Rumble Strip Noise Study

Technical Report

Prepared for
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Executive Summary

On behalf of the Minnesota Department of Transportation (MnDOT), HDR Engineering, Inc. (HDR) measured ambient noise levels along portions of Trunk Highway (TH) 61 containing centerline rumble strips. The project area included sections of two-lane highway north of Two Harbors and north of Grand Marais. During October and November 2013, HDR performed measurements to document the current traffic noise levels, evaluate compliance with MPCA noise standards, and identify unique noise characteristics produced by vehicles driving over the centerline rumble strips.

Long-term monitoring was performed at nine locations with monitoring periods approximately one week in length. MPCA compliance was evaluated, and high compliance percentages were found for the hourly L_{50} at all locations. The hourly L_{10} at locations more than 100 feet from the highway also had high compliance percentages, but the hourly L_{10} at locations within 100 feet had generally low compliance percentages.

Controlled vehicle pass-by monitoring was performed at three locations with centerline rumble strips and a fourth control location without centerline rumble strips. The selection of controlled pass-by monitoring location was found to have a just noticeable effect on typical vehicle pass-by events, but the rumble strip hit noise levels were nearly identical across locations. The driving maneuver performed, and lane of travel were found to have a noticeable effect on noise levels produced by the rumble strips, with a vehicle in the far lane driving continuously on the rumble strip being the loudest combination. The rumble strip hits produced distinct low-frequency tones, which are dependent on the vehicle speed. At distances up to 100 feet, noise levels from the rumble strip noise attenuate less than noise from typical vehicle pass-by events. Spectral rumble strip noise levels were extrapolated using the software Cadna-A. These illustrate the distances required for the rumble strip noise to be reduced to noise levels measured during the long-term noise monitoring.

The distinctly audible rumble strip hit characteristics were used in an attempt to calculate the rumble strip hit rate from the long-term measurement data. Audio from select hours was reviewed to provide data with known vehicle pass-by events and rumble strip hits. The reviewed hours were used to test criteria capable of identifying vehicle pass-by events and rumble strip hits, but the resulting criteria could not provide reliable results for higher traffic periods. A visual component is recommended to study the hit rate, which is capable of identifying vehicles passing simultaneously or in groups.

HDR documented the project area noise levels through long-term monitoring and documented centerline rumble strip noise levels by measuring noise emissions from controlled vehicle pass-by events. Compliance with MPCA noise standards was evaluated, and distinct rumble strip characteristics were identified. Hit rates from limited data sets are presented.

1 Introduction

On behalf of the Minnesota Department of Transportation (MnDOT) HDR Engineering, Inc. (HDR) studied noise from traffic driving on centerline rumble strips along Trunk Highway (TH) 61. TH 61 extends from Duluth, Minnesota to the Canadian border, and generally follows the shoreline of Lake Superior. The project area consisted of two main sections of two-lane highway: north of Two Harbors, between mile markers 31 and 51, and north of Grand Marais, between mile markers 112 and 123. In 2012, the annual average daily traffic (AADT) ranged from 4,250 to 5,900 vehicles for the section north of Two Harbors and from 2,250 to 2,600 vehicles for the section north of Grand Marais (MnDOT 2012).

In the summer of 2012 and 2013, MnDOT installed rumble strips on the centerline of TH 61 highway throughout the project area. In the summer of 2013, residents contacted MnDOT to express concerns regarding rumble strip noise. In the fall of 2013, MnDOT initiated a contract with a third party to conduct a noise study and assessment. HDR measured outdoor noise levels during the months of October and November 2013. These measurements included long-term monitoring (periods of approximately one week) along TH 61 and controlled vehicle pass-by monitoring adjacent to TH 61. At select locations mitigation measures are being discussed to reduce the depth of the centerline rumble strips, which reduces the loudness.

The goal of the study was to create a record of the rumble strip noise levels before mitigation measures were implemented, compare measured noise levels to Minnesota Pollution Control Agency (MPCA) noise standards, and characterize the centerline rumble strips in terms of noise level and frequency content.

1.1 Acoustic Concepts

Sound is made up of tiny fluctuations in air pressure. Sound is characterized by both its amplitude (how loud it is) and frequency (or pitch). Sound, within the range of human hearing, can vary in amplitude by over one million units. Therefore, a logarithmic scale, known as the decibel (dB) scale, is used to quantify sound intensity and to compress the scale to a more manageable range. Noise is simply defined as unwanted sound; the terms noise and sound are often used interchangeably.

The human ear does not hear all frequencies equally. In fact, the human hearing organs of the inner ear deemphasize very low and very high frequencies. The most common weighting scale used to reflect this selective sensitivity of human hearing is the A-weighted decibel (dBA). Unweighted noise levels are unaltered and given the unit dB or dBL (L stands for linear). The human range of hearing extends from approximately 3 dBA to around 140 dBA. Table 1-1 provides typical A-weighted levels for various noise sources.

Table 1-1 Typical Noise Levels

Sound Pressure Level, dBA (re 20 μPa)	Noise Source
140	Jet Engine (at 80 feet)
130	Jet Aircraft (at 300 feet)
120	Rock Concert
110	Pneumatic Chipper
100	Jackhammer (at 3 feet)
90	Chainsaw, Lawn Mower (at 3 feet)
80	Heavy Truck Traffic
70	Business Office, Vacuum Cleaner
60	Conversational Speech, Typical TV Volume
50	Library
40	Bedroom
30	Secluded Woods
20	Whisper

Source: MPCA 2008.

Because of the logarithmic scale, noise levels cannot be simply added or subtracted. If noise energy (i.e. the number of identical noise sources) is doubled, the noise level only increases by 3 dBA. A doubling of noise energy is not perceived by humans as a doubling of loudness. A 3 dBA change is considered the lowest limit of noticeable difference, a 5 dBA change is considered a noticeable difference, and a 10 dBA change is considered a doubling or halving of loudness.

Most noises are made up of a wide range of frequencies, and are termed broadband noises. Noises that are focused to a particular frequency (and harmonic multiples of that frequency) are tonal noises. Noise sources can be constant or time-varying. Environmental noise monitoring is often performed over periods of time, allowing time-varying signals to be represented by noise levels averaged over intervals (e.g. an hour).

1.2 Acoustic Metrics

Equivalent Average Sound Level (L_{eq}). The L_{eq} represents a constant sound that, over the specified period (e.g. one second or one hour), has the same acoustic energy as the time-varying signal.

Maximum Sound Level (L_{max}). The L_{max} represents the maximum sound pressure level measured during a certain period.

Minimum Sound Level (L_{min}). The L_{min} represents the minimum sound pressure level measured during a certain period.

Centile Levels (L_x). L_{10} and L_{50} are centile metrics representing the noise levels exceeded for 10 and 50 percent of the hour, respectively.

Measured Vehicle Noise Level (L_{veh}). The L_{veh} is the noise level corresponding to the designated speed on a linear regression line of L_{max} versus the logarithm of the vehicle speed for a sample of vehicle pass-by events.

Reference Vehicle Noise Level ($L_{veh, ref}$). The $L_{veh, ref}$ is calculated using the designated speed and the Reference Noise Curve from AASHTO TP 98-12.

Statistical Isolated Pass-By Index (SIPI). The SIPI is the difference between L_{veh} and $L_{veh, ref}$, and can be used to compare pass-by events from different pavements.

1.3 MPCA Noise Standard

Minnesota Rules Section 7030.0000 contains the MPCA noise standards. Section 7030.0050 of the Rules categorizes residential land use activities under Noise Area Classification 1 (NAC-1). Table 1-2 summarizes the noise limits for NAC-1, which exist in Section 7030.0040.

Table 1-2. MPCA Noise Standards

Daytime Noise Limits (7:00 a.m. – 10:00 p.m.), dBA (re 20 Pa)		Nighttime Noise Limits (10:00 p.m. – 7:00 a.m.), dBA (re 20 µPa)	
L_{10}	L_{50}	L_{10}	L_{50}
65	60	55	50

Source: MPCA 2008.

The L_{10} is more influenced by shorter-term noise events, and L_{50} is representative of more constant noises. Measured, hourly L_{10} and L_{50} values are compared to the stated noise limits to determine compliance with the MPCA noise standard. Note that noise levels in compliance with the MPCA noise standard, or any noise standard, could still be considered unsatisfactory or annoying. Tonal sources in particular are perceived as more distinct than broadband noises. Rumble strip noise events are short duration and infrequent, and are unlikely to have an accumulated duration of more than ten percent of the hour (6 minutes of the hour). As such, other noise sources would be needed to exceed the MPCA noise limits.

2 Measurement Methods

HDR's measurement methodology generally followed the MnDOT Noise Policy (MnDOT 2011) and MPCA method NTP-1, *Measurement Procedure for Non-Impulsive Noise* (MPCA 2008). Ambient temperatures below the recommended range of the MnDOT Noise Policy did occur during monitoring. Where feasible, the controlled vehicle pass-by measurements followed the methods of AASHTO TP 98-12, *Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-By (SIP) Method* (AASHTO 2012).

2.1 Instrumentation

The instrumentation used for the project included the following.

- Larson Davis (LD) digital sound level meters with 1/3 octave band filters
- Environmental microphones and preamplifiers, complete with large wind screens and bird spikes
- RM Young anemometers
- Edirol R09 digital audio recorders
- Pelican cases used to store the sound level meter, Edirol R09, and batteries
- Tripods to hold each microphone/preamplifier/meter and each RM Young anemometer
- Handheld precision acoustic calibrator

The acoustic instrumentation and the handheld calibrator meet Class 1/Type 1 precision requirements of ANSI and IEC standards and are calibrated on a regular basis by an independent accredited calibration laboratory using standards traceable to the National Institute of Standards and Technology. The noise measurement equipment was also adjusted to a reference level traceable to the National Institute of Standards and Technology using a battery operated precision microphone calibrator. The noise measurement equipment was calibrated and adjusted in HDR's office prior to transportation to the measurement site. Calibration checks were performed in the field before the first measurement and after completion of each series of measurements. Table 2-1 provides a summary of the monitoring equipment used at each location.

Table 2-1. Monitoring Equipment Summary

Sound Level Meter	Preamplifier	Microphone	Monitoring Location
LD-831 #1 (SN 2197)	LD-426A12 (SN 016386)	See preamplifier	ML6, PB1, PB2, PB3, PBC
LD-831 #2 (SN 2196)	LD-PRM831 (SN 016876)	PCB Piezotronics 377B02 (SN 116131)	ML4, ML8, PB1, PB3
LD-831 #3 (SN 2195)	LD-426A12 (SN 016615)	See preamplifier	ML2, ML7, PB1*
LD-831 #4 (SN 2194)	LD-426A12 (SN 016614)	See preamplifier	ML1, ML9
LD-831 #5 (SN 3006)	LD-PRM831 (SN 026012)	PCB Piezotronics 377B02 (SN 135962)	ML3, ML5, PB3
LD-824 #1 (SN 3204)	LD-PRM902 (SN 3380)	PCB Piezotronics 377B41 (SN 1004)	ROW
LD-824 #2 (SN 2636)	LD-PRM902 (SN 2618)	LD-2541 (SN 7490)	PB2, PBC, ROW
LD-824 #3 (SN 0764)	LD-PRM902 (SN 1207)	LD-2541 (SN 4185)	PB2, PBC

*The LD-PRM831 (SN 026012) preamplifier and PCB Piezotronics 377B02 (SN 135962) microphone were used in place of the LD-426A12 (SN 016615) at this monitoring location.

The ML abbreviation is used for the long-term monitoring locations, PB is used for the controlled vehicle pass-by locations, and ROW represents short-term right-of-way measurements performed adjacent to TH 61 and corresponding to each long-term monitoring location. The ROW measurements are not specifically presented in this report, but were performed to help identify rumble strip hits in the long-term data.

2.2 Long-Term Data Collection

Long-term monitoring was performed at seven single-family homes, a lodge, and a clearing along TH 61. Monitoring was conducted over a one week period at each location, with the nine locations divided into two phases. Following the MnDOT Noise Policy (MnDOT 2011) and MPCA guidance document (MPCA 2008), data was collected at each long-term location as follows.

- The monitoring system either operated on AC power or battery power with connected solar panels.

- The microphone was installed approximately six feet above the ground, and was located at least 20 feet from large reflecting surfaces.
- The sound level meter continuously integrated sound pressure level measurements using a fast response time and stored data every hour on the hour.
- The sound level meter additionally recorded sound pressure levels every second.
- The acoustic measurement data included A-weighted L_{eq}, L_{min}, L_{max}, L_{10}, L_{50}, and unweighted spectral (frequency) data.
- A continuous audio file was recorded for selective audio review.
- Wind speed at the microphone height was measured at several locations, and a log of hourly wind speeds was obtained from the nearest weather tower.
- A log of precipitation events was obtained from the nearest weather tower.

HDR performed long-term and short-term measurements by configuring sound level meters to log data in one-second and one-hour intervals. Using the audio recordings and the one-second data, extraneous noise events were identified and removed from the measurement data. Extraneous noise events confirmed by selective audio review included construction activities, lawnmowers, and airplane flyovers. Removing these events from the measurement data provides results that are more representative of project-related noise levels. While selective audio review helps identify easily distinguishable extraneous noise, some extraneous events are expected to still be present in the data. Per the MPCA, hours containing precipitation events or average winds equal to or exceeding 11 miles per hour (mph) were removed.

2.3 Controlled Pass-By Data Collection

HDR performed controlled pass-by measurements at three locations with centerline rumble strips and a fourth control location (which had no centerline rumble strips). The same Chevrolet Malibu was used at all four locations, and traffic control was used to perform isolated pass-by events. Data was collected at each pass-by location as follows.

- Sound level meters were located perpendicular to the road at distances of 25, 50, and 100 feet from the centerline of the road (the center of the rumble strip).
- At 25-feet, the microphone was installed approximately five feet above the pavement. The other two microphones (at the farther distances) were as close to the same height relative to the pavement as possible. No microphone was within 50 feet of large vertical reflecting surfaces.
- The sound level meters continuously integrated sound pressure level measurements using a fast response time.
- The LD-831 sound level meters recorded data every 100 ms, and the LD-824 sound level meters recorded data every 125 ms (spectral data was limited to every second for the LD-824).

- The acoustic measurement data included A-weighted L_{eq}, L_{min}, L_{max}, and unweighted spectral L_{eq} and L_{max}.
- A digital audio file was recorded at a minimum of one of the measurement distances.
- Wind speed was recorded at the microphone height at the 50-foot distance.
- Vehicle speed was measured using a Bushnell Speedster handheld radar gun.
- Three passes were performed for three different maneuvers, and three vehicle speeds (27 total passes at each location).
    1. The three maneuvers were a control pass-by in the near lane, a continuous rumble strip hit simulating a drifting vehicle (alternated between the near, far, and near lane), and a merging rumble strip hit simulating a vehicle passing another vehicle (alternated between the near, far, and near lane).
    2. The three vehicle speeds were 45, 55, and 65 mph.

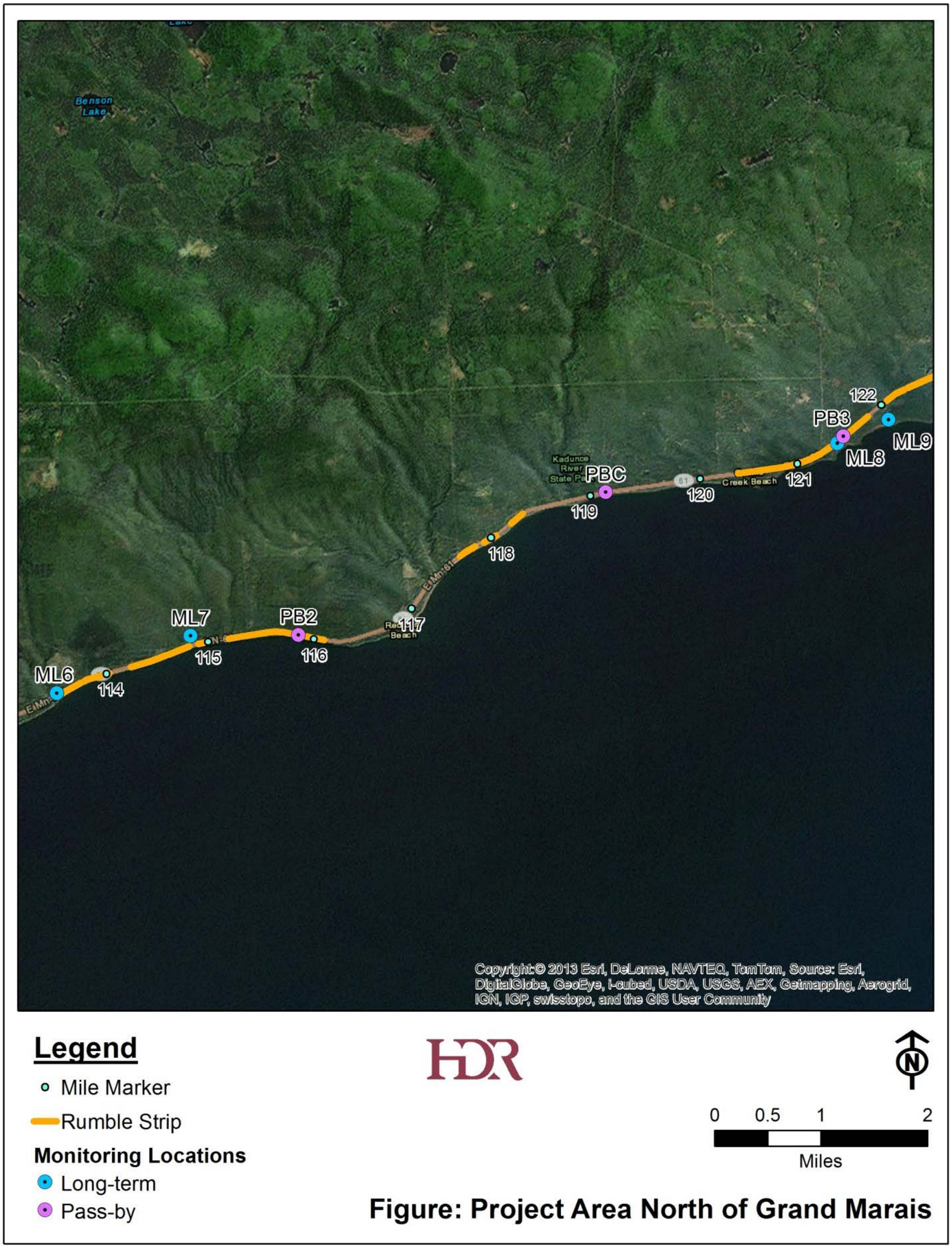
Regression analyses were performed on the overall L_{max} and 1/3 octave band L_{max} values to determine the effects of monitoring location, maneuver, lane of travel, vehicle speed, and distance.

3 Monitoring Locations

HDR performed long-term noise monitoring at nine locations and controlled vehicle pass-by monitoring at four locations throughout the project area. Figure 3-1 and Figure 3-2 show the monitoring locations.

Figure 3-1. Project Area North of Two Harbors

Figure 3-2. Project Area North of Grand Marais



The nine long-term monitoring locations represented various sections of rumble strips, a range of distances from the highway, both sides of the highway, locations uphill and downhill, and a range of landscapes. Table 3-1 provides a summary of the long-term monitoring locations.

Table 3-1. Summary of Long-Term Monitoring Locations

Monitoring Location	Distance to TH 61, feet	Monitoring Period	Description
ML1	130	Oct. 24 – Nov. 2	A residence on the lakeside of the highway between mile markers 31 and 32. A wooden fence stood between the home and the highway.
ML2	60	Oct. 24 – Nov. 2	A residence with direct line of sight on the landside of the highway between mile markers 32 and 33.
ML3	900	Oct. 25 – Nov. 2	A lodge on the lakeside of the highway between mile markers 32 and 33. The land separating the lodge from the highway was heavily wooded.
ML4	30	Oct. 25 – Nov. 2	A residence directly on the landside of the highway between mile markers 41 and 42.
ML5	430	Oct. 17 – Oct. 24	A residence on the lakeside of the highway between mile markers 46 and 47. The residence was downhill from the highway in a wooded area.
ML6	80	Oct. 16 – Oct. 23	A residence directly on the landside of the highway between mile markers 113 and 114.
ML7	450	Oct. 16 – Oct. 23	A residence on the landside of the highway between mile markers 114 and 115. The residence was uphill but had direct line of sight.
ML8	60	Oct. 16 – Oct. 23	A clearing along the lakeside of the highway between mile markers 121 and 122.
ML9	800	Oct. 16 – Oct. 24*	A residence on the lakeside of the highway between mile makers 121 and 122. The land separating the residence from the highway was wooded.

*Monitoring system was not collecting data from October 21 to October 23 due to a power outage and technical difficulties.

The three locations where HDR measured noise during controlled pass-bys represented different sections of rumble strips, varying landscapes, and both sides of the highway. The control location was a typical landscape for the area, allowing for comparison with the three rumble strip locations. Table 3-2 provides a summary of the controlled pass-by monitoring locations.

Table 3-2. Summary of Pass-By Monitoring Locations

Monitoring Location	Monitoring Date	Description
PB1	Oct. 24	A clearing on the lakeside of the highway between mile markers 46 and 47. The vegetation was short grass, but the highway had a slight slope in the direction of travel.
PB2	Oct. 29	A clearing on the landside of the highway between mile markers 115 and 116. The highway was adjacent to the lake, and a thin tree line provided shielding for the widest angles at 100 feet.
PB3	Oct. 25	A clearing along the lakeside of the highway between mile markers 121 and 122. The same clearing as ML8.
PBC (Control)	Oct. 29	A clearing in a residential area on the landside of the highway between mile markers 119 and 120. The highway was adjacent to the lake, and the vegetation was knee-high grass.

The monitoring locations were selected to represent the entire project area.

4 Long-Term Monitoring Results

This section contains a summary of the long-term monitoring results. Detailed results for each monitoring location can be found in Section 9 (Appendix A). Each location's complete data set was reduced to exclude hours with precipitation, hours with high winds, and periods of extraneous noise per MPCA guidance. The reduced data set was used to calculate overall noise levels and determine compliance with the MPCA noise standard. Table 4-1 contains a summary of noise levels across the entire monitoring period at each monitoring location, sorted by distance from TH 61.

Table 4-1. Summary of Long-Term Monitoring Levels

Monitoring Location	Distance to TH 61, feet	Median of Hourly L_{50}, dBA (re 20 μPa)
ML4	30	47
ML2	60	49
ML8	60	47
ML6	80	47
ML1	130	42
ML5	430	41
ML7	450	42
ML9	800	41
ML3	900	38

The overall noise level is clearly dependent upon the distance from TH 61. With increasing distance from the highway, the noise levels generally decrease.

Each complete data set was reduced to exclude hours with precipitation, hours with average microphone-height wind speeds of 11 mph or more, and periods of extraneous noise (construction activities, airplane flyovers, etc.) per MPCA guidance. If at least half of the hour contained extraneous noise, the full hour was excluded. These three exclusions remove events that could skew the measured data, and therefore results in a more accurate representation of project-related noise levels. Table 4-2 provides a summary of the exclusions in terms of percentage of the monitoring period and the number of hours.

Table 4-2. Summary of Long-Term Monitoring Exclusions

Monitoring Location	Precipitation		High Winds		Extraneous		Remaining	
	%	Hours	%	Hours	%	Hours	%	Hours
ML1	13	30	3	7	2	5	81	181
ML2	13	30	3	7	1	2	83	185
ML3	14	29	2	5	1	2	83	167
ML4	8	11	2	3	2	3	88	116
ML5	24	41	0	0	1	3	75	128
ML6	27	46	11	19	2	4	65	110
ML7	27	46	11	19	1	2	66	112
ML8	27	46	11	19	1	2	66	113
ML9	26	37	3	5	4	6	67	97

Note: A single hour can have multiple reasons for exclusion, so the four percentages for each location do not necessarily sum to 100 percent.

The majority of the exclusions were due to precipitation. More precipitation and high wind hours occurred during the first week of monitoring, as shown by the higher weather-related percentages and counts for ML5 through ML9. Anemometers were used at all but two locations to measure wind speeds at the microphone height, but in the end wind speeds from the nearest weather tower were used for all locations. This approach was more consistent and considered conservative as weather towers typically measure wind speeds at elevations higher than microphone-height.

The hourly L_{10} and L_{50} values of the reduced data sets were compared to the MPCA noise standard. Compliance percentages were calculated as the percentage of hours in the reduced data sets that comply with the MPCA noise limits. The reduced data sets are used as they follow the exclusion methodology of the MPCA. Table 4-3 contains the compliance percentages for each location.

Table 4-3. Summary of Long-Term Monitoring MPCA Compliance

Monitoring Location	Distance to TH 61, feet	Percentage of Hours Compliant with MPCA			
		Daytime (7:00 a.m. – 10:00 p.m.)		Nighttime (10:00 p.m. – 7:00 a.m.)	
		L_{10}	L_{50}	L_{10}	L_{50}
ML1	130	100	100	95	100
ML2	60	26	97	59	94
ML3	900	100	100	100	100
ML4	30	10	96	70	96
ML5	430	100	100	100	100
ML6	80	32	100	81	100
ML7	450	100	100	100	100
ML8	60	100	100	85	94
ML9	800	100	100	100	100

Compliance percentages are shown for all four noise limits: L_{10} and L_{50} for daytime and nighttime hours. The results indicate high compliance percentages for the L_{50} noise limits for all locations. The L_{50} metric is heavily influenced by noises that occur for more than 50 percent of the hour (i.e. more constant noises), which makes sense because it is the level exceeded for 50 percent of the hour. The traffic on TH 61 appears to be light enough that measured hourly L_{50} values generally complied with MPCA noise standards.

For locations more than 100 feet from the highway, high compliance percentages are also seen for L_{10}. Very low daytime L_{10} compliance percentages are seen for ML2, ML4, and ML6, with fairly low percentages for nighttime L_{10}. These results indicate locations near the highway are heavily affected by highway noise. When traffic is reduced at night, the compliance percentages are higher even though the noise limits are stricter. The higher L_{10} compliance percentages at ML6 compared to ML2 and ML4 could be due to increased distance or lower traffic volumes in the area north of Grand Marais.

The outlier of the group is ML8. Despite being the same distance from the highway as ML2 and closer to the highway than ML6, ML8 displayed much higher compliance percentages and lower overall levels (Table 4-1). ML8 was the only location without nearby buildings, but at all locations the microphones were placed as far from buildings as possible to avoid acoustical reflections. ML8 also had the unique characteristic of being at a lower grade than the pavement (by a few feet); ML2, ML4, and ML6 were at approximately the same grade as the pavement.

This difference in grade put the microphone at ML8 close to the elevation of the pavement, while the microphones at ML2, ML4, and ML6 were approximately 5 feet above pavement. The trend of lower noise levels at lower grades also appears when comparing levels at ML5 (downhill of TH 61) to ML7 (uphill of TH 61), but the difference in grade was substantially greater at those locations. Regardless, uphill locations are more likely to maintain a direct line of sight with the traffic (particularly the tire-pavement interaction) and are therefore generally expected to experience higher noise levels.

5 Controlled Pass-By Monitoring Results

This section contains a summary of the pass-by monitoring results. Appendix B contains detailed results for each monitoring location.

Vehicle pass-bys produce a distinct peak in noise level. Relative to a stationary roadside observer, the noise level increases as the vehicle approaches, then hits a maximum noise level adjacent to the observer, and then decreases as the vehicle continues away from the observer. Due to these characteristic, the goal of vehicle pass-by measurements is to obtain the maximum noise level. For this study, the highway was temporarily closed to ensure a controlled test environment for analyzing a single vehicle’s pass-by noise levels.

At each pass-by monitoring location there were three vehicle pass-bys for each of three maneuvers and three speeds for a total of 27 pass-by events. Each maneuver was performed over a 100-foot test distance, which began 50 feet before the perpendicular line of sound level meters and ended 50 feet after the sound level meters. Table 5-1 lists the nine passes performed for each maneuver.

Table 5-1. Summary of Controlled Vehicle Pass-By Events

Pass	Speed, mph	Maneuver		
		Control	Drift	Merge
1	45	Near Lane	Near Lane	Near Lane
2	45	Near Lane	Far Lane	Far Lane
3	45	Near Lane	Near Lane	Near Lane
4	55	Near Lane	Near Lane	Near Lane
5	55	Near Lane	Far Lane	Far Lane
6	55	Near Lane	Near Lane	Near Lane
7	65	Near Lane	Near Lane	Near Lane
8	65	Near Lane	Far Lane	Far Lane
9	65	Near Lane	Near Lane	Near Lane

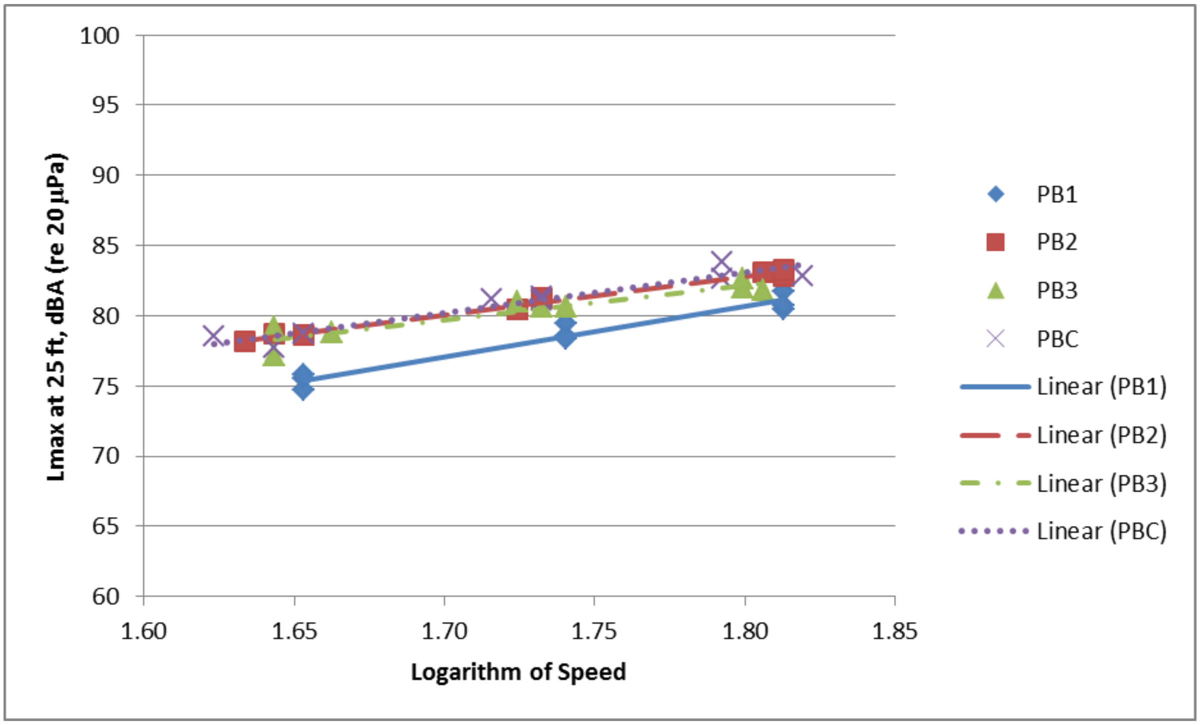
The monitoring location, maneuver, speed, lane of travel, and distance from the centerline of TH 61 served as independent variables for the study. The control maneuver was just a basic vehicle pass-by with no rumble strip hits, so this maneuver was always performed in the near lane. For the drift maneuver, the vehicle traveled in the stated lane and simply drifted onto the centerline rumble strip for a continuous rumble strip hit. The vehicle was on the centerline rumble strip for the entirety of the 100-foot test distance. For the merge maneuver, the stated lane of travel is the initial lane of travel. The vehicle began to merge into the opposite lane at the beginning of the 100-foot test distance, so the vehicle hit the centerline rumble strip as close to the centerline of the test distance as possible. The vehicle then merged back into the initial lane of travel; however, the maximum noise level should have occurred during the initial merge into the opposite lane.

Despite having a control maneuver, the control monitoring location with no centerline rumble strips was used to replicate the drift and merge maneuvers in the absence of rumble strips. HDR performed linear regressions on the measurement data to determine the effects of each independent variable. The regression analyses used the measured L_{max} values to determine the measured vehicle noise level (L_{veh}), which was calculated following the methodology of AASHTO TP 98-12. An additional analysis was performed to compare results of this study to results of a previous MnDOT study of shoulder rumble strips.

5.1 Location Analysis

The first analysis explored the effects of monitoring location on the overall maximum noise level. The measured speeds and L_{max} values were divided by monitoring location and maneuver. The L_{max} at 25 feet was used to provide the greatest signal-to-noise ratio. The regression results are presented as scatter plots of the L_{max} versus the logarithmic speed. Each data set has the associated linear regression line plotted. A summary table containing the sample size and calculated values is also given for each regression. Figure 5-1 shows the control maneuver results by monitoring location.

Figure 5-1. Monitoring Location Linear Regression with Control Maneuver



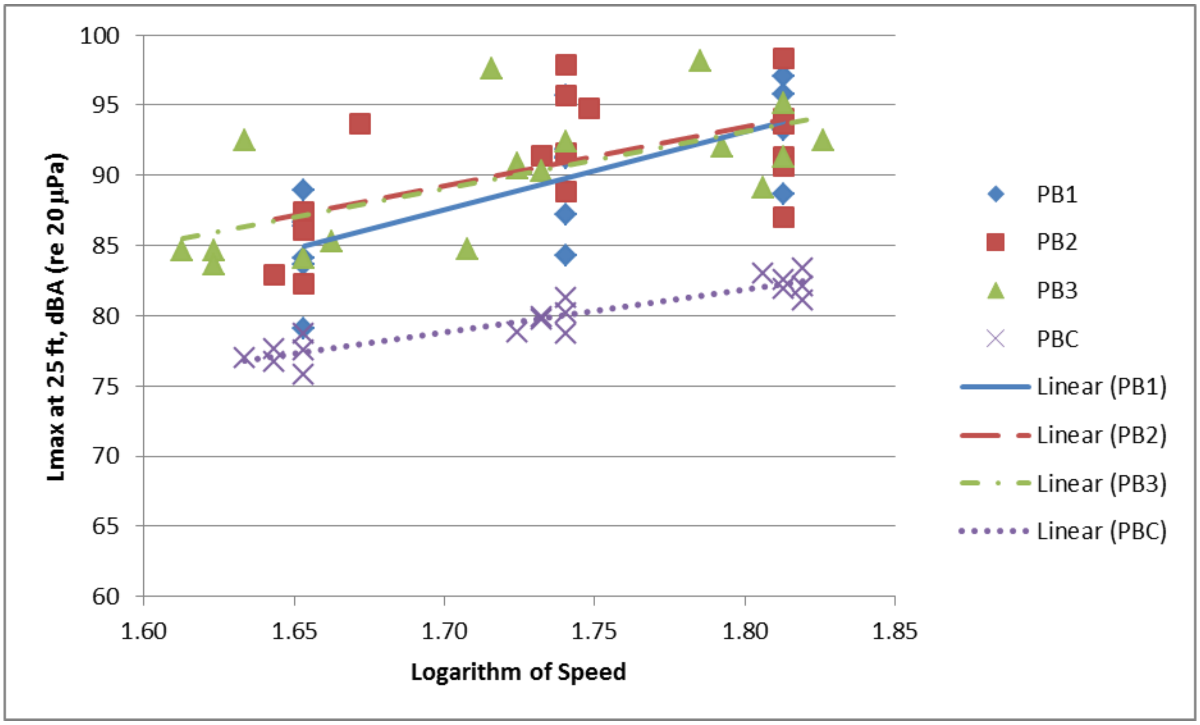
PB1 was found to be quieter than the other three locations. Table 5-2 summarizes the control maneuver results by monitoring location.

Table 5-2. Monitoring Location Linear Regression with Control Maneuver

Parameter	Monitoring Location			
	PB1	PB2	PB3	PBC
Number of Vehicles	9	9	9	9
Regression Slope	35.3	27.3	24.7	28.6
Regression Intercept	16.8	33.6	37.7	31.5
Average Speed, mph	54	53	53	53
L_{veh}, dBA (re 20 µPa)	78	81	80	81
$L_{veh, ref}$, dBA (re 20 µPa)	79	78	78	78
SIPI	-0.3	2.4	2.1	2.7

The measured L_{veh} for the control maneuver (i.e. a basic vehicle pass-by) at PB2, PB3, and PBC were found to be within 1 dBA of each other. However, the L_{veh} at PB1 was found to be 2 to 3 dBA lower than the other three locations. This result suggests the pavement in the project area north of Grand Marais is slightly louder than the pavement in the project area north of Two Harbors, but is at most a just noticeable difference. PB1 had a vertical rock outcropping on the side of the road opposite of the sound level meters, but it is clear the rocks had no effect or less of an effect than the differences in pavement. Figure 5-2 shows the rumble strip hit results (with the drift and merge maneuvers combined) by monitoring location.

Figure 5-2. Monitoring Location Linear Regression with Drift and Merge Maneuvers



The data points from the locations with rumble strips are too sporadic to draw meaningful conclusions. Table 5-3 summarizes the rumble strip hit results by monitoring location.

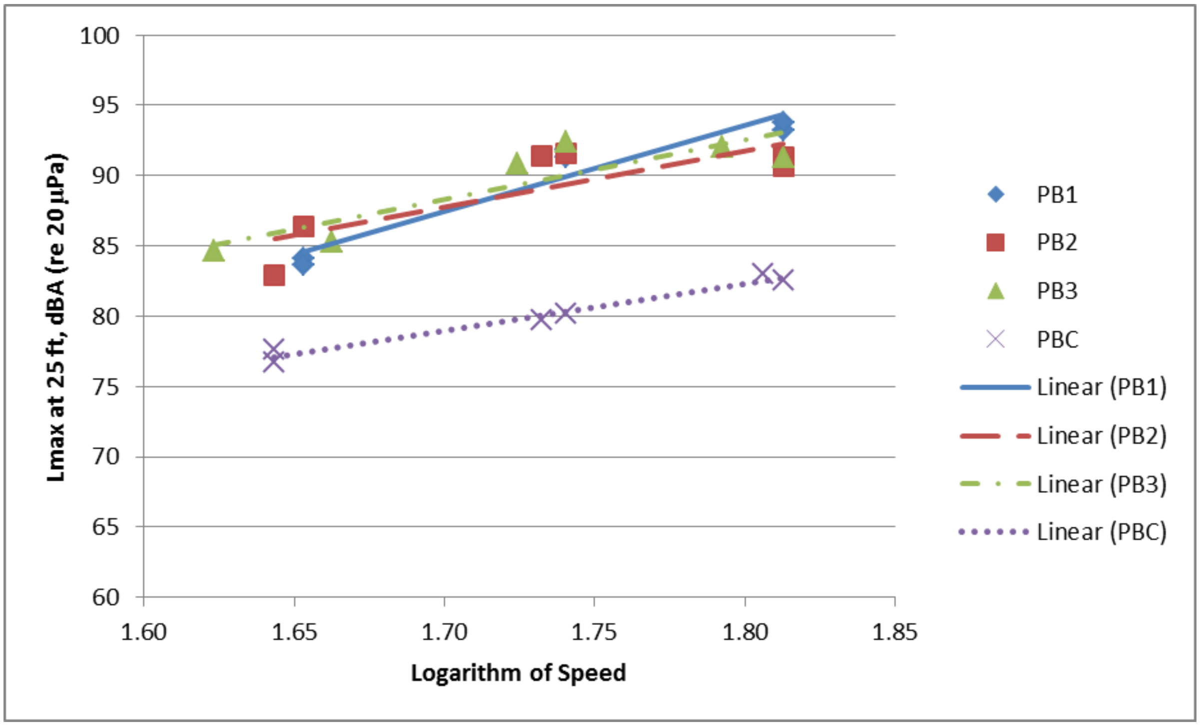
Table 5-3. Monitoring Location Linear Regression with Drift and Merge Maneuvers

Parameter	Monitoring Location			
	PB1	PB2	PB3	PBC
Number of Vehicles	18	18	18	18
Regression Slope	55.4	41.7	40.7	30.3
Regression Intercept	-6.6	18.3	19.9	27.3
Average Speed, mph	54	54	53	54
L_{veh}, dBA (re 20 μPa)	90	91	90	80
$L_{veh, ref}$, dBA (re 20 μPa)	79	79	78	79
SIPI	10.9	12.1	11.9	1.2

The measured levels with rumble strip hits (PB1, PB2, and PB3) were found to be extremely variable. Because of the variation in the plotted values, the monitoring locations could not be accurately compared. However, it is clear the lack of rumble strips at PBC yielded lower noise levels. This regression illustrates the need to further explore variables influencing the rumble strip hits.

To better compare the rumble strip hit noise levels across monitoring locations, the drift maneuver in the near lane was selected. This subset of data is a little smaller, but is the only option for an accurate comparison given the variability of the rumble strip hit noise levels. Figure 5-3 shows the noise levels for the drift maneuver in the near lane for each monitoring location.

Figure 5-3. Monitoring Location Linear Regression with the Drift Near Maneuver



The locations with rumble strips (PB1, PB2, and PB3) produced similar results across the locations, indicating the monitoring location had little to no effect on the measured rumble strip noise levels. The noise levels are much lower than no rumble strips are present (PBC). Table 5-4 summarizes the drift maneuver in the near lane results by monitoring location.

Table 5-4. Monitoring Location Linear Regression with the Drift Near Maneuver

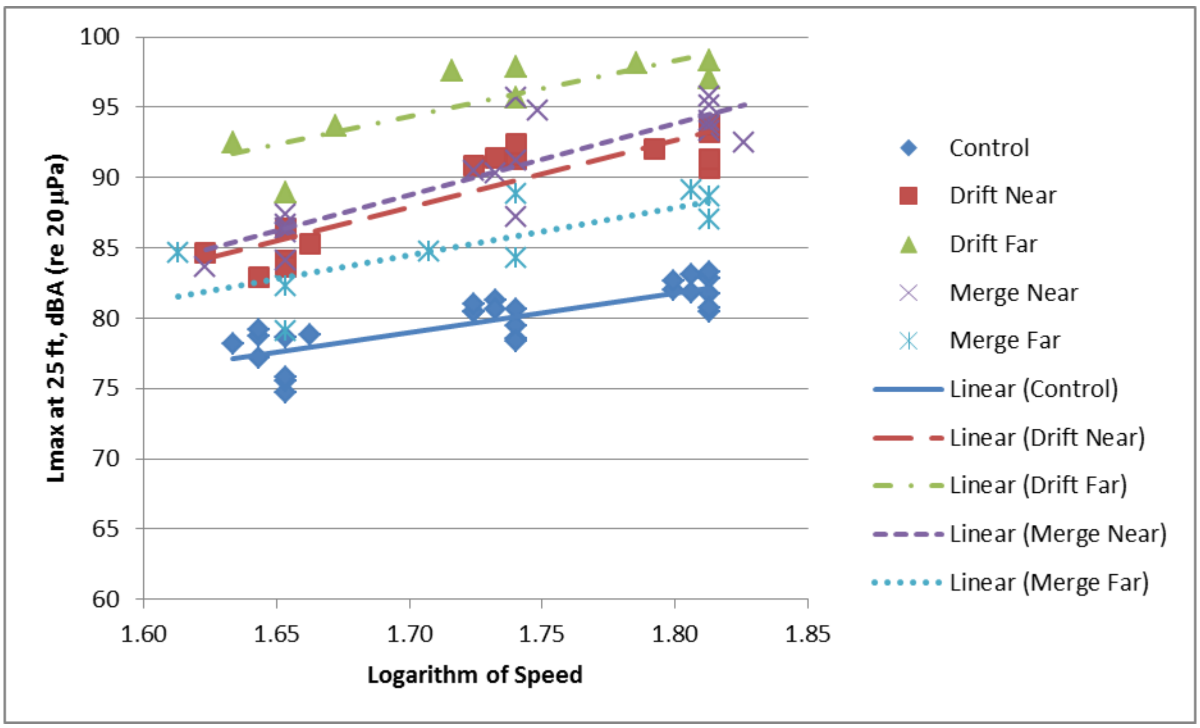
Parameter	Monitoring Location			
	PB1	PB2	PB3	PBC
Number of Vehicles	6	6	6	6
Regression Slope	61.1	40.1	42.4	33.5
Regression Intercept	-16.5	19.6	16.3	22.0
Average Speed, mph	54	54	53	54
L_{veh}, dBA (re 20 µPa)	90	89	89	80
$L_{veh, ref}$, dBA (re 20 µPa)	79	79	78	78
SIPI	11.0	10.5	11.2	1.5

The L_{veh} at PB1, PB2, and PB3 were nearly identical, with a significantly lower L_{veh} found at PBC. With similar $L_{veh, ref}$ values across each location, the SIPI illustrates the same trend. This means there is no perceptible difference in rumble strip loudness across the monitoring locations.

5.2 Maneuver and Lane Analysis

The second analysis explored the effects of maneuver and lane of travel on the overall maximum noise level. The L_{max} at 25 feet was used to provide the greatest signal-to-noise ratio. The measured L_{max} data was divided into groups based upon the maneuver and lane of travel, so the monitoring locations were grouped together. The locations with centerline rumble strips (PB1, PB2, and PB3) were divided into five groups: control maneuver in the near lane, drift maneuver in the near lane, drift maneuver in the far lane, merge maneuver in the near lane, and merge maneuver in the far lane. Figure 5-4 presents the results for the locations with centerline rumble strips.

Figure 5-4. Maneuver and Lane Linear Regression with Rumble Strips



The above figure illustrates the type of the rumble strip hit can drastic effect the noise levels. The drift maneuver in the far lane was the loudest, and the control maneuver was the quietest. The merge maneuver in the near lane and the drift maneuver in the near lane produced similar noise levels. Table 5-5 summarizes the maneuver and lane regression results at locations with centerline rumble strips.

Table 5-5. Maneuver and Lane Linear Regression with Rumble Strips

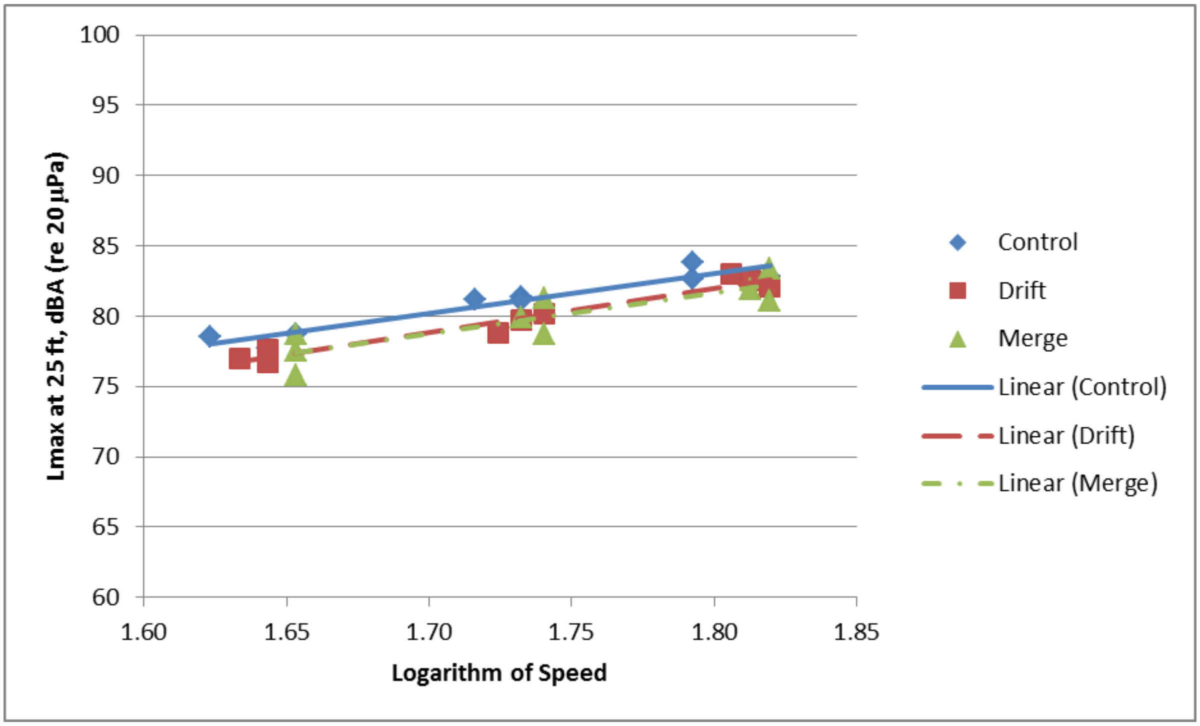
Parameter	Maneuver and Lane				
	Control Near	Drift Near	Drift Far	Merge Near	Merge Far
Number of Vehicles	27	18	9	18	9
Regression Slope	28.2	47.5	39.3	50.8	33.6
Regression Intercept	31.0	7.1	27.6	2.4	27.3
Average Speed, mph	54	54	54	54	53
L_{veh}, dBA (re 20 μPa)	80	89	96	90	85
$L_{veh, ref}$, dBA (re 20 μPa)	78	78	78	79	78
SIPI	1.4	10.9	17.1	11.9	7.1

The drift maneuver in the far lane produced an L_{veh} value 16 dBA higher than the control maneuver. The merge maneuver in the near lane and the drift maneuver in the near lane produced L_{veh} values 10 dBA and 9 dBA higher than the control maneuver, respectively. Finally, the merge maneuver in the far lane yielded an L_{veh} value 5 dBA higher than the control maneuver.

These results highlight the variable nature of rumble strip hits, which can have a dramatic effect on the noise levels. For the drift maneuver, it is clear the vehicle itself provides acoustic shielding when traveling in the near lane (it blocks the rumble strip noise from reaching the listener). When traveling in the far lane, the direct line of sight with the tires as they hit the centerline rumble strips yielded higher rumble strip noise levels. For the merge maneuver, the direct line of sight with the tires was reversed. The near lane levels were higher indicating the tires nearest the sound level meters must have been crossing the rumble strips as the vehicle merged into the far lane.

PBC, the control location which had no rumble strips, was used to ensure the testing methodology was producing accurate results. The lane of travel was not distinguished yielding three subdivisions in the data: control, drift, and merge maneuver. Figure 5-5 presents the maneuver results for PBC.

Figure 5-5. Maneuver Linear Regression without Rumble Strips



When no rumble strips are present, the noise levels are nearly identical. The drift and merge maneuvers were slightly quieter because the vehicle alternated between the near and far lanes (the far lane put the vehicle further from the sound level meter). Table 5-6 summarizes the maneuver regression results at PBC.

Table 5-6. Maneuver Linear Regression without Rumble Strips

Parameter	Maneuver		
	Control	Drift	Merge
Number of Vehicles	9	9	9
Regression Slope	28.6	31.3	29.3
Regression Intercept	31.5	25.7	29.0
Average Speed, mph	53	54	54
L_{veh}, dBA (re 20 µPa)	81	80	80
$L_{veh, ref}$, dBA (re 20 µPa)	78	78	79
SIPI	2.7	1.4	1.1

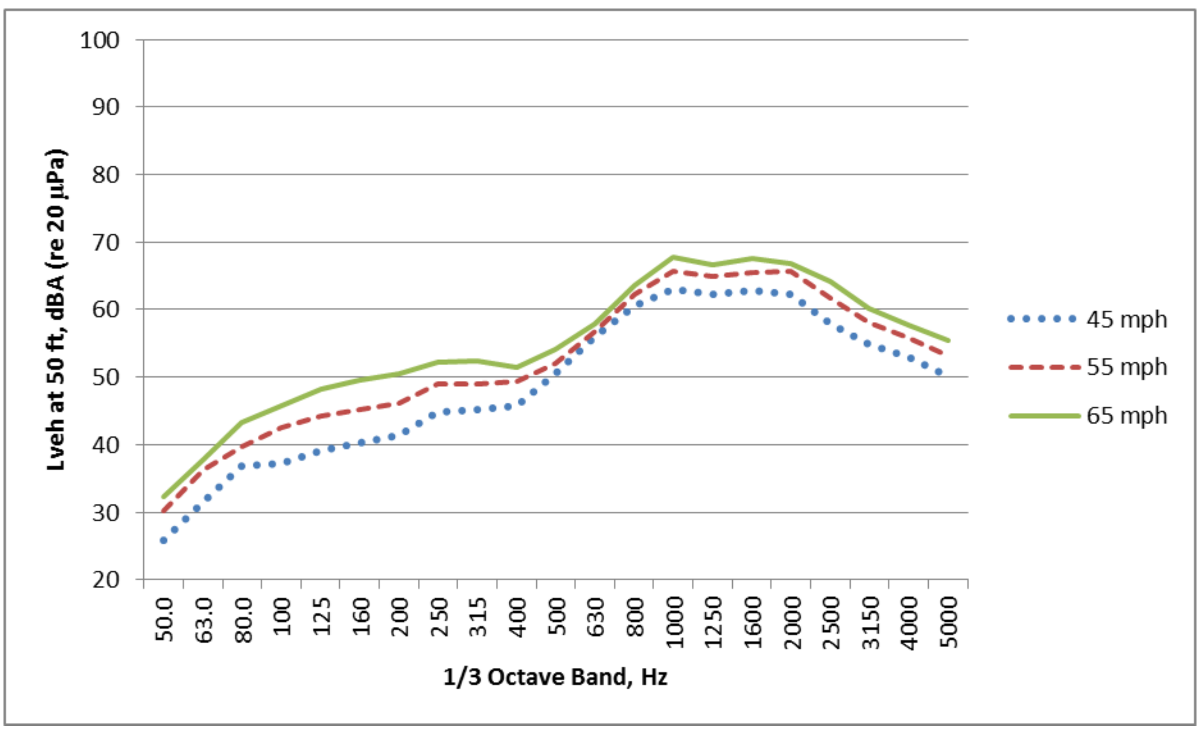
The drift and merge maneuvers yielded identical results, with the control maneuver producing an L_{veh} value 1 dBA higher. As the drift and merge maneuvers alternated between the near and far lanes, it would be expected for the noise level to be slightly lower (compared to the control maneuver which was always in the near lane). These results verified the test methodology.

5.3 Spectral Analysis

The third analysis explored the effects of maneuver and speed on 1/3 octave band maximum noise levels. The goal of these results was to identify distinct characteristics in the noise produced by centerline rumble strip hits. If unique cues could be found, rumble strip hits could be identified in the long-term data. No long-term monitoring locations were within 25 feet of highway, so the L_{max} at 50 feet was used. The monitoring locations with centerline rumble strips (PB1, PB2, and PB3) were grouped together, and then divided by maneuver and reference speed (45, 55, and 65 mph).

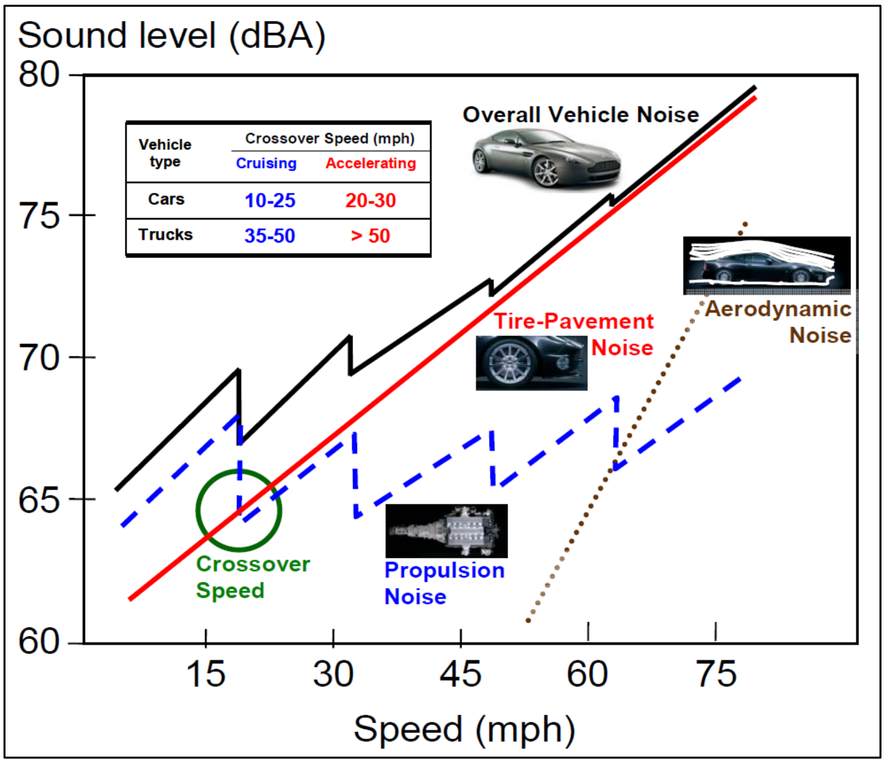
Calculations were performed on "bin max" L_{max} values, meaning the maximum noise levels over the pass-by were found individually for each 1/3 octave band (i.e. each bin). Using this approach, the L_{max} values do not necessarily all occur at the exact same instant. This methodology was adopted to evaluate the strongest spectral content occurring during the vehicle pass-by. Regressions were run for each 1/3 octave band from 50 to 5000 Hz, and the results are presented as plots of L_{veh} relative to the 1/3 octave band. Each maneuver and speed combination had a sample size of nine. Figure 5-6 presents the spectral results at each speed for the control maneuver.

Figure 5-6. Spectral Linear Regression for the Control Maneuver



The speed limit throughout the project area is 55 mph, but vehicles travel at lower and higher speeds. For a simple vehicle pass-by, it is no surprise to see an increase in noise level as the speed increases. The highest noise levels are between 1000 and 2000 Hz, which is typical of tire-pavement noise. Vehicle noise is the combined effects of power train noise (i.e. propulsion noise from the engine, exhaust, etc.), tire-pavement noise, and aerodynamic noise from air turbulence (Sandberg and Ejsmont 2002). Heavy vehicles have an additional component of special equipment, which includes pneumatic and hydraulic systems. Figure 5-7 illustrates the attribution of the primary vehicle noise sources by vehicle speed.

Figure 5-7. Vehicle Noise Attribution

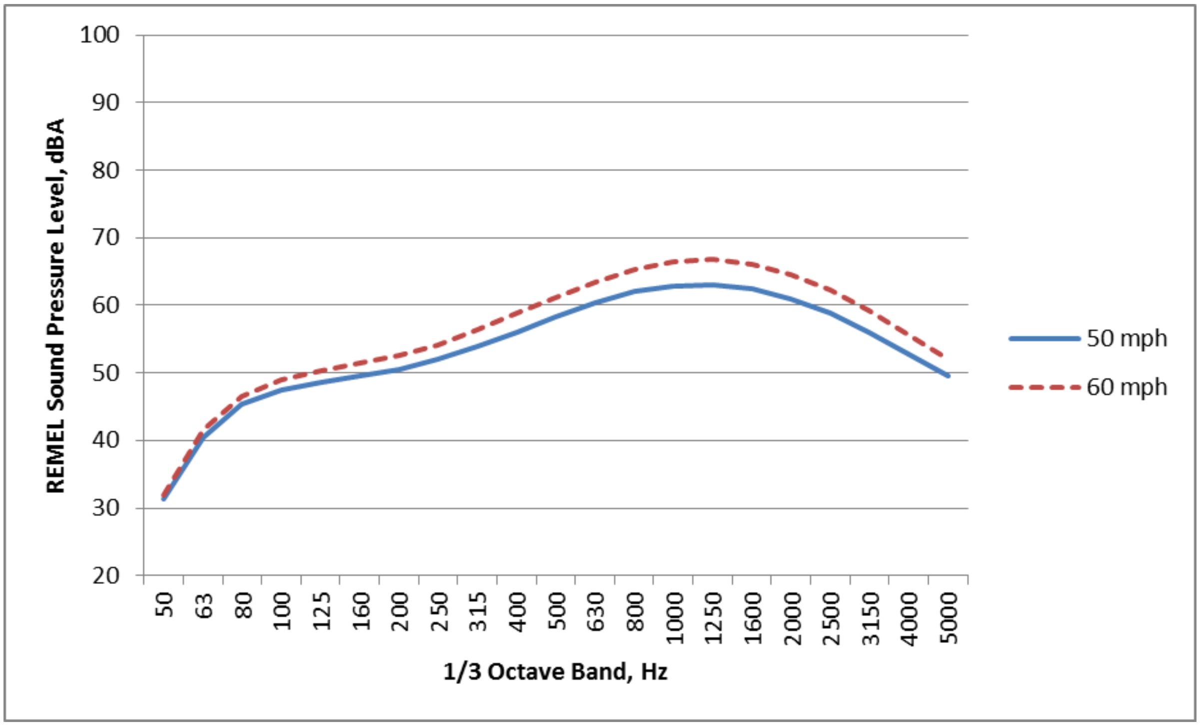


Source: Rasmussen et al. 2007

At low speeds vehicle noise is dominated by propulsion or power train noise. Above the illustrated crossover speed, tire-pavement noise becomes the dominant source. At speeds around 55 mph the vehicle noise is almost entirely due to tire-pavement noise. The primary exception would be vehicles entering or exiting the highway.

The Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) uses Reference Energy Mean Emission Levels (REMELs) for its noise source calculations. The REMELs are based upon a large collection of measured noise levels covering different pavements, operating conditions, vehicle types, and vehicle speeds. Figure 5-8 contains example REMEL frequency spectrums at 50 and 60 mph.

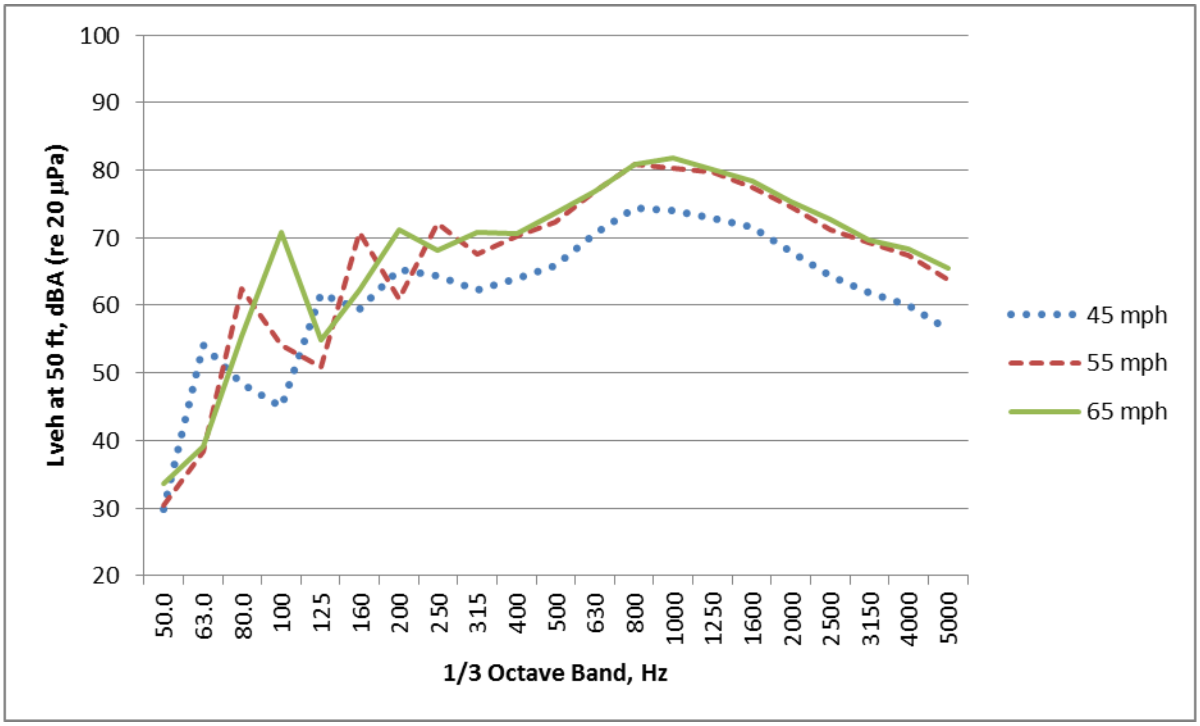
Figure 5-8. Example REMEL Frequency Spectrums



Source: Data from FHWA 2012.

The example REMEL spectrums illustrate typical vehicle pass-by spectrums, which are very similar in shape to the measured spectrums of Figure 5-6. The measured spectrums feature a slight dip at 400 Hz and a slight peak at 2000 Hz which are not seen in the REMEL spectrums. Differences between the REMEL spectrums and measured spectrums are attributed to variations in pavement and vehicle. Figure 5-9 presents the spectral results at each speed for the drift maneuver.

Figure 5-9. Spectral Linear Regression for the Drift Maneuver



The continuous rumble strip hits of the drift maneuver produced strong low-frequency peaks (i.e. tones), which are dependent upon the vehicle speed. At 45 mph, the strongest peak is at 63 Hz, with harmonics in the 125- and 200-Hz bands. At 55 mph, the peaks are shifted to the 80-, 160-, and 250-Hz bands. At 65 mph, the peaks are further shifted to the 100-, 200-, and 315-Hz bands. For each speed, the peaks are generally decreasing in relative amplitude with increased frequency. All speeds contain the 1000-Hz peak typical of tire-pavement noise; however, the noise levels in this range are elevated compared to the control maneuver. From 400 Hz and above, nearly identical noise levels were found at 55 and 65 mph, while 45 mph was significantly lower.

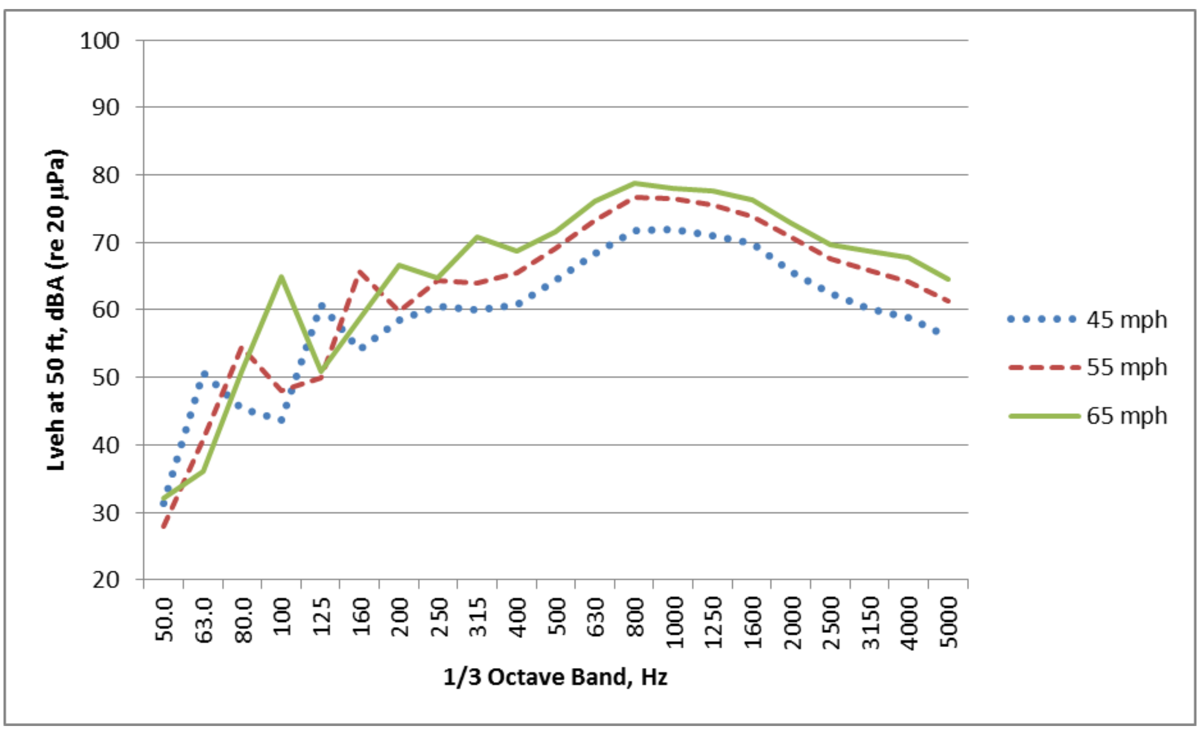
The locations of the rumble strip tones within the frequency spectrum are dependent on the vehicle speeds. The centerline rumble strips are 7 inches long with 5 inches between consecutive rumbles, which creates a 1-foot center-to-center spacing for the rumbles. The vehicle tires hit a rumble every foot, so the individual rumbles are hit at a rate equal to the vehicle speed in feet per second (fps). Therefore, the vehicle speed in fps is equal to the number of rumbles hit per second (i.e. the *frequency* of rumble hits). Table 5-7 contains multiples of the vehicle speeds in fps and the associated 1/3 octave band containing each frequency (1/3 octave bands cover a range of frequencies and are labeled using the center frequency).

Table 5-7. Relating Vehicle Speed and Noise Level Peaks

1/3 Octave Band, Hz	Frequency Range, Hz	45 mph			55 mph			65 mph		
		fps	fps*2	fps*3	fps	fps*2	fps*3	fps	fps*2	fps*3
63	56 - 71	66								
80	71 - 90				81					
100	90 - 112							95		
125	112 - 140		132							
160	140 - 180					161				
200	180 - 224			198					191	
250	224 - 280						242			
315	280 - 355									286

The corresponding 1/3 octave bands are identical to the 1/3 octave bands identified in Figure 5-9, confirming the relationship between vehicle speed and the frequency of the produced tones. Figure 5-10 presents the spectral results at each speed for the merge maneuver.

Figure 5-10. Spectral Linear Regression for the Merge Maneuver



Low-frequency peaks were found in the same bands for the merge maneuver, but the magnitudes were reduced compared to the drift maneuver. The relative amplitudes of the peaks were more variable, and did not clearly step down from the first peak to the second and third. The spectrums feature the typical tire-pavement noise peak around 1000 Hz, but the levels in this range are again higher than the control maneuver. While the rumble strip hit pass-bys still contain significant tire-pavement noise, the rumble strips add additional noise in the 1000-Hz range.

The tonal characteristics of the rumble strip hits are an important consideration in the assessment of potential human annoyance. Tonal noise is perceived as more noticeable than broadband noise, and can therefore be considered annoying at lower levels than broadband noise.

5.4 Distance Analysis

The effect of distance on rumble strip hit sound levels is analyzed by repeating regressions for the 25-, 50-, and 100-foot distance measurement data. The overall L_{veh} is analyzed using the techniques of the lane and maneuver analysis of Section 5.2. Figure 5-11 contains the L_{veh} at 25, 50, and 100 feet calculated for the locations with centerline rumble strips (PB1, PB2, and PB3).

Figure 5-11. Overall L_{veh} Reductions Due to Distance

The top blue columns represent the L_{veh} at 25 feet and the difference in L_{veh} from 25 to 50 feet. The middle red columns represent the L_{veh} at 50 feet and the difference in L_{veh} from 50 to 100 feet. The bottom green columns represent the L_{veh} at 100 feet. Despite having the lowest L_{veh}

magnitudes, the control maneuver is the most affected by distance (i.e. the levels are reduced the most with increasing distance). The merge maneuver in the far lane is the least affected by distance (i.e. the levels are reduced the least with increasing distance). These results indicate the overall rumble strip sound levels can be less affected by distance than basic vehicle pass-by events, meaning the rumble strip hits can propagate more efficiently than the control maneuver.

The rumble strip hits won't diminish to the levels produced by automobile pass-bys, but will eventually diminish to "ambient" levels. The L_{50} is used here to represent an "ambient" condition containing constant highway sound levels, but eliminating sporadic, short-term noise events. The median hourly L_{50} at each of the nine long-term monitoring locations ranged from 38 to 49 dBA (re 20 μPa) with a median across the locations of 42 dBA (re 20 μPa).

A linear regression was performed over all rumble strip pass-by events from PB1, PB2, and PB3, and resulted in an L_{veh} of 90 dBA (re 20 μPa) at 25 feet. The L_{veh} at 25 feet was extrapolated assuming free field conditions, which represent an environment free from obstructions that could affect the way sound travels away from the noise source. In reality, the presence of buildings, varying geography, and varying meteorological conditions would positively or negatively influence sound propagation. Table 5-8 contains the distances required for the average rumble strip hit level measured at 25 feet to be reduced to the maximum, median, and minimum "ambient" levels.

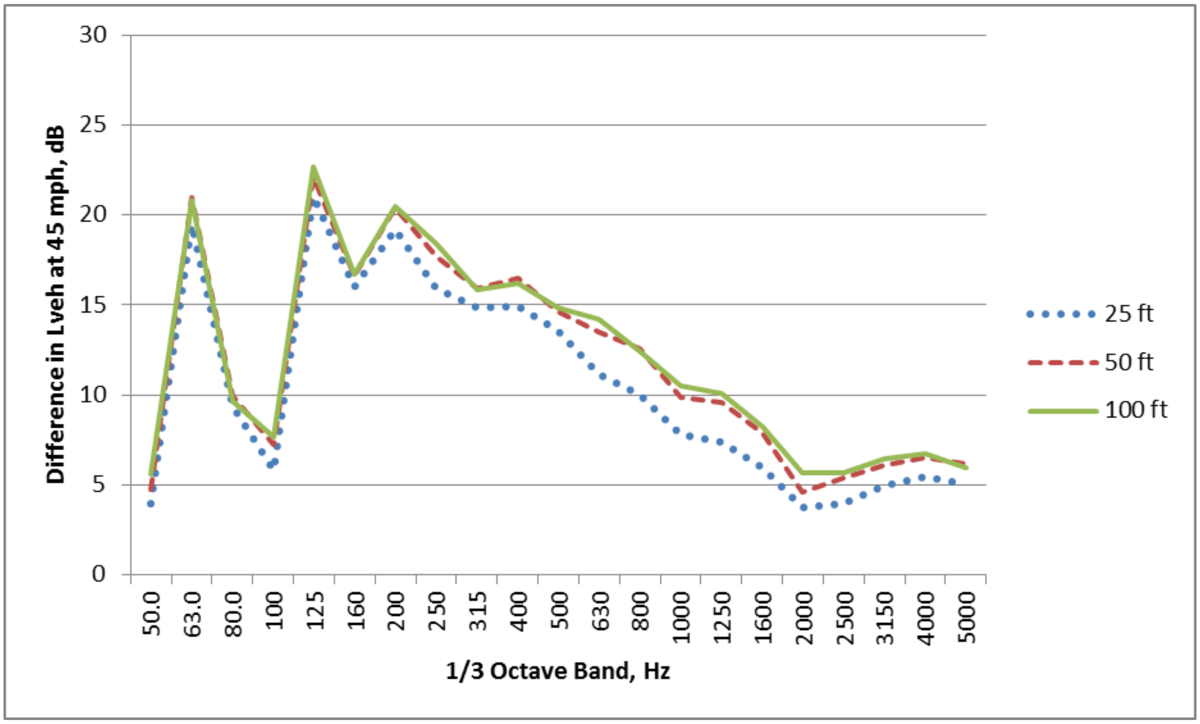
Table 5-8. Distances for Rumble Strip Hit to Reach Background Noise

	Average Hourly L_{50}, dBA (re 20 Pa)	Distance, feet
Maximum "Ambient" Level	49	2,900
Median "Ambient" Level	42	6,400
Minimum "Ambient" Level	38	10,100

The results indicate that a large distance is required for the rumble strip noise levels to reach the "ambient" levels assuming free field conditions. While these distances consider the overall noise level, the tonal characteristics of the rumble strip hits are more distinct than the control maneuver. To analyze the effect of distance on these tonal characteristics, the 1/3 octave band measurement data from PB1, PB2, and PB3 were subdivided based on vehicle speed group and whether or not a rumble strip hit occurred.

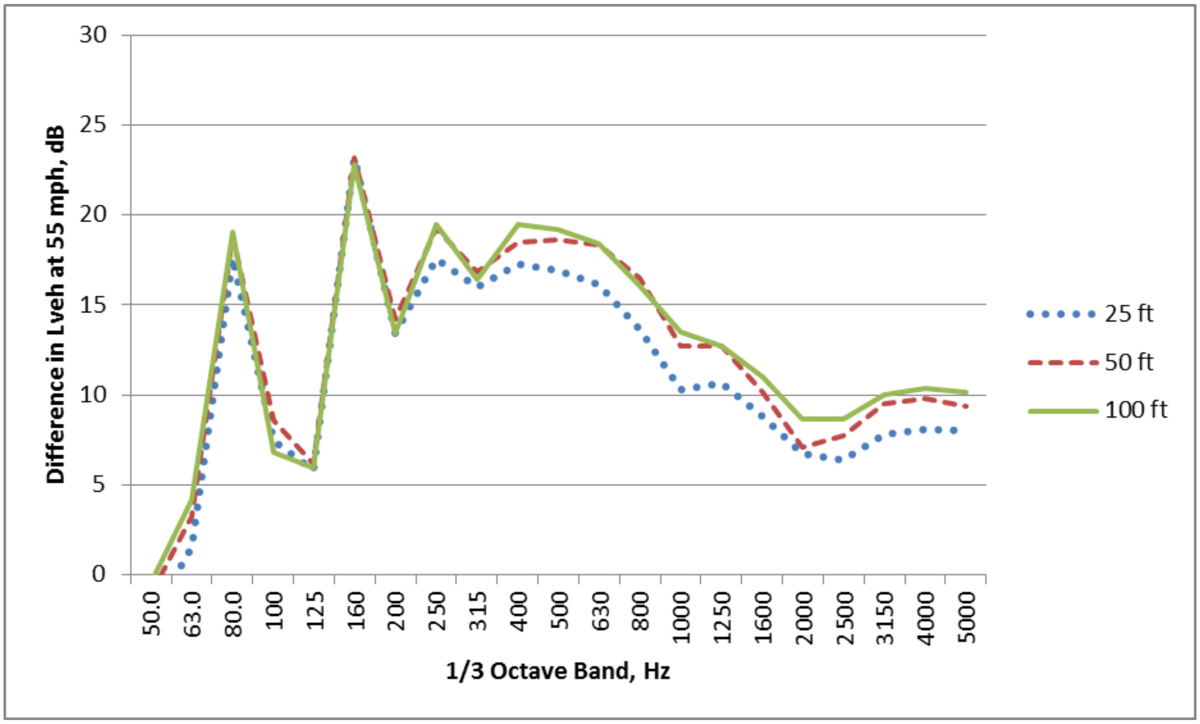
The drift and merge maneuver were not separated due to the similar spectral characteristics. The control maneuver L_{veh} values were subtracted from the rumble strip hit L_{veh} values to determine the increase in noise levels caused by rumble strip hits. This increase in level is analyzed at 25, 50, and 100 feet. Figure 5-12 presents the increase in sound level from the rumble strip hits at 45 mph and varying distances.

Figure 5-12. Rumble Strip Hit Spectral L_{veh} Increase at 45 mph



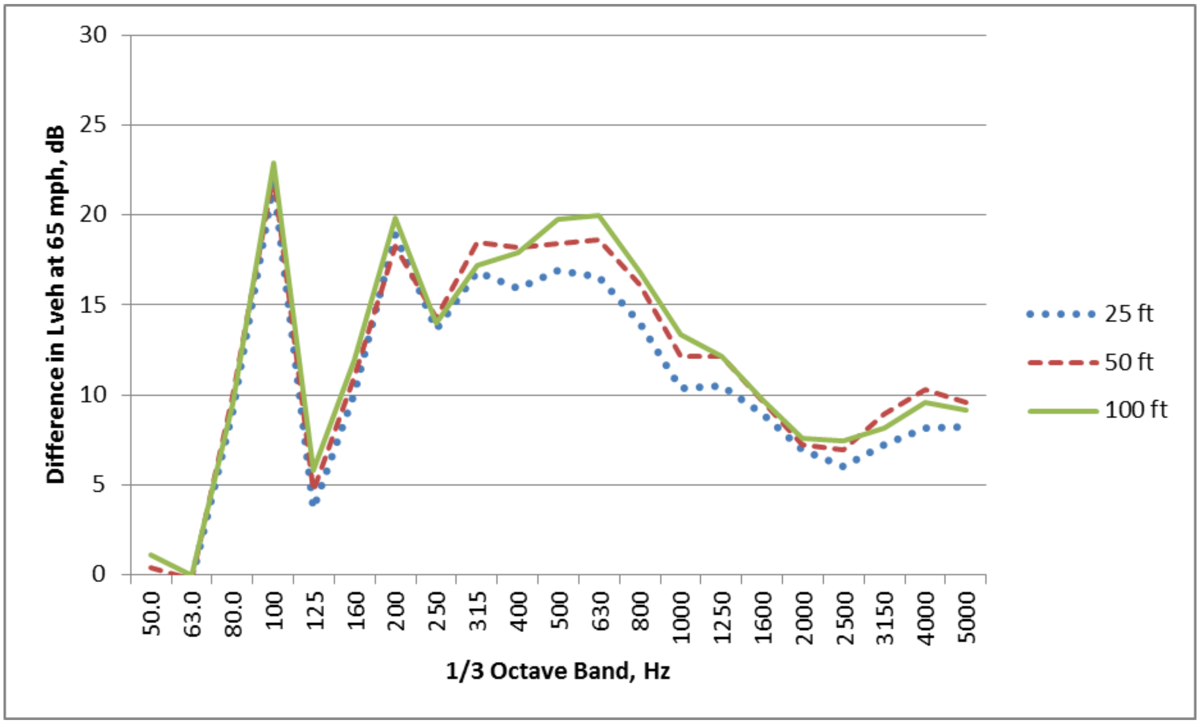
As expected, the three 45-mph low-frequency peaks are the most prominent differences from the control maneuver. While sound levels from both the control maneuver and rumble strip hit maneuvers are diminishing with distance, the difference between them is not. The difference between them actually tends to increase from 25 to 50 feet and holds fairly steady from 50 to 100 feet. Figure 5-13 presents the increase in sound level from rumble strip hits at 55 mph and varying distances.

Figure 5-13. Rumble Strip Hit Spectral L_{veh} Increase at 55 mph



The three low-frequency peaks are again present, and are in the 1/3 octave bands associated with the 55-mph rumble strip hits. Another broader peak is present at 500 Hz, which was not present in Figure 5-12. Just as with the 45-mph results, the difference in sound level from the control maneuver to the rumble strip hit maneuvers increases or stays constant with increasing distance. Figure 5-14 presents the increase in sound level from rumble strip hits at 65 mph and varying distances.

Figure 5-14. Rumble Strip Hit Spectral L_{veh} Increase at 65 mph



The three peaks characteristic of the 65-mph rumble strip hits are present, as well as the additional peak at 500 Hz seen in Figure 5-13. Again the differences between the rumble strip hit maneuvers and the control maneuver either increase or remain fairly constant with increased distance.

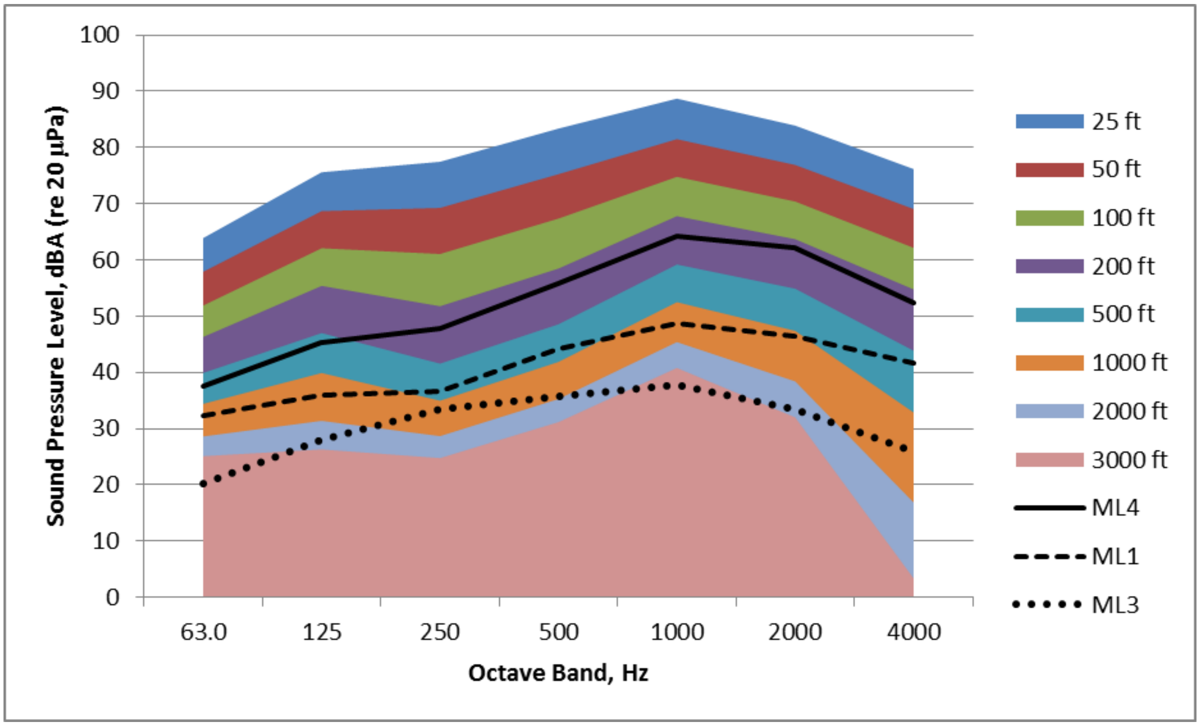
For distances beyond 100 feet, spectral rumble strip noise levels were extrapolated using the acoustical analysis software Cadna-A and compared to “ambient” sound levels from the long-term measurements. Cadna-A is based on ISO 9613, “Attenuation of Sound during Propagation Outdoors.” Spectral sound levels representative of typical rumble strip hits were calculated by performing a regression using just rumble strip hit pass-by events (drift and control maneuvers from PB1, PB2, and PB3). The 55-mph pass-bys were used to match the posted speed limit, and the measured levels were from the 25-foot microphone distance. The resulting L_{veh} values were used as spectral source terms in Cadna-A. A point source was placed on the centerline of a reflective pavement and shoulder surface, with a perpendicular line of receivers extending from the roadway. If evaluating receivers at other angles from the highway, the sound levels could be increased due to an increased area of reflective pavement in the propagation path. Table 5-9 describes the input parameters used in the model.

Table 5-9. Cadna-A Modeling Parameters

Sound Modeling Parameter	Input Parameter
Ground Factor	The pavement was reflective (0% absorptive) and all other ground was 100% absorptive.
Terrain	Terrain was not modeled, resulting in conservatively high sound levels.
Buildings and Barriers	Buildings and barriers were not modeled, resulting in conservatively high sound levels.
Meteorology	A site-specific wind rose was not modeled, resulting in conservatively high sound levels.
Temperature and Relative Humidity	The modeled temperature of 10 degrees Celsius and relative humidity of 70% were based on average climate data for Grand Marais.

Spectral sound levels representative of the “ambient” conditions in the project area were determined by calculating the spectral L_{eq} over the full monitoring period (with exclusions for precipitation, high winds, and extraneous noise) for each of the nine long-term monitoring locations. Unfortunately the L_{eq} includes rumble strip hits, which likely increased the “ambient” levels. Measured sound levels at locations along TH 61 but not near rumble strips would have been preferred, but were not available for this analysis. Figure 5-15 presents the Cadna-A results and “ambient” levels from three long-term locations.

Figure 5-15. Spectral Distance Extrapolation



The colored areas represent the typical rumble strip hit levels at increasing distances. The curves represent the “ambient” noise levels at ML4, ML1, and ML3 which are 30, 130, and 900 feet from TH 61, respectively. This figure compares the extrapolated rumble strip noise levels to the “ambient” noise levels. For example, “ambient” levels at locations 30 feet from the highway (ML4) are predicted to be louder than rumble strip hits that are 1000 feet away, but hits 500 feet away are louder than the “ambient” levels at 63 and 125 Hz. For locations 900 feet from the highway (ML3), rumble strip hits 3,000 feet away are predicted to exceed the “ambient” levels at 63 and 1,000 Hz. Because of the distinct rumble strip peaks at 125 and 1,000 Hz, increased distances are often needed for the “ambient” levels to exceed the rumble strip hit levels at all octave bands.

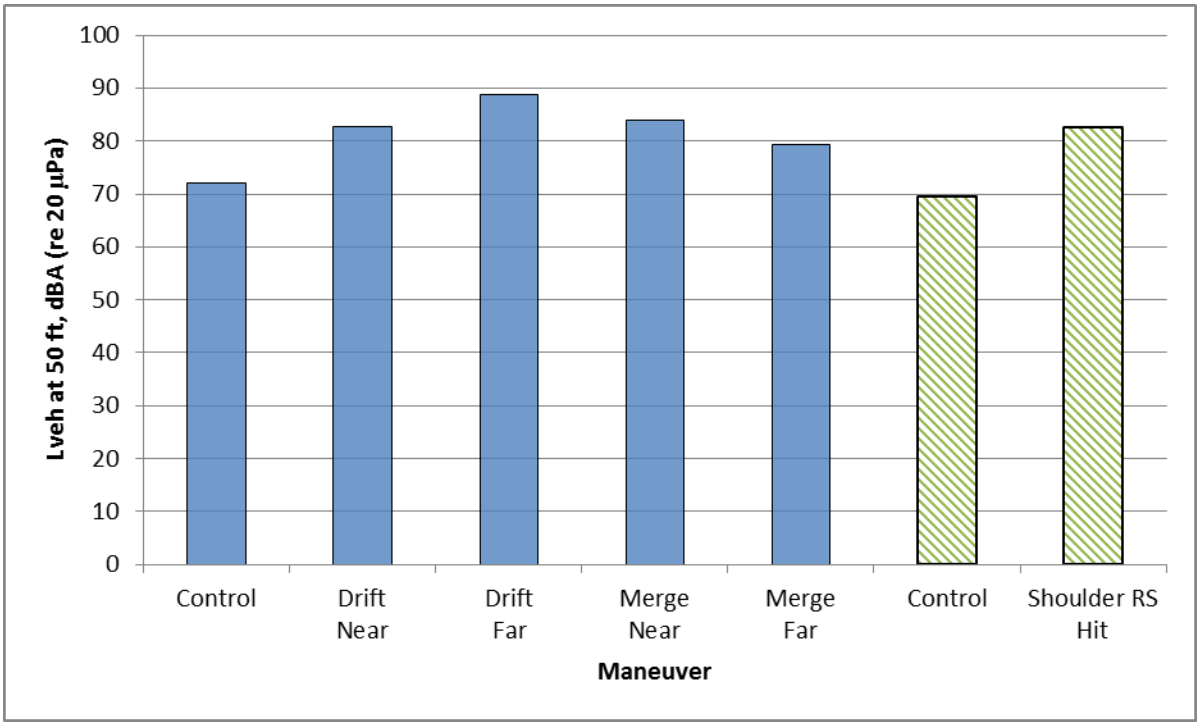
By comparing overall and spectral noise levels from the control maneuver and the rumble strip hit maneuvers at varying distances, analysis results indicate that that rumble strip hits can propagate as efficiently as or more efficiently than basic vehicle pass-bys. The rumble strip hits are louder to start with, which compounds with the efficient propagation.

5.5 Comparison Analysis

MnDOT performed a rumble strip noise study in 2009 for rumble strips on the shoulder of a road. Results from this study included sound measurements 50 feet from the path of travel for control pass-bys and shoulder rumble strip hits. The vehicle was travelling in the near lane, and the shoulder rumble strip hits were continuous through the test area. Four general speeds of 35, 45, 55, and 65 mph were measured, with three passes for each speed and each maneuver. For comparison purposes, the 45, 55, and 65 mph data were divided into control pass-by and rumple strip hit groups. The measured L_{max} values and measured vehicle speeds were used to calculate L_{veh} for the two maneuver groups.

From the present study, the maneuver and lane analysis using the L_{max} at 50 feet was selected for comparison. This regression divided HDR's data from PB1, PB2, and PB3 into five groups: control maneuver, drift maneuver in the near lane, drift maneuver in the far lane, merge maneuver in the near lane, and merge maneuver in the far lane. Figure 5-16 shows the L_{veh} values calculated at 50 feet compared to the 2009 results for a control pass-by and shoulder rumble strip hit.

Figure 5-16. Previous Study Comparison Regression



The solid blue bars indicate the results from HDR's data, and the striped green bars indicate the results from the 2009 MnDOT data. The control maneuver from each study were similar, but the MnDOT shoulder rumble strip hit was most similar to HDR's drift near and merge near maneuvers. Table 5-10 summarizes the regression results from HDR's data and MnDOT's data.

Table 5-10. Previous Study Comparison Linear Regression

Parameter	Maneuver and Lane						
	HDR Data					MnDOT Data	
	Control Near	Drift Near	Drift Far	Merge Near	Merge Far	Control Near	RS Hit Near
Number of Vehicles	27	18	9	18	9	9	9
Regression Slope	27.7	49.9	39.3	49.3	26.9	32.2	35.1
Regression Intercept	24.1	-3.7	20.8	-1.6	32.9	13.3	21.5
Average Speed, mph	54	54	54	54	53	55	55
L_{veh}, dBA (re 20 μPa)	72	83	89	84	79	69	83
$L_{veh, ref}$, dBA (re 20 μPa)	72	72	72	73	72	73	73
SIPI	-0.4	10.2	16.4	11.3	7.1	-3.5	9.7

The control pass-by maneuver L_{veh} from HDR's data is 3 dBA higher than the MnDOT data, indicating a just noticeably louder pass-by event. A small difference in measurement distance was present, but a doubling of distance would be needed to achieve a 3 dBA change for a line source (e.g. highway noise). The focus of HDR's study was the centerline rumble strips, so the 50-foot measurement distance was taken from the centerline of the road. The MnDOT distance measurements were generally taken from the outside of the near lane or the shoulder rumble strip, which places the sound level meter further from the vehicle. As the difference in distance is less than a doubling of distance, other factors influenced the higher L_{veh} from HDR's result.

The MnDOT shoulder rumble strip data is within the range of rumble strip noise levels from HDR's data, but not all maneuvers from the present study are directly comparable. In MnDOT's study, the continuous shoulder rumble strip hit meant the rumbles were between the vehicle and the sound level meter. The most similar maneuver from HDR's study was the drift maneuver in the far lane. The L_{veh} for the drift maneuver in the far lane is 6 dBA higher than the shoulder hit. This difference of 6 dBA is greater than the difference between control pass-bys, so other factors influenced the difference in level.

The centerline rumble strips of HDR's study have an increased area of pavement between the rumble strips and the sound level meter, which provides a larger reflective surface. The shoulder rumble strips of MnDOT's study have more vegetated ground between the rumble strips and the sound level meter, which provides more sound absorption. HDR assumes that the increased ground absorption from the increased area of vegetated ground in the MnDOT study is partially responsible for the lower sound level at the receiver. Due to the inconsistent ground conditions, it is impossible to know if characteristics of the rumble strips themselves influenced the difference in level.

6 Rumble Strip Hit Identification

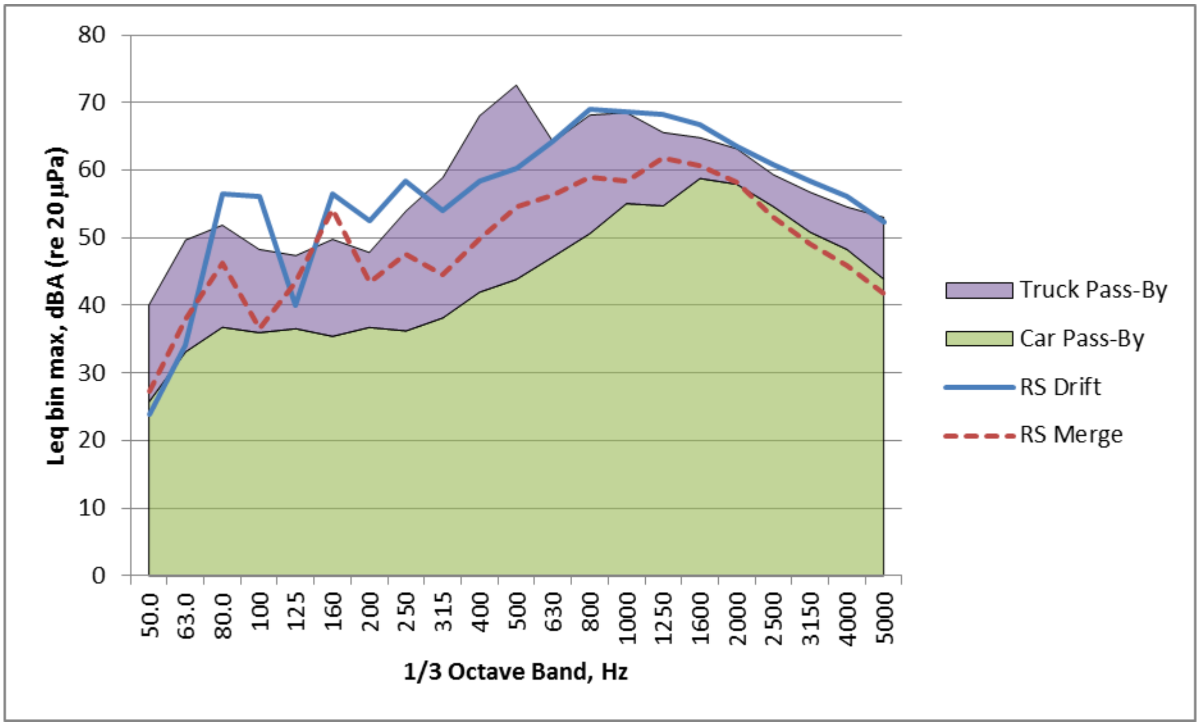
This section discusses the identification of rumble strip hits in the long-term monitoring data. The controlled vehicle pass-by measurements were designed to quantify and characterize the sound produced by vehicles hitting the centerline rumble strips. A goal was established to use the distinct characteristics of the rumble strip hits to calculate a hit rate at the long-term monitoring locations. The hit rate is simply the percentage of vehicles that hit the rumble strips.

6.1 Rumble Strip Hit Timestamps

To aid the task of identifying rumble strip hits, right-of-way (ROW) measurements were performed at the roadside nearest each long-term monitoring location while the long-term systems were running. As part of the ROW measurements, the same Chevrolet Malibu used for the controlled vehicle pass-by measurements performed drift and merge maneuvers on the nearest centerline rumble strips (some of which were down the highway from the monitoring location). By manually inducing rumble strip hits, timestamps of known hits were logged. The actual levels measured at the roadside are insignificant as the goal was the levels measured by the long-term systems. Spectral results from the long-term monitoring systems were compared to the controlled vehicle pass-by results to see if the characteristics of the rumble strip hits changed at locations further from the highway.

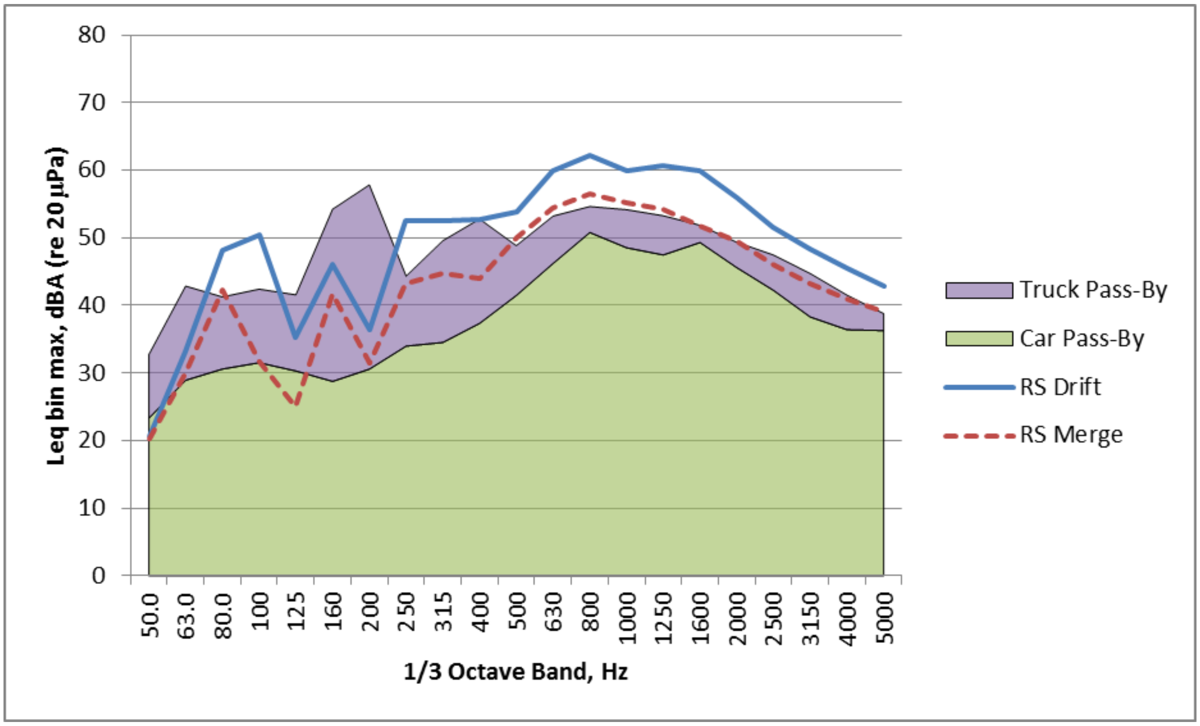
The one-second interval spectral data from the long-term locations was analyzed using the timestamps of known rumble strip hits. Through audio review, car and truck pass-bys with no rumble strip hits were also identified. Bin max 1/3 octave band levels were calculated from the L_{eq} data of each pass-by event. Note that while the controlled pass-by analysis presented levels averaged over several pass-by events, the levels presented here are from single pass-by events. Figure 6-1 provides a spectral comparison of the pass-bys at ML8, one of the nearest locations at 60 feet from the highway.

Figure 6-1. ML8 Spectral Comparison



The blue solid line indicates the drift maneuver rumble strip hit, and the red dotted line represents the merge maneuver rumble strip hit. The lower green shaded area illustrates a car pass-by event, and the upper purple shaded area shows a truck pass-by event. The drift curve from ML8 is similar to the 55-mph controlled environment drift curve of Figure 5-9, with the exception of a wider peak at 80 and 100 Hz and a less pronounced dip at 200 Hz. The merge curve from ML8 is also very similar to the 55-mph controlled environment merge curve of Figure 5-10. The measured car pass-by is fairly typical of the controlled pass-bys, but the inclusion of trucks complicates the identification of rumble strip events. The truck levels are in the range of the rumble strip hit levels, and can exceed the rumble strip hits. Figure 6-2 provides a spectral comparison for ML1, a location 130 feet from the highway with an intervening wooden fence.

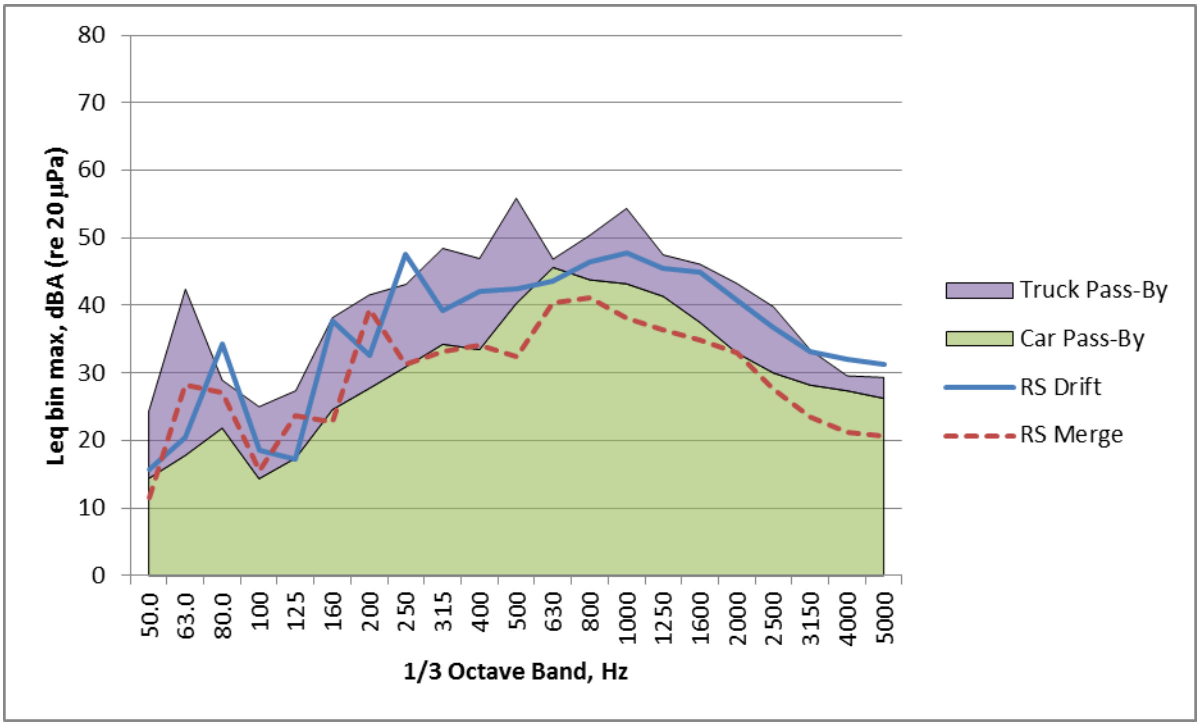
Figure 6-2. ML1 Spectral Comparison



Again the drift, merge, and car pass-by levels were found to be similar to the 55-mph results from the controlled pass-by measurements. However, the truck pass-by at this location was found to have a strong peak at 160 and 200 Hz and lesser pronounced peaks in the 400- to 800-Hz range as compared to ML8. These results illustrate the variability of the sound levels produced by trucks. The overall levels are reduced when compared to ML8, which is expected for a location further from the highway.

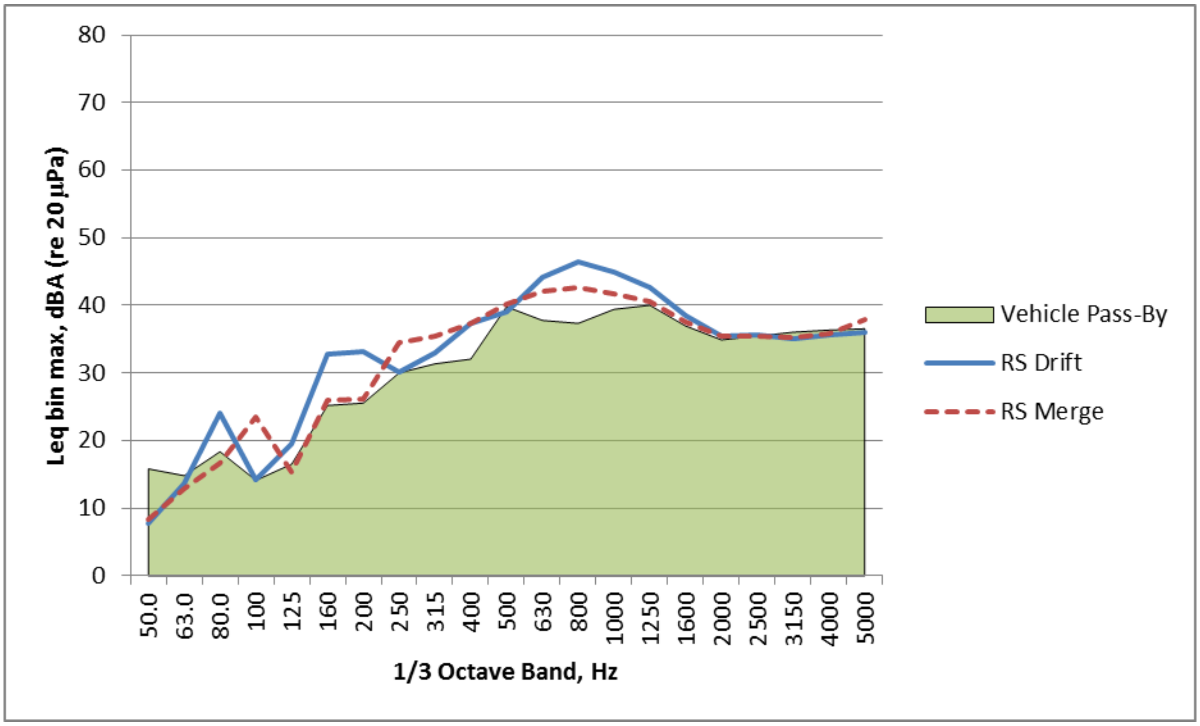
Figure 6-3 provides a spectral comparison for ML5, a location another step further at 430 feet from TH 61.

Figure 6-3. ML5 Spectral Comparison



The drift rumble strip hit still contains the three peaks of 80, 160, and 250 Hz at this greater distance. However, the merge rumble strip hit curve has peaks which are shifted closer to the 45-mph controlled pass-by result. Of the three typical low-frequency peaks, the middle peak is greatly diminished. It is possible the vehicle was travelling closer to 45 mph when the merge rumble strip hit was performed. The truck pass-by data yielded a third distinct spectrum, with a broader range of higher levels from 160 to 2500 Hz. The increased distance from TH 61 resulted in still lower overall sound levels. Figure 6-4 contains a spectral comparison for ML9, one of the locations furthest from the highway at 800 feet.

Figure 6-4. ML9 Spectral Comparison



For ML9, the rumble strip hit events are presented with a single vehicle pass-by. At this location the sound levels are greatly reduced, and are near the levels of the typical ambient condition. As a result a vehicle pass-by could be heard in the audio recording, but not clearly identified as a car or truck. The rumble strip hits still contain some peaks, but the magnitudes of the peaks are near a typical vehicle pass-by. With less distinct characteristics, the rumble strip hits are more difficult to identify in the data. At 800 feet from TH 61, ML9 was beyond the general 500-foot cutoff distance for highway noise evaluations using the Federal Highway Administration's Traffic Noise Model.

These examples have illustrated the effect of distance on identifying rumble strip hits in the long-term data. With increasing distance, the sound levels are reduced and approaching ambient sound levels. While the maximum distance discussed here is only 800 feet from TH 61, the rumble strips were not always adjacent to the monitoring locations (i.e. the distance from the monitoring location to the nearest rumble strip was greater than the distance from the monitoring location to TH 61 at some locations). The distance analysis of Section 5.4 was an ideal situation where the measurements were made adjacent to centerline rumble strips. The ideal conditions resulted in significantly greater distances for the sound levels to diminish to approximated background sound levels.

The results at ML8, ML1, and ML5 show the noise levels produced by truck pass-bys are within the range of the rumble strip noise levels. Trucks can produce similarly tonal peaks, but their frequency spectrums can vary greatly. Calculating a hit rate from the long-term data requires clearly identifiable level and frequency cues from the rumble strip hits. Decreased levels make identification difficult for some locations, and some trucks could be falsely identified as rumble strip hits.

6.2 Rumble Strip Hit Rate Calculation

Due to the number of hours contained in a weeklong monitoring period, an automated hit rate calculation approach is desired. An automated approach requires certain criteria to be established based upon distinct characteristics of vehicle pass-by events and rumble strip hits. Monitoring locations furthest from the highway may lack the sound levels needed for these distinct characteristics. Some locations are close enough together that similar hit rates are expected (such as ML1, ML2, and ML3 or ML8 and ML9), so the analysis focused on the locations nearest TH 61. With unique characteristics already identified, select audio review was performed to provide a means of testing and evaluating criteria. Audio from a few full hours at ML2 and ML8 were reviewed, and vehicle pass-bys and rumble strip hits were noted. Table 6-1 contains the results of the select audio review, which covered peak traffic, midday, and overnight hours.

Table 6-1. Hit Rates from Select Audio Review

Monitoring Location	Date and Hour	Hourly L_{eq}, dBA (re 20 μPa)	Number of Pass-By Events	Number of Rumble Strip Hits	Hit Rate, %
ML2	Fri. Oct. 25 01:00	43.8	4	0	0.0
ML2	Mon. Oct. 28 17:00	62.5	206	16	7.8
ML8	Wed. Oct. 23 01:00	43.3	3	1	33.3
ML8	Wed. Oct. 23 08:00	60.6	80	5	6.3
ML8	Wed. Oct. 16 13:00	58.3	95	6	6.3
Overall	N/A	N/A	388	28	7.2

One-second interval data from the reviewed hours at ML8 were used to evaluate criteria for counting vehicle pass-bys and rumble strip noise events. For vehicle pass-by events, the following criteria resulted in the highest correlation with the audio review data.

- L_{eq} at 2000 Hz > 47 dB (re 20 μPa)
- Difference between L_{eq} at 1000 Hz and L_{eq} at 1000 Hz two seconds before > 1 dB
- Difference between L_{eq} at 1000 Hz and L_{eq} at 1000 Hz two seconds after > 1 dB
- Difference between L_{eq} at 1000 Hz and L_{eq} at 80 Hz < 9 dB
- No vehicle pass-by events occurred in previous two seconds

The criteria are essentially a peak counter with additional restrictions. The minimum level requirement is strategically placed in the 2000-Hz 1/3 octave band due to the spectral characteristics of the control maneuver from the controlled vehicle pass-by measurements. In terms of unweighted sound levels, vehicles actually produce similar sound levels at low and high frequencies. To eliminate sources only containing high-frequency sound energy, the levels at 80 and 1000 Hz are compared. To prevent single peaks from being counted multiple times, a two-second window is established.

For rumble strip hits, the following criteria resulted in the highest correlation with the audio review data.

- L_{eq} at 80 Hz > 63 dB (re 20 μPa)
- Difference between L_{eq} at 80 Hz and L_{eq} at 125 Hz > 22 dB
- No rumble strip hits occurred in previous three seconds

The criteria are designed to identify the 80-Hz peak found in the 55-mph controlled vehicle pass-by data, which is followed by a relative minimum at 125 Hz. A minimum level requirement was also included, and a three-second window was established to prevent hits from being counted multiple times. Due to the minimum level requirement, rumble strip hits occurring far from the monitoring location are likely excluded. Additionally, hits from vehicles travelling at speeds closer to 45 and 65 mph are likely excluded due to the shifted peaks.

Table 6-2 compares the pass-by event and rumble strip hit counts from the audio review and calculation methodology.

Table 6-2. Hit Rate Calculation Accuracy

Monitoring Location	Date and Hour	Audio Review		Calculated		Pass-By Events % Error	Rumble Strip Hits Difference
		Pass-bys	RS Hits	Pass-bys	RS Hits		
ML2	Fri. Oct. 25 01:00	4	0	6	0	50	0
ML2	Mon. Oct. 28 17:00	206	16	140	3	32	13
ML8	Wed. Oct. 23 01:00	3	1	3	0	0	1
ML8	Wed. Oct. 23 08:00	80	5	79	3	1	2
ML8	Wed. Oct. 16 13:00	95	6	94	4	1	2

The criteria were designed using the hours at ML8, so high accuracy is found for those hours. The audio review yielded higher rumble strip hit counts, which is attributed to quieter hits occurring farther from the monitoring location. When the criteria were applied to the audio reviewed hours at ML2, the accuracy was reduced substantially. Due to the higher traffic volumes, pass-by events containing groups of vehicles were more common. In this situation, the vehicles blend in to a single peak making it difficult to identify individual vehicles from one-second interval data. If vehicles are missed, it leads to an overestimation of the hit rate.

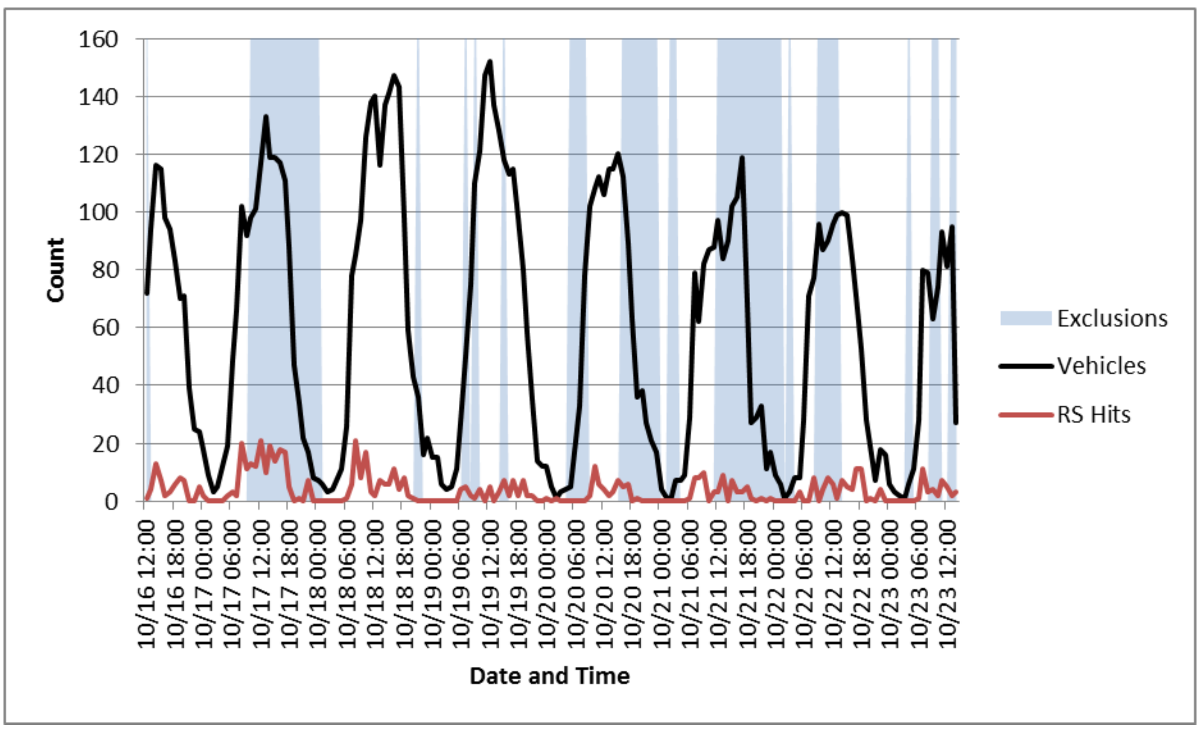
With high correlation found at ML8, the criteria were applied to the full monitoring period. Table 6-3 contains the overall hit rates calculated for the full monitoring period and the full monitoring period after the exclusions for precipitation, high wind speeds, and extraneous noise.

Table 6-3. ML8 Approximate Hit Rate Calculation

	Number of Pass-By Events	Number of Rumble Strip Hits	Hit Rate, %
Full Monitoring Period	10,145	613	6.0
After Exclusions	6,635	389	5.9

At approximately 6%, the calculated hit rate is lower than the overall 7.2% from the audio reviewed hours. The presence of precipitation, high winds, and extraneous noise were found to have minimal influence on the calculated hit rate. Figure 6-5 presents the hourly counts for vehicle pass-by events and rumble strip hits at ML8.

Figure 6-5. ML8 Approximate Hit Rate Calculation



The upper black curve represents the number of vehicle pass-by events, and the lower red curve represents the number of rumble strip hit events. Hours containing exclusions are marked with the blue shaded bars. The number of vehicle pass-bys and number of rumble strip hits varied from day to day. Traffic volumes were increased on Thursday October 17, Friday October 18, and Saturday October 19. As seen at ML2, the vehicle count accuracy is likely diminished at higher traffic volumes.

While more time and effort could be spent refining the hit rate calculation, only a certain level of accuracy is attainable. Some amount of error is expected from the calculation criteria used, but even the select audio review likely contained some error. During the audio review it was difficult to distinguish individual vehicles when a group of vehicles passed simultaneously. This was especially apparent with truck pass-by events, which are loud enough to mask automobiles. A visual component, whether through video recording or attended measurement periods, would provide the most accurate analysis of rumble strip hit rates.

7 Conclusion

HDR measured outdoor noise levels along sections of TH 61 containing centerline rumble strips. Long-term monitoring occurred for weeklong periods to create a record of traffic noise levels before MnDOT modified the centerline rumble strips, and the resulting data was compared to the MPCA noise standards. The overall sound levels generally diminished with increasing distance from the highway. All monitoring locations were found to have high MPCA compliance percentages for hourly L_{50}, and locations over 100 feet from the highway had high compliance percentages for hourly L_{10}. Poor L_{10} compliance percentages were found for the locations within 100 feet of TH 61, with the exception of daytime hours at ML8.

This study also included measurements of controlled vehicle pass-bys to create a record of pre-mitigation rumble strip noise levels in a controlled environment and to characterize the centerline rumble strips in terms of overall noise level and frequency. The study team performed regression analyses to determine the effects of monitoring location, maneuver, lane of travel, speed, and distance from TH 61 on the measured sound levels. Monitoring location was found to have a just noticeable difference on the controlled vehicle pass-by noise levels, but the rumble strip noise levels were nearly identical across locations. The driving maneuver and lane of travel were found to heavily influence rumble strip hit noise levels, with the drift maneuver in the far lane being the loudest. The spectral results identified the influence of speed on the rumble strip noise levels and illustrated distinct rumble strip tonal characteristics. At distances up to 100 feet, the rumble strip hit noise levels were found to experience less reduction than basic vehicle pass-by events. For distances beyond 100 feet, spectral rumble strip hit sound levels were extrapolated using Cadna-A and compared to sound levels from the long-term monitoring locations.

Finally, rumble strip hit identification was explored to facilitate the calculation of a hit rate. Audio review was performed for five hours, and resulted in an overall hit rate of 7.2%. Calculation criteria were established to identify vehicle pass-by events and rumble strip hits, but were found to not be universally accurate. Due to vehicles passing simultaneously or in groups, it is recommended to study the hit rate using video recordings or attended measurements.

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9 Appendix A: Long-Term Monitoring Detailed Results

This appendix contains the detailed results for the long-term monitoring. Each monitoring location is discussed individually with detailed figures that follow identical formatting. The following sections address the sound levels on a broad level, and don't distinguish rumble strip hit events. Rumble strip hit identification is discussed in Section 6.

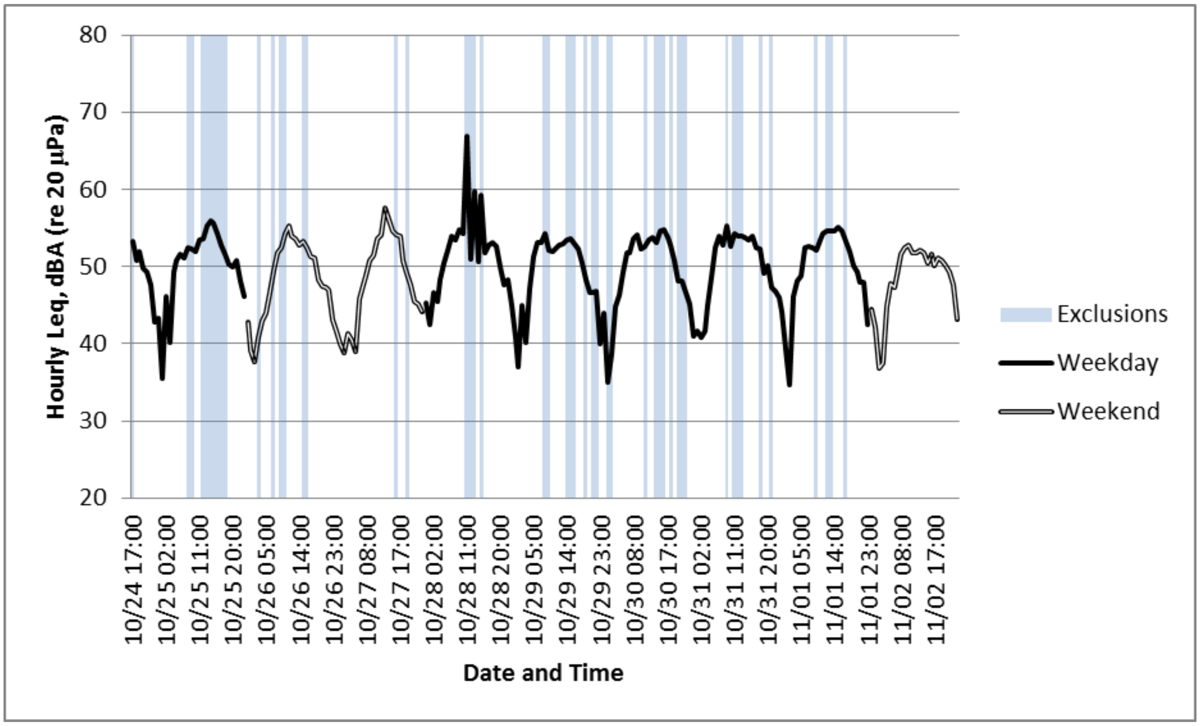
9.1 ML1 Detailed Results

Monitoring at ML1 occurred from Thursday October 24 to Saturday November 2, 2013. ML1 was located at a residence between TH 61 and Lake Superior, in an area with low vegetation. Line of sight with TH 61 was blocked by a wooden fence. Figure 9-1 shows the monitoring setup next to the residence.

Figure 9-1. ML1 Monitoring Setup

Other sources of potential noise included minimal cul-de-sac traffic and construction equipment and activities. Wind speeds and precipitation events from the Two Harbors Airport were used to identify weather-related exclusions. Figure 9-2 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

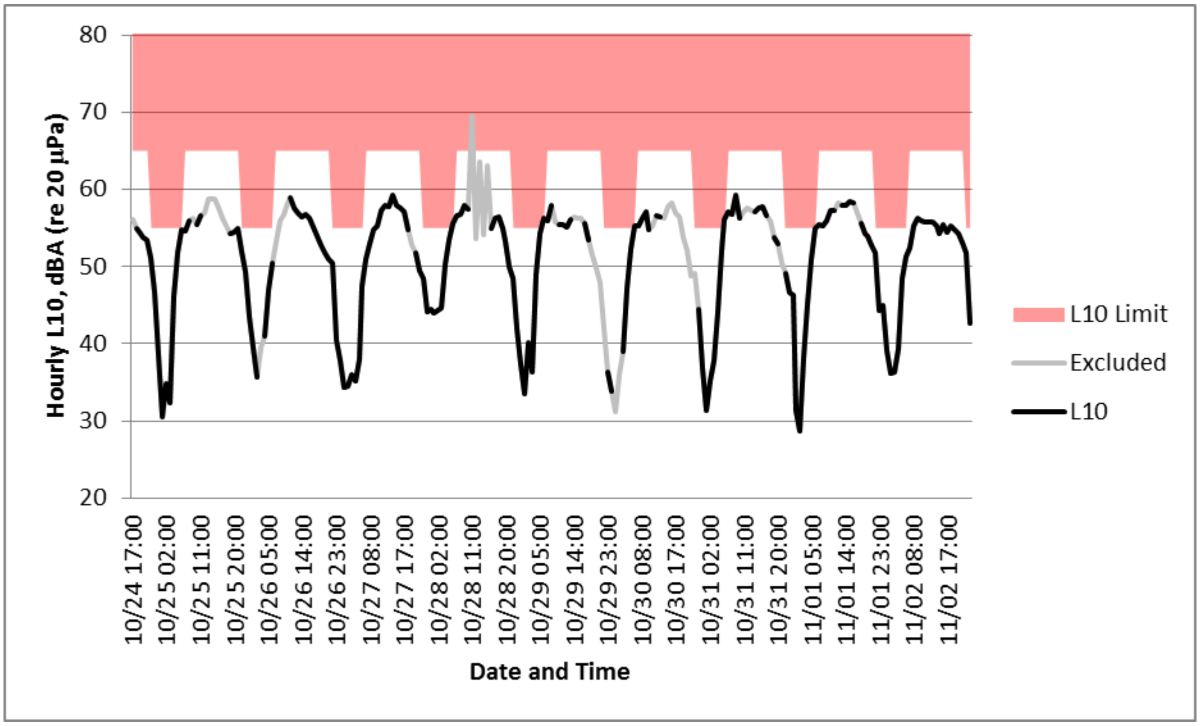
Figure 9-2. ML1 Hourly L_{eq} with Exclusions



The black curve represents the measured hourly L_{eq} and is divided into solid weekday (Monday through Friday) portions and hollow weekend (Saturday and Sunday) portions to illustrate any day to day variations in sound level. Gaps can be present between the weekday and weekend portions. Hours containing precipitation events, wind speeds of 11 mph or above, or extraneous noise are marked with the light blue shaded bars.

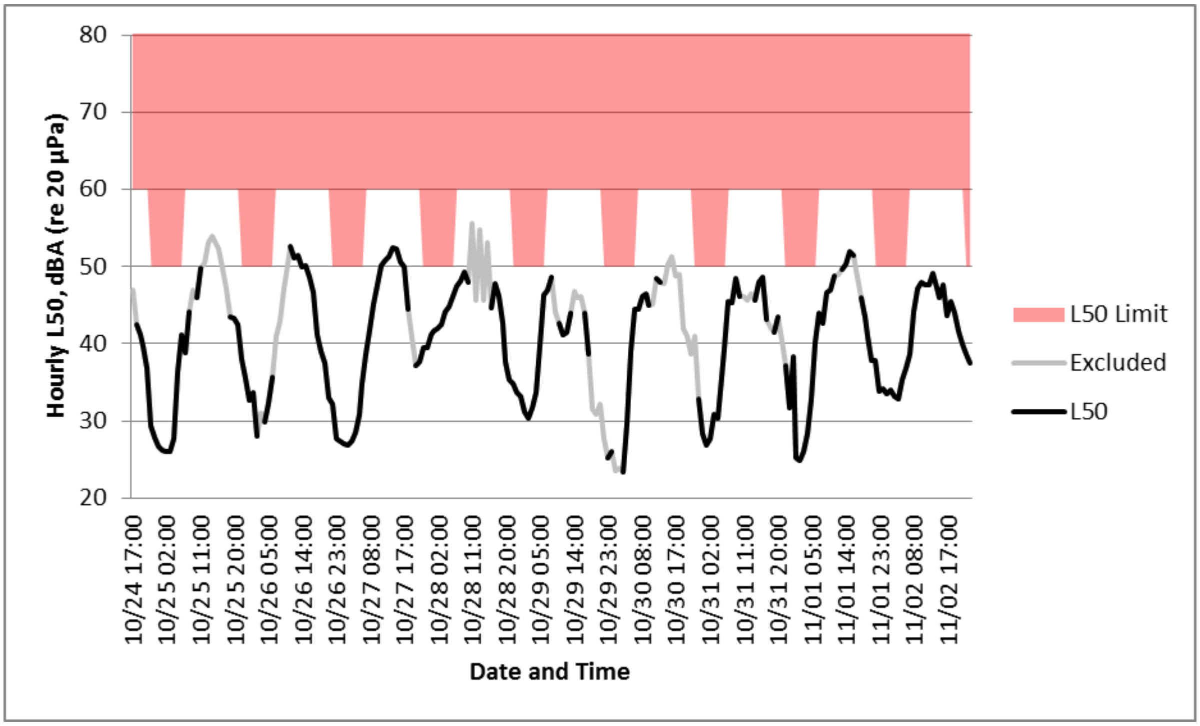
The most prominent trend illustrated by the figure is the difference between daytime and nighttime sound levels. This trend is typical for outdoor environments, and is likely amplified by TH 61 where daytime traffic is heavier than nighttime traffic. There are no particularly strong trends from day to day or from weekday to weekend. The highest sound level in the figure occurred during an excluded period. Figure 9-3 shows the measured hourly L_{10} relative to the MPCA noise limits.

Figure 9-3. ML1 Hourly L_{10} with MPCA Limits



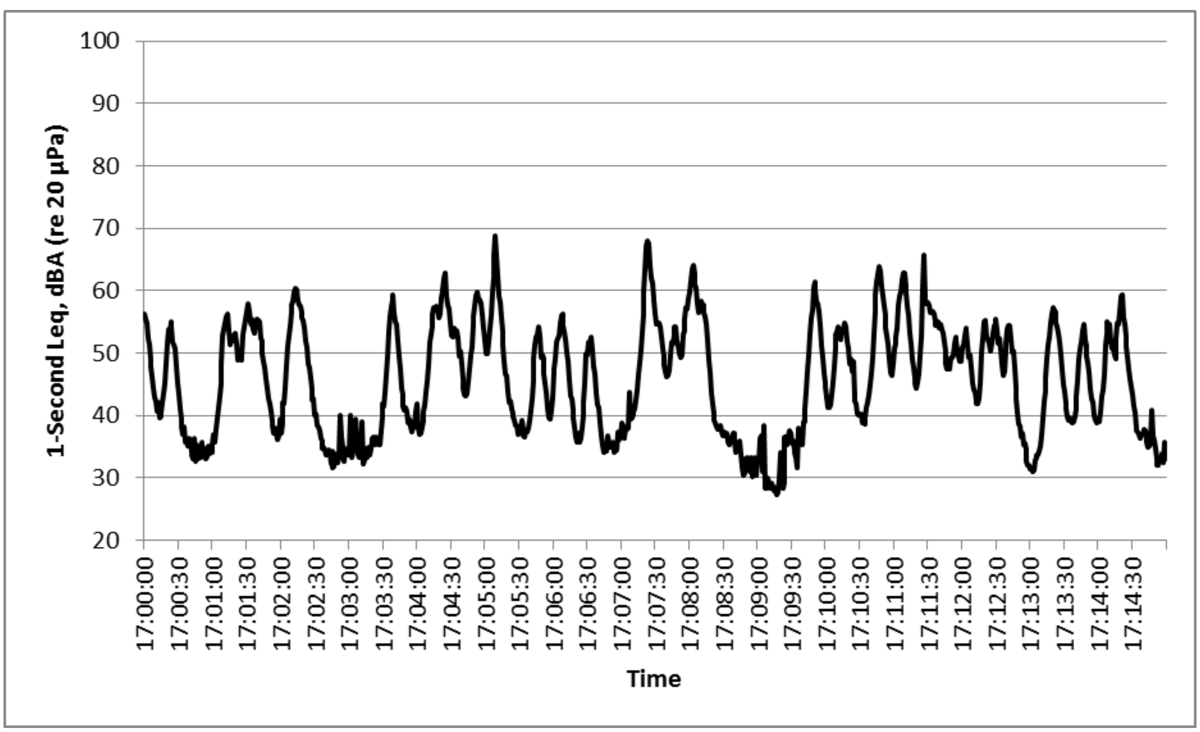
The measured hourly L_{10} curve contains dark and light portions to indicate the reduced data set and the excluded periods, respectively. The red shaded area represents levels that would exceed the MPCA noise limits; the noise limits are stricter (lower) at night. This location had four hours which exceeded the nighttime L_{10} limit, and all occurred at 6:00 a.m. on weekdays. By acoustic definitions the 6:00 a.m. hour is considered nighttime, however, it is likely traffic volumes are increased at this hour compared to the other nighttime hours. Figure 9-4 shows the measured hourly L_{50} relative to the MPCA noise limits.

Figure 9-4. ML1 Hourly L_{50} with MPCA Limits



The L_{50} levels are well within the MPCA noise limits. Figure 9-5 illustrates the one-second interval L_{eq} over a 15-minute period during the peak traffic period of 5:00 p.m. on Thursday October 31, 2013.

Figure 9-5. ML1 Peak Traffic Period



This detailed 15-minute period illustrates individual vehicle pass-by events. ML1 is close to the highway, so vehicle pass-bys produce strong peaks well above the background noise level. The amount of variability is noticeable as different vehicles, differing speeds, lane of travel, and presence of a rumble strip hit all influence the produced sound level and frequency content of the sound.

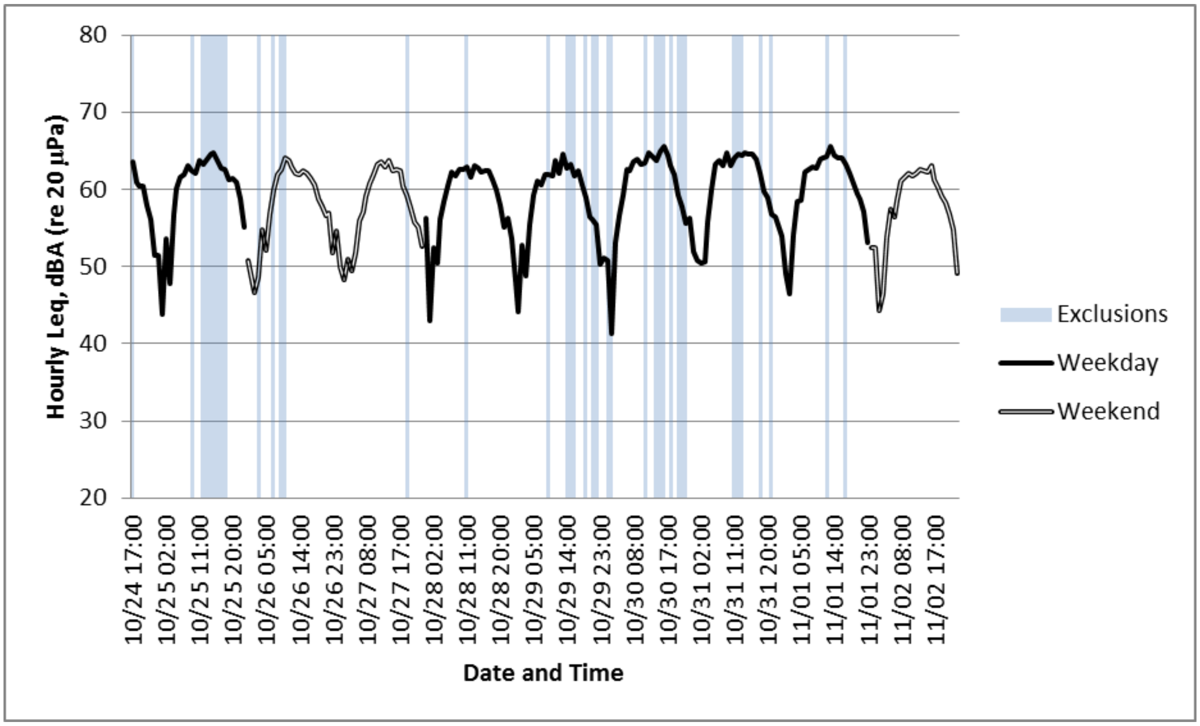
9.2 ML2 Detailed Results

Monitoring at ML2 occurred from Thursday October 24 to Saturday November 2, 2013. ML2 was located at a residence adjacent to the landside of TH 61. The monitoring equipment was located on a grassy patch within a circle driveway, and had direct line of sight with TH 61. Figure 9-6 shows the monitoring setup, the circle driveway, and the highway in the background.

Figure 9-6. ML2 Monitoring Setup

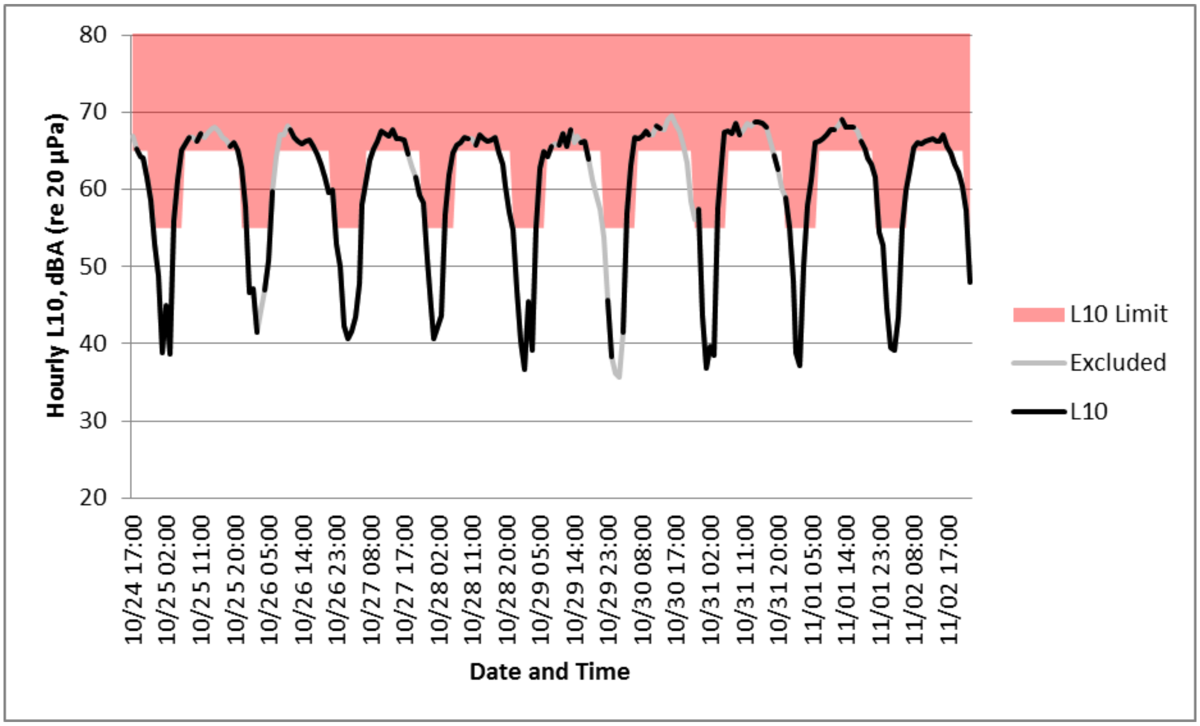
Other sources of potential noise included minimal driveway traffic and residential activities. Wind speeds and precipitation events from the Two Harbors Airport were used to identify weather-related exclusions. Figure 9-7 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-7. ML2 Hourly L_{eq} with Exclusions



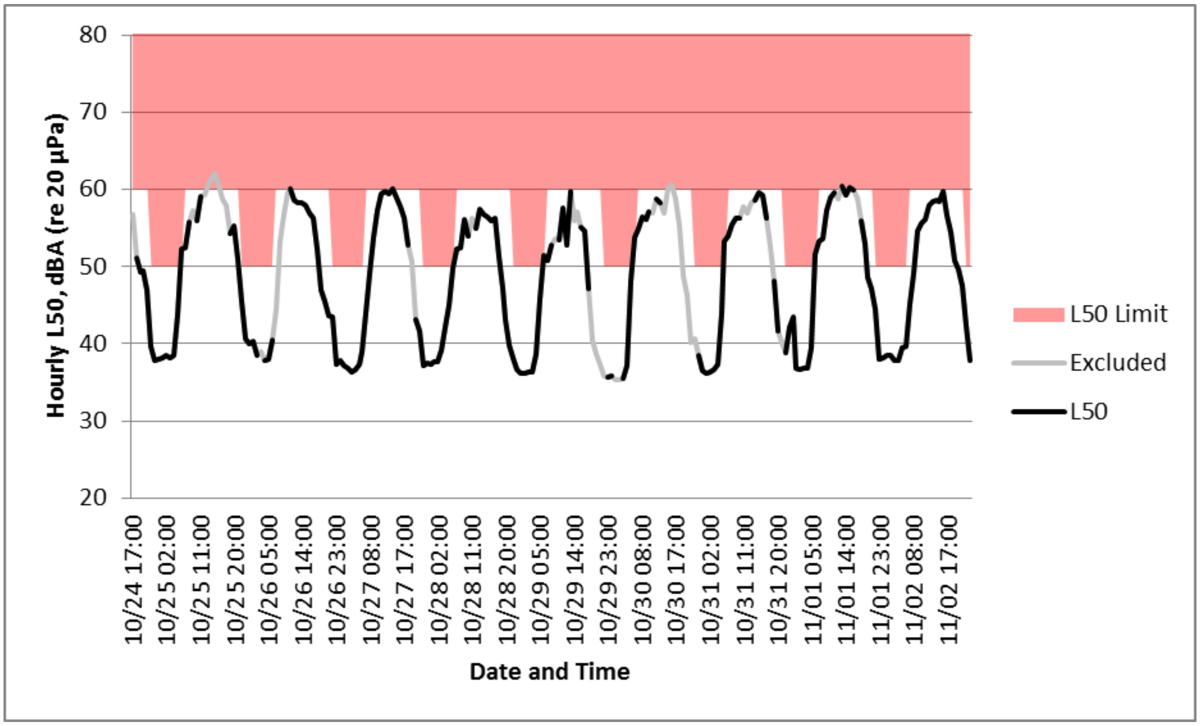
The strongest trend is the difference in level from daytime to nighttime. There appears to be a minor increase in daytime weekday levels from Monday October 28 to Friday November 1, but the increase is minimal. Saturday November 2 appears to peak slightly lower than the preceding weekdays, but the trend is not consistent. Figure 9-8 shows the measured hourly L_{10} relative to the MPCA noise limits.

Figure 9-8. ML2 Hourly L_{10} with MPCA Limits



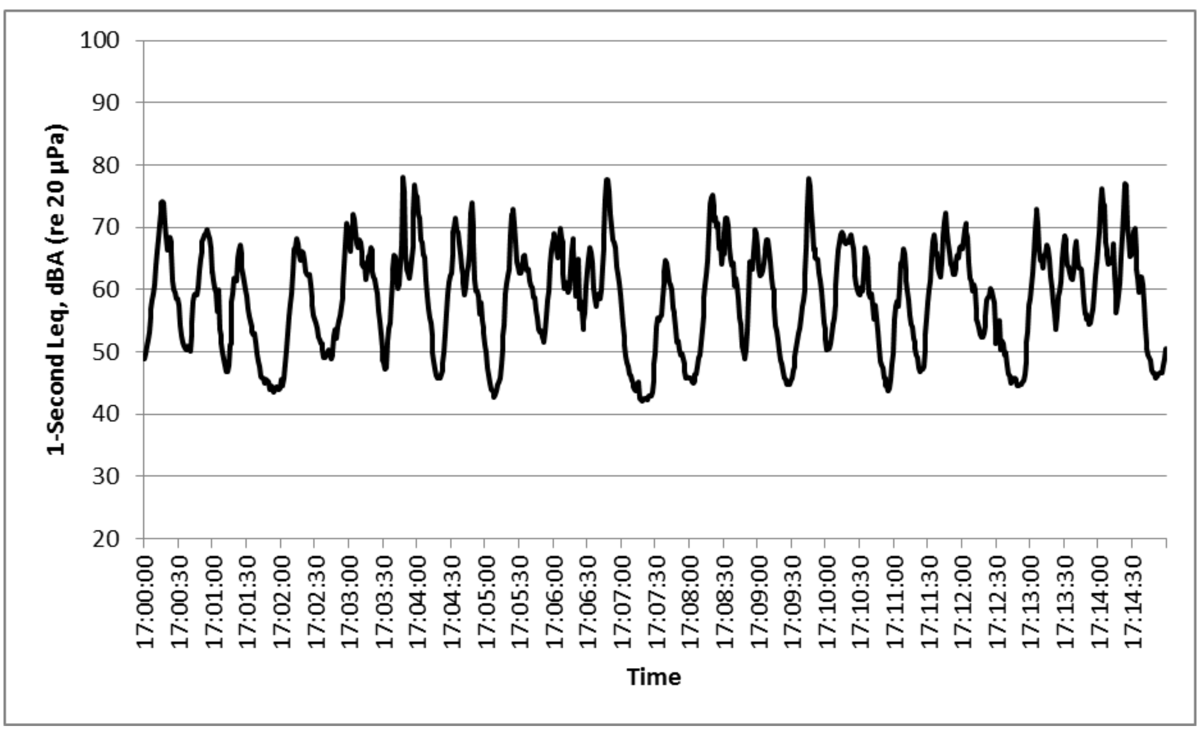
ML2 was located adjacent to TH 61, and the measured L_{10} was clearly influenced by highway noise as it repeatedly exceeds the MPCA noise limit during daytime hours. Exceeding hours also occurred at the beginning and end of the nighttime period as the highway traffic was likely high enough to produce exceeding levels. Figure 9-9 shows the measured hourly L_{50} compared to the MPCA noise limits.

Figure 9-9. ML2 Hourly L_{50} with MPCA Limits



While a higher compliance percentage was found for L_{50}, three exceeding hours occurred during the day and five at night. All of the nighttime exceeding hours occurred during the 6:00 a.m. hour on weekdays. Figure 9-10 illustrates a detailed 15-minute period during the peak traffic period at 5:00 p.m. on Thursday October 31, 2013.

Figure 9-10. ML2 Peak Traffic Period



As expected for a location adjacent to TH 61, vehicle pass-by events produce strong peaks. The peaks do display variability as vehicle pass-by levels are influenced by several factors.

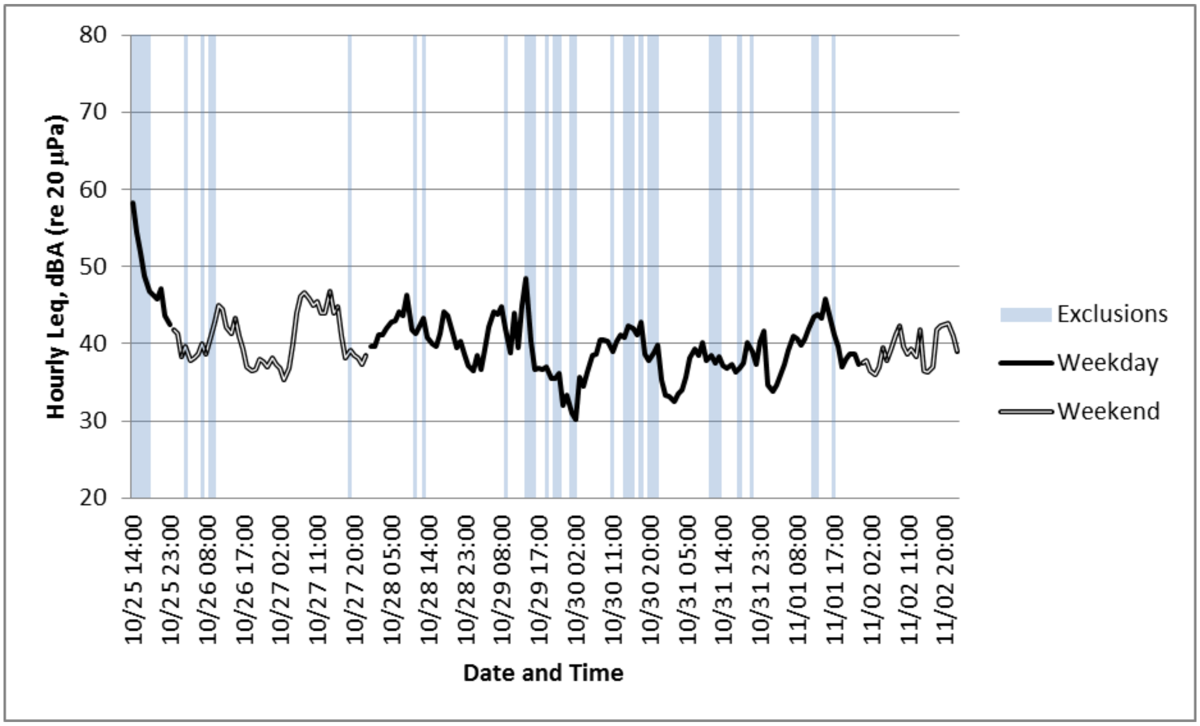
9.3 ML3 Detailed Results

Monitoring at ML3 occurred from Friday October 25 to Saturday November 2, 2013. ML3 was located at a lodge 900 feet from the lakeside of TH 61. The area was wooded, but the monitoring equipment was located on a grassy patch next to the landside of the lodge. Figure 9-11 shows the monitoring setup.

Figure 9-11. ML3 Monitoring Setup

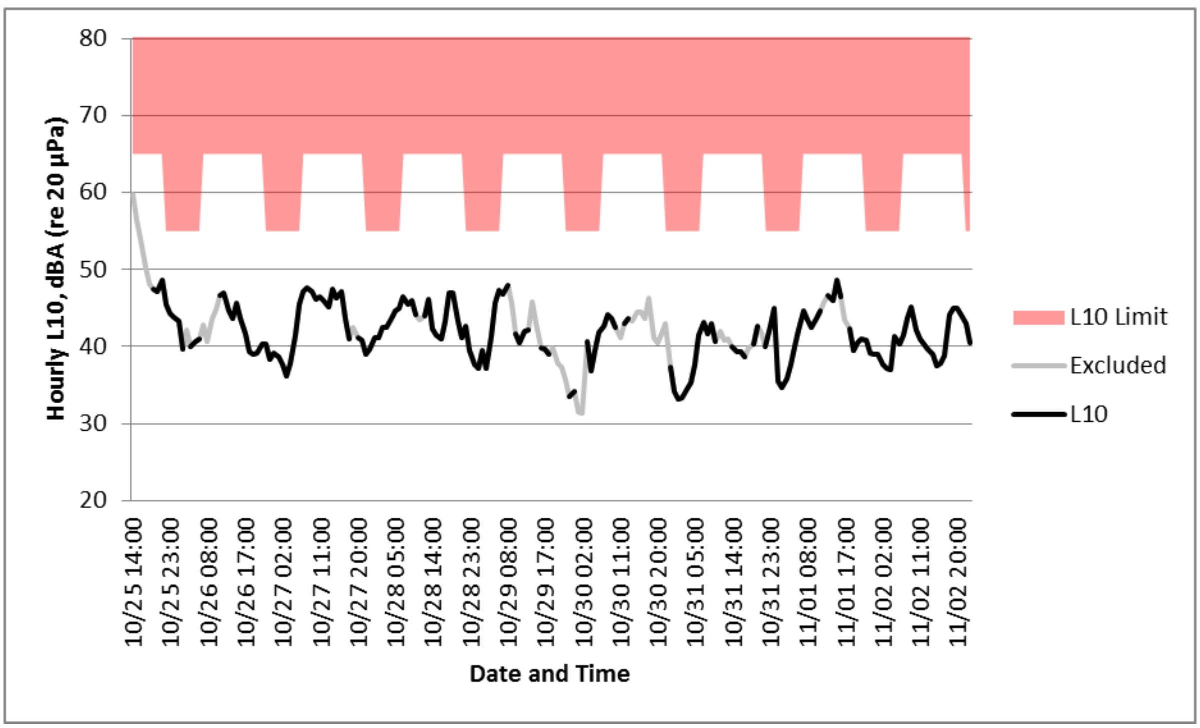
Other sources of potential noise were expected to be minimal, but could have included local traffic. Wind speeds and precipitation events from the Two Harbors Airport were used to identify weather-related exclusions. Figure 9-12 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-12. ML3 Hourly L_{eq} with Exclusions



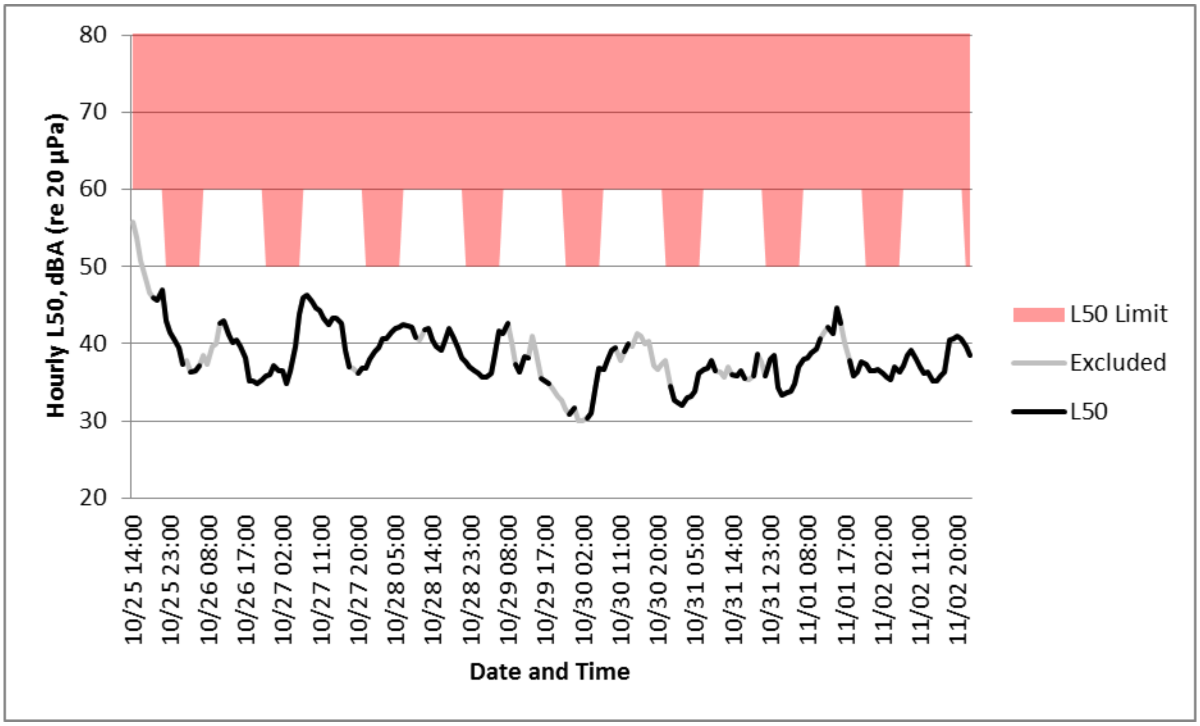
Compared to locations adjacent to the highway, trends in the hourly L_{eq} at ML3 are much less distinguishable. With significantly lower sound levels from the highway, the measured levels are more heavily influenced by ambient noises. As a result, the levels are more sporadic. Figure 9-13 shows the measured hourly L_{10} with the MPCA limits.

Figure 9-13. ML3 Hourly L_{10} with MPCA Limits



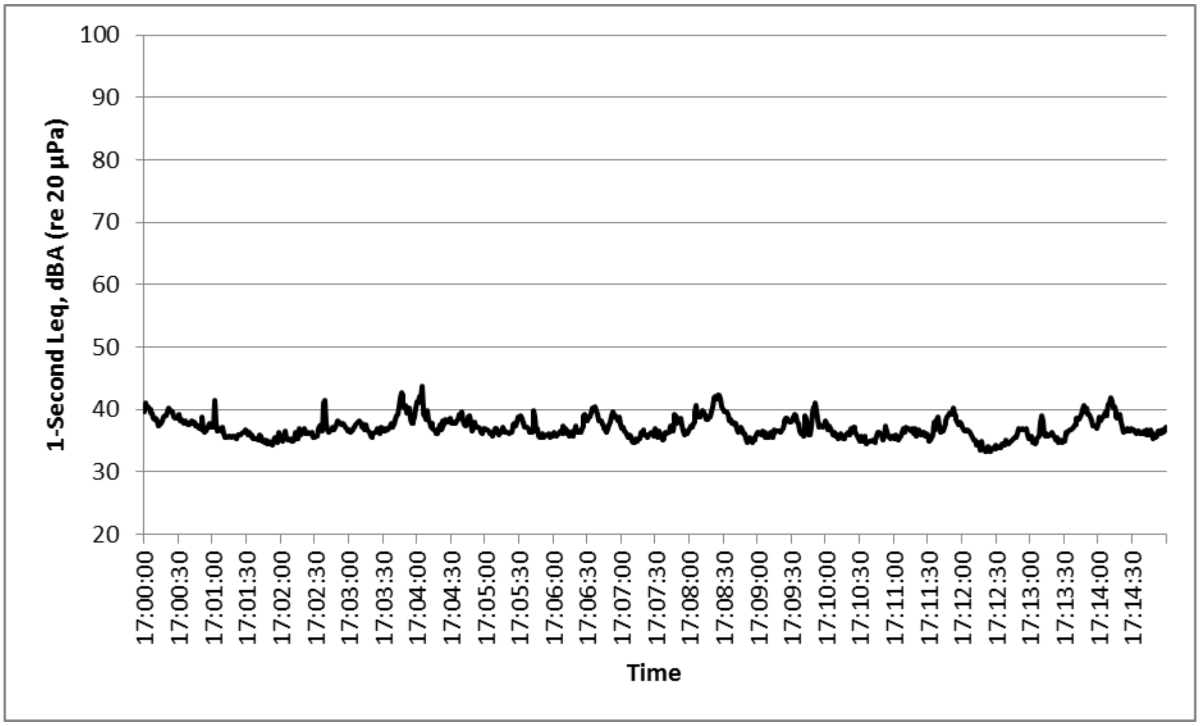
The lower sound levels were well within the MPCA noise limits. Figure 9-14 shows the measured hourly L_{50} with the MPCA noise limits.

Figure 9-14. ML3 Hourly L_{50} with MPCA Limits



Again the lower sound levels were well within the MPCA noise limits. Figure 9-15 illustrates the sound level during a peak traffic period at 5:00 p.m. on Thursday October 31, 2013.

Figure 9-15. ML3 Peak Traffic Period



Further from TH 61, the vehicle pass-by events are difficult to identify. Some peaks are visible, but others are indistinguishable from the background noise. As the levels become indistinguishable from other sources, frequency characteristics also become more difficult to recognize.

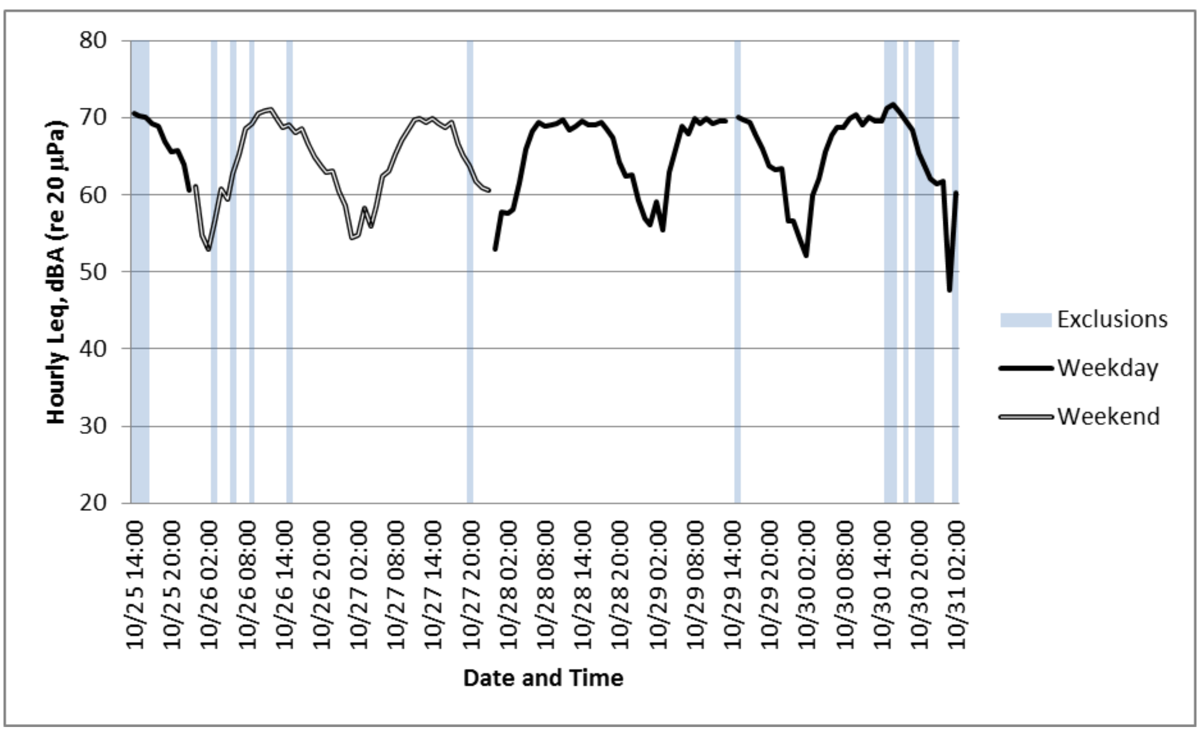
9.4 ML4 Detailed Results

Monitoring at ML4 occurred from Friday October 25 to Thursday October 31, 2013. The monitoring period was cut short due to technical difficulties with the monitoring equipment. ML4 was located at a residence directly on the landside of TH 61. The monitoring equipment was located on a grass lawn with direct line of sight with TH 61. Figure 9-16 shows the monitoring setup and the highway.

Figure 9-16. ML4 Monitoring Setup

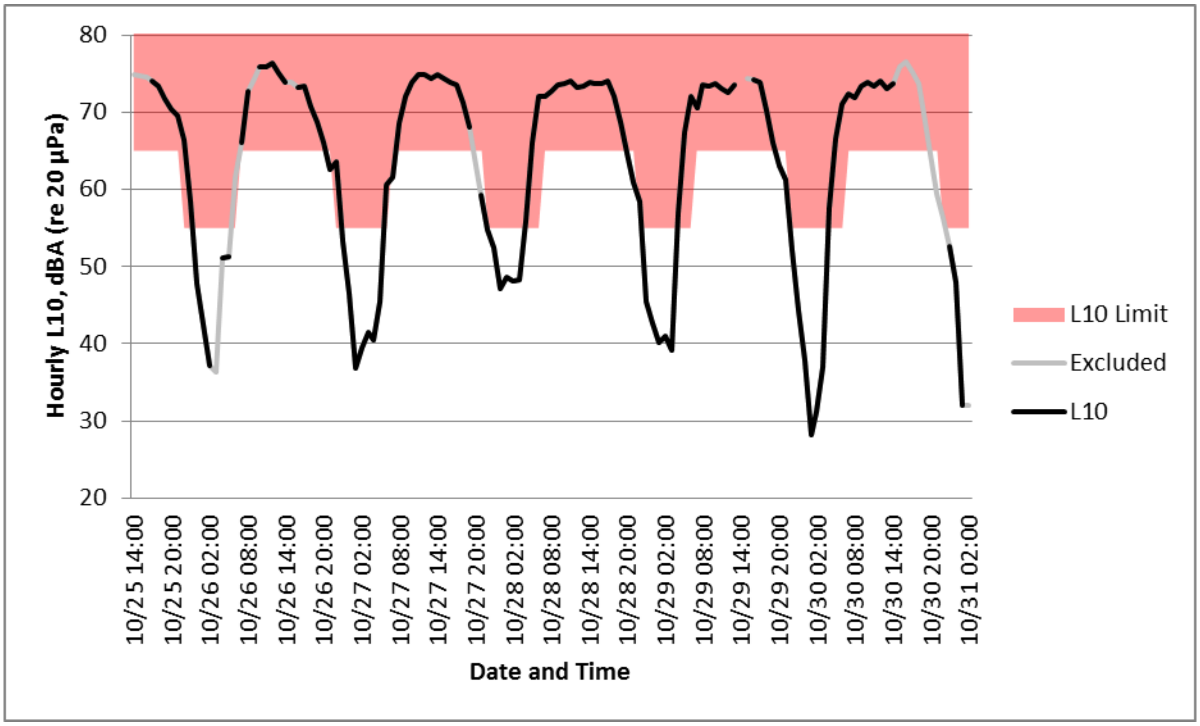
Other sources of potential noise included local traffic specific to the residence. Wind speeds and precipitation events from the Silver Bay Airport were used to identify weather-related exclusions. Figure 9-17 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-17. ML4 Hourly L_{eq} with Exclusions



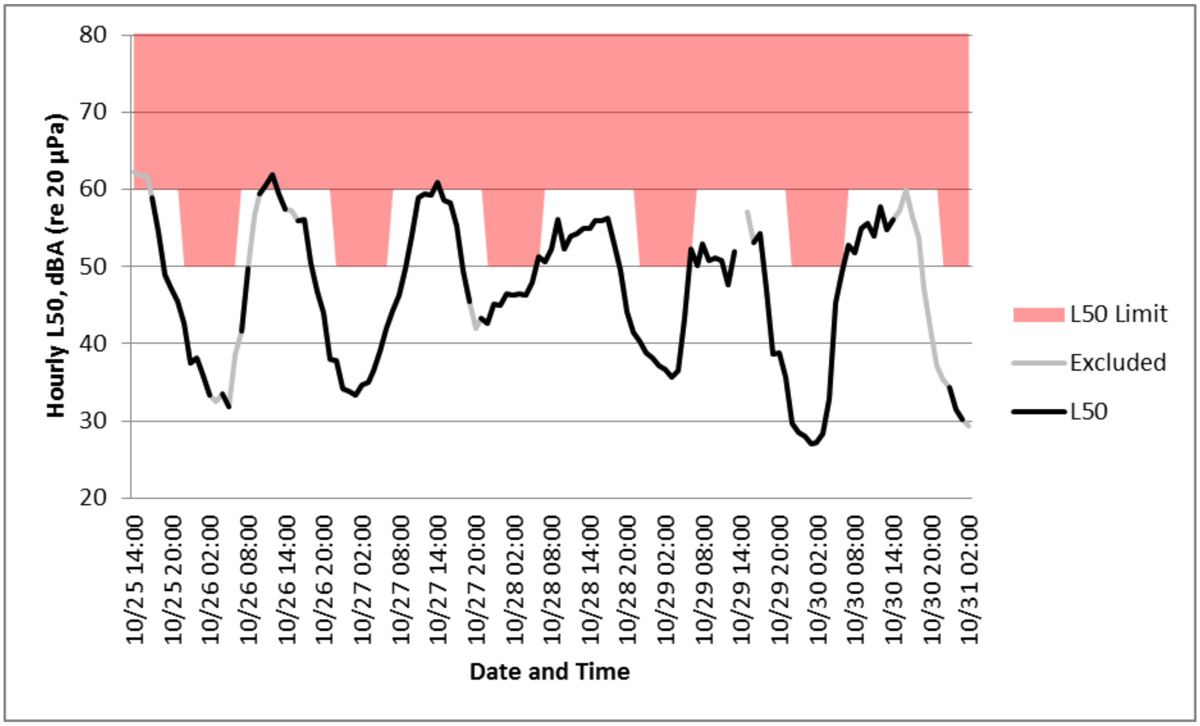
Some of the sound monitoring equipment was replaced on October 29, 2013; the gap in the solid L_{eq} curve illustrates the transition period where no sound level meter was running. The primary source for ML4 was expected to be the highway itself, and the hourly L_{eq} supports this expectation. The levels are consistently increased during the day and decreased at night. Figure 9-18 shows the measured hourly L_{10} compared to the MPCA noise limits.

Figure 9-18. ML4 Hourly L_{10} with MPCA Limits



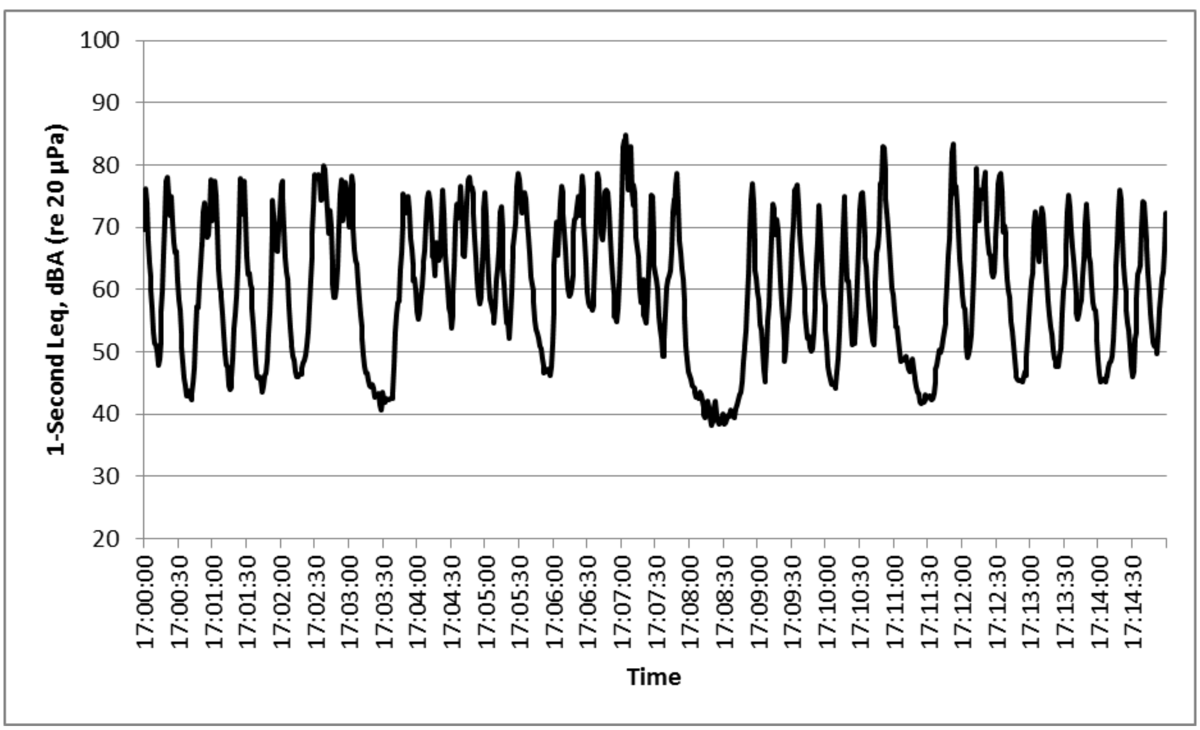
Due to the proximity to TH 61, the sound levels repeatedly exceed the MPCA limits during the day. Hours at the beginning and end of the nighttime period also exceed the nighttime limits. Figure 9-19 shows the measured hourly L_{50} relative to the MPCA limits.

Figure 9-19. ML4 Hourly L_{50} with MPCA Limits



A majority of the monitoring period complies with the MPCA, but three daytime hours and two nighttime hours exceed the L_{50} limits. Both of the nighttime exceeding hours occurred at 6:00 a.m. on weekday mornings. Figure 9-20 shows a 15-minute period during the peak traffic time of 5:00 p.m. on Monday October 28, 2013.

Figure 9-20. ML4 Peak Traffic Period



As the monitoring location was very close to the highway, the vehicle pass-by events produced strong peaks. As peaks overlap one another it becomes difficult to determine if peaks are due to a single vehicle or multiple vehicles.

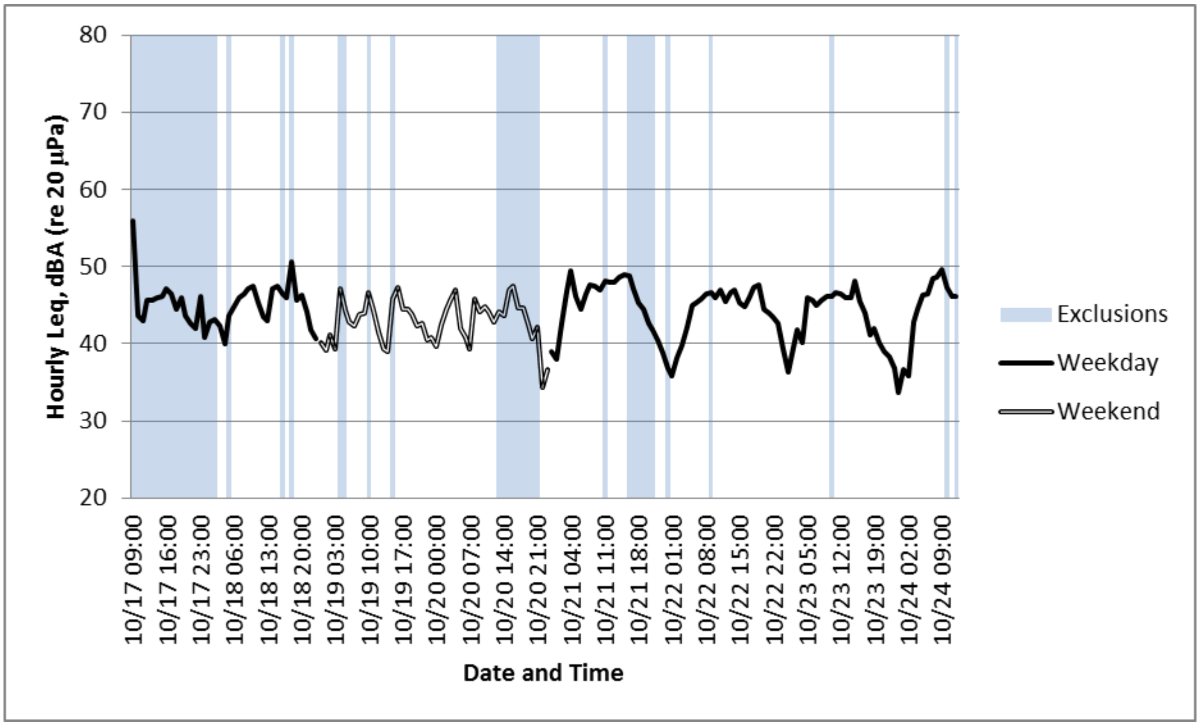
9.5 ML5 Detailed Results

Monitoring at ML5 occurred from Thursday October 17 to Thursday October 24, 2013. ML5 was located at a residence downhill from the lakeside of TH 61. The monitoring equipment was located on a grass lawn on the highway-side of the residence. A wooded area with a bike trail separated the residence and the highway. Figure 9-21 shows the monitoring setup.

Figure 9-21. ML5 Monitoring Setup

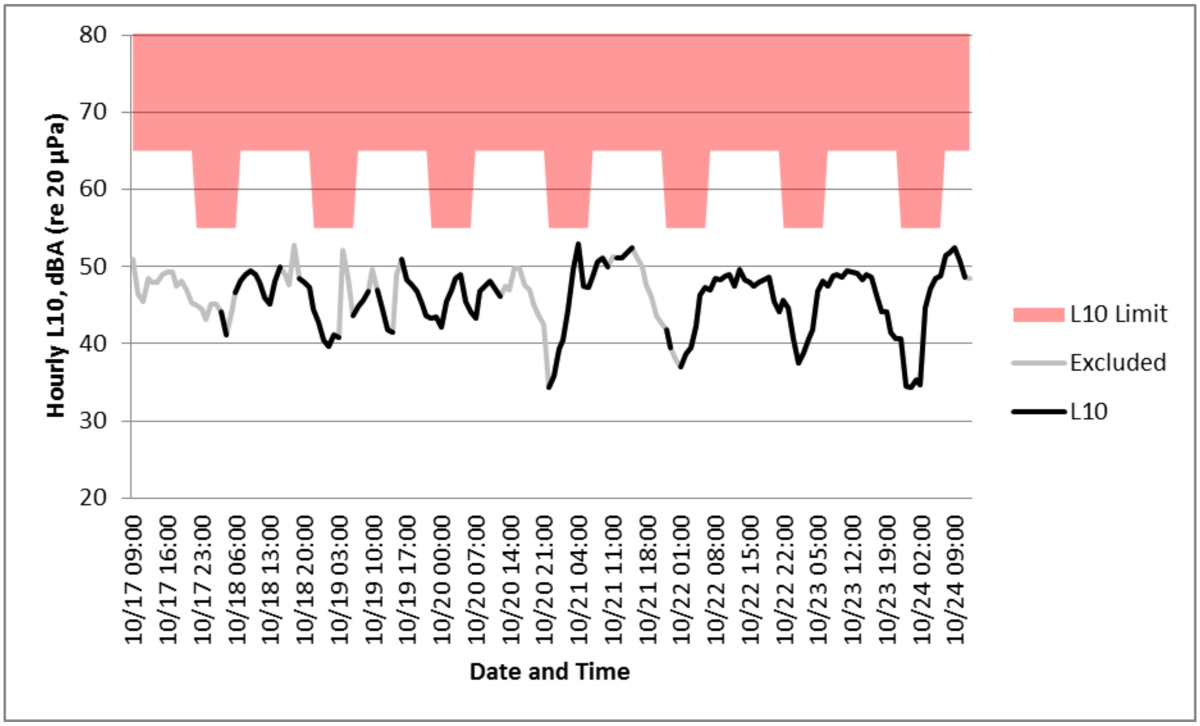
Other sources of potential noise included local traffic specific to the residence and pedestrians on the nearby bike trail. Wind speeds and precipitation events from the Silver Bay Airport were used to identify weather-related exclusions. Figure 9-22 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-22. ML5 Hourly L_{eq} with Exclusions



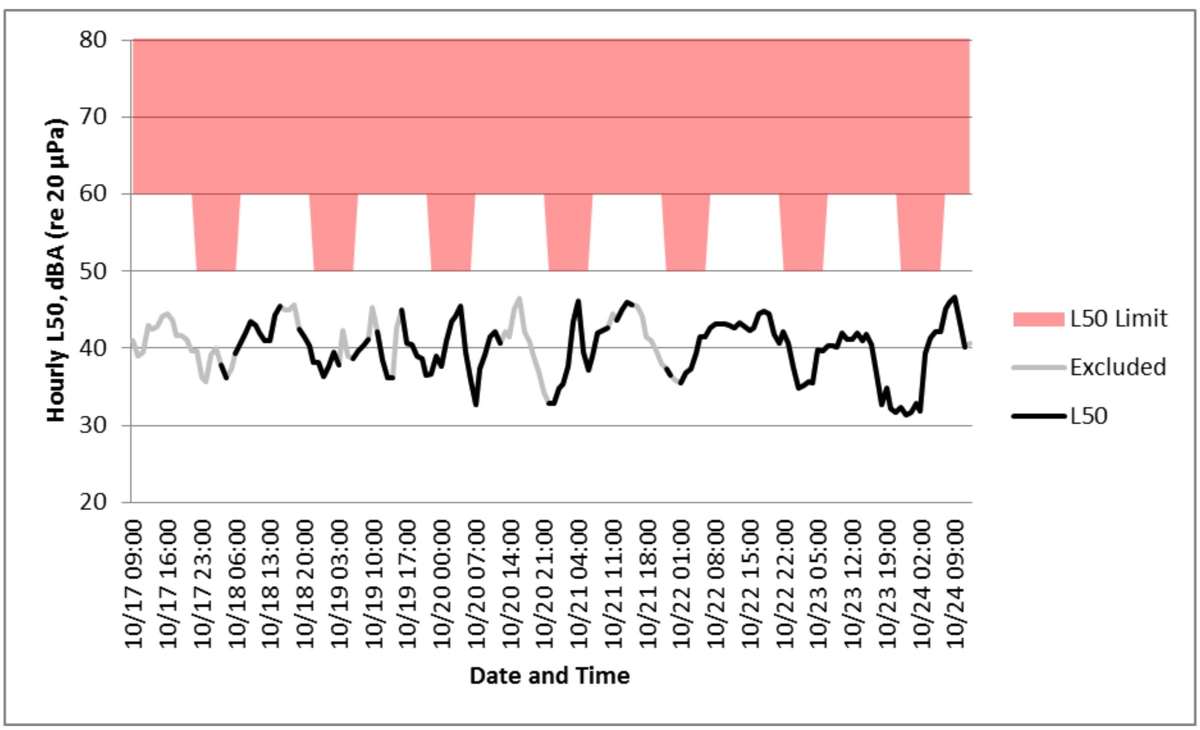
The first half of the monitoring period contains sporadic levels, but the second half develops a clear daytime to nighttime trend. Due to the sporadic levels of the first half, it is difficult to draw comparisons between weekdays and weekends. This location is not completely dominated by highway noise, but some influence is present. Figure 9-23 shows the measured hourly L_{10} and MPCA noise limits.

Figure 9-23. ML5 Hourly L_{10} with MPCA Limits



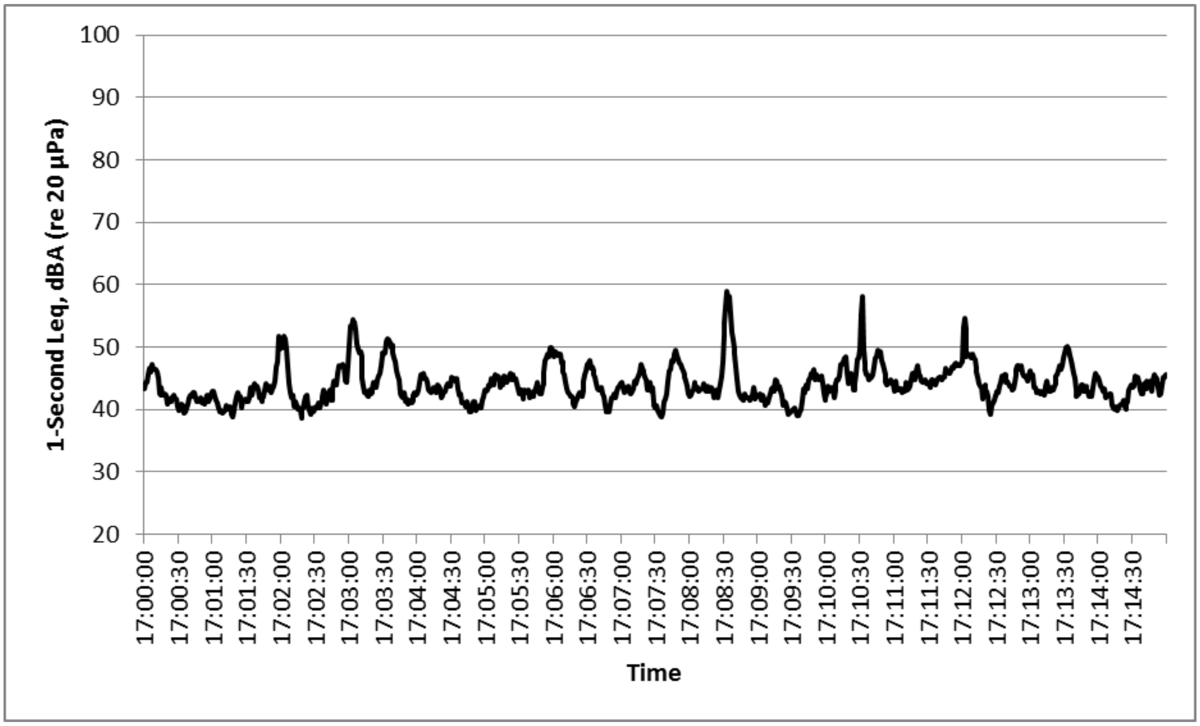
The measured L_{10} is within the MPCA noise limits. This result is expected as ML5 was 430 feet from TH 61. Figure 9-24 compares the measured hourly L_{50} to the MPCA noise limits.

Figure 9-24. ML5 Hourly L_{50} with MPCA Limits



The measured L_{50} is in compliance with the MPCA noise limits. Figure 9-25 illustrates the sound levels during a peak traffic period at 5:00 p.m. on Tuesday October 22, 2013.

Figure 9-25. ML5 Peak Traffic Period



Some clear peaks appear in the data, but minor peaks could either be vehicle pass-by events or background noise. This result suggests the loudest highway noise events affect the levels measured at ML5, but quieter events have little influence.

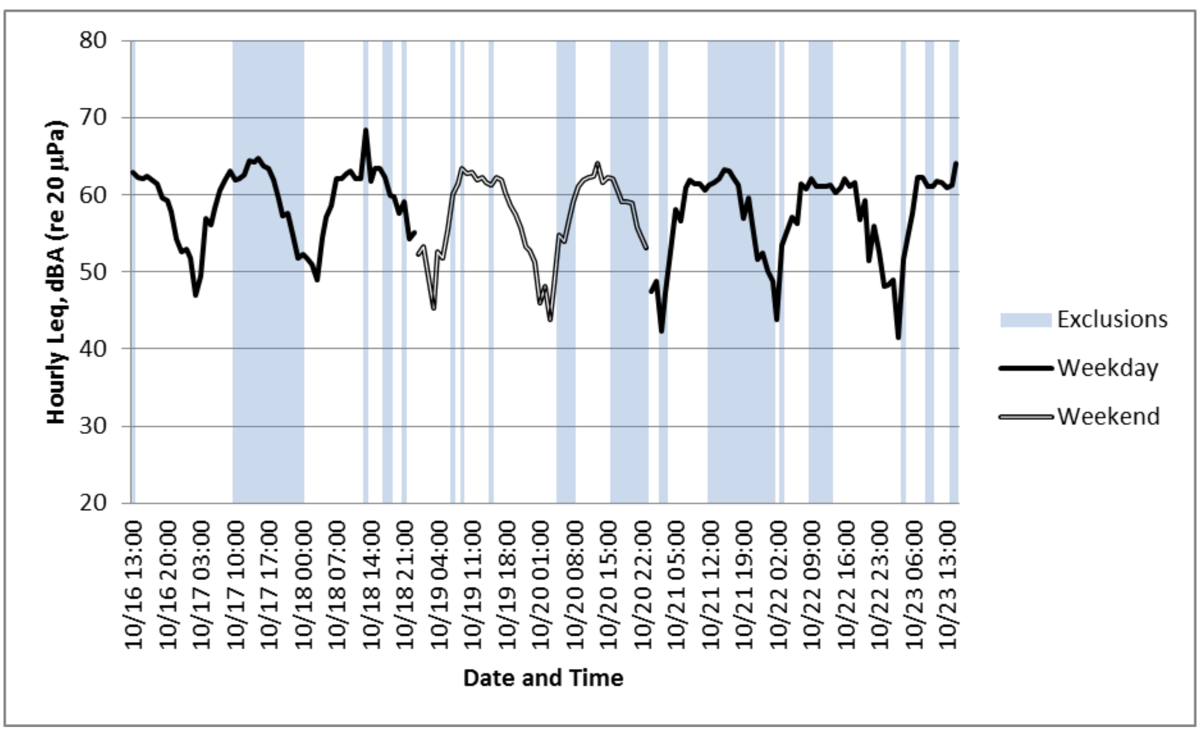
9.6 ML6 Detailed Results

Monitoring at ML6 occurred from Wednesday October 16 to Wednesday October 23, 2013. ML6 was located at a residence directly on the landside of TH 61. The monitoring equipment was located on a grassy patch within a circle driveway, and had direct line of sight with the highway. Figure 9-26 shows the monitoring setup and TH 61.

Figure 9-26. ML6 Monitoring Setup

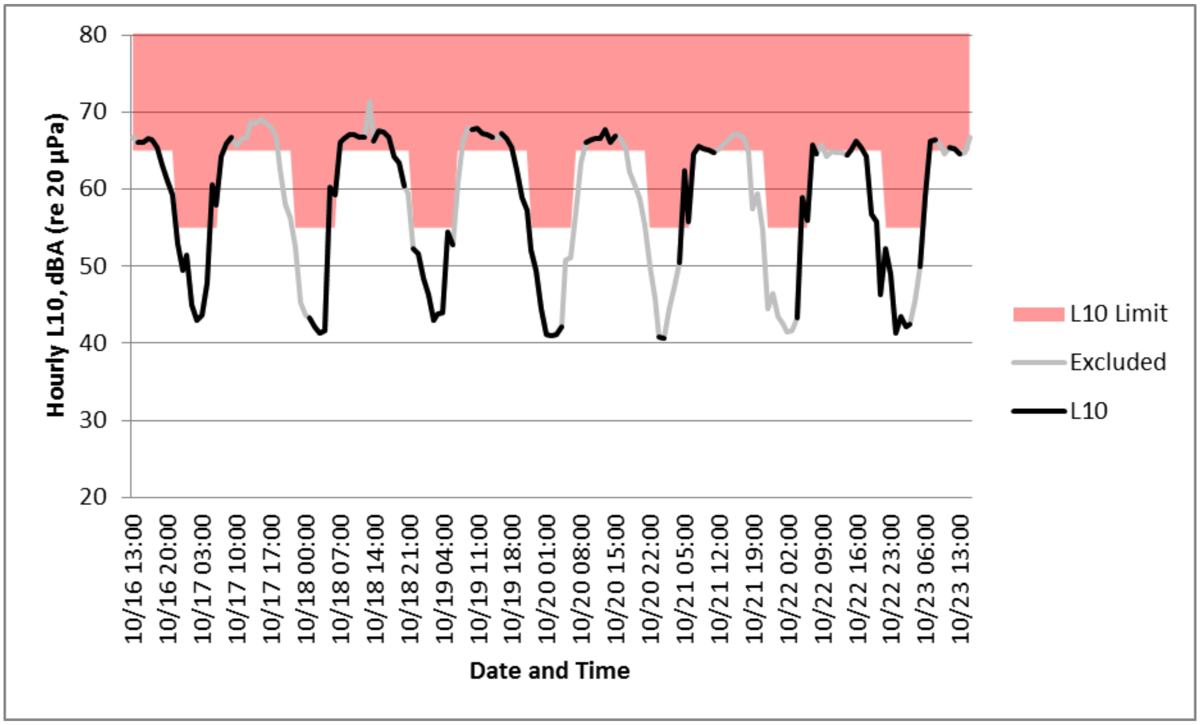
Other sources of potential noise included construction activities and yard work. Wind speeds and precipitation events from the Grand Marais Airport were used to identify weather-related exclusions. Figure 9-27 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-27. ML6 Hourly L_{eq} with Exclusions



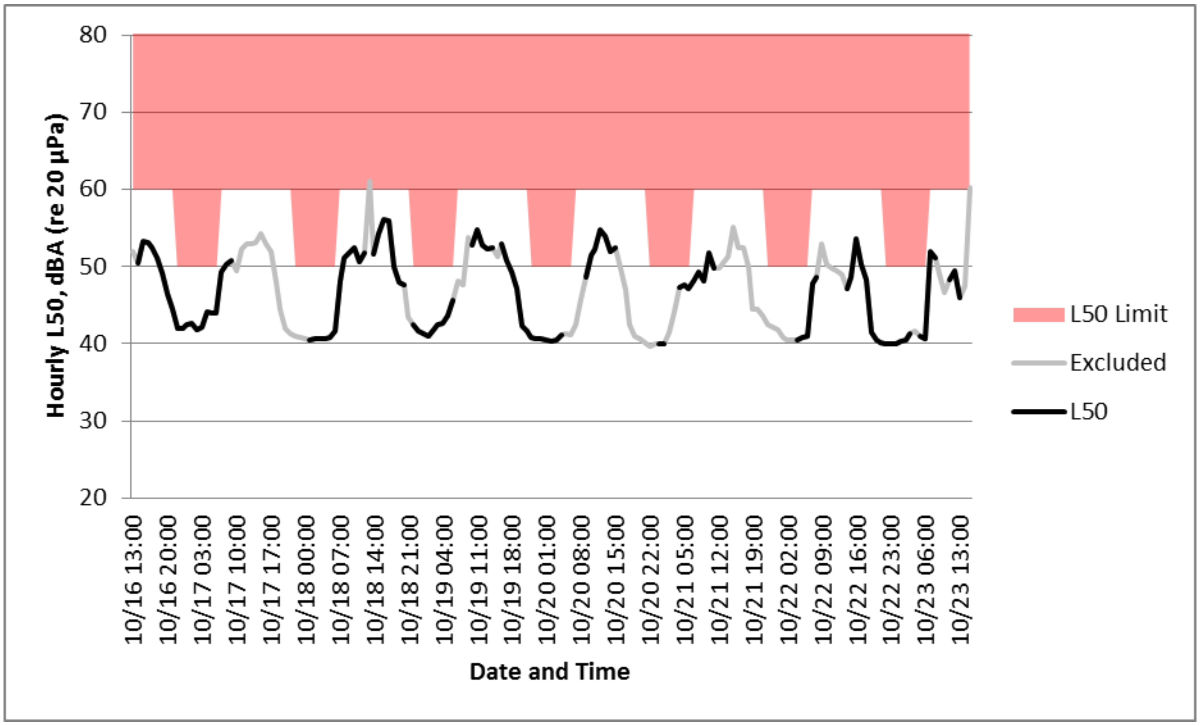
ML6 was directly on TH 61, and the measured L_{eq} reflects a consistent pattern of increased sound levels during daytime hours. The levels were consistent from day to day, with no clear difference between weekday and weekend levels. Figure 9-28 shows the measured hourly L_{10} with the MPCA noise limits.

Figure 9-28. ML6 Hourly L_{10} with MPCA Limits



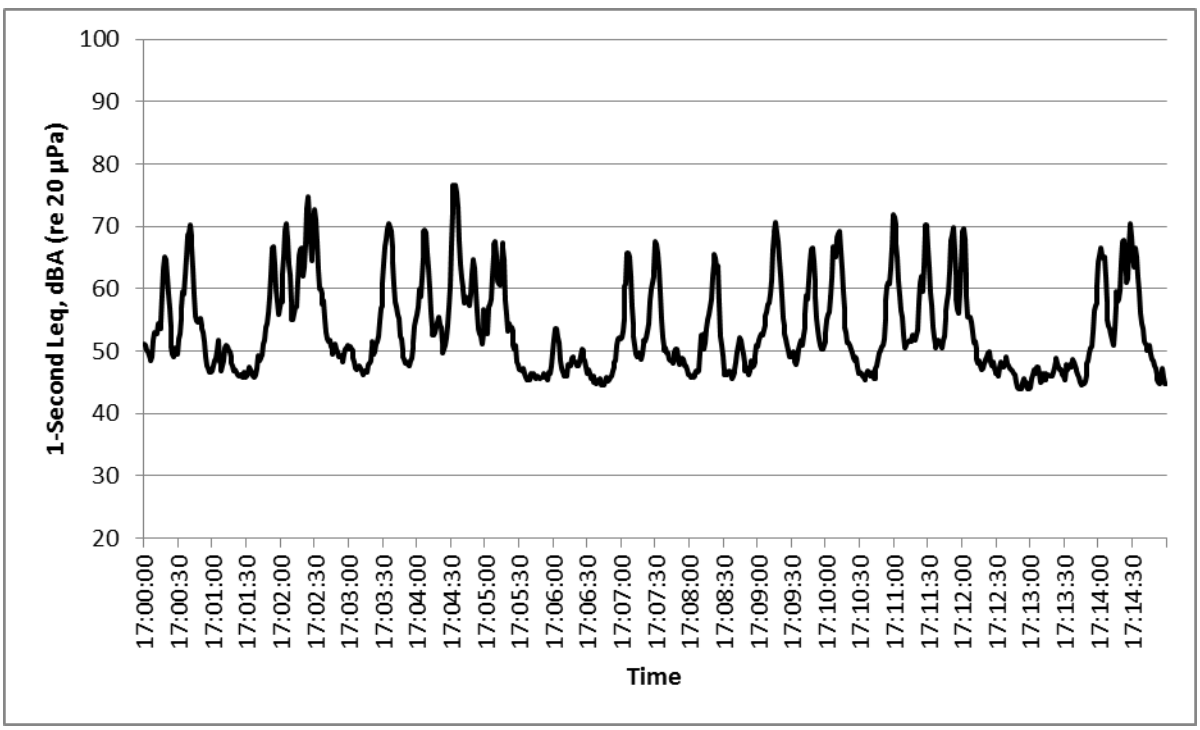
The measured L_{10} repeatedly exceeds the MPCA daytime noise limit, and nine nighttime hours exceeded the nighttime noise limit. The exceeding nighttime hours all occurred at 5:00 and 6:00 a.m. on weekdays. Figure 9-29 compares the measured hourly L_{50} to the MPCA noise limits.

Figure 9-29. ML6 Hourly L_{50} with MPCA Limits



The L_{50} is within the MPCA noise limits at all hours measured. Figure 9-30 depicts a 15-minute period at the peak traffic time of 5:00 p.m. on Tuesday October 22, 2013.

Figure 9-30. ML6 Peak Traffic Period



With the monitoring location close to the highway, the vehicle pass-by events produce strong peaks. This period illustrates some overlapping peaks, which cannot be clearly identified as being produced by a single vehicle or multiple vehicles from this curve alone.

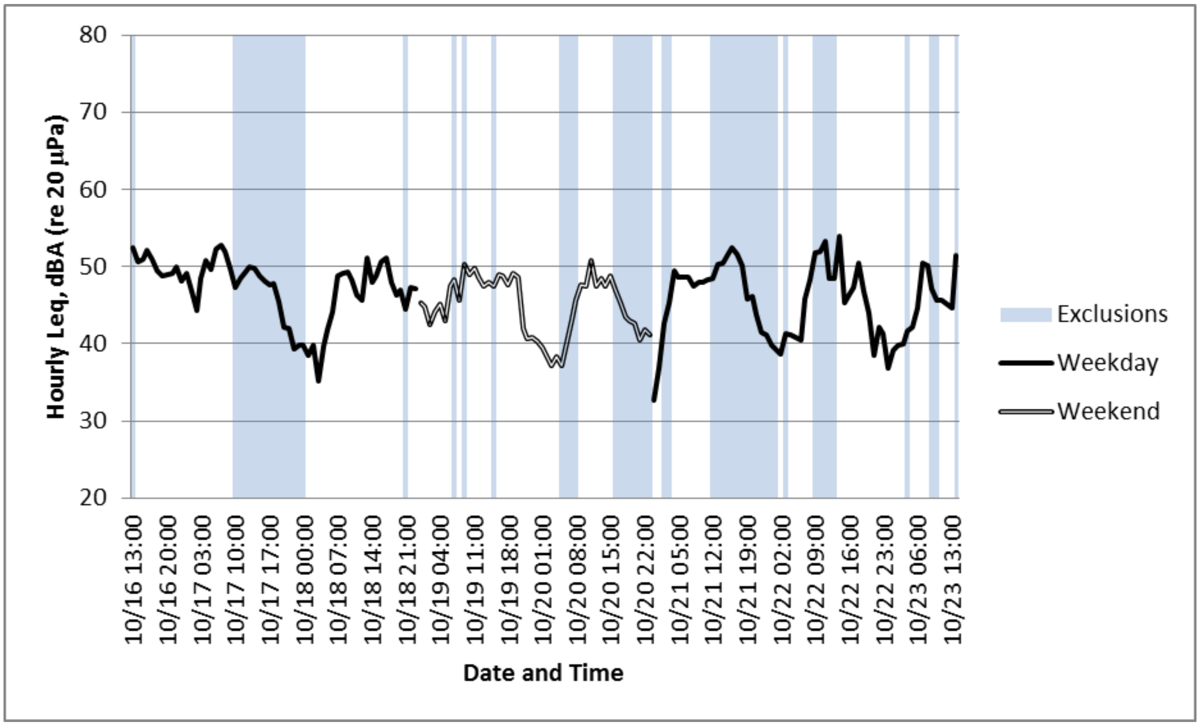
9.7 ML7 Detailed Results

Monitoring at ML7 occurred from Wednesday October 16 to Wednesday October 23, 2013. ML7 was located at a residence 450 feet from the landside of TH 61, and was uphill from the highway. The monitoring equipment was located on landscape rock, and had direct line of sight with a portion of the highway. Figure 9-31 shows the monitoring setup, and TH 61 can be seen in the background.

Figure 9-31. ML7 Monitoring Setup

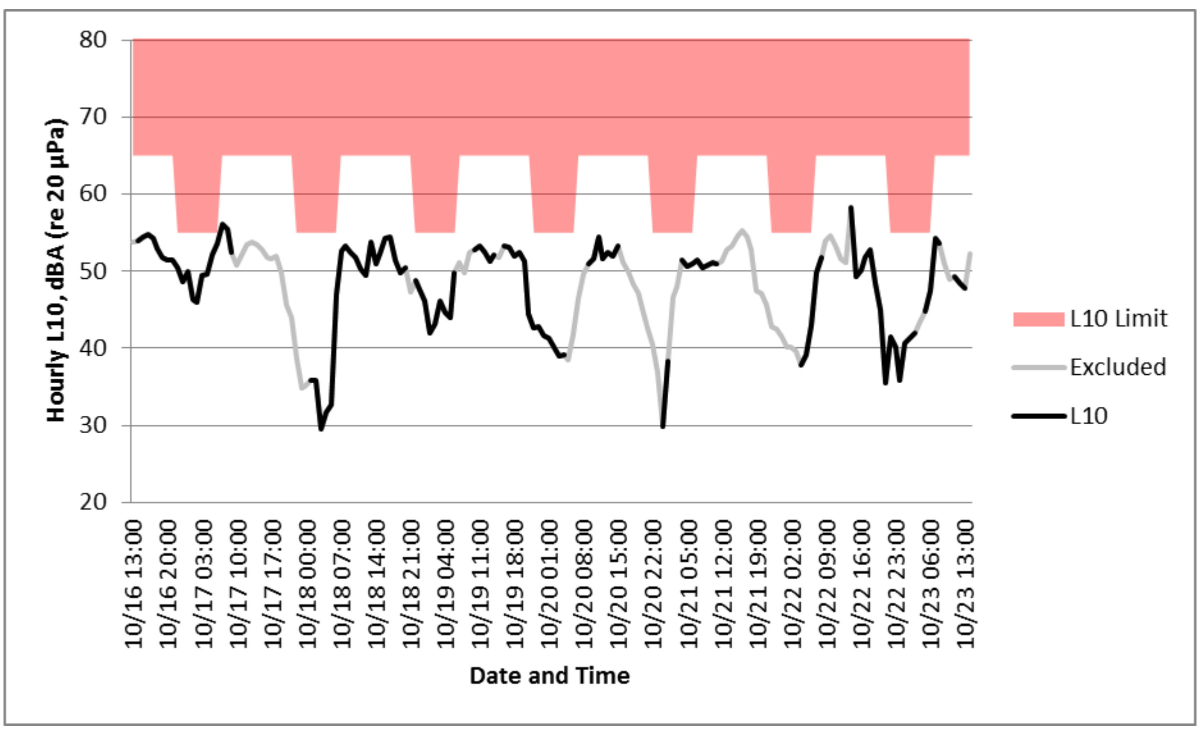
Other sources of potential noise included local vehicle traffic. Wind speeds and precipitation events from the Grand Marais Airport were used to identify weather-related exclusions. Figure 9-32 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-32. ML7 Hourly L_{eq} with Exclusions



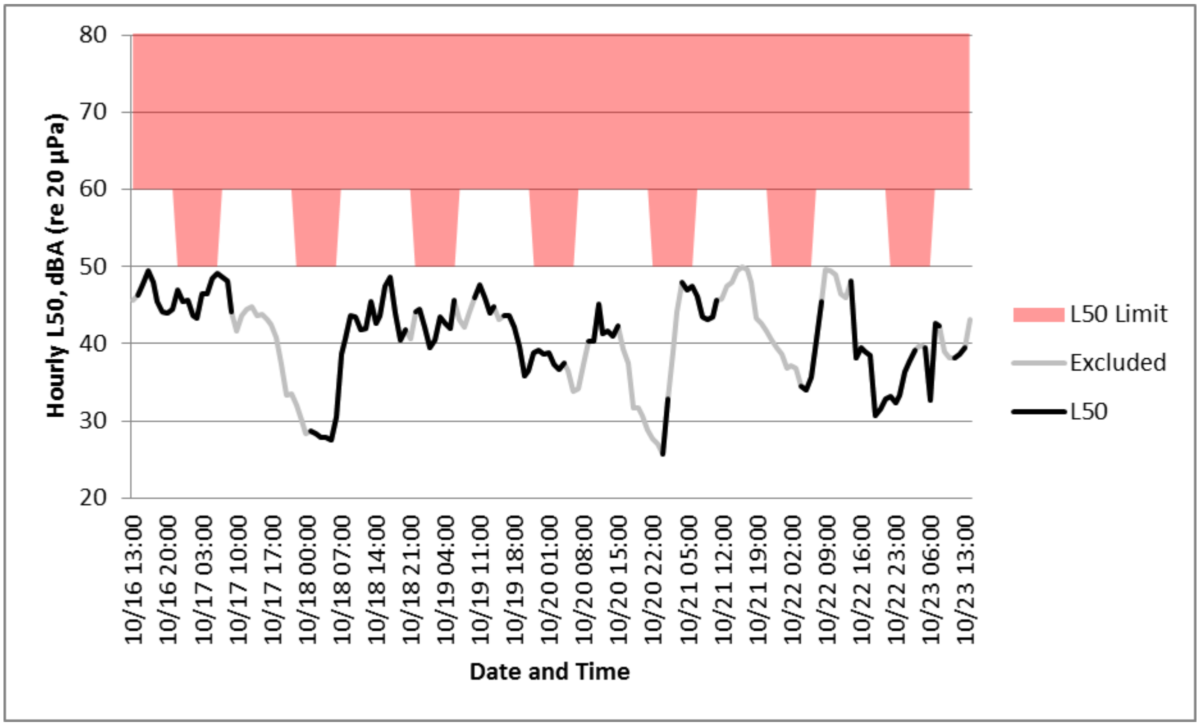
Clear daytime peaks are visible at times, but some periods contained sporadic sound levels. This mixed result is expected for a location that was some distance from the highway, but still had direct line of sight. Figure 9-33 shows the measured hourly L_{10} with the MPCA noise limits.

Figure 9-33. ML7 Hourly L_{10} with MPCA Limits



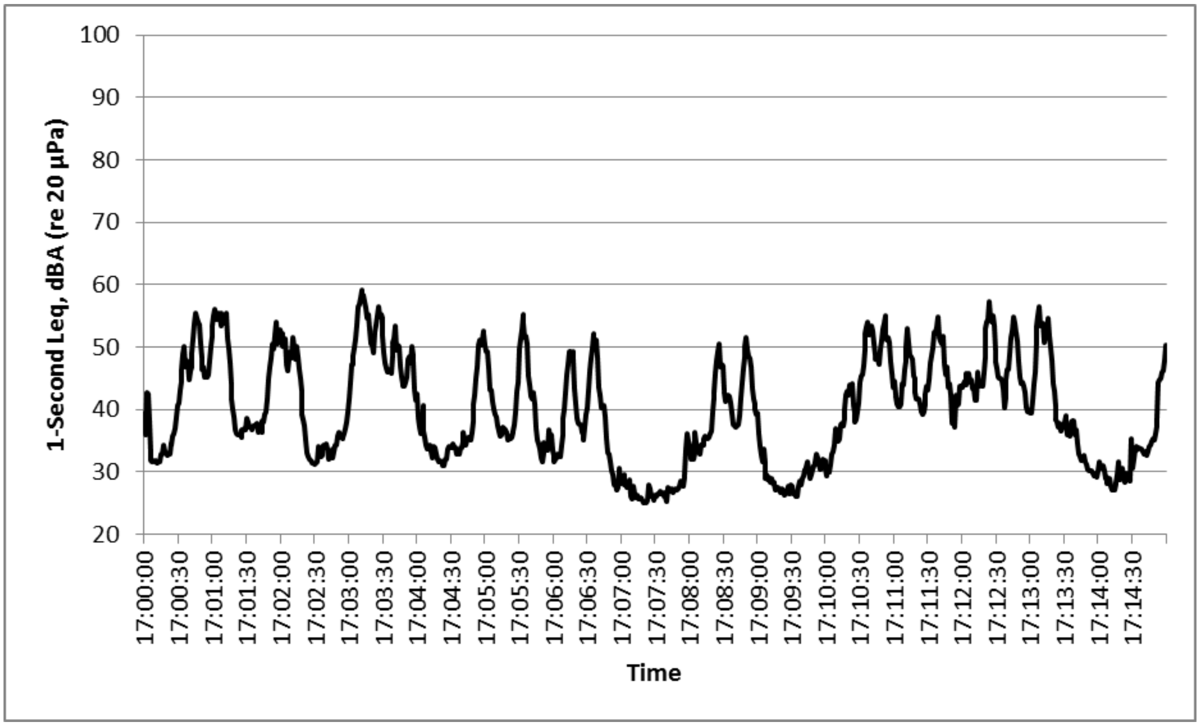
The measured L_{10} was within the MPCA noise limits throughout the entire monitoring period. The daytime levels were within a certain range, but the nighttime levels varied widely. This location was expected to be more influenced by local noise events. The results indicate this was the case for nighttime levels in particular. Figure 9-34 illustrates the measured hourly L_{50} relative to the MPCA noise limits.

Figure 9-34. ML7 Hourly L_{50} with MPCA Limits



The measured L_{50} is within the MPCA noise limits throughout the monitoring period. The variation in nighttime levels from day to day is again depicted. Figure 9-35 shows the sound level during a peak traffic period at 5:00 p.m. on Tuesday October 22, 2013.

Figure 9-35. ML7 Peak Traffic Period



Prominent peaks are still seen, despite being located a considerable distance from TH 61. A low background noise level appears to keep the vehicle pass-by events rather distinct. Compared to locations closer to the highway, the peak sound levels are reduced. This 15-minute period contains groupings of peaks where traffic is heavier.

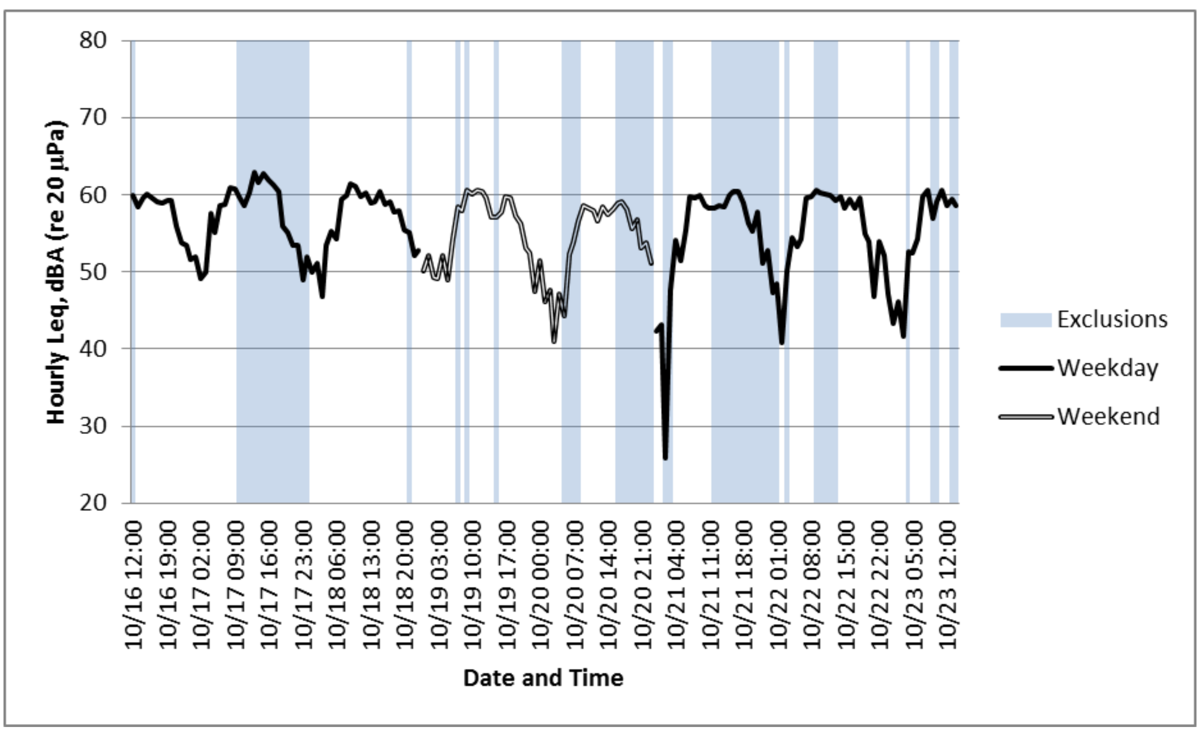
9.8 ML8 Detailed Results

Monitoring at ML8 occurred from Wednesday October 16 to Wednesday October 23, 2013. ML8 was located in a grassy clearing adjacent to the lakeside of TH 61, and was a few feet below pavement level. Figure 9-36 shows the monitoring setup and the highway in the background.

Figure 9-36. ML8 Monitoring Setup

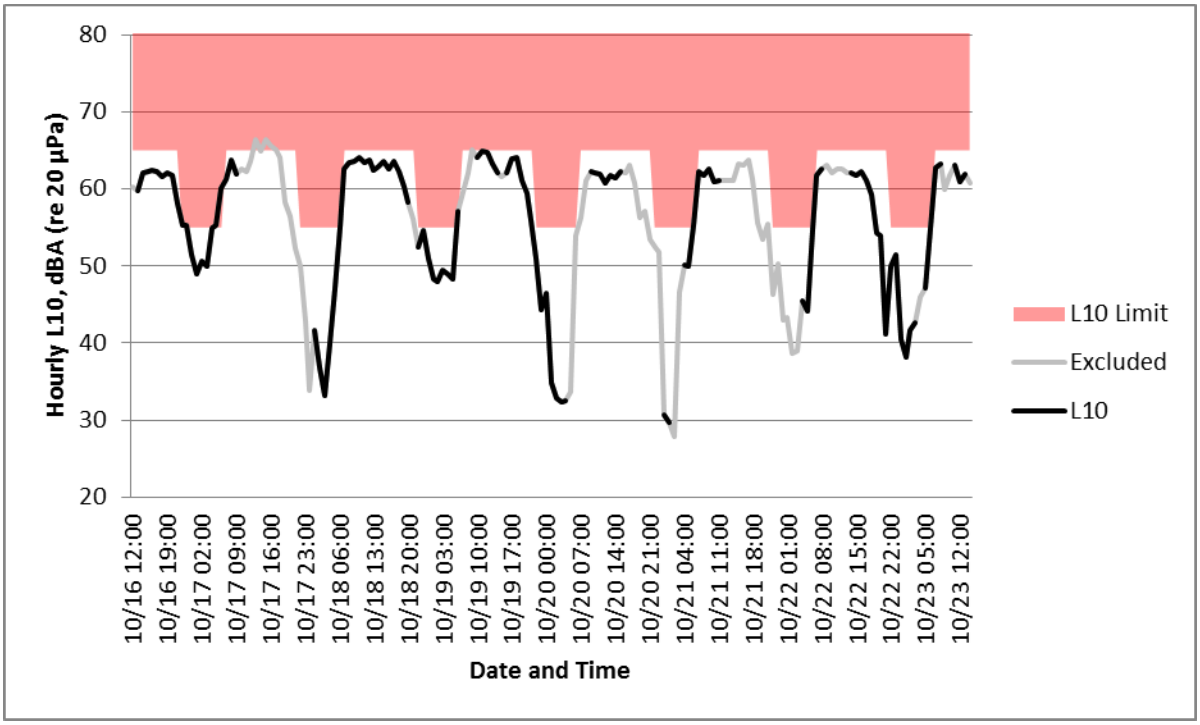
No human traffic was expected within the immediate vicinity, so other sources of potential noise were limited to ambient sounds. Wind speeds and precipitation events from the Grand Marais Airport were used to identify weather-related exclusions. Figure 9-37 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-37. ML8 Hourly L_{eq} with Exclusions



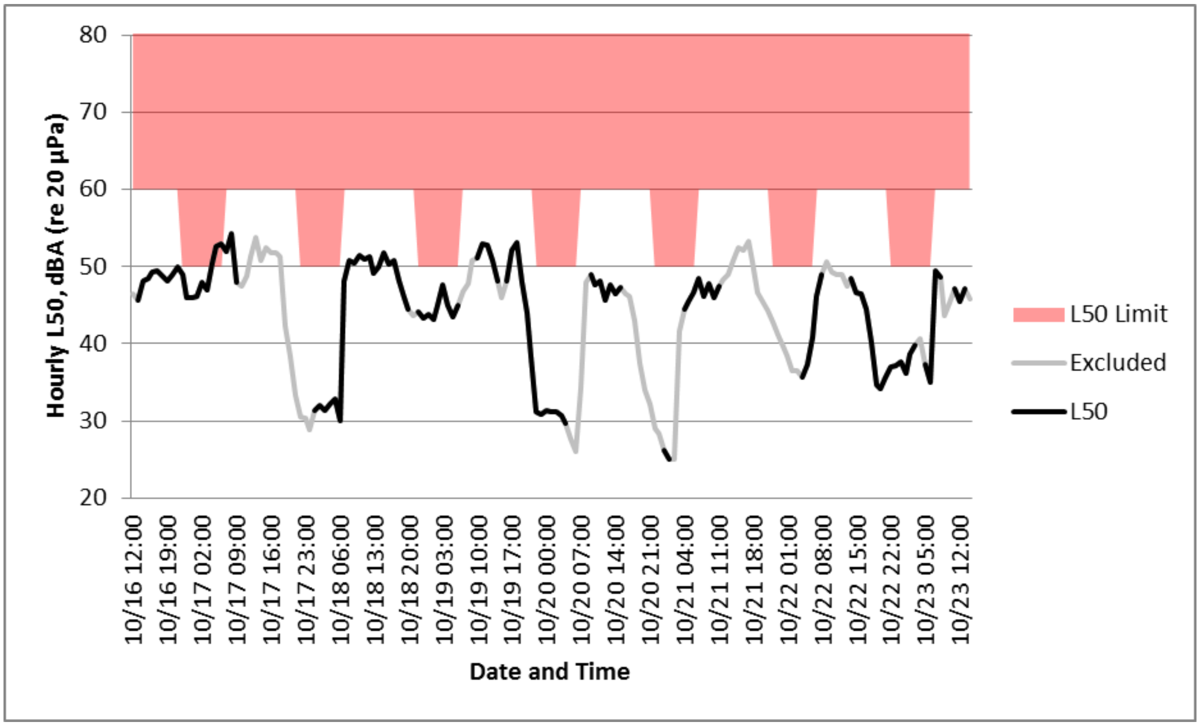
Distinct daytime peaks are present as the levels were elevated during the day compared to during the night. An unusually quiet night occurred during the early hours of Monday October 21. As the highway is expected to particularly dominate this uninhabited location, the traffic was likely particularly light when the low sound levels occurred. The daytime levels were fairly consistent from day to day, with the exception of higher levels during the rainy day of Thursday October 17 and slightly lower levels on Sunday October 20. Figure 9-38 compares the measured hourly L_{10} to the MPCA noise limits.

Figure 9-38. ML8 Hourly L_{10} with MPCA Limits



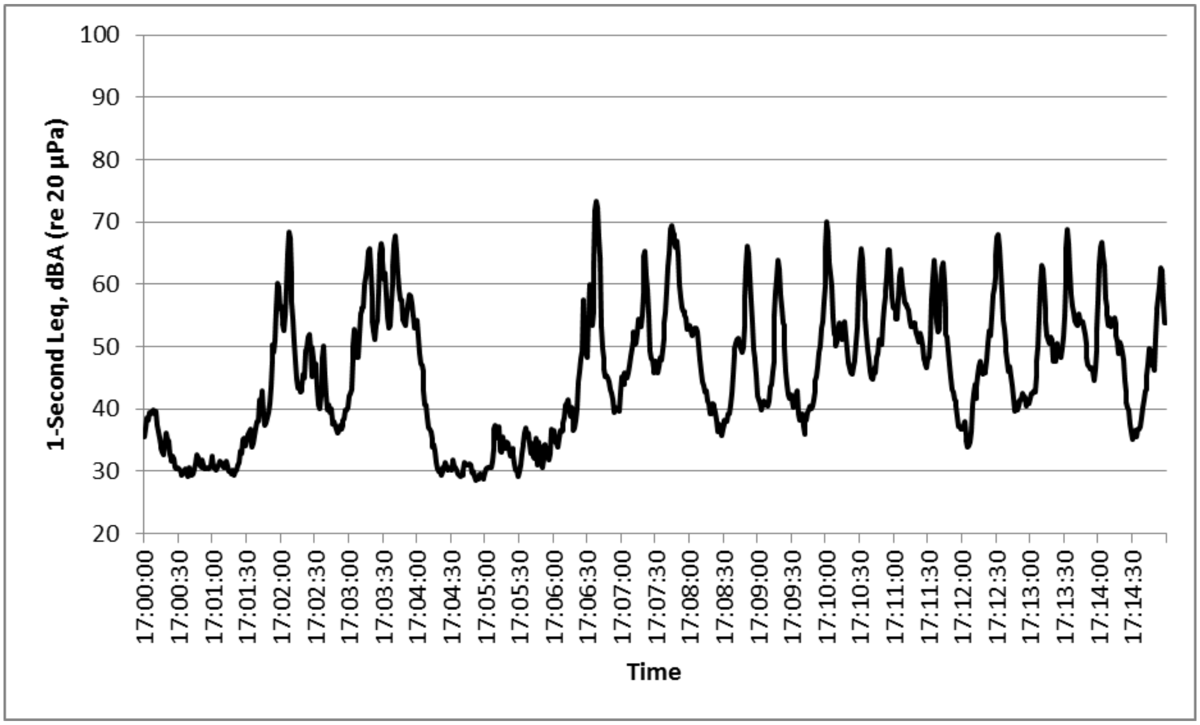
Surprisingly for a location so close to the highway, the daytime levels are all within the MPCA noise limit. Seven nighttime hours exceeded the nighttime limit; two of which occurred at the beginning of the nighttime period, four occurred at 5:00 and 6:00 a.m. on weekday mornings, and one occurred at 6:00 a.m. on a Saturday. Figure 9-39 shows the measured hourly L_{50} relative to the MPCA noise limits.

Figure 9-39. ML8 Hourly L_{50} with MPCA Limits



The only L_{50} exceeding hours occurred from 4:00 to 6:00 a.m. on Thursday October 17. A selective audio review suggested the elevated L_{50} levels were due to localized winds and noise from waves on the lake. Figure 9-40 shows a 15-minute period during the peak traffic period at 5:00 p.m. on Tuesday October 22, 2013.

Figure 9-40. ML8 Peak Traffic Period



The location adjacent to the highway yielded strong peaks for the vehicle pass-by events. The uninhabited area has a low background noise level, as seen by the low levels at times where no high level peaks are occurring.

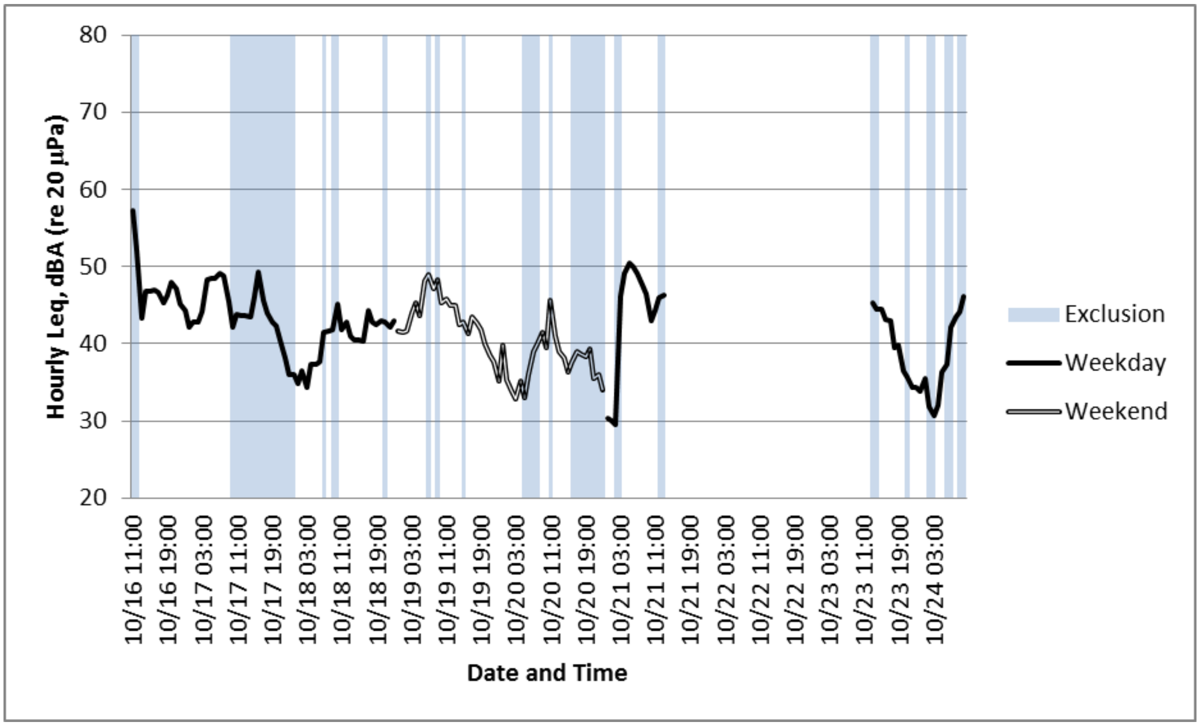
9.9 ML9 Detailed Results

Monitoring at ML9 occurred from Wednesday October 16 to Thursday October 24, 2013. A power outage combined with technical difficulties resulted in a two-day period when the monitoring system was non-operational. ML9 was located at a residence between TH 61 and Lake Superior. The area was wooded with no line of sight with the highway, and the monitoring system was placed on low vegetation. Figure 9-41 shows the monitoring setup and a shed on the residence.

Figure 9-41. ML9 Monitoring Setup

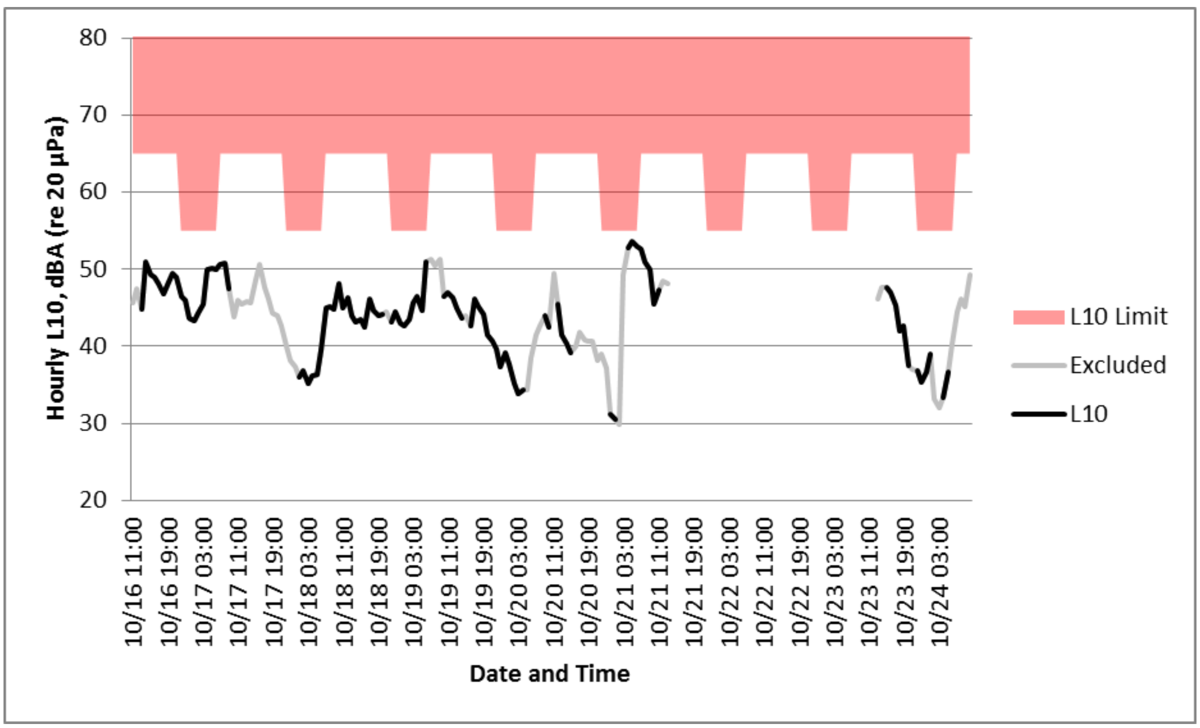
Other sources of potential noise included traffic specific to the residence and yard work. Wind speeds and precipitation events from the Grand Marais Airport were used to identify weather-related exclusions. Figure 9-42 illustrates the measured hourly L_{eq} over the complete monitoring period and hours containing exclusions.

Figure 9-42. ML9 Hourly L_{eq} with Exclusions



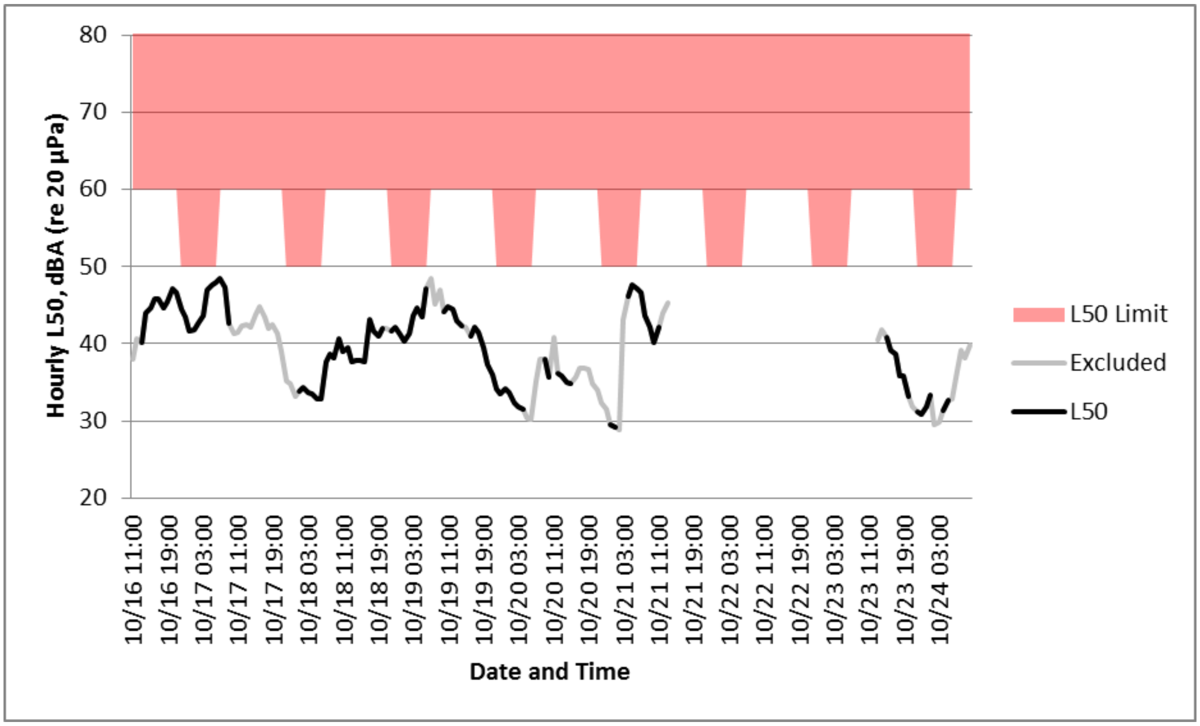
The hourly L_{eq} is sporadic with no clear trend, which is expected for a location 800 feet from TH 61. The sound levels appear to be dominated by local sound sources. Figure 9-43 compares the measured hourly L_{10} to the MPCA noise limits.

Figure 9-43. ML9 Hourly L_{10} with MPCA Limits



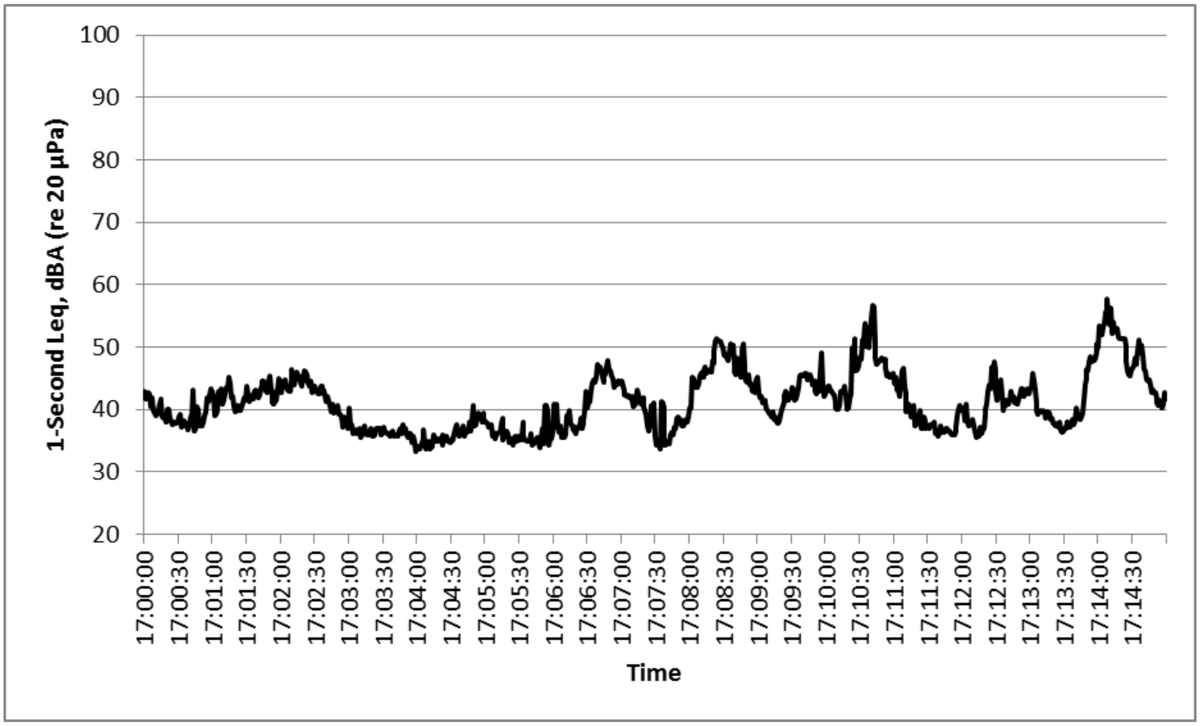
No measured levels were found to exceed the MPCA noise limits. Figure 9-44 shows the measured hourly L_{50} relative to the MPCA noise limits.

Figure 9-44. ML9 Hourly L_{50} with MPCA Limits



Again, no measured levels were found to exceed the MPCA noise limits. Figure 9-45 shows the sound levels of the peak traffic period at 5:00 p.m. on Wednesday October 23, 2013.

Figure 9-45. ML9 Peak Traffic Period



The 15-minute monitoring period contains elevated sound levels, but the peaks are much wider making vehicle pass-by identification more difficult. Except for the loudest highway noise events, individual pass-by events are difficult to clearly identify at locations far from TH 61.

10 Appendix B: Controlled Pass-By Monitoring Detailed Results

This appendix contains the detailed results for each pass-by monitoring location. Each location is discussed individually, and detailed measurement data is included.

10.1 PB1 Detailed Results

PB1 was located on the lakeside of TH 61 between mile markers 46 and 47 north of Two Harbors. Monitoring occurred between 1:30 and 2:30 p.m. on Thursday October 24, 2013. Figure 10-1 shows the monitoring location, which was a clearing with grassy vegetation.

Figure 10-1. PB1 Monitoring Setup

TH 61 had a slight slope at this location, and a bike trail was located approximately 90 feet from the highway (placing it between the highway and the 100-foot monitoring location). Opposite of the sound level meters was a vertical rock outcropping. Wet pavement is generally louder than dry pavement, so it was particularly important for the pass-by measurements to be made on dry pavement. The last precipitation event recorded at the Silver Bay Airport prior to the measurements occurred just after 12:00 a.m. on October 22, 2013. Gust wind speeds exceeding the recommended limit of 11 mph were measured during the control and merge maneuvers, but no wind distortion was present in the audio recordings. The handheld radar gun was unavailable during these measurements, so the general speeds of 45, 55, and 65 mph were assumed. Table 10-1 contains the L_{max} values measured at 25, 50, and 100 feet from the centerline of the road.

Table 10-1. PB1 Measurement Data

Maneuver	Pass	Speed, mph	L_{max} at Distance, dBA (re 20 µPa)		
			25 ft.	50 ft.	100 ft.
Control	1	45	75	68	59
Control	2	45	75	68	58
Control	3	45	76	68	60
Control	4	55	79	71	62
Control	5	55	79	71	65
Control	6	55	78	71	63
Control	7	65	82	73	65
Control	8	65	80	72	64
Control	9	65	81	73	65
Drift	1	45	84	77	71
Drift	2	45	89	83	75
Drift	3	45	84	79	70
Drift	4	55	92	83	77
Drift	5	55	96	90	82
Drift	6	55	91	85	78
Drift	7	65	93	87	79
Drift	8	65	97	90	83
Drift	9	65	94	88	80
Merge	1	45	86	80	73
Merge	2	45	79	76	68
Merge	3	45	87	80	74
Merge	4	55	91	85	77
Merge	5	55	84	78	73
Merge	6	55	87	82	75
Merge	7	65	96	89	81
Merge	8	65	89	82	75
Merge	9	65	93	87	80

The measured results of PB1 were used in the regression analyses of Section 5.

10.2 PB2 Detailed Results

PB2 was located on the landside of TH 61 between mile markers 115 and 116 north of Grand Marais. Monitoring occurred between 11:15 a.m. and 12:15 p.m. on Tuesday October 29, 2013. Figure 10-2 shows the monitoring location, which was a grass clearing between fairly thin lines of trees.

Figure 10-2. PB2 Monitoring Setup

The line of trees did provide minor shielding for the 100-foot monitoring location, but the meter had direct line of sight to the full 100-foot measurement distance on the highway. The last precipitation event recorded at the Grand Marais Airport prior to the measurements occurred at 6:30 p.m. on October 27, 2013. The measured microphone-height wind speeds were below 11 mph during all measurements. Table 10-2 contains the vehicle speeds measured with the handheld radar gun and the measured L_{max} values.

Table 10-2. PB2 Measurement Data

Maneuver	Pass	Speed, mph	L_{max} at Distance, dBA (re 20 μPa)		
			25 ft.	50 ft.	100 ft.
Control	1	45	79	72	66
Control	2	44	79	71	65
Control	3	43	78	71	65
Control	4	53	80	74	69
Control	5	54	81	74	68
Control	6	53	80	74	68
Control	7	65	83	76	70
Control	8	65	83	76	71
Control	9	64	83	76	71
Drift	1	44	83	77	71
Drift	2	47	94	87	82
Drift	3	45	86	80	74
Drift	4	55	92	87	80
Drift	5	55	98	92	85
Drift	6	54	91	86	80
Drift	7	65	91	86	81
Drift	8	65	98	92	86
Drift	9	65	91	86	80
Merge	1	45	87	81	75
Merge	2	45	82	76	73
Merge	3	45	86	80	72
Merge	4	56	95	88	81
Merge	5	55	89	83	81
Merge	6	55	96	89	84
Merge	7	65	94	87	81
Merge	8	65	87	83	79
Merge	9	65	94	88	81

The measured results of PB2 were used in the regression analyses of Section 5.

10.3 PB3 Detailed Results

PB3 was located on the lakeside of TH 61 between mile markers 121 and 122 north of Grand Marais. Monitoring occurred between 9:15 and 10:15 a.m. on Friday October 25, 2013. Figure 10-3 shows the monitoring location, which was a grass clearing at an elevation slightly lower than the pavement.

Figure 10-3. PB3 Monitoring Setup

The pavement appeared dry, but the Grand Marais Airport recorded light snow at 7:00 a.m. on October 24 and light snow at 2:00 a.m. on October 25, 2013. Microphone-height wind gusts exceeding 11 mph were measured during the monitoring period, but the exceeding gusts did not occur during vehicle pass-bys. Table 10-3 contains the measured vehicle speeds and L_{max} values.

Table 10-3. PB3 Measurement Data

Maneuver	Pass	Speed, mph	L_{max} at Distance, dBA (re 20 µPa)		
			25 ft.	50 ft.	100 ft.
Control	1	44	79	70	64
Control	2	46	79	70	63
Control	3	44	77	69	62
Control	4	55	81	72	65
Control	5	54	81	72	65
Control	6	53	81	71	65
Control	7	63	82	73	67
Control	8	63	83	74	67
Control	9	64	82	73	67
Drift	1	42	85	76	71
Drift	2	43	92	85	80
Drift	3	46	85	77	71
Drift	4	53	91	83	77
Drift	5	52	98	90	84
Drift	6	55	92	84	80
Drift	7	62	92	84	78
Drift	8	61	98	90	84
Drift	9	65	91	83	77
Merge	1	42	84	77	70
Merge	2	41	85	80	73
Merge	3	45	84	78	71
Merge	4	53	90	83	76
Merge	5	51	85	76	74
Merge	6	54	90	83	78
Merge	7	65	95	88	81
Merge	8	64	89	80	77
Merge	9	67	92	86	80

The measured results of PB3 were used in the regression analyses of Section 5.

10.4 PBC Detailed Results

PBC was located on the landside of TH 61 between mile markers 119 and 120 north of Grand Marais. This location was a control location with no centerline rumble strips. Monitoring occurred between 10:15 and 11:00 a.m. on Tuesday October 29, 2013. Figure 10-4 shows the monitoring location, which had knee-high grassy vegetation and a ditch around the 50-foot sound level meter.

Figure 10-4. PBC Monitoring Setup

Despite the ditch, the tripods were adjusted to maintain approximately uniform microphone heights relative to the pavement. The last precipitation event recorded at the Grand Marais Airport prior to the measurements occurred at 6:30 p.m. on October 27, 2013. The measured microphone-height wind speeds were below 11 mph during all measurements. Table 10-4 contains the measured vehicle speeds and L_{max} values.

Table 10-4. PBC Measurement Data

Maneuver	Pass	Speed, mph	L_{max} at Distance, dBA (re 20 μPa)		
			25 ft.	50 ft.	100 ft.
Control	1	44	78	70	65
Control	2	45	79	71	65
Control	3	42	79	70	66
Control	4	54	81	73	68
Control	5	52	81	73	68
Control	6	54	81	73	67
Control	7	62	84	75	70
Control	8	62	83	75	70
Control	9	66	83	75	70
Drift	1	44	77	70	63
Drift	2	43	77	70	65
Drift	3	44	78	69	63
Drift	4	55	80	73	67
Drift	5	53	79	73	68
Drift	6	54	80	73	67
Drift	7	64	83	75	69
Drift	8	66	82	76	71
Drift	9	65	83	75	70
Merge	1	45	78	71	65
Merge	2	45	79	72	65
Merge	3	45	76	69	65
Merge	4	54	80	73	67
Merge	5	55	81	74	68
Merge	6	55	79	72	67
Merge	7	66	81	75	69
Merge	8	66	83	76	70
Merge	9	65	82	76	69

The measured results of PBC were used in the regression analyses of Section 5.