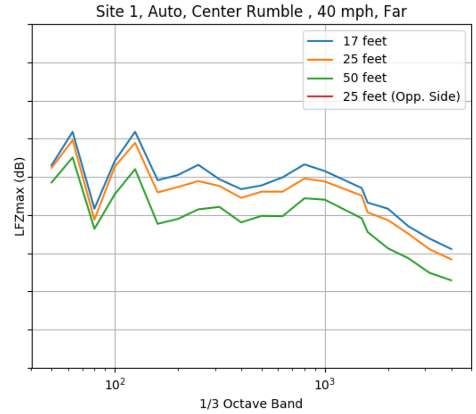

Site 1, Auto (CSN), Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

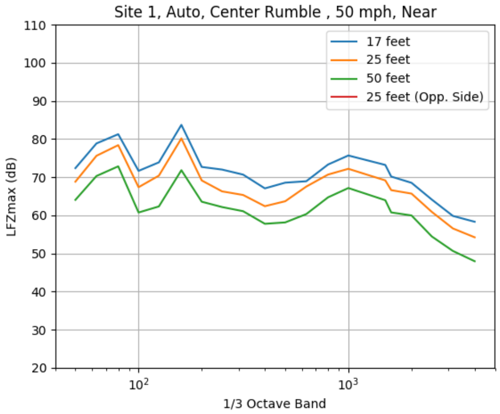

Site 1, Auto (CSN), Smooth, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

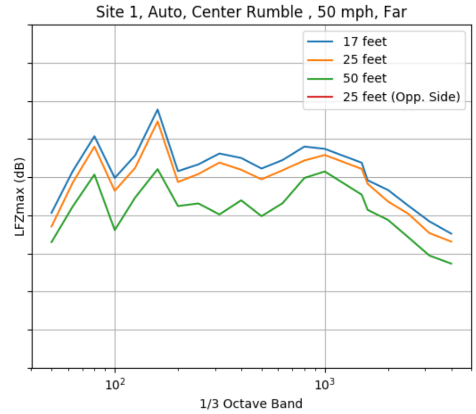

Site 1, Auto (CSN), Smooth, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

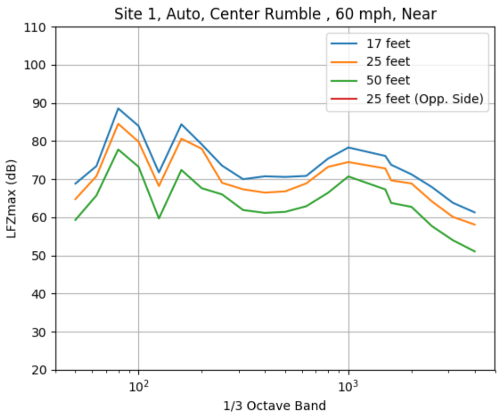

12' AGL
5' AGL
3' AGL
50'
25'
17'
Near Lane
Far Lane

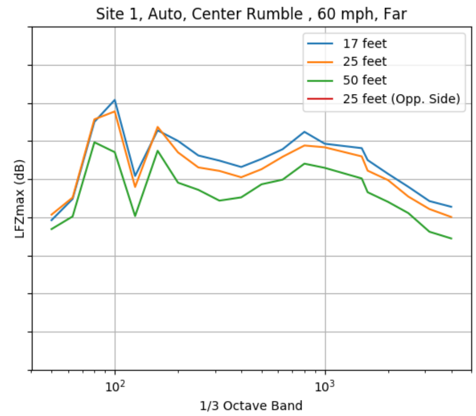

Site 1, Auto, Center Rumble , 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

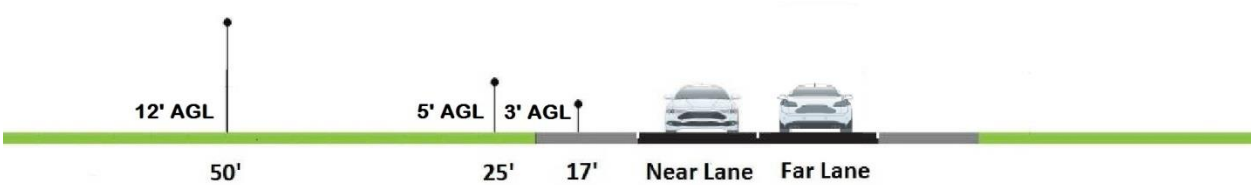

Site 1, Auto, Center Rumble , 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

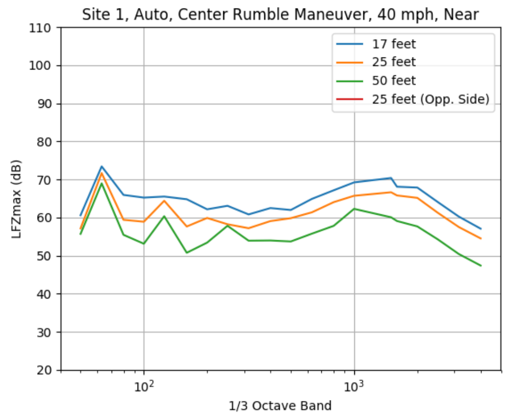

Site 1, Auto, Center Rumble , 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

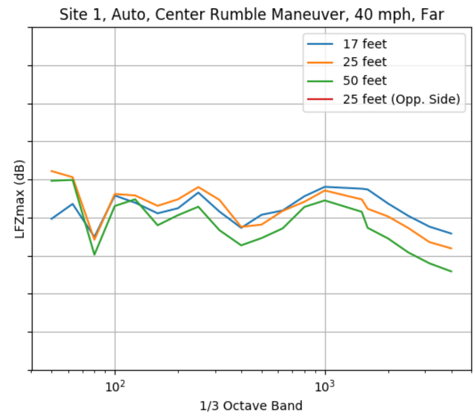

Site 1, Auto, Center Rumble , 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

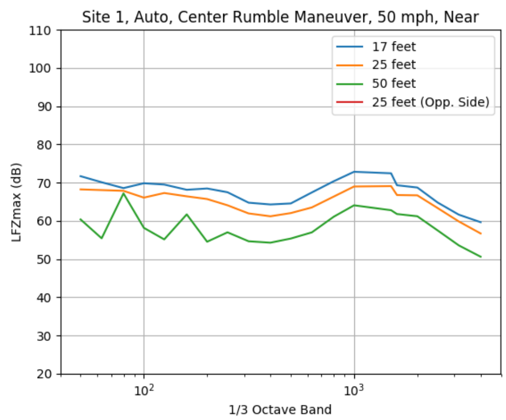

Site 1, Auto, Center Rumble , 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

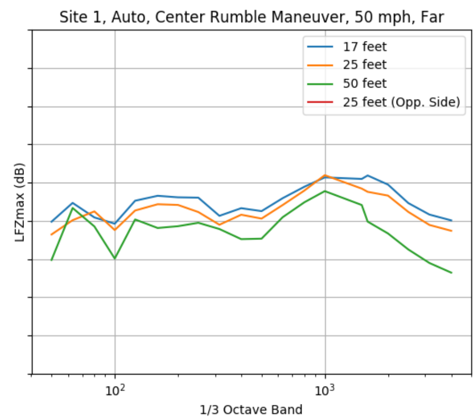

Site 1, Auto, Center Rumble , 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

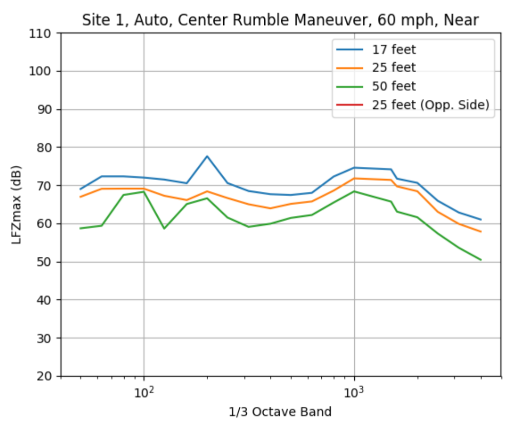

12' AGL
5' AGL
3' AGL
50'
25'
17'
Near Lane
Far Lane

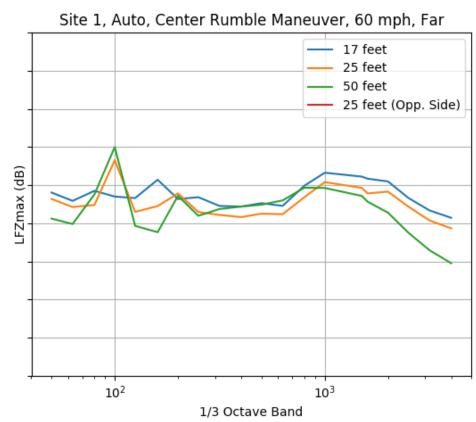

Site 1, Auto, Center Rumble Maneuver, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

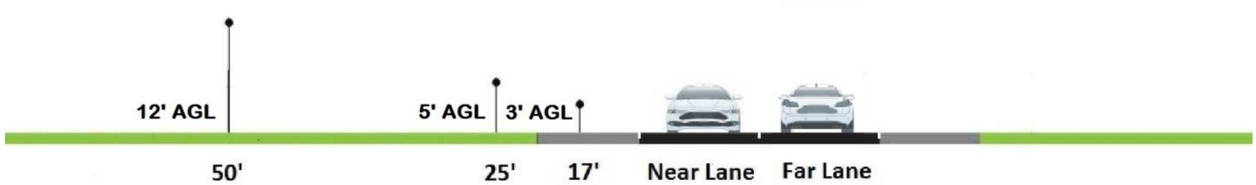

Site 1, Auto, Center Rumble Maneuver, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

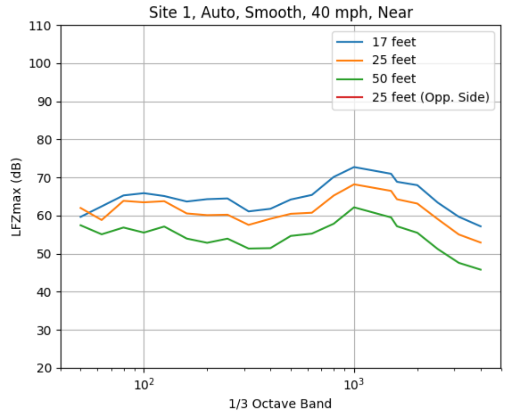

Site 1, Auto, Center Rumble Maneuver, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

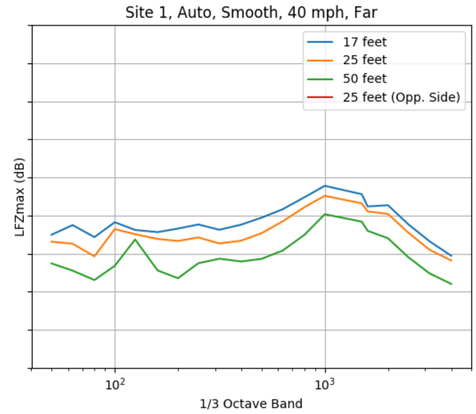

Site 1, Auto, Center Rumble Maneuver, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

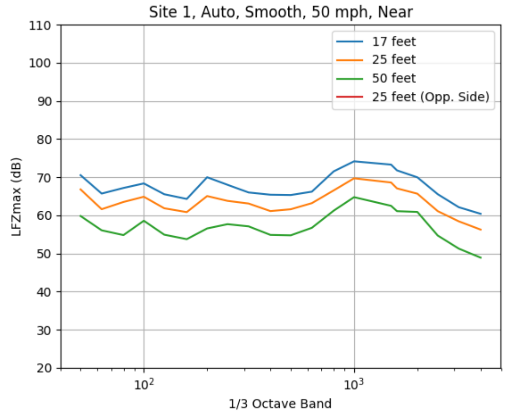

Site 1, Auto, Center Rumble Maneuver, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

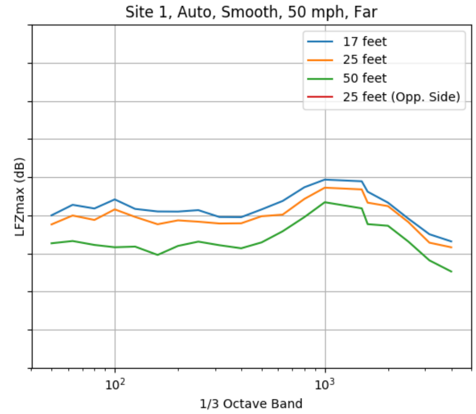

Site 1, Auto, Center Rumble Maneuver, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

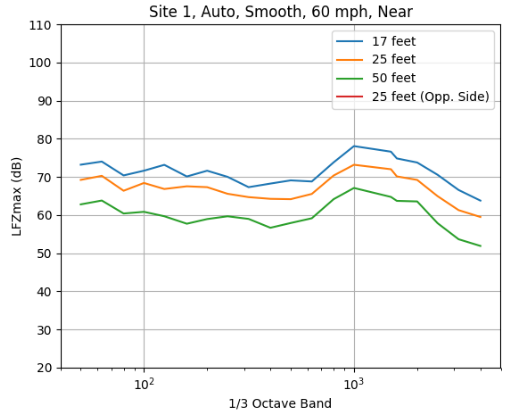

12' AGL
5' AGL
3' AGL
50'
25'
17'
Near Lane
Far Lane

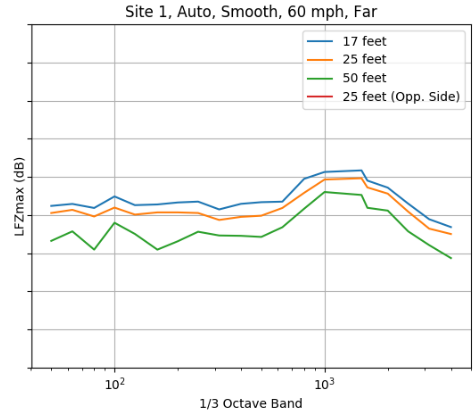

Site 1, Auto, Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

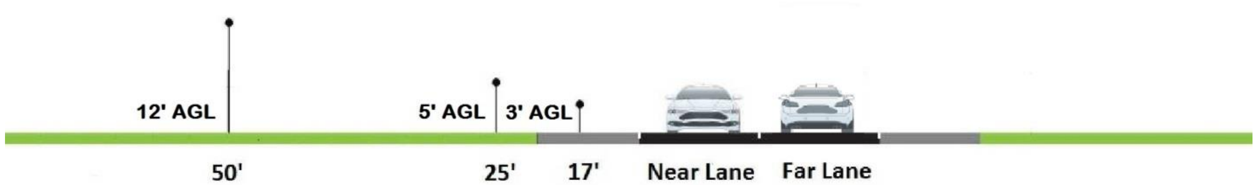

Site 1, Auto, Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 1, Auto, Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 1, Auto, Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 1, Auto, Smooth, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

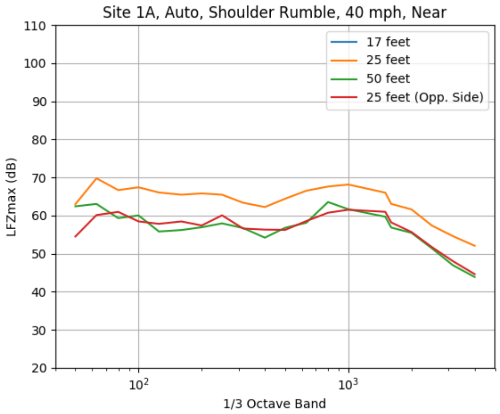

Site 1, Auto, Smooth, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

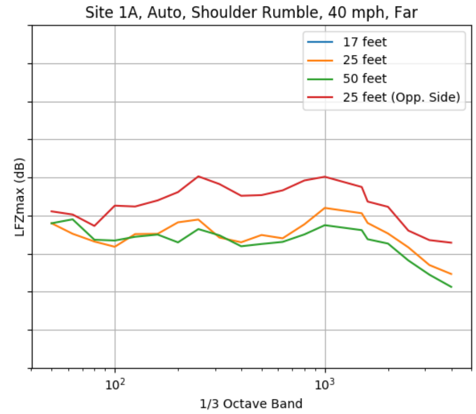

12' AGL
5' AGL
3' AGL
50'
25'
17'
Near Lane
Far Lane

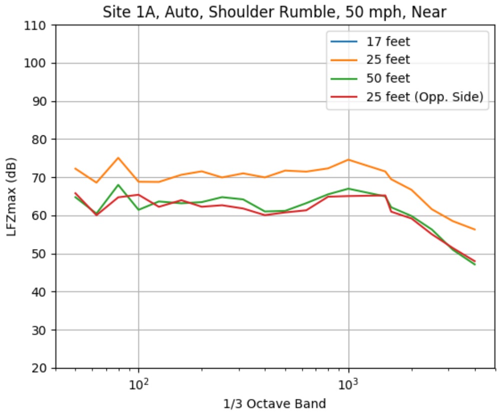
C.2 Site 1A: NH Route 111, Danville (Shoulder Rumble Stripes)

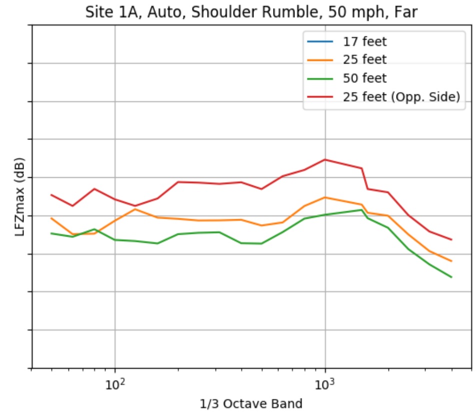

Site 1A – 25-foot (opposite) microphone location

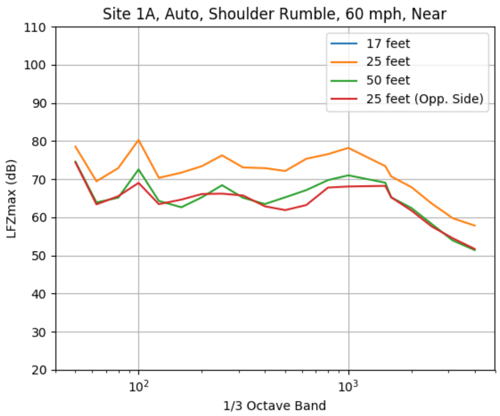

Site 1A – shoulder rumble stripe along near lane (southbound side)

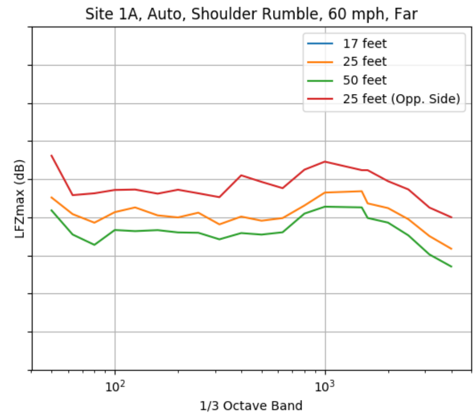

Site 1A, Auto, Shoulder Rumble, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

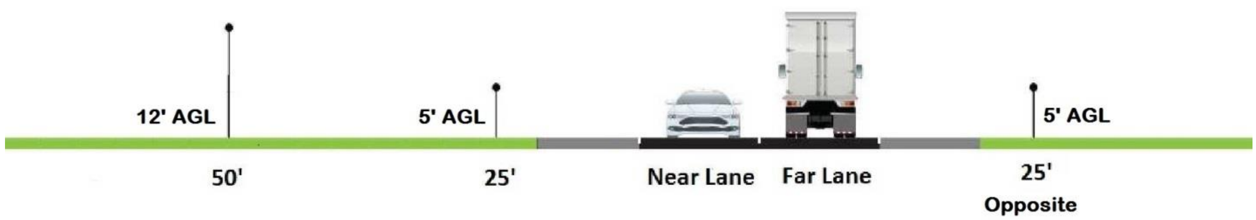

Site 1A, Auto, Shoulder Rumble, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

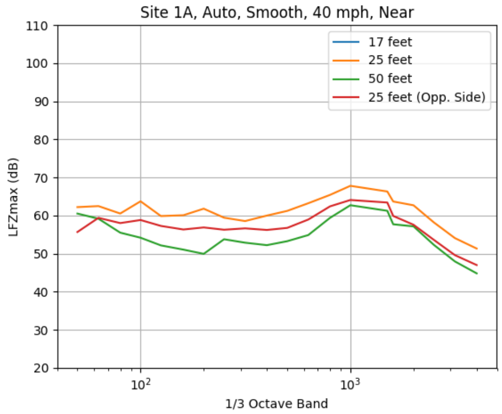

Site 1A, Auto, Shoulder Rumble, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

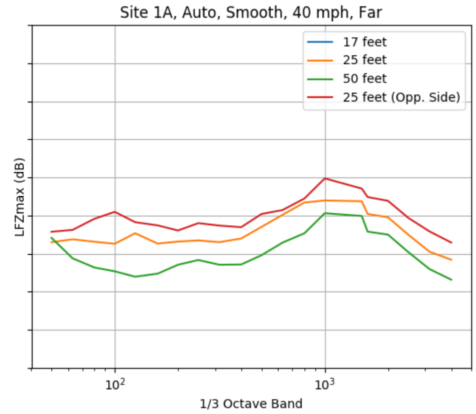

Site 1A, Auto, Shoulder Rumble, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

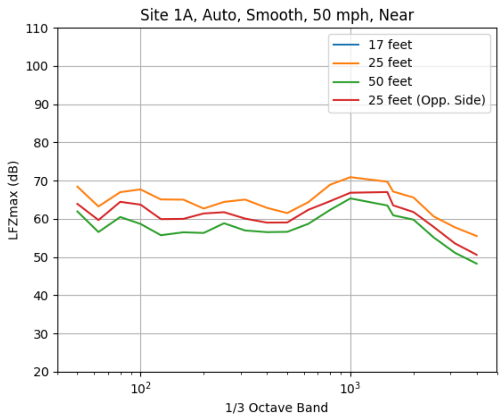

Site 1A, Auto, Shoulder Rumble, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

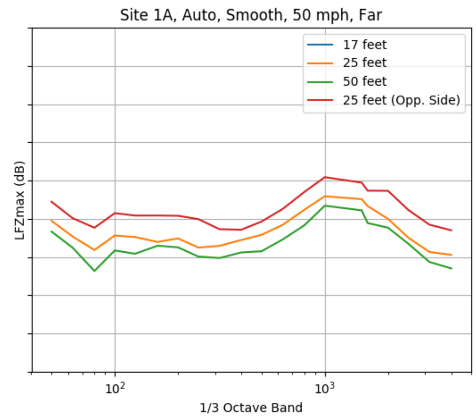

Site 1A, Auto, Shoulder Rumble, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

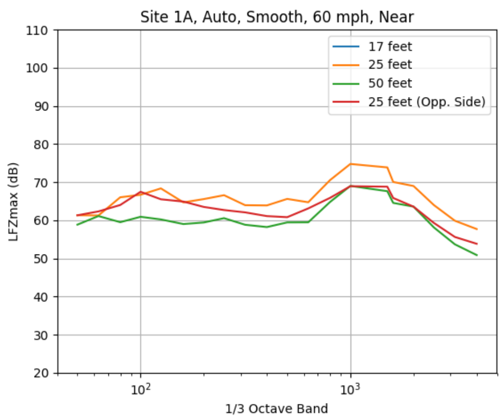

12' AGL
5' AGL
5' AGL
50'
25'
Near Lane
Far Lane
25'
Opposite

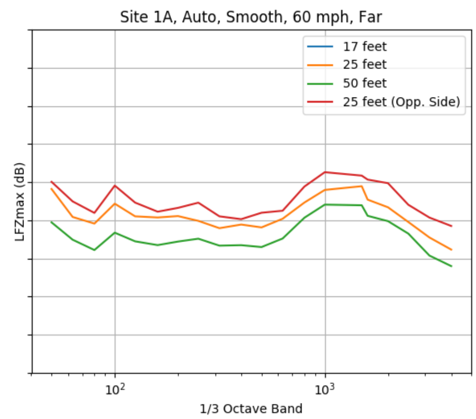

Site 1A, Auto, Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

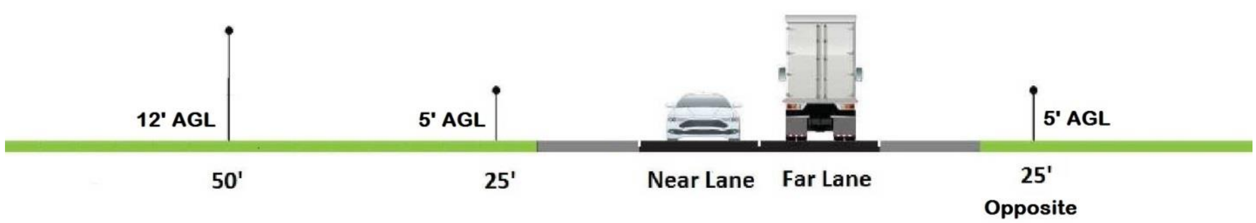

Site 1A, Auto, Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

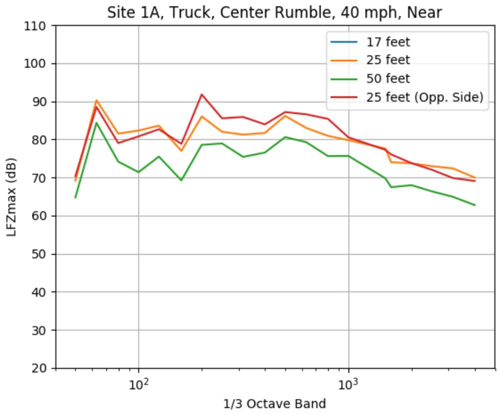

Site 1A, Auto, Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

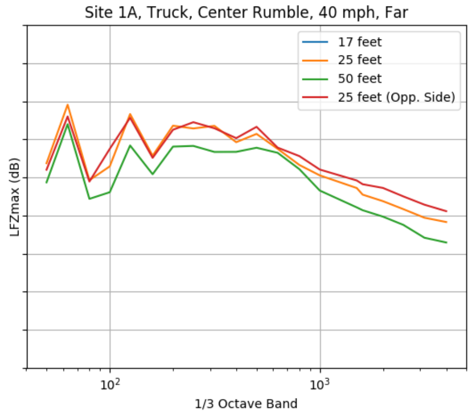

Site 1A, Auto, Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

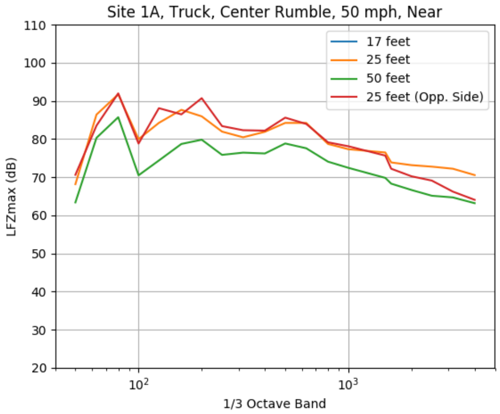

Site 1A, Auto, Smooth, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

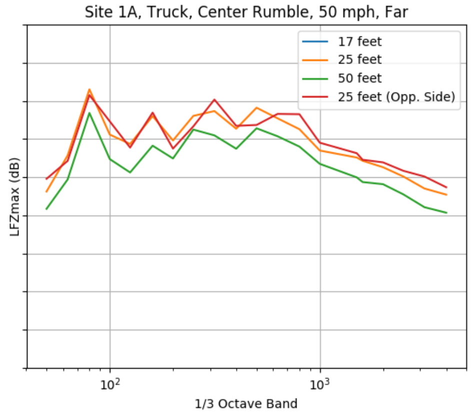

Site 1A, Auto, Smooth, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

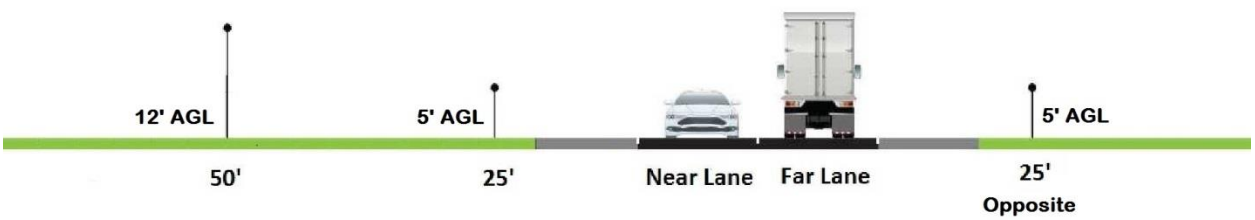

12' AGL
5' AGL
5' AGL
50'
25'
Near Lane
Far Lane
25'
Opposite

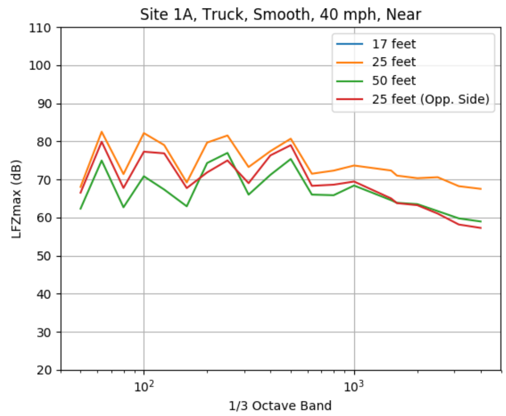

Site 1A, Truck, Center Rumble, 40 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

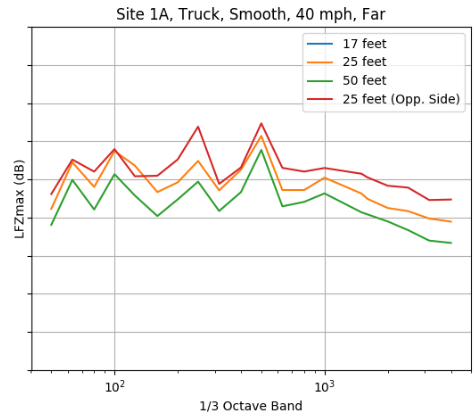

Site 1A, Truck, Center Rumble, 40 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

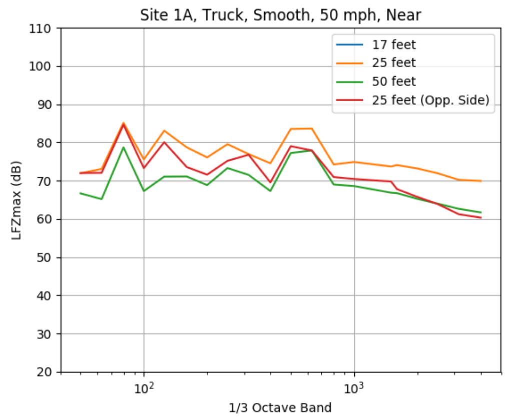

Site 1A, Truck, Center Rumble, 50 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

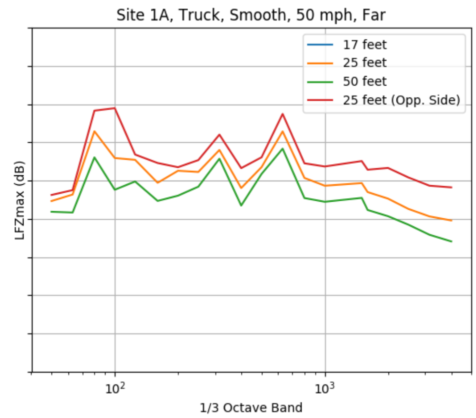

Site 1A, Truck, Center Rumble, 50 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)


12' AGL
5' AGL
5' AGL
50'
25'
Near Lane
Far Lane
25'
Opposite


Site 1A, Truck, Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

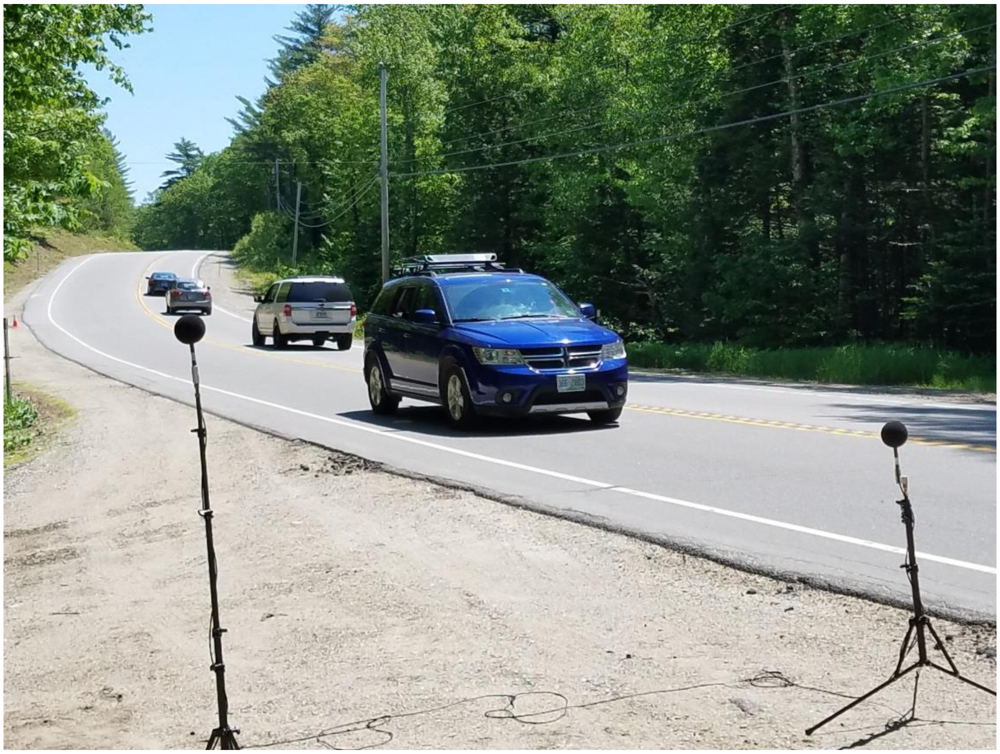

Site 1A, Truck, Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 1A, Truck, Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

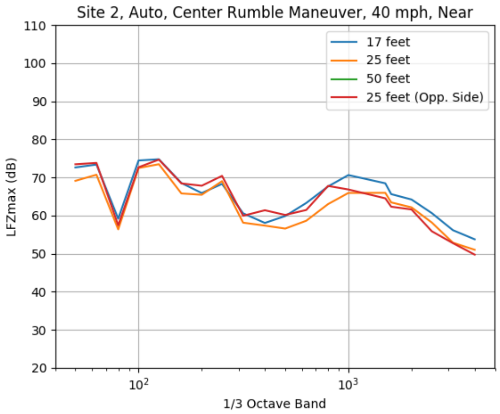

Site 1A, Truck, Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

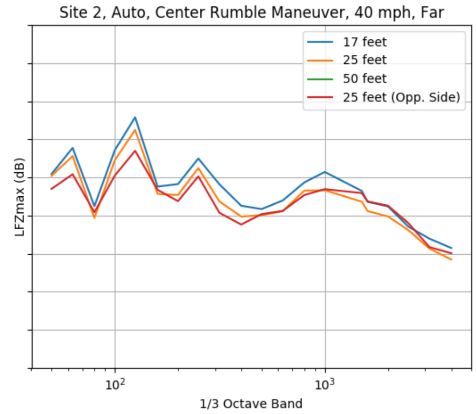

12' AGL
5' AGL
5' AGL
50'
25'
Near Lane
Far Lane
25'
Opposite

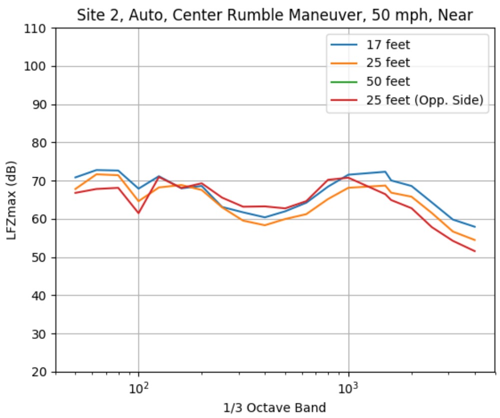
C.3 Site 2: NH Route 16, Madison

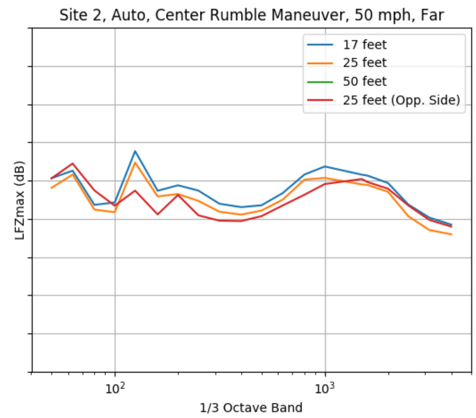


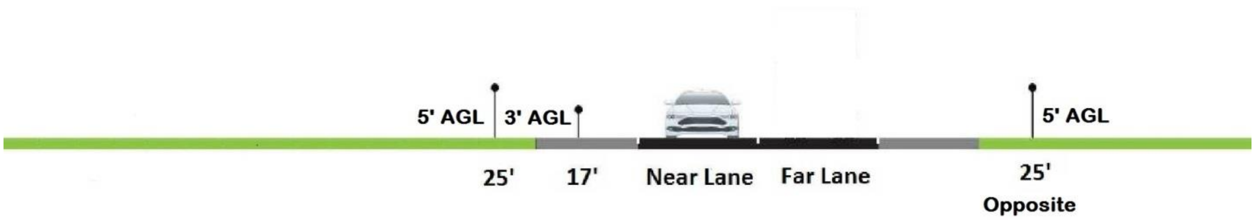
Site 2 – the 17-foot and the 25-foot microphone installed along the southbound lane

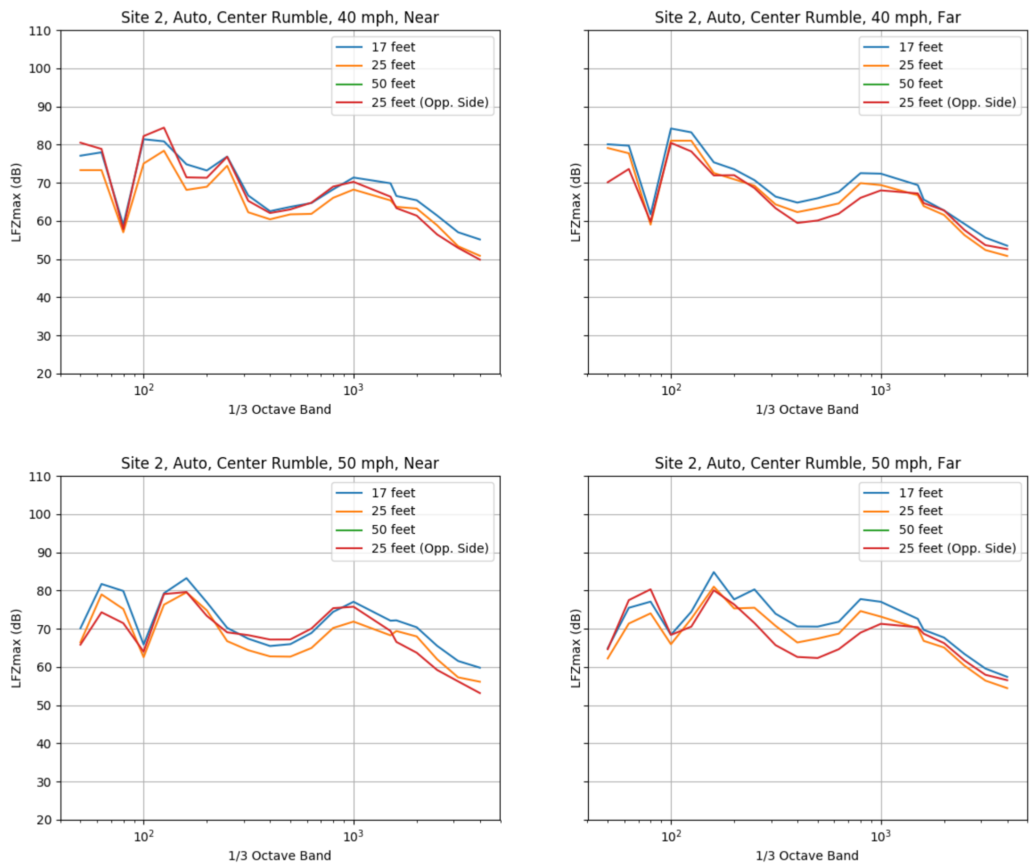

Site 2, Auto, Center Rumble Maneuver, 40 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

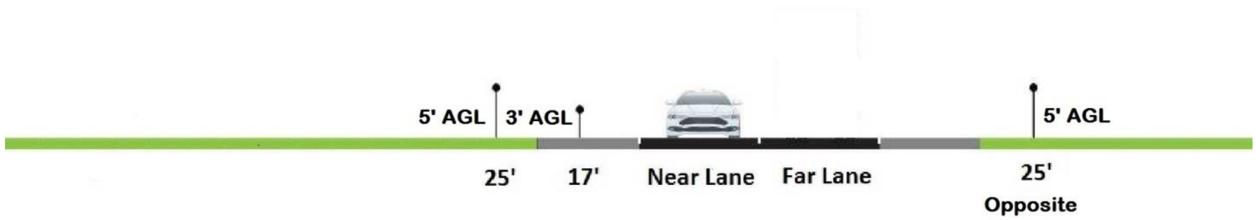

Site 2, Auto, Center Rumble Maneuver, 40 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

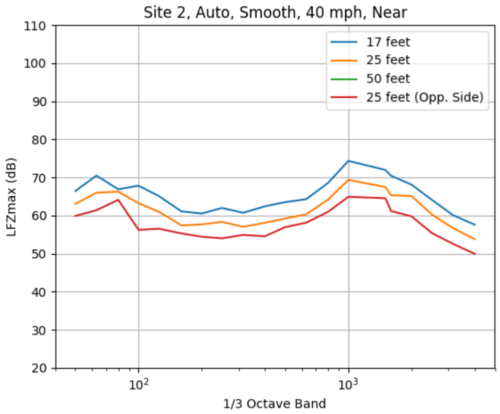

Site 2, Auto, Center Rumble Maneuver, 50 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

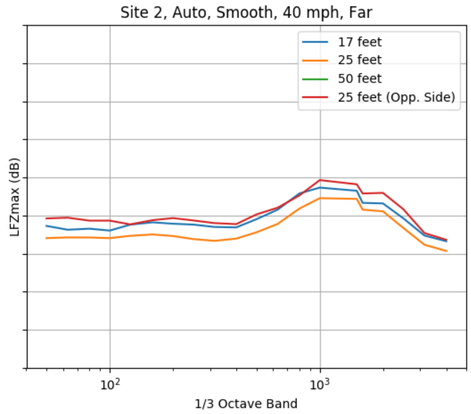

Site 2, Auto, Center Rumble Maneuver, 50 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

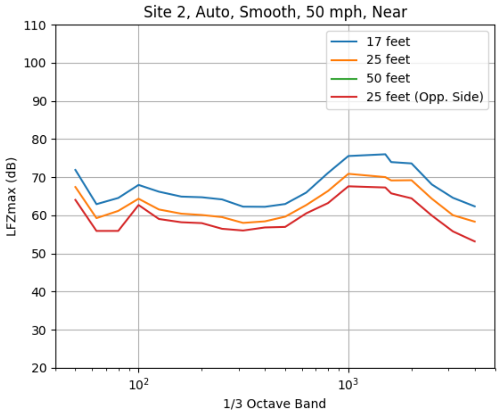

5' AGL
3' AGL
5' AGL
25'
17'
Near Lane
Far Lane
25'
Opposite

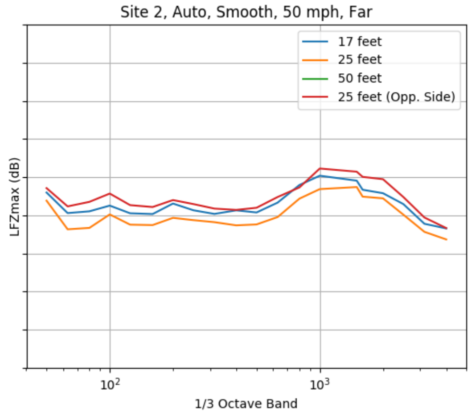

Site 2, Auto, Center Rumble, 40 mph, Near
Site 2, Auto, Center Rumble, 40 mph, Far
Site 2, Auto, Center Rumble, 50 mph, Near
Site 2, Auto, Center Rumble, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

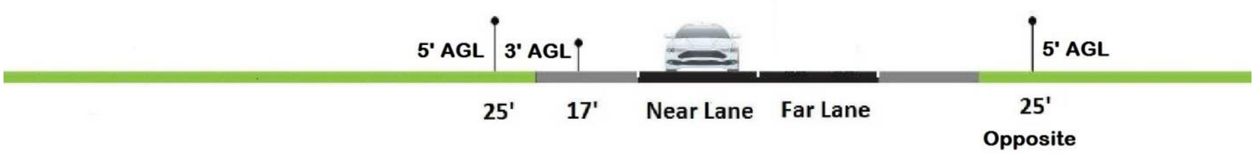

5' AGL
3' AGL
5' AGL
25'
17'
Near Lane
Far Lane
25'
Opposite


Site 2, Auto, Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 2, Auto, Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 2, Auto, Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

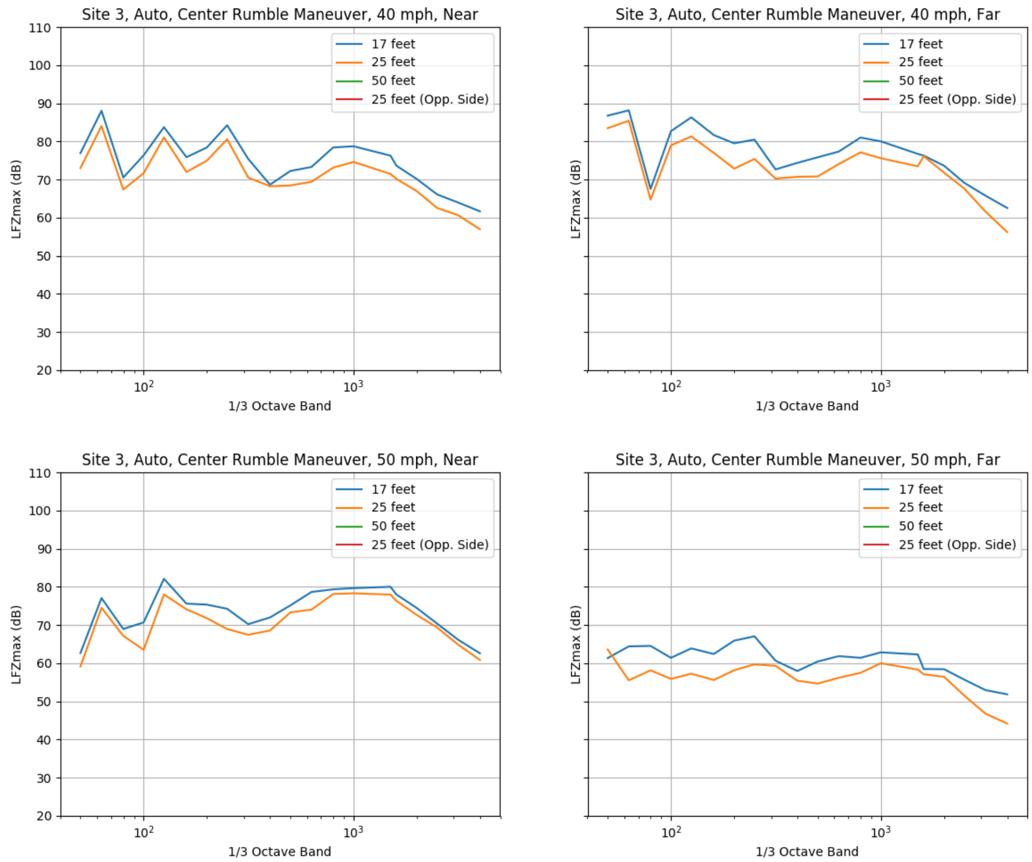

Site 2, Auto, Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

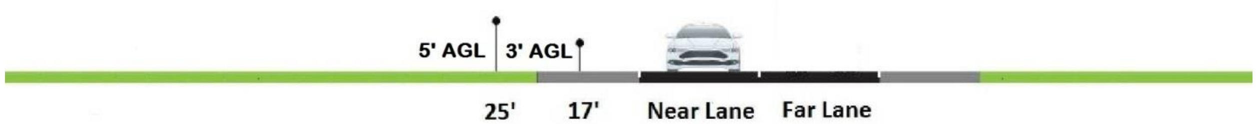

5' AGL
3' AGL
5' AGL
25'
17'
Near Lane
Far Lane
25'
Opposite

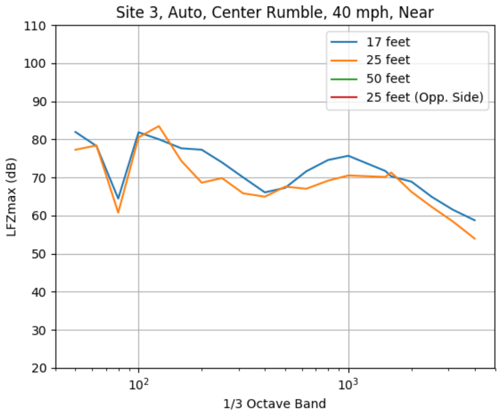
C.4 Site 3: NH Route 25/Tenney Mountain Highway, Plymouth

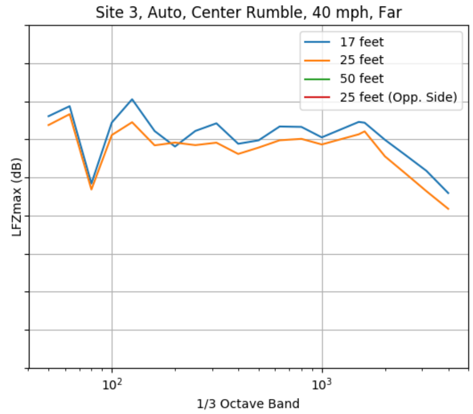
Site 3 - microphones at the 17-foot and 25-foot position; truck in far lane

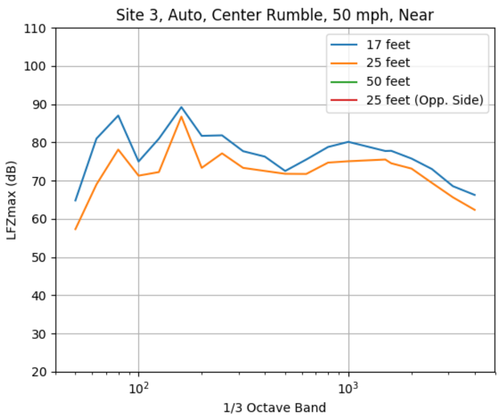
Site 3 – centerline rumble strip

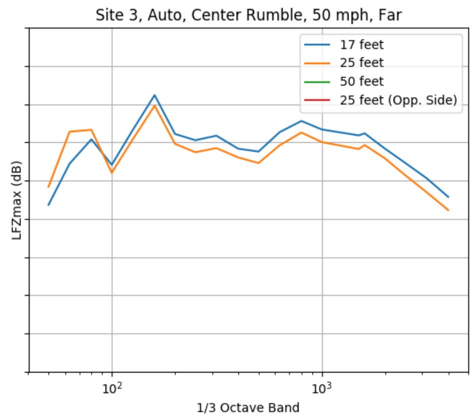

Site 3, Auto, Center Rumble Maneuver, 40 mph, Near
Site 3, Auto, Center Rumble Maneuver, 40 mph, Far
Site 3, Auto, Center Rumble Maneuver, 50 mph, Near
Site 3, Auto, Center Rumble Maneuver, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

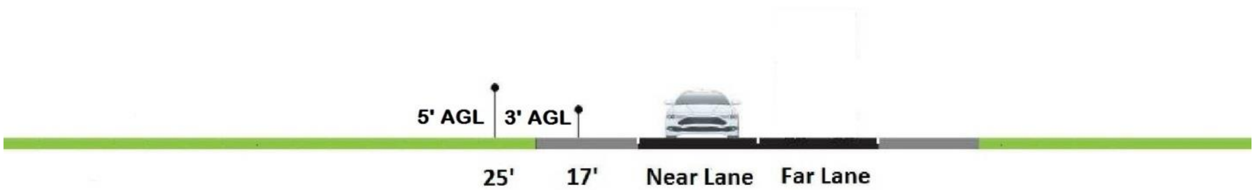

5' AGL
3' AGL
25'
17'
Near Lane
Far Lane

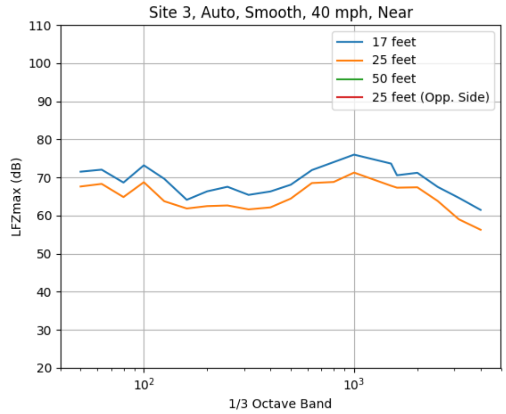

Site 3, Auto, Center Rumble, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

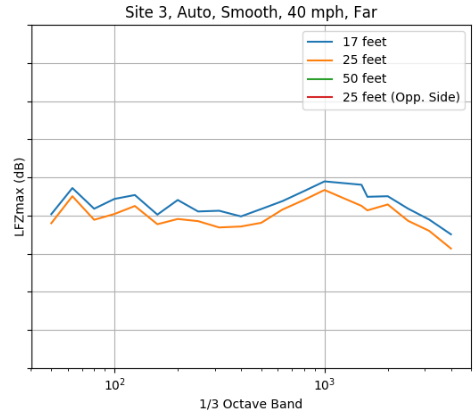

Site 3, Auto, Center Rumble, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

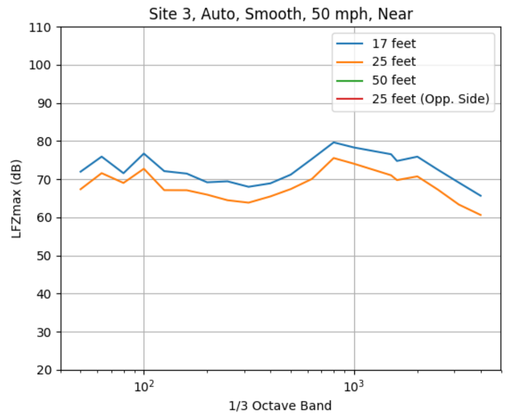

Site 3, Auto, Center Rumble, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

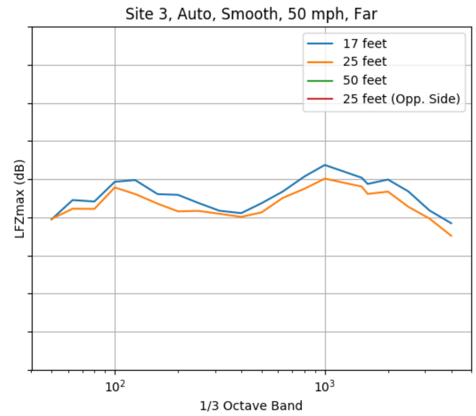

Site 3, Auto, Center Rumble, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

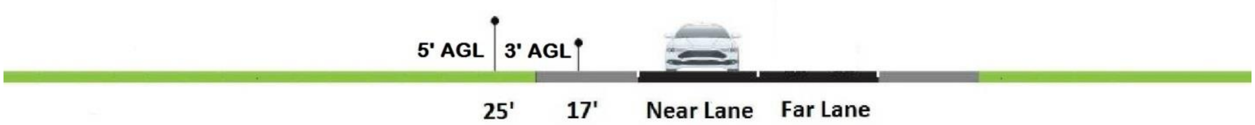

5' AGL
3' AGL
25'
17'
Near Lane
Far Lane


Site 3, Auto, Smooth, 40 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)


Site 3, Auto, Smooth, 40 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)


Site 3, Auto, Smooth, 50 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

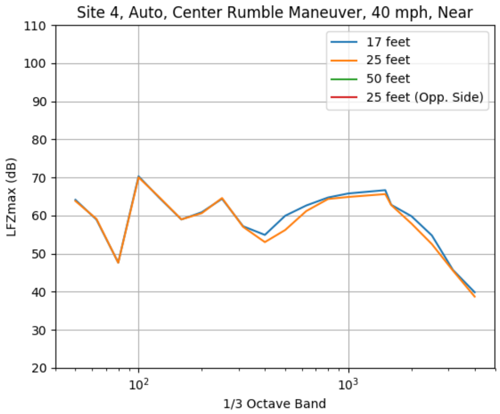

Site 3, Auto, Smooth, 50 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

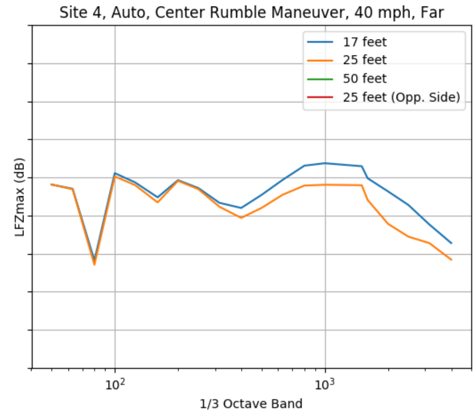

5' AGL
3' AGL
25'
17'
Near Lane
Far Lane

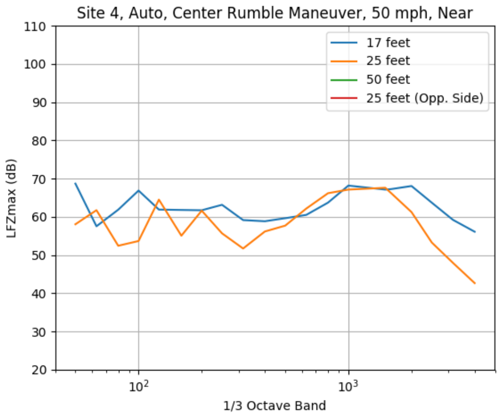
C.5 Site 4: NH Route 28, Alton

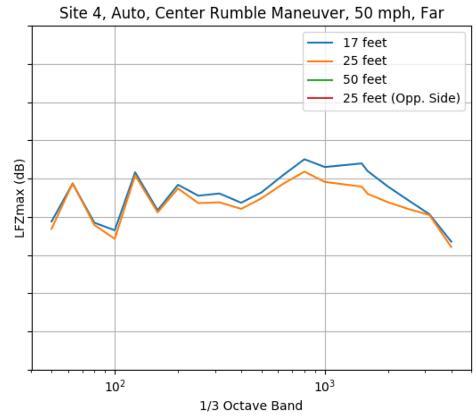
Site 4 – looking south with NHDOT truck in far lane

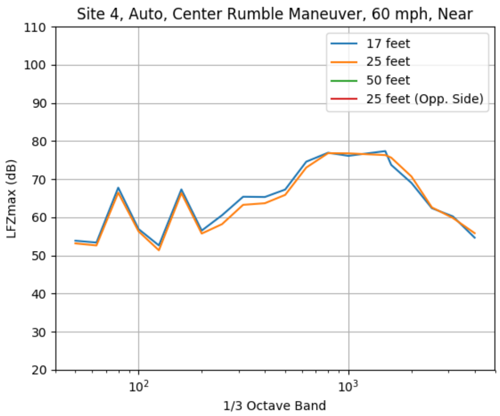
Site 4 – centerline rumble strip

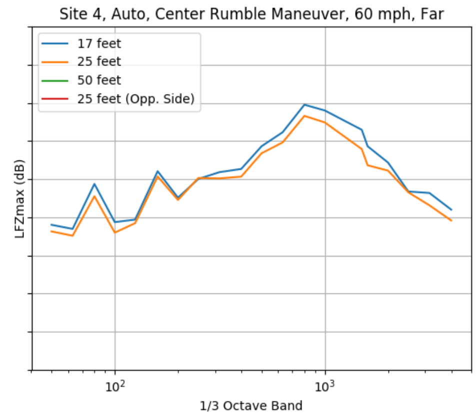

Site 4, Auto, Center Rumble Maneuver, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

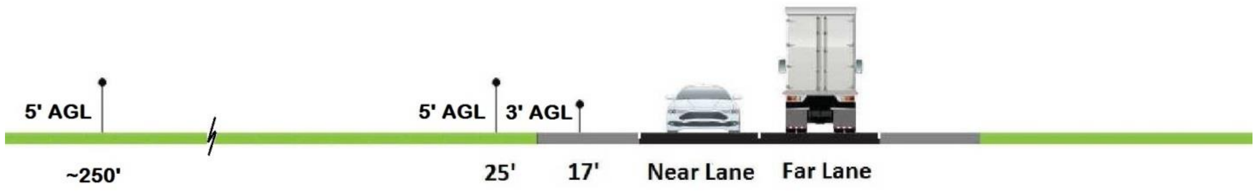

Site 4, Auto, Center Rumble Maneuver, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

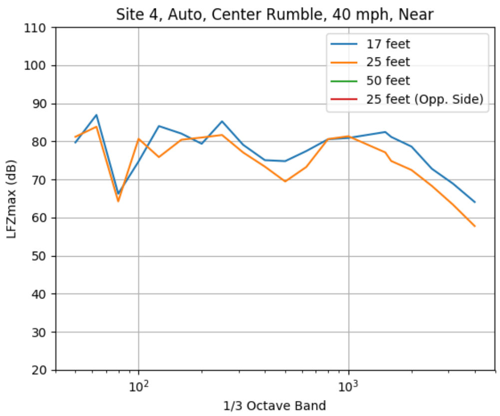

Site 4, Auto, Center Rumble Maneuver, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

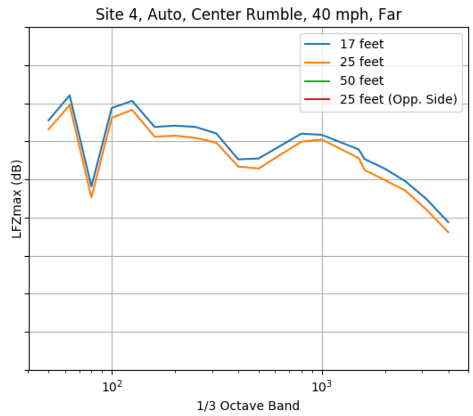

Site 4, Auto, Center Rumble Maneuver, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

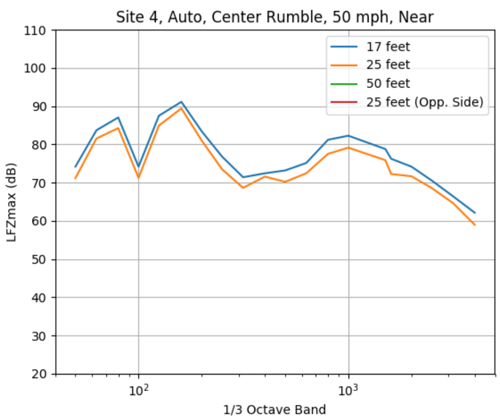

Site 4, Auto, Center Rumble Maneuver, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

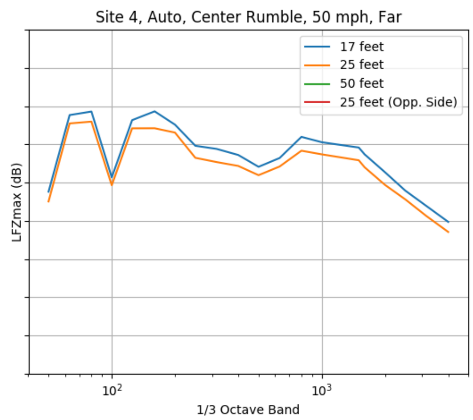

Site 4, Auto, Center Rumble Maneuver, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

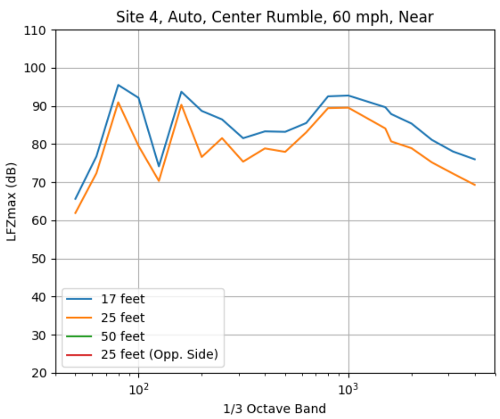

5' AGL
5' AGL
3' AGL
~250'
25'
17'
Near Lane
Far Lane

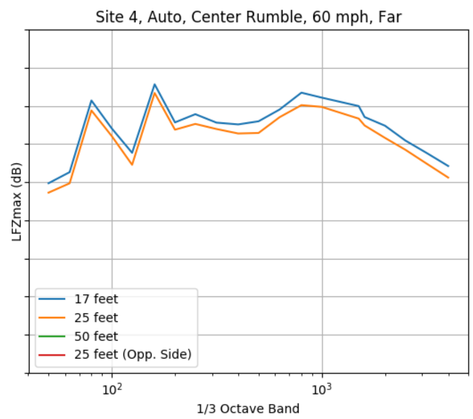

Site 4, Auto, Center Rumble, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

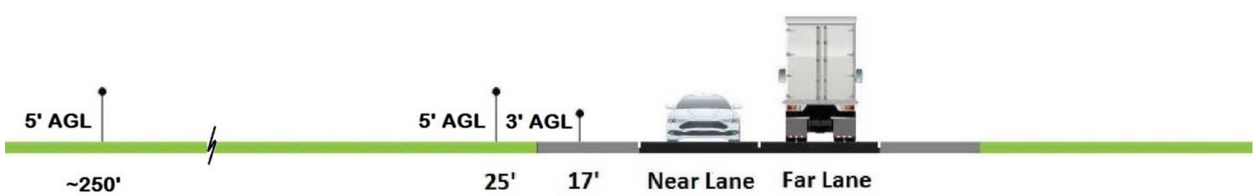

Site 4, Auto, Center Rumble, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

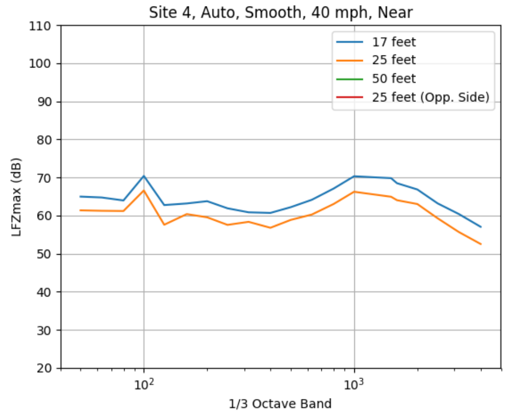

Site 4, Auto, Center Rumble, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

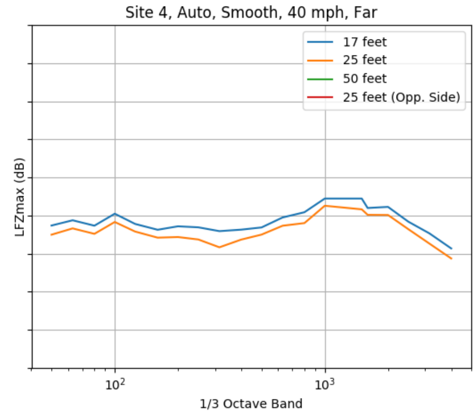

Site 4, Auto, Center Rumble, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

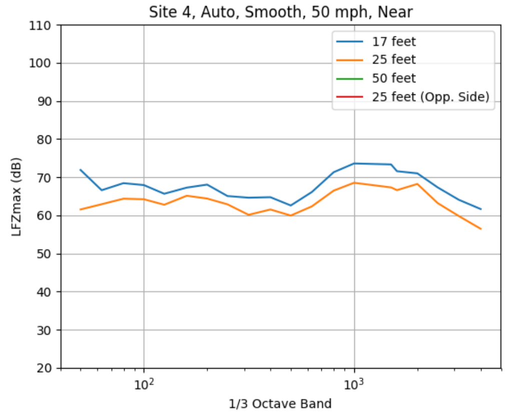

Site 4, Auto, Center Rumble, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

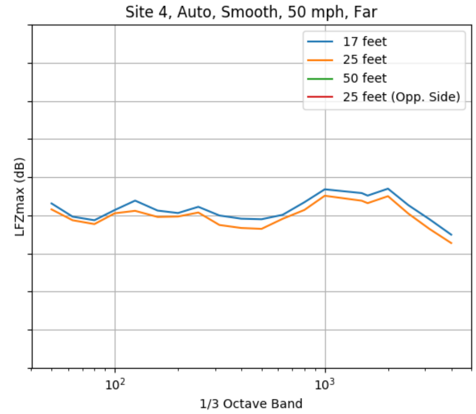

Site 4, Auto, Center Rumble, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

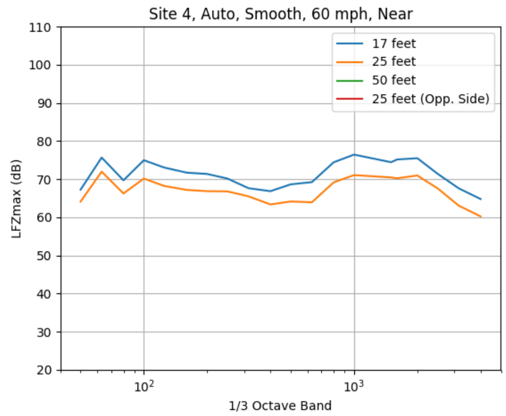

5' AGL
5' AGL
3' AGL
~250'
25'
17'
Near Lane
Far Lane

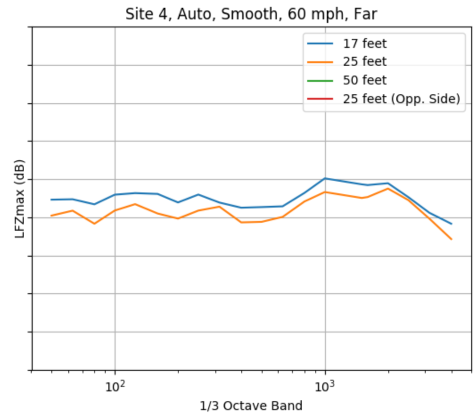

Site 4, Auto, Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
110
100
90
80
70
60
50
40
30
20
10^2
10^3
1/3 Octave Band

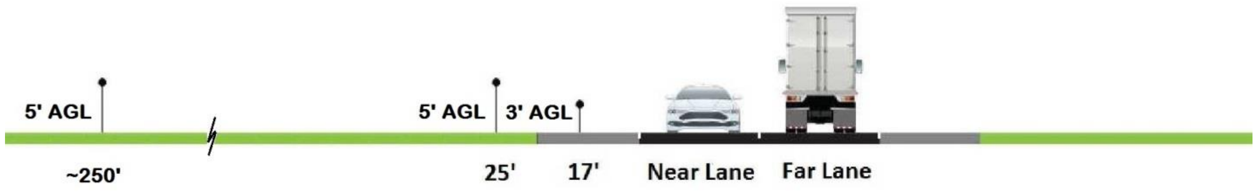

Site 4, Auto, Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
10^2
10^3
1/3 Octave Band

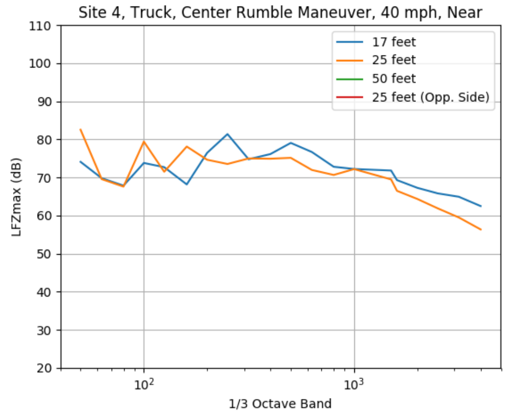

Site 4, Auto, Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
110
100
90
80
70
60
50
40
30
20
10^2
10^3
1/3 Octave Band

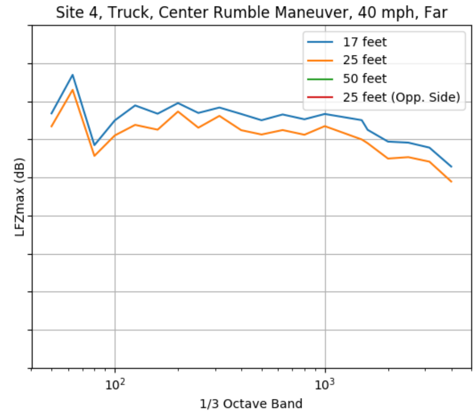

Site 4, Auto, Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
10^2
10^3
1/3 Octave Band

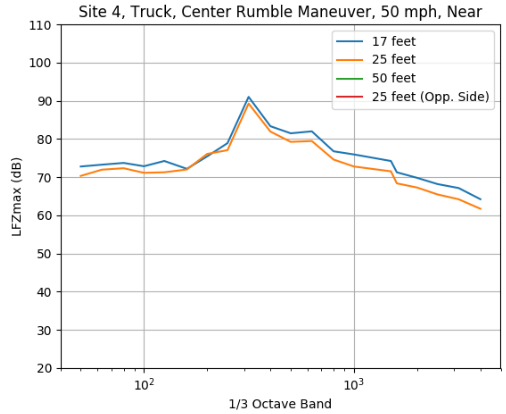

Site 4, Auto, Smooth, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
110
100
90
80
70
60
50
40
30
20
10^2
10^3
1/3 Octave Band

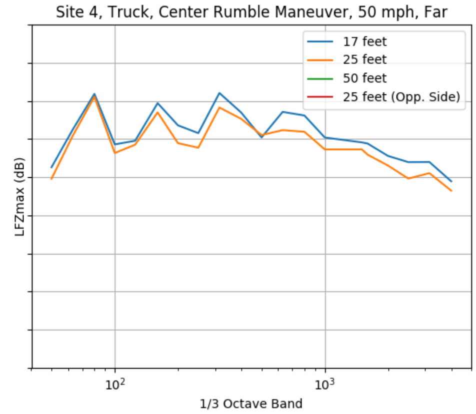

Site 4, Auto, Smooth, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
10^2
10^3
1/3 Octave Band

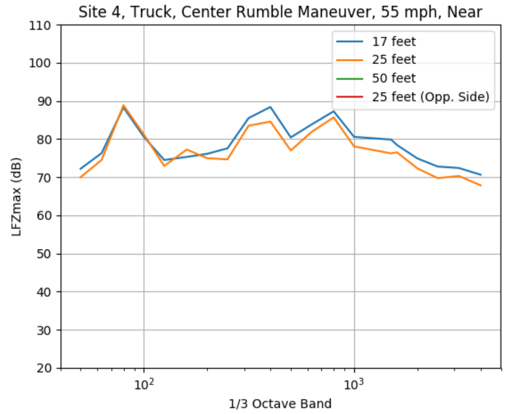

5' AGL
5' AGL
3' AGL
~250'
25'
17'
Near Lane
Far Lane

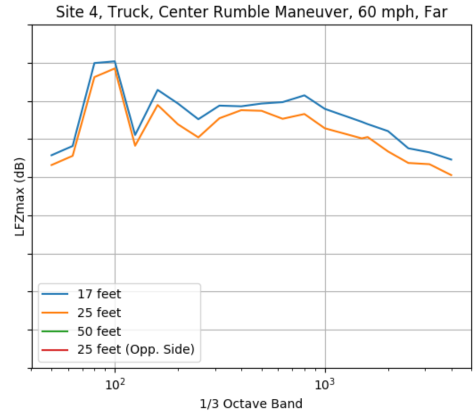

Site 4, Truck, Center Rumble Maneuver, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

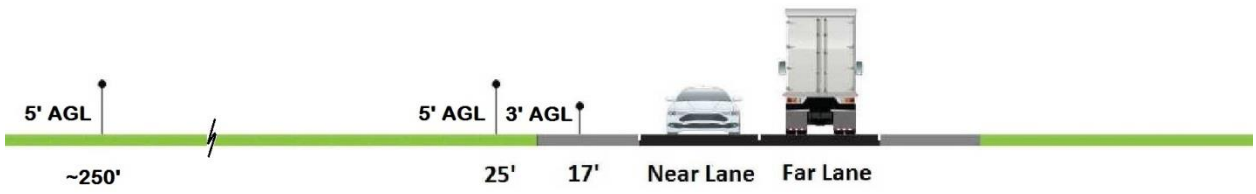

Site 4, Truck, Center Rumble Maneuver, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

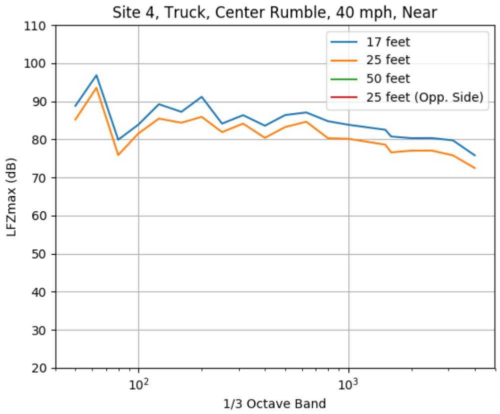

Site 4, Truck, Center Rumble Maneuver, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

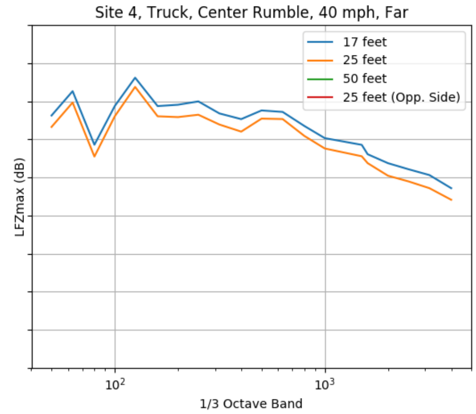

Site 4, Truck, Center Rumble Maneuver, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

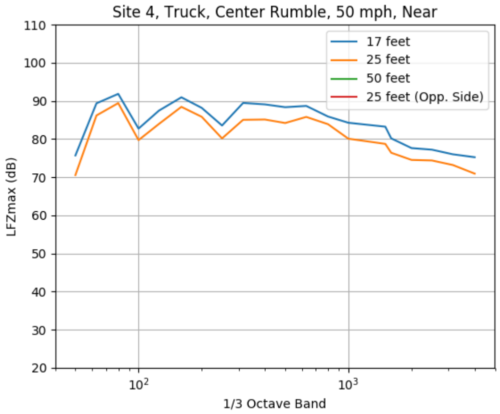

Site 4, Truck, Center Rumble Maneuver, 55 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

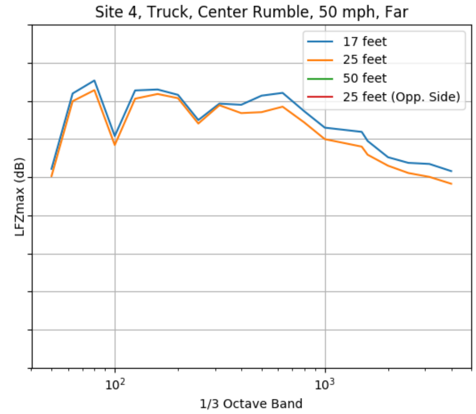

Site 4, Truck, Center Rumble Maneuver, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

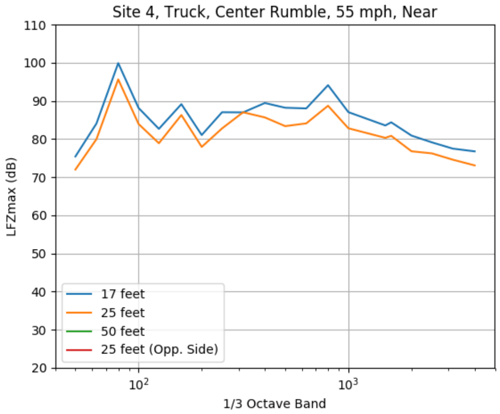

5' AGL
5' AGL
3' AGL
~250'
25'
17'
Near Lane
Far Lane

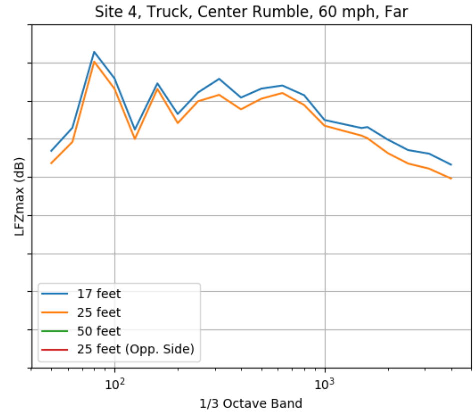

Site 4, Truck, Center Rumble, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

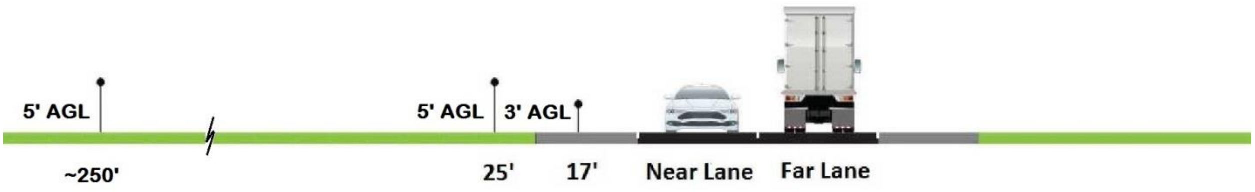

Site 4, Truck, Center Rumble, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

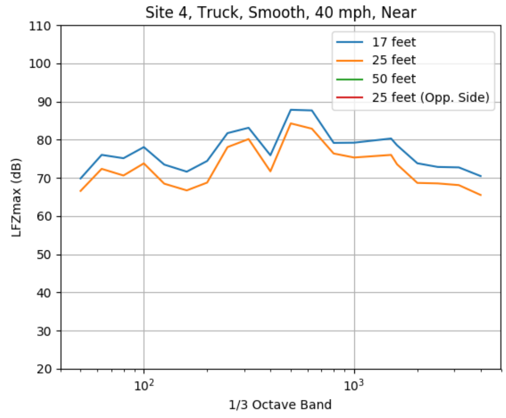

Site 4, Truck, Center Rumble, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

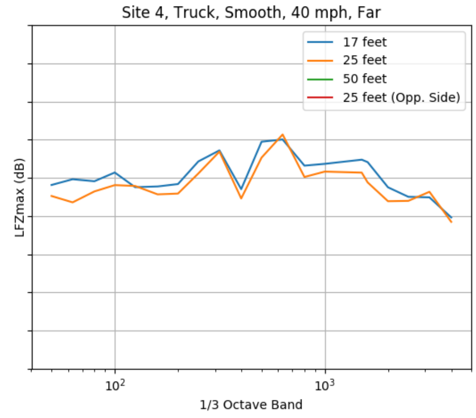

Site 4, Truck, Center Rumble, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

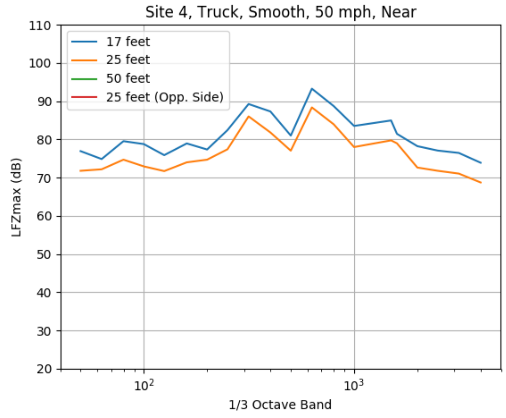

Site 4, Truck, Center Rumble, 55 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

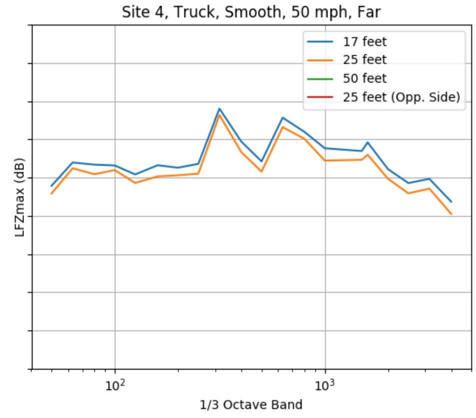

Site 4, Truck, Center Rumble, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

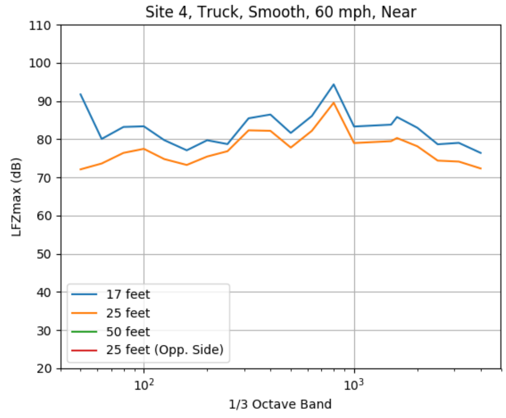

5' AGL
5' AGL
3' AGL
~250'
25'
17'
Near Lane
Far Lane

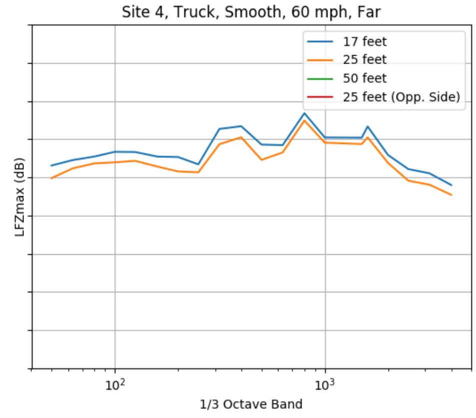

Site 4, Truck, Smooth, 40 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

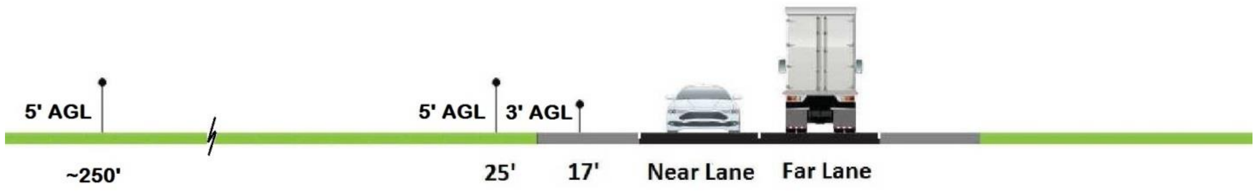

Site 4, Truck, Smooth, 40 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 4, Truck, Smooth, 50 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 4, Truck, Smooth, 50 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 4, Truck, Smooth, 60 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

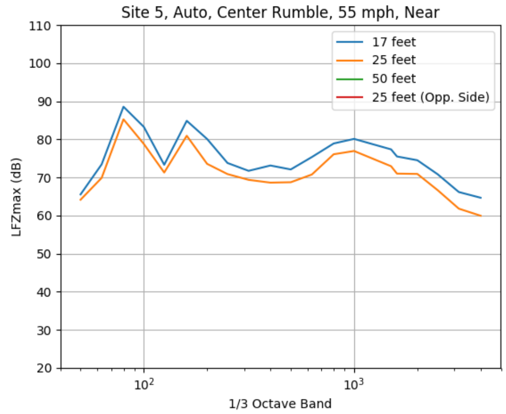

Site 4, Truck, Smooth, 60 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

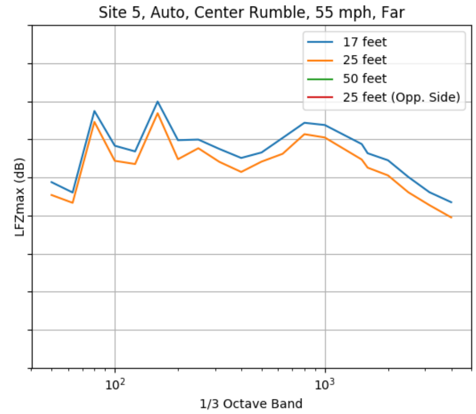

5' AGL
5' AGL
3' AGL
~250'
25'
17'
Near Lane
Far Lane

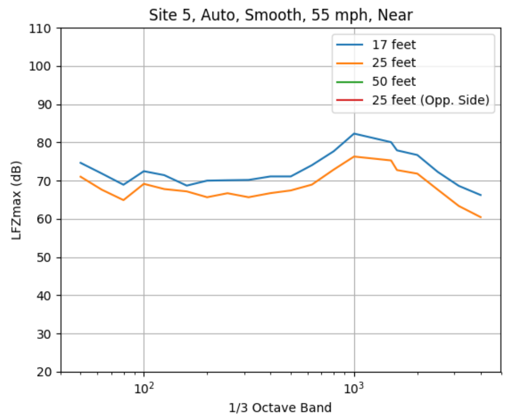
C.6 Site 5: U.S. Route 202/NH Route 9, Henniker

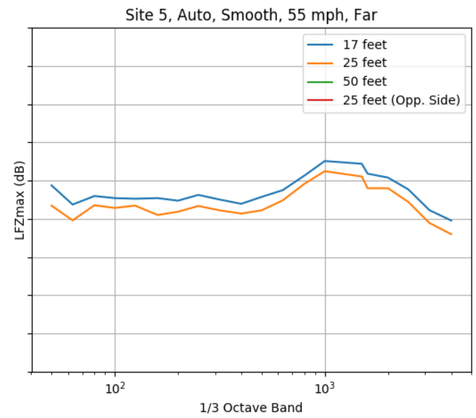
Site 5 – microphones at the 17-foot and 25-foot positions

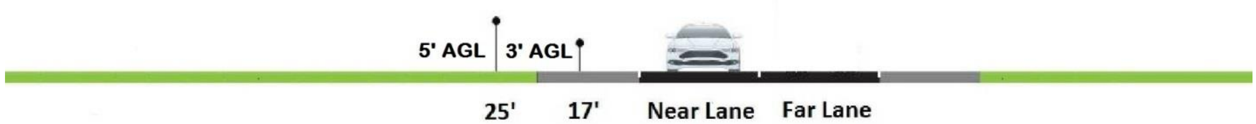
Site 5 – centerline rumble strip


Site 5, Auto, Center Rumble, 55 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 5, Auto, Center Rumble, 55 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band


Site 5, Auto, Smooth, 55 mph, Near
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

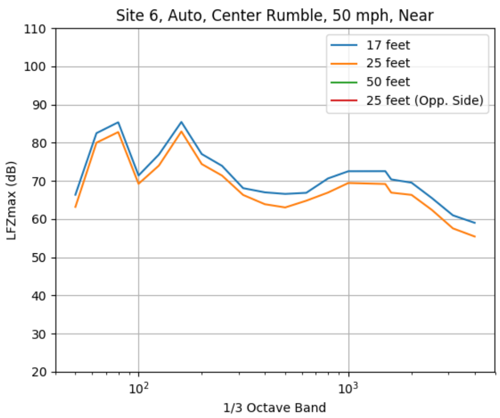

Site 5, Auto, Smooth, 55 mph, Far
17 feet
25 feet
50 feet
25 feet (Opp. Side)
LFZmax (dB)
1/3 Octave Band

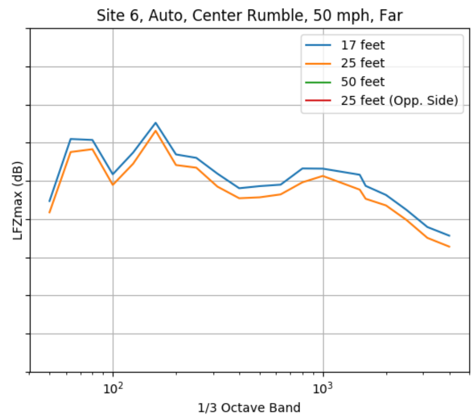

5' AGL
3' AGL
25'
17'
Near Lane
Far Lane

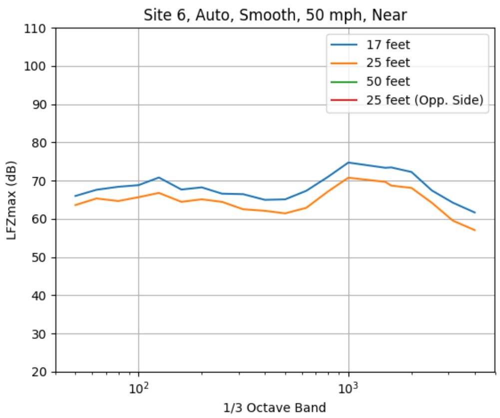
C.7 Site 6: NH Route 9, Chesterfield

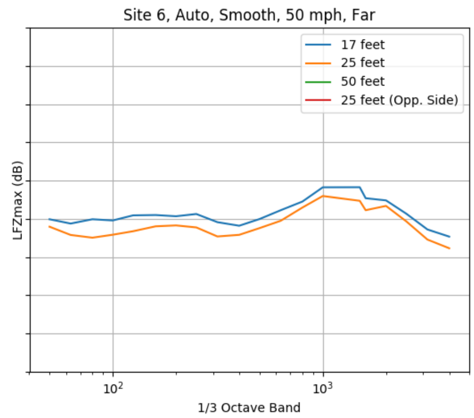

Site 6 – microphones at the 17-foot and the 25-foot positions

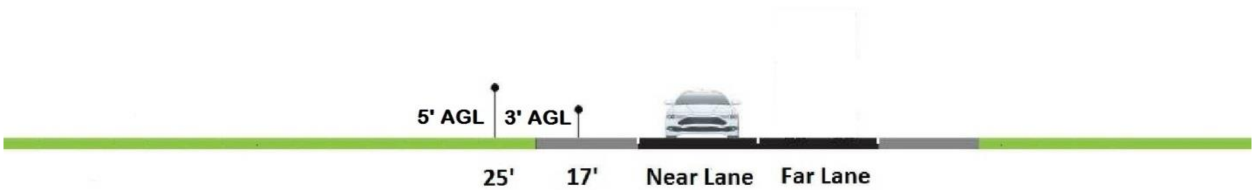

Site 6 – centerline rumble strip


Site 6, Auto, Center Rumble, 50 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)


Site 6, Auto, Center Rumble, 50 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)

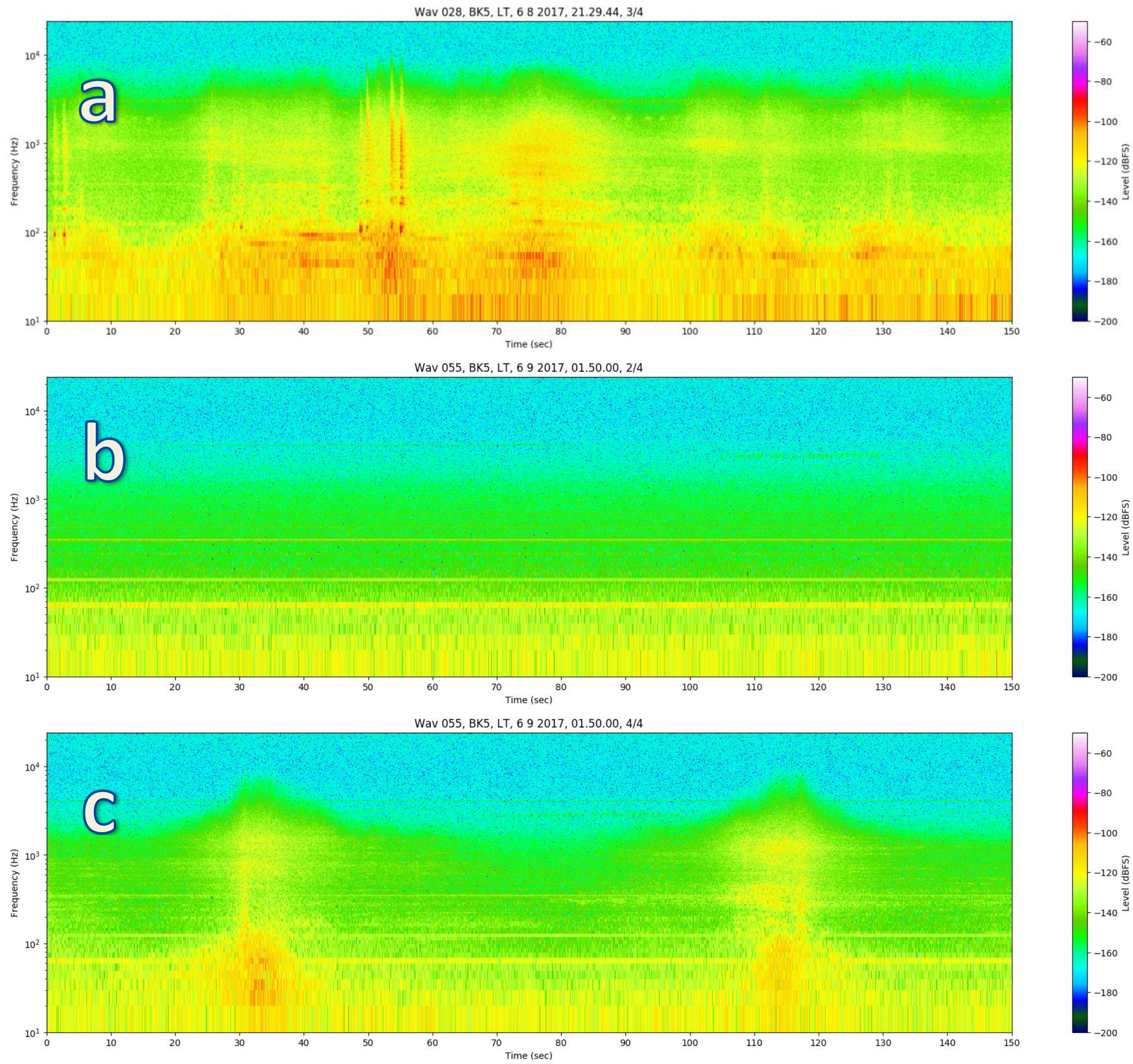

Site 6, Auto, Smooth, 50 mph, Near
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)


Site 6, Auto, Smooth, 50 mph, Far
LFZmax (dB)
1/3 Octave Band
17 feet
25 feet
50 feet
25 feet (Opp. Side)


5' AGL
3' AGL
25'
17'
Near Lane
Far Lane

C.8 Spectrograms for Selected Nighttime Periods at the Long-term Monitor

The figures in this subsection are spectrograms for selected nighttime periods between the hours of 5:00 PM on June 8 and 10:00 AM on June 9, 2017, from the long-term noise monitor that was installed at the Robert Knolls Campground. A spectrogram shows a history of the changing spectral content of an acoustic environment over time. In the following graphs, the 1/3 octave band center frequency is plotted on the vertical axis and time is plotted on the horizontal axis. The shading indicates the 1/3 octave band sound pressure level in units of decibels full-scale (DBFS) – “warmer” colors (e.g. orange, red) represent higher sound levels and “cooler” colors (e.g. blue) represent lower sound levels.

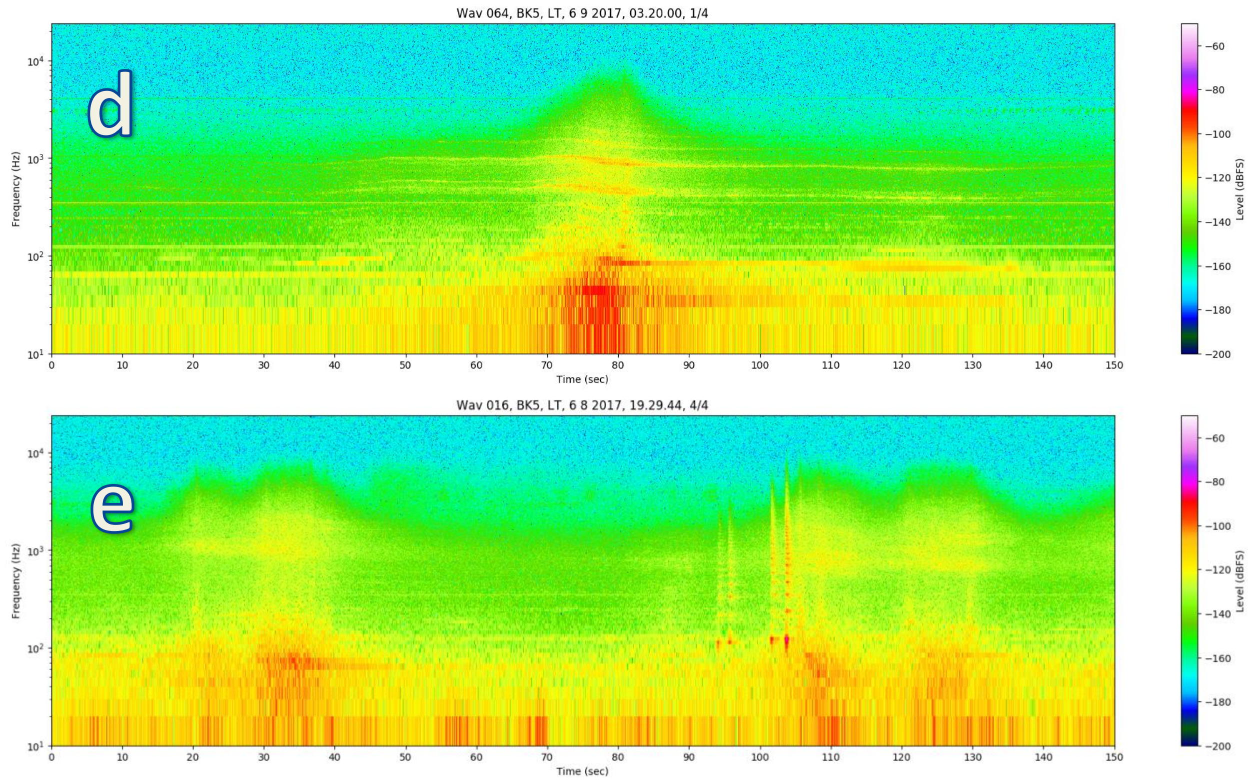


Spectrograms of Vehicle Pass-bys at the Campground: a) 2017 Nissan Altima; b) Ambient; and c) Two Automobile Pass-bys on Smooth Pavement

Figure (a) shows a full maneuver of the 2017 Nissan Altima from a running time of 50 seconds to 55 seconds. The rumble strip event is characterized by two yellow/red “spikes” that coincide with the front and the rear axle of the test vehicle crossing the centerline rumble strip, followed in succession by two additional yellow/red spikes as the vehicle returns to the original lane of travel.

Figure (b) shows a period of quiet ambient during which there were no vehicle pass-bys. Note the horizontal yellow “line” at approximately 63 Hz (the vertical axis is a log scale). This line is evidence of a tone produced by a pump or other mechanical equipment associated with the swimming pool. The first harmonic of this tone is also present in the 120 Hz band.

Figure (c) shows two car pass-bys on smooth pavement. Note the absence of the yellow/red “spikes” that are characteristic of a passing maneuver.



Spectrograms of Vehicle Pass-bys at Campground: d) Heavy Truck; and e) Rumble Strip Maneuver Preceding Two Automobile Pass-bys

Figure (d) shows a heavy truck pass-by on smooth pavement from a running time of approximately 70 seconds to 80 seconds.

Figure (e) shows a passing maneuver starting at a running time of approximately 95 seconds to 105 seconds followed in succession by automobile pass-bys from about 107 seconds to 109 seconds and again from about 120 seconds to 130 seconds.

Appendix D Table of Measured Rumble Strip Depths

NHDOT's Custom Depth Gage

(Courtesy Dean Wilson, District Construction Engineer)

Route 28 Alton Heading South

Location/Landmark	Centerline Depth (in)
Alton TL	1/2
mm 71.8	1/2
Road Narrows sign (NB)	1/2
55 mph sign	1/2
Gould Rd. (private)	5/8
	1/2
mm 71.6	5/8
	5/8
	1/2
40 mph ahead (NB)	1/2
W2-1	5/8
Passing Zone Pendents	5/8
mm 71.4	1/2
	1/2
	5/8
	1/2
Stage Coach Rd.	
	1/2
mm 71.2	5/8
	5/8
	1/2
	1/2
	1/2
Roberts Cove Rd.	
mm 71.0	1/2
	5/8
	5/8
W2-2L Drew Hill Rd.	5/8
mm 70.8	5/8
	1/2
	1/2
Drew Hill Rd.	
mm 70.6	1/2
	1/2
W2-2R/Drew Hill Rd ahead sign(NB)	5/8
	5/8

Location/Landmark	Centerline Depth (in)
mm 70.4	5/8
	5/8
	1/2
No Passing Pendent	5/8
	1/2
Roberts Knoll Camp Ground	
mm 70.2	5/8
end GR run (NB)	1/2
	5/8
mm 70.0	1/2
	1/2
	1/2
Picnic area 1/2 mile sign	5/8
mm 69.8	5/8
No Passing Pendent	1/2
	1/2
	1/2
mm 69.6	5/8
W2-1 Quarry Rd/Roberts Cove Rd	5/8
	5/8
mm 69.4/Roberts Cove Rd	
SOUTH 28 sign	5/8
begin GR run (SB)	5/8
W2-1 Quarry Rd/Roberts Cove Rd	1/2
mm 69.2	5/8
Camp Brookwoods - 1 mile	5/8
W1-10L	5/8
mm 69.0	5/8
	1/2
Chestnut Cove Rd.	
	5/8
	5/8
mm 68.8	1/2
Scenic View 500'	1/2
	1/2
Scenic View turn	

Location/Landmark	Centerline Depth (in)
mm 68.6/South 28 sign	5/8
start GR Run	1/2
	5/8
	5/8
	5/8
Gilman's CRN Rd.	
Hidden Springs Rd ahead sign	5/8
	5/8
Hidden Springs Rd.	
	1/2
mm 68.0	5/8
JCT 28 A Sign	5/8
W2-1 Old Wolfeboro Rd.	1/2
start of right turn lane	5/8
	5/8
	5/8
mm 67.6	5/8
end of GR run (SB)	3/4
	5/8
W1-10L Miramichie Rd.	5/8
mm 67.4	5/8
	1/2
mm 67.2	1/2
W2-2R Bowman Rd.	
	1/2
	5/8
mm 67.0	1/2
Calef DR.	
	1/2
	1/2
mm 66.8	5/8
W2-7L Lily Pond/Swan lake	5/8
mm 66.6	1/2
	5/8
Swan Lake Trail	
	5/8

Location/Landmark	Centerline Depth (in)
mm 66.4	5/8
	1/2
	1/2
mm 66.2	1/2
	1/2
	1/2
mm 66.0	1/2
	1/2
	5/8
mm 65.8	1/2
	5/8
	5/8
mm 65.6	5/8
start passing zone	5/8
Bay Hill Rd.	1/2
mm 65.4	5/8
	1/2
	5/8
mm 65.2	5/8
	1/2
	1/2
Ashton Self Storage	5/8
	1/2
	1/2
W2-7L Old Wolfeboro Rd.	1/2
mm 64.6	1/2
Old Wolfeboro Rd.	
Speed Limit 40 ahead sign	1/2
mm 64.2	1/2
	1/2
	5/8
Drive to Patrol Shed	
mm 64.0	1/2

AVERAGE DEPTH (IN) =	**5/8**
MAXIMUM DEPTH (IN)	**3/4**
MINIMUM DEPTH (IN)	**1/2**

Route 25 Plymouth Heading East

Location/Landmark	Centerline Depth (in)
mm 39.8	3/8
	3/8
	3/4
	3/4
Bridge	
	5/8
	5/8
mm 40.0	5/8
55 mph sign	5/8
	5/8
	5/8
	5/8
mm 40.2	1/2
end GR Run	1/2
Begin GR Run	1/2
	3/8
mm 40.4*	1/2
*	7/8
	3/8
Speed Limit 35 ahead sign	1/2
	1/2
	1/2
mm 40.6	1/2
divided island sign	1/2
	1/2
	5/8
mm 40.8	5/8
speed limit 35 sign	3/8

* These two rumble strips were next to each other with cracked pavement, which was somewhat heaved

AVERAGE DEPTH (IN) =	1/2
MAXIMUM DEPTH (IN) =	7/8
MINIMUM DEPTH (IN) =	3/8

Route 102 Heading East Starting at Alverine High School

Location/Landmark	Centerline Depth (in)
Alverine High School	1/2
	1/2
Old Derry Rd.	1/2
Litchfield town line	1/2
	3/8
	3/8
Cutler Rd.	1/2
	1/2
Hudson town line	5/8
	5/8

AVERAGE DEPTH (IN) =	**1/2**
MAXIMUM DEPTH (IN)=	**5/8**
MINIMUM DEPTH (IN)=	**3/8**

Route 102 Heading East Starting at High Range Rd

Location/Landmark	Centerline Depth (in)	Edgeline Depth (in)
	3/8	1/2
	3/8	3/8
	3/8	3/8
	1/4	3/8
	1/4	1/4
Parmenter Rd.		
	3/8	3/8
	1/4	3/8
Charles George Companies	3/8	1/2
	1/4	3/8
Old Nashua Rd.		
	1/4	3/8
	3/8	3/8
JCT 128		
	3/8	3/8
Horizon Dr.		
	1/4	3/8
	3/8	1/2
	1/4	1/2
	3/8	1/2
	1/4	1/2
Butrick Rd.		

AVERAGE DEPTH (IN)=	**3/8**	**3/8**
MAXIMUM DEPTH (IN)=	**3/8**	**1/2**
MINIMUM DEPTH (IN)=	**1/4**	**1/4**

Route 102 Heading East Starting at Edwards Mill Rd. (Chester)

Location/Landmark	Centerline Depth (in)
Edwards Mill Rd.	
	3/8
	1/4
	3/8
Fremont Rd.	
	1/2
	3/8
	1/4
	3/8
	3/8
	3/8
	3/8
	3/8
	3/8
Wason Rd.	
	3/8
	1/4
	3/8
Towle Rd.	
	3/8
	3/8
Shaker Heights	
	3/8
	3/8
	1/4
	1/4
Dump Rd.	
NHDOT Patrol Shed (513)	3/8
	1/2
	3/8

Location/Landmark	Centerline Depth (in)
	3/8
Hamson Rd/Raymond TL	
	3/8
	1/2
	3/8
Ida Ln.	
	3/8
	3/8
Ventira Dr.	
	3/8
	3/8
Darren Dr.	
	3/8
	1/2
	3/8
Morgan Farm Rd.	
	3/8
	3/8
Brown Rd.	
	1/2
	1/2
Route 107	

AVERAGE DEPTH (IN) =	**3/8**
MAXIMUM DEPTH (IN) =	**1/2**
MINIMUM DEPTH (IN) =	**1/4**

Route 109 Chesterfield heading East

Location/Landmark	Centerline Depth (in)	Edgeline Depth (in)
mm 0.6	3/8	
	3/8	
	1/2	
	1/2	
	3/8	
	3/8	
mm 0.8	3/8	
	1/2	
	1/2	
	1/2	
mm 1.0	1/2	
	3/8	
	3/8	
	3/8	
	3/8	
mm 1.2	1/2	
	1/2	
	1/2	
	1/2	
	1/2	
mm 2.6	1/2	
	3/8	
	3/8	
	3/8	
	1/2	
	1/2	
	1/2	
	1/2	
	3/8	

Location/Landmark	Centerline Depth (in)	Edgeline Depth (in)
mm 4.6	3/8	5/8
	1/2	1/2
	3/8	5/8
	3/8	1/2
	1/2	1/2
	1/2	1/2
	3/8	1/2
	3/8	1/2
	1/2	1/2
	1/2	1/2
mm 6.6	1/2	1/2
	1/2	1/2
	1/2	5/8
	3/8	5/8
	3/8	5/8
	3/8	1/2
	3/8	3/8
	1/2	3/8
	1/2	1/2
	3/8	1/2
mm 8.6	1/4	1/2
	3/8	1/2
	3/8	1/2
	1/2	5/8
	1/2	5/8
	1/2	5/8
	1/2	1/2
	1/2	1/2
	3/8	1/2
	3/8	1/2

Location/Landmark	Centerline Depth (in)	Edgeline Depth (in)
mm 10.6	1/4	
	3/8	1/2
	3/8	3/8
	3/8	3/8
	1/2	1/2
	1/2	1/2
Keen town line	3/8	1/2
	1/2	3/8
	1/2	1/2
	3/8	1/2
mm 12.6	3/8	3/8
	3/8	
	3/8	3/8
	3/8	1/2
	3/8	3/8

AVERAGE DEPTH (IN) =	**3/8**	**1/2**
MAXIMUM DEPTH (IN) =	**1/2**	**5/8**
MINIMUM DEPTH (IN) =	**1/4**	**3/8**

Chris J. Bajdek

From: Evans, Jonathan <Jonathan.Evans@dot.nh.gov>
Sent: Wednesday, August 09, 2017 11:44 AM
To: Chris J. Bajdek
Subject: RE: Material for HMMH

Categories: 306610 NHDOT

Hi Chris,

See Below in RED. I had to round to the nearest 0.1 miles, so they are approximate. Let me know if you have any other questions.

-Jon

From: Chris J. Bajdek [mailto:cbajdek@hmmh.com]
Sent: Wednesday, August 09, 2017 11:26 AM
To: Evans, Jonathan
Subject: RE: Material for HMMH

Route 111 Danville: Site 1 42.90685, -71.09700 MM 29.6
Route 111 Danville: Site 1A 42.90725, -71.09467 MM 29.7
Route 16 Madison: Site 2 43.95827, -71.16228 MM 73.4
Route 25 Plymouth: Site 3 43.76825, -071.70242 MM 40.3
Route 28 Alton: Site 4 43.53058, -71.20429 MM 70.0 (Campground is at MM 70.2)
Route 9 Henniker: Site 5 43.17432, -71.84708 MM 38.6
Route 9 Chesterfield: Site 6 42.89965, -72.43227 MM 6.8

Regards,

Chris Bajdek
HMMH O 781.229.0707 x3128 | M 339.234.2522
cbajdek@hmmh.com

From: Evans, Jonathan [mailto:Jonathan.Evans@dot.nh.gov]
Sent: Wednesday, August 09, 2017 11:13 AM
To: Chris J. Bajdek
Subject: RE: Material for HMMH

Gottcha. I can get you those. Did you get coordinates? I have a pretty good idea of where you took the measurements, but I would want to make sure. The only location where I am unsure of exactly where you took the measurements is Chesterfield.

From: Chris J. Bajdek [mailto:cbajdek@hmmh.com]
Sent: Wednesday, August 09, 2017 11:10 AM
To: Evans, Jonathan
Subject: RE: Material for HMMH

Noise measurements.

Regards,

Chris Bajdek
HMMH O 781.229.0707 x3128 | M 339.234.2522
cbajdek@hmmh.com

From: Evans, Jonathan [mailto:Jonathan.Evans@dot.nh.gov]
Sent: Wednesday, August 09, 2017 10:31 AM
To: Chris J. Bajdek
Subject: RE: Material for HMMH

For the depth measurements? Or for your noise measurements?

From: Chris J. Bajdek [mailto:cbajdek@hmmh.com]
Sent: Wednesday, August 09, 2017 10:15 AM
To: Evans, Jonathan
Subject: RE: Material for HMMH

Would you know the approximate mile-marker of the measurement sites?

Regards,

Chris Bajdek
HMMH O 781.229.0707 x3128 | M 339.234.2522
cbajdek@hmmh.com

From: Evans, Jonathan [mailto:Jonathan.Evans@dot.nh.gov]
Sent: Monday, August 07, 2017 11:58 AM
To: Chris J. Bajdek; Zachary F. Weiss
Cc: Grandmaison, Ronald
Subject: FW: Material for HMMH

Chris and Zach,

Thank you again for taking the time to come up and discuss the project results with the Department today. Attached, please find the rumble strip information that Ron mentioned earlier. Should you have any questions, please let us know.

-Jon
~~~~~~~~~~~~

Jonathan Evans, Air & Noise Program Manager
NH Department of Transportation, Bureau of Environment
7 Hazen Dr., PO Box 483, Concord, NH 03302-0483
~~~~~~~~~~~~

Email: Jonathan.Evans@dot.nh.gov
Phone: (603)271-4048 M-F 7AM-3PM

From: Grandmaison, Ronald
Sent: Monday, August 07, 2017 11:51 AM
To: Evans, Jonathan
Subject: Material for HMMH

Could you please send these off to Chris and Zach, as we discussed?

Thanks

Ronald J. Grandmaison, PE

New Hampshire Department of Transportation
Bureau of Highway Design
Chief of Consultant Design
Phone: 603-271-6198
Fax : 603-271-7025
E-Mail: Ronald.Grandmaison@dot.nh.gov
Website: http://www.nhdot.com

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Appendix E Contents of the DVD

HMMH submitted additional files and data to NHDOT on a DVD, including:

- Audio recordings for all of the controlled pass-bys at the 25-foot microphone position adjacent to the near lane;
- Difference spectra that show vehicle pass-by levels on rumble strips relative to the corresponding pass-by on smooth pavement in 1/3 octave bands;
- Audio recordings for events identified as potential rumble strip incursions obtained from the unattended noise monitor at the Roberts Knoll Campground over the period from 5 PM on June 8 to 10 AM on June 9, 2017; and
- Spectrograms from the unattended noise monitor at the Roberts Knoll Campground for the entire nighttime period.

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Appendix F References and Endnotes

[i] This study focused on the measurement of controlled vehicle pass-bys along the side of the road (i.e. at the wayside) near a rumble strip. That is, the measurements were made at the exterior of the vehicle. In-vehicle measurements of noise and/or vibration were not included in the scope of this study.

[ii] FHWA, *Technical Advisory Center Line Rumble Strips*, T5040.40, Revision 1, November 7, 2011.

[iii] FHWA, *Technical Advisory Shoulder and Edge Line Rumble Strips*, T5040.39, Revision 1, November 7, 2011.

[iv] Terhaar, Edward and Braslau, David, *Rumble Strip Noise Evaluation*, Minnesota Department of Transportation, Report No. MN/RC 2015-07, February 2015.

[v] Fidell, S, and Bishop, D, *Prediction of Acoustic Detectability*, U.S. Army Tank Automotive, Command, Washington, DC, 1974.

[vi] Sexton, Timothy V., *Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety*, Washington State Department of Transportation, Report No. WA-RD 835.1, September 2014.

[vii] National Cooperative Highway Research Program, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, D.C., 2009.

[viii] Note that HMMH measured the depth of the rumble strips at Sites 5 and 6 on the first day of testing. We refined our method for measuring depth by the time we performed measurements at the other sites. So, there may be greater uncertainty in our depth measurement at Site 6.

[ix] At Sites 3 and 4, we simply note the trends in measured noise levels at 50 mph. At this time, we don't have an explanation for the decrease in rumble strip noise level from 40 to 50 mph. Note that if one were to extrapolate a noise level from the measured LAF_{max} at 40 mph at Site 4, we expect that the resultant noise level would be in agreement with the actual measured value at 60 mph.

[x] At 10 Hz, the wavelength of sound traveling through air is 113 feet. At 100 Hz, it is 11 feet and at 1,000 Hz it is approximately 1 foot.

[xi] U.S. Department of Transportation, Federal Highway Administration, *Highway Traffic Noise: Analysis and Abatement Guidance*, FHWA-HEP-10-26, December 2011.

[xii] U.S. Environmental Protection Agency, *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*, 550/9-74-004, March 1974.

[xiii] ANSI S12.9-2005/Part 4, *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long-term Community Response*, Annex C Sounds with tonal content, 2005.

[xiv] The method for classifying pass-by events on the rumble strip at Site 4 during the overnight period is approximate. We first examined the spectrograms for the nighttime period to identify events that appeared to be vehicle incursions onto the rumble strip. Then, we listened to the audio recordings to refine our classification. The method yields approximately the maximum number of rumble strip events that a person with normal hearing and actively listening could detect.

[xv] International Organization for Standardization, *Acoustics – Reference zero for the calibration of audiometric equipment – Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions*, ISO 389-7:2005(E).

[xvi] For example, the Massachusetts Department of Environmental Protection defines ambient as the sound level that is exceeded for 90% of the time (L_{90}). Their policy is available at the following link (accessed on 8/15/2017): http://www.mass.gov/eea/docs/dep/air/community/noisepolicy.pdf

[xvii] 23 CFR Part 772, as amended 75 FR 39820, July 13, 2010; Effective date July 13, 2011 – *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, Federal Highway Administration, U.S. Department of Transportation. http://www.fhwa.dot.gov/environment/noise/regulations_and_guidance/

[xviii] *Policy and Procedural Guidelines for the Assessment and Abatement of Highway Traffic Noise for Type I Highway Projects*, New Hampshire Department of Transportation, April 2011. http://www.nh.gov/dot/org/projectdevelopment/environment/units/program-management/documents/2011NHDOTNoisePolicy.pdf