Noise Model-to-Monitor Case Study

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16. Abstract

The Ohio Department of Transportation (ODOT) noise program includes an inventory of more than 250 miles of noise barriers around the state. Each noise barrier constructed must be analyzed using the FHWA Traffic Noise Model (TNM) software program to determine if the construction of the barrier is justified. This research study was initiated to identify opportunities to improve the accuracy and validity of ODOT's traffic noise analysis and TNM modeling specifications with specific attention made to the modeling of heavy trucks. Over 44 hours of traffic noise data were collected at noise-sensitive areas at a Type II noise wall project being constructed along Interstate 270 in southeast Columbus. A "model-to-monitor" approach was used to analyze the field-measured noise data and compare the measured traffic noise levels with the traffic noise levels predicted using a robust TNM layout developed by the research team. The results of the analysis were consistent with other national research studies on the topic of meteorological effects, modeling residential building structures, and vegetation effects. Consequently, several useful strategies to aid in improving the accuracy of the traffic noise analysis and modeling process were identified. It is recommended that ODOT revise its traffic noise analysis procedures to carry out field studies only under calm (e.g., no wind) conditions. Additionally, ODOT's TNM specifications should be revised to include modeling of residential structures near the freeway as TNM noise barrier objects and that greater attention be paid to roadside vegetation in the modeling process and highway construction process.

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PROBLEM STATEMENT

In accordance with 23 CFR Part 772, State DOTs maintain primary responsibility for mitigating the adverse impacts of traffic noise associated with major highways. Ohio Department of Transportation (ODOT) policies and practices for analysis and abatement of traffic noise impacts are described in the *ODOT Highway Traffic Noise Analysis Manual* (ODOT OES, 2015). As of December 31, 2020, approximately 250 miles of noise walls have been constructed along Ohio's roadways, with an average height between 12 and 16 feet. On average, ODOT spends $12 million per year on new noise wall construction. The project development process for noise wall projects includes a comprehensive and detailed traffic noise analysis study that establishes existing noise levels at affected locations near the freeway and models future noise levels utilizing the FHWA Traffic Noise Model (TNM) 2.5 software program. The use of TNM 2.5 (or equivalent) for prediction of future traffic noise levels is mandated for any traffic noise analysis conducted under the scope of FHWA traffic noise regulations (23 CFR Part 772.9). TNM 2.5 is a state-of-the-art software program, allowing the analyst to estimate traffic noise levels at receiver locations by the freeway accounting for different traffic noise sources, roadway configuration, and propagation characteristics over different topography and ground types, and shielding from barriers, building rows, and vegetation (FHWA, 2017b).

Multiple validation studies (Rochat and Fleming, 2002; 2004) have demonstrated that the noise prediction and propagation functions of TNM 2.5 are performing in a satisfactory manner under most conditions encountered by State DOTs. To aid TNM users in carrying out traffic noise modeling requirements, there have been several national-level research studies undertaken to provide guidance on the applicability of TNM for different contexts and model sensitivity for different input objects (Harris Miller Miller & Hansen, Inc., et al., 2014) and best practices for TNM input and quality assurance (Bajdek, et al., 2015). The TNM 2.5 software is also used to determine the dimensions and specifications for any noise barriers that are determined to be reasonable and feasible based on ODOT's established criteria. Based on the results of the noise study, the noise barrier design is developed using professional consultant or in-house design staff. Noise barriers can be constructed as part of highway construction projects which add capacity to the freeway (known as a Type 1 project) or can be built to provide noise abatement for communities that were built prior to construction of the freeway (Type 2 projects). However, despite an expenditure of over $12 million per year on noise barrier construction, ODOT OES generally does not measure post-construction noise levels to determine if the in-service noise wall met the expected noise reduction targets that were established in the noise analysis study that was prepared to justify construction of the noise wall.

The ODOT noise program is committed to continuously improving its analysis processes and modeling specifications to ensure that its noise barrier projects achieve FHWA requirements for traffic noise abatement (23 CFR Part 772) in a cost-effective manner. Because the decision-making process for noise abatement projects is highly dependent on the output of the TNM 2.5 modeling, it is essential that this model provide an accurate representation of the noise environment in areas near the freeway. Ohio's noise model validation data shows that out of 106 noise reports prepared in recent the years, 419 out of 682 modeled results (61%) were higher than the measured result; hence, the model seems to be overpredicting noise levels in most cases in Ohio (N. Alcala, Personal Communication, May 11, 2021). There are some concerns about how the noise profile of heavy trucks is incorporated into the TNM algorithms; in particular, the calculations assume that approximately half of the sound energy generated by heavy trucks is placed at the upper source height (12 feet). It is felt that this aspect of the TNM algorithms results in modeled noise levels that are higher than measured noise levels, particularly when there is a high percentage of heavy trucks in the traffic stream. The TNM 2.5 software allows the analyst to input rows of buildings parallel to the freeway as objects that can shield traffic noise propagation; however, some State DOTs prefer to have buildings adjacent to the freeway represented as barrier objects in the TNM interface. Similarly, TNM 2.5 allows the analyst to account for noise reductions attributed to dense vegetation between the freeway and nearby receiver locations. Current research indicates that more detailed modeling is justified in providing a more accurate model of the traffic noise levels for receivers near the freeway. Finally, current approaches used for traffic noise modeling do not provide any means to address the various atmospheric conditions that may affect how noise is received by nearby residences (e.g., locations upwind or downwind from the freeway may be different). Consequently, this research was initiated to identify opportunities to improve the accuracy and validity of ODOT's traffic noise analysis and modeling specifications, thereby providing greater confidence to ODOT that its noise barrier projects are being constructed to meet all of its noise abatement objectives in a cost-effective manner. The research team for this project consisted of faculty researchers and staff from the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University (OU) with support from subcontractors MS Consultants, Inc., and Cross-Spectrum Acoustics, Inc.

RESEARCH BACKGROUND

Research Objectives and Tasks

The goal of this research project was to improve the accuracy of ODOT's existing noise modeling and analysis methods using the experience from an actual Type II noise wall construction project as a case study. A "model-to-monitor" approach was used for this research, comparing the modeled noise levels for the project site with monitored noise levels at the project site under different shielding (i.e., barrier or building row), traffic, and atmospheric conditions. To accomplish the project goal, the ORITE research team pursued the following specific objectives:

- Complete an extensive and comprehensive literature review on all relevant project topics, including noise reduction performance of noise barriers and building rows, addressing heavy trucks in noise modeling software, and atmospheric effects on traffic noise;
- Conduct field monitoring of traffic noise levels at the case study project site under different shielding (i.e., barrier or building row), traffic, and

atmospheric conditions. The project that was selected for this case study is the IR-270 Type II noise wall project (PID #93359);

- Based on the existing TNM 2.5 model used in the IR-270 Type II Noise Abatement Study, perform a detailed review to determine if any enhancements could be made based on national best practices for TNM 2.5 modeling. Using the enhanced model, estimate the modeled noise levels that correspond to the conditions associated with the field-monitored noise levels;
- Assemble a database of modeled and monitored noise levels corresponding to different shielding (i.e., barrier or building row), traffic, and atmospheric conditions. Using this database, conduct a detailed "model-to-monitor" analysis to estimate the barrier insertion loss and the noise reduction attributed to building rows parallel to the freeway, as well as the traffic or environmental conditions for which the modeled and monitored noise levels have the greatest discrepancy;
- Based on the results of the "model-to-monitor" analysis, develop recommendations for improvements to ODOT's existing noise modeling and analysis methods to address noise reduction from shielding, heavy truck traffic levels, and atmospheric conditions; and
- Develop this Final Report and accompanying Fact Sheet documenting all project-related activities, "model-to-monitor" analysis findings, and recommendations for improving current practices.

To accomplish the above research objectives, the ORITE research team completed the following 12 tasks over a duration of 24 months:

- Task 1: Project Start-Up Meeting;
- Task 2: Literature Review;
- Task 3: Development of Detailed Field Measurement Plan;
- Task 4: Existing TNM Review;
- Task 5: Building Row Field Study;
- Task 6: Meteorological Field Study;
- Task 7: Research Review Session;
- Task 8: Model-to-Monitor Analysis;
- Task 9: Synthesis and Recommendations;
- Task 10: Draft Final Report and Fact Sheet;
- Task 11: Revised Final Report and Fact Sheet; and
- Task 12: Project Management.

It is noted that due to a change in the operating procedures of the ODOT Research Office during the study, Task #7 (Research Review Session) was not carried out. In lieu of a Research Review Session, monthly project update phone calls were held including the research team, the ODOT TAC, and the ODOT research office.

Literature Review

A literature review was carried out by the ORITE research team with a specific focus on topics relevant to the case study project. A brief summary of the literature review findings is presented in this section. The propagation of sound between the sound source and the receiver is affected by several factors, including:

- Geometric spreading (e.g., weakening of the sound signal over distance);
- Ground effects (e.g., absorption over soft ground cover);
- Shielding by natural (i.e., topography or vegetation) or man-made (i.e., barriers) objects that interrupt the source-receiver path; and
- Atmospheric effects.

The propagation of sound can be heavily influenced by atmospheric conditions. As noted in *NCHRP Report 886* (Kaliski, et al., 2018), there are two types of atmospheric effects that are thought to be most influential: absorption of sound waves within the air and the effects of wind and temperature gradients. Absorption of sound waves in air is dependent on both the air temperature and the humidity of the air. Laboratory and field research have established accurate methods for calculating absorption based on temperature and humidity, and the effects are also varied based on the frequency of the sound wave. The effect of wind and temperature gradients is more complex, but it is generally assumed that sound levels are higher if the receivers are located downwind from the sound source and during periods of temperature inversion (i.e., the temperature is cooler at ground level). A study from the Arizona DOT found that the effect of nighttime temperature inversion was shown to increase noise levels between 5 and 8 dB up to 400 meters from the highway (Saurenman, et al., 2005). A more recent study found that, within typical traffic noise evaluation distances (500 feet), the effect could be ±6 dB without a barrier and between -5 and +9 dB with a barrier, depending on barrier geometry (Kaliski, et al., 2018). It is noted that there is limited ability for TNM to address these concerns in the modeling. However, reference tables are available that provide SHAs with guidance on how sound levels are affected by wind conditions and temperature lapse rate (Harris Miller Miller & Hansen, Inc., et al., 2014; Kaliski, et al., 2018).

Heavy and medium trucks are significant sources of noise within the traffic stream due to the additional tire-pavement interaction, louder engines, and elevated exhaust stacks. To account for these different source heights, the TNM software program distributes the sound energy between two different source heights based on frequency, vehicle type, and operating condition. Recent research has indicated that the 12-foot height for the exhaust stack of a heavy truck is valid but that most of the sound energy is originating at ground level from tire-pavement interaction (Gurovich, et al, 2009; Donovan and Janello, 2017). Nevertheless, some analysts feel that the heavy truck upper source height in TNM is placed too high and that a direct effect of this issue is that noise barriers are being designed with unnecessary excess height. To rectify this issue, it has been proposed that all heavy and medium trucks in TNM be modeled as medium trucks with a volume multiplier to "convert" heavy trucks to medium trucks based on the relative sound levels of each vehicle type. The research team analyzed this proposal using simulations and real-world examples from TNM. The results of this analysis are detailed in Appendix A of this report.

Residential buildings and other structures in the sound propagation path can be modeled in TNM as a building row object (Menge, et al., 1998; 2004). The building row object is a linear object which behaves similarly to a low-density barrier; the analyst specifies the average building row height and the percentage of the building row length which is covered by structures. The most significant limitation of the building row object is that the noise attenuation is uniform across the entire length of the building row, even though the noise received at locations behind the building row can vary significantly depending on if the receiver is behind a structure or in a gap between buildings. To overcome this limitation, residential buildings and other structures may be modeled as three-sided TNM barrier objects instead of the building row object. This method was examined in *NCHRP Report 791* (Harris Miller Miller & Hansen, Inc., et al., 2014) and it was concluded that the TNM model validations were more accurate with the alternative representation. Some state DOTs have formalized this method into their noise policies and TNM specifications.

Research on the noise reduction characteristics of vegetation along the sound propagation path (usually in the form of tree belts or low-level shrubs) is extensive. Variables that have been examined in past research include the effects of planting depth along the propagation path, tree height, species, trunk diameter, presence and shape of the canopy and leaves, and the pattern of the planting within the foliage. A minimum vegetation depth of 10 to 12 meters is desired for perceptible noise reduction (Martens, 1981; Van Renterghem, 2014; Ow and Ghosh, 2017); the TNM calculations requires high-density vegetation (i.e., no roadway view is provided) with a minimum of 10 meters of depth for any attenuation to occur (Menge, et al., 1998; 2004). Research conducted by Fang and Ling (2003) utilized the “visibility distance” into the vegetation as a proxy for density, finding significant correlations between the visibility distance and noise reduction across 35 species tested.

Additional details of the literature review task are presented in Appendix A.

RESEARCH APPROACH

The ORITE research team approached the research goals and objectives with three key activities, described as follows. Additional details of the setting for the research and the research approach components are described in this section.

- Design and implement a field data collection plan consisting of traffic noise data measurement and collection of other relevant traffic and weather data;
- Compilation of noise, traffic, and weather data into an organized database for more detailed analysis to identify trends and patterns in traffic noise; and
- Modeling of traffic noise using the FHWA Traffic Noise Model (TNM) software and comparison of the modeled sound levels with the measured sound levels based on a “model-to-monitor” approach.

Case Study Setting

The case study noise wall project that was selected for more detailed analysis in this research study was the PID #93359 (FRA-270-39.68 – Noise Walls) project. The location of the project site was along Interstate 270 on the southeast side of Columbus in Franklin County. The project consisted of the construction of four sets of reflective noise barriers along both sides of Interstate 270 starting at the Livingston

Avenue overpass on the southern end of the project and ending at the East Broad Street interchange on the northern end. A map showing the location of the case study noise barrier project and the field study areas for this case study is displayed in Figure 1. An area within NSA 7 on the grounds of Yorktown Middle School (YMS) was selected for the meteorological field study and the heavy truck substitution analysis. The school location was ideal for these aspects of the study as the athletic fields north of the school building provided a nearly wide-open area for traffic noise measurement (see Figure 2 for measurement locations). The area designated Noise Sensitive Area (NSA) 2, the Shady Lane (SL) Neighborhood, was selected for the building row field study and the vegetation impacts field study. The Shady Lane site was particularly well-suited for the building row field study aspect of this project as the entire neighborhood is representative of typical neighborhood locations near Ohio freeways (see Figure 3 for measurement locations). The first three rows of residential structures away from the Interstate 270 freeway were well-organized into building rows with the building percentage estimated to be 65 to 70% of the street frontage.

Figure 1: Case Study Setting along Interstate 270 in Southeast Columbus

Figure 2: Setting of the Yorktown Middle School (NSA 7) Site

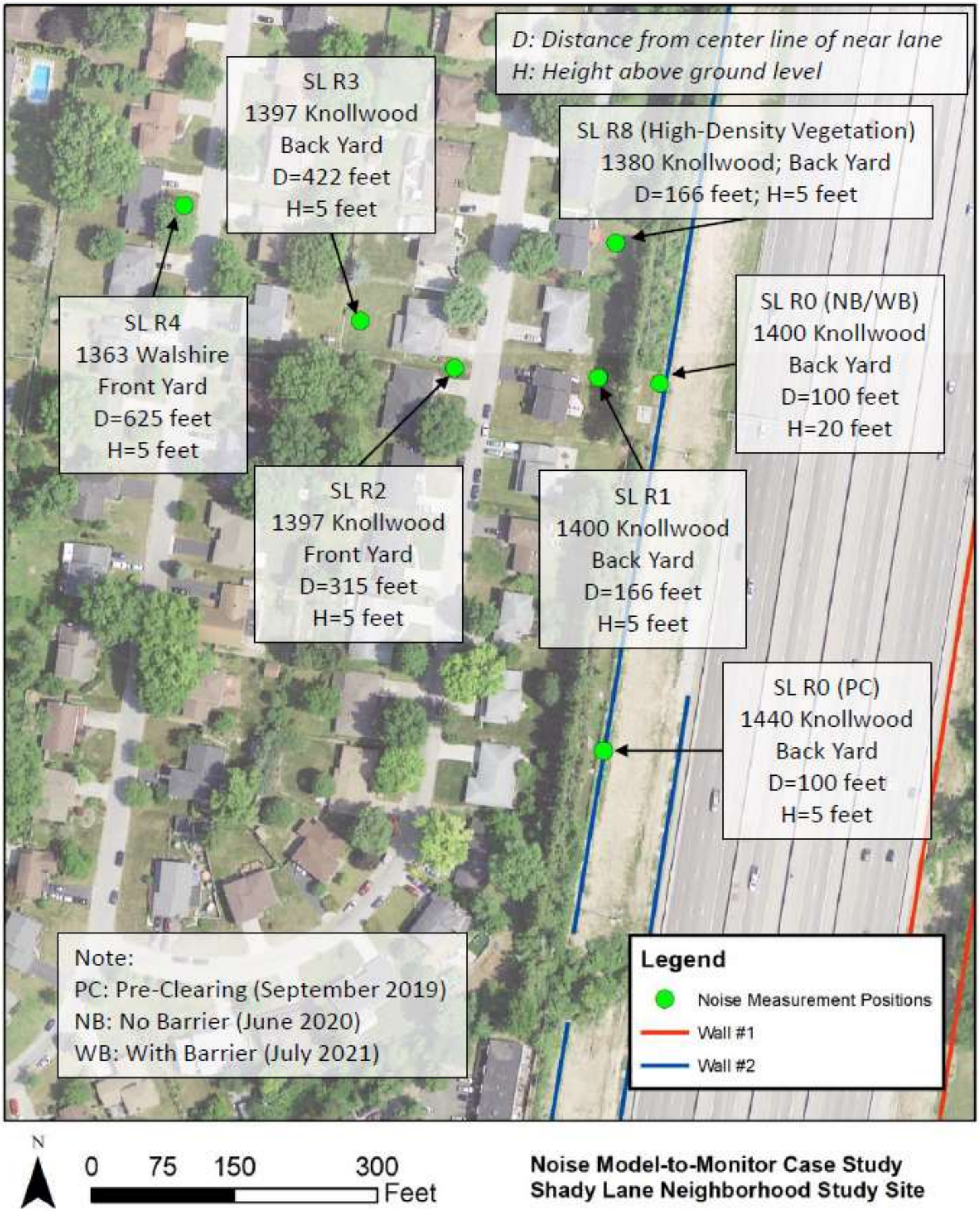


Figure 3: Setting of the Shady Lane Neighborhood (NSA 2) Study Site

Traffic Noise Data Collection

Field data collection of traffic noise and related data for this study was carried out in three waves: 1) "pre-clearing" data, collected before any construction activities had started; 2) "no barrier" data, collected after the tree clearing and site preparation had been carried out, but no vertical barrier components installed; and 3) "with barrier" data, collected after barrier construction at the subject NSA. All data collection procedures followed requirements outlined by FHWA guidelines (FHWA, 2018) and ODOT policies (ODOT OES, 2015).

Data that were collected during the field measurements carried out for this project included traffic noise data, meteorological data, traffic data, and manual observations associated with highway and background noise events. Microphone positions were established at each study site based on the desired research objectives for each site; exact locations are shown in Figure 2 (YMS study site) and Figure 3 (SL study site). A reference microphone with a height of approximately 20 feet was used at each site to establish equivalency for different time periods. The other locations were positioned at a height of 5 feet above the ground. A digital audio recording device was attached to the sound level meters (SLM) at each measurement position to create WAV files of each measurement period. A typical setup for a measurement position including the SLM and audio recorder is shown in Figure 4.

Figure 4: Typical Setup for Traffic Noise Measurement Equipment

Data on weather conditions were collected using a weather station with automatic logging of temperature, humidity, and wind speed/direction in one-minute increments. Traffic data were obtained using an infrared sensor device that permitted recording of the pass-by time, vehicle length, vehicle speed, and travel lane for each vehicle that passed the measurement area. Throughout the data collection, the research team recorded details of any loud or unusual noise events that were detected and noted sound levels directly from the SLM units associated with these events. Noise from background activities was particularly evident at the SL locations furthest from the freeway including vehicle pass-by traffic on the local streets, grass cutting, air conditioning units, and other human activities. Cloud cover conditions were also noted via manual observation to supplement the weather station data. The specific data collection periods, study locations, and objectives for each data collection period are described in Table 1 on the following page. Also displayed in Table 1 is a summary of the meteorological and traffic conditions encountered during each date of field studies conducted for this project. The research team also collected detailed topographic survey data at each study site to support the development of the TNM layouts. Additional details of the data collection are described in Appendix B.

Traffic Noise Data Analysis

The objective of the data analysis task was to review and process all traffic noise and other data that were obtained in the field studies. A large database of consisting of measured traffic noise levels, weather condition data, and traffic data (volume and speed) was assembled in one-minute data blocks. From the one-minute data, five-minute data blocks were formed with the meteorological condition defined based on the atmospheric conditions of wind and temperature lapse state for at least four of the five minutes of each block. Time blocks with unusual noise events, excessive background noise, or other types of incursions were removed from the analysis at this processing stage. Background noise was particularly frequent at the SL study site in the form of residential activities and vehicle pass-by on the local streets. The total number of valid five-minute blocks for analysis during each data collection wave is also summarized in Table 1. The dominant meteorological conditions encountered by the research team included Calm Lapse and Calm Neutral conditions. The SL study site data were limited to only Calm Lapse conditions since this was the dominant condition during the data collection work. Analysis of this database carried out by the ORITE research team provided insight on several key research questions being examined in this case study. Calculation procedures followed FHWA (2018) methods as applicable. Additional details of the traffic noise database analysis are presented in Appendix C.

Table 1: Summary of Data Collection Activities for Research Study

Date	Time	Location	Objective/Scenario # of 5-Minute Analysis Blocks	Summary of Meteorological and Traffic Conditions
9/17/2019	9:00 A.M. to 2:00 P.M.	SL	Building Rows/Pre-Clearing Analysis Blocks = 324	Sunny/Clear; Temp: 69°-77°; Humidity: 57%-80% Wind Condition: Calm (1-2 mi/h) Traffic: 2,244-3,720 veh/hr; 4.7%-13.2% HT
9/19/2019	9:00 A.M. to 2:00 P.M.	SL		Sunny/Clear; Temp: 66°-80°; Humidity: 46%-65% Wind Condition: Calm (< 1 mi/h) Traffic: 2,184-3,660 veh/hr; 4.1%-13.2% HT
9/24/2019	9:00 A.M. to 1:00 P.M.	SL	Vegetation Impacts Analysis Blocks = 136	Sunny/Clear; Temp: 60°-74°; Humidity: 39%-76% Wind Condition: Calm (< 1 mi/h) Traffic: 2,124-3,396 veh/hr; 2.6%-12.9% HT
5/26/2020	2:00 P.M. to 8:00 P.M.	YMS	Meteorological/No Barrier Analysis Blocks = 442	Sunny/Clear; Temp: 85°-90°; Humidity: 29%-38% Wind Condition: Upwind (2-3 mi/h) Traffic: 2,076-3,912 veh/hr; 2.1%-7.0% HT
5/27/2020	6:00 A.M. to 12:00 P.M.	YMS		Overcast; Temp: 70°-80°; Humidity: 53%-69% Wind Condition: Calm (< 1 mi/h) Traffic: 2,028-4,080 veh/hr; 2.7%-10.9% HT
6/1/2020	9:30 A.M. to 1:00 P.M.	SL	Building Rows/No Barrier Analysis Blocks = 155	Sunny/Clear; Temp: 58°-70°; Humidity: 29%-56% Wind Condition: Calm (< 1 mi/h) Traffic: 1,836-3,289 veh/hr; 5.5%-12.8% HT
10/8/2020	2:30 P.M. to 7:30 P.M.	YMS	Meteorological/With Barrier Analysis Blocks = 446	Sunny/Clear; Temp: 62°-72°; Humidity: 30%-50% Wind Condition: Calm (< 1 mi/h) Traffic: 2,220-4,896 veh/hr; 3.6%-11.9% HT
10/9/2020	7:00 A.M. to 12:00 P.M.	YMS		Sunny/Clear; Temp: 45°-70°; Humidity: 45%-90% Wind Condition: Calm (< 1 mi/h) Traffic: 2,713-4,788 veh/hr; 5.1%-11.4% HT
7/23/2021	9:30 A.M. to 1:30 P.M.	SL	Building Rows/With Barrier Analysis Blocks = 223	Light Overcast; Temp: 72°-80°; Humidity: 45%-61% Wind Condition: Calm (1-2 mi/h) Traffic: 2,304-3,972 veh/hr; 3.4%-12.4% HT

Note: Number of analysis blocks indicates number of 5-minute time blocks extracted for traffic noise database analysis.
Traffic data provided for IR-270 for direction of travel closest to study site (NB for YMS; SB for SL)

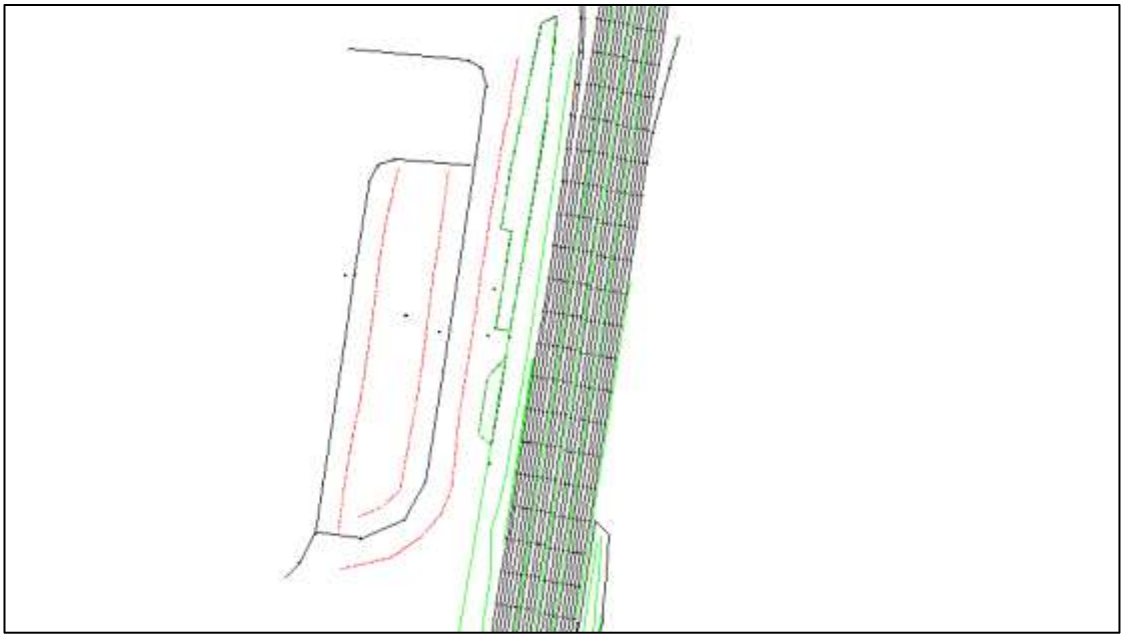
Traffic Noise Modeling

The ORITE research team developed detailed models of each of the two study sites using the FHWA Traffic Noise Model (TNM) version 2.5 software package (FHWA, 2017b). All best practices and recommended procedures for TNM layout development (Harris Miller Miller & Hansen, Inc., et al., 2014; Bajdek, et al., 2015) were utilized in the model creation. All roadway lanes along Interstate 270, six in each direction plus shoulders for both local and express lane groups, were modeled as individual TNM roadway objects with a length of roadway extending at least 1,500 feet beyond the receiver lines both north and south of the study area. A high-precision GPS unit was utilized to identify the coordinates of all relevant features in the sound propagation path, including temporary portable concrete barriers (PCB), terrain lines, tree zones, ground zones, local streets, and buildings. All microphone positions were located with the GPS unit as well. The coordinates and height of the noise barriers were estimated using station data and layout angles from the ODOT construction plans.

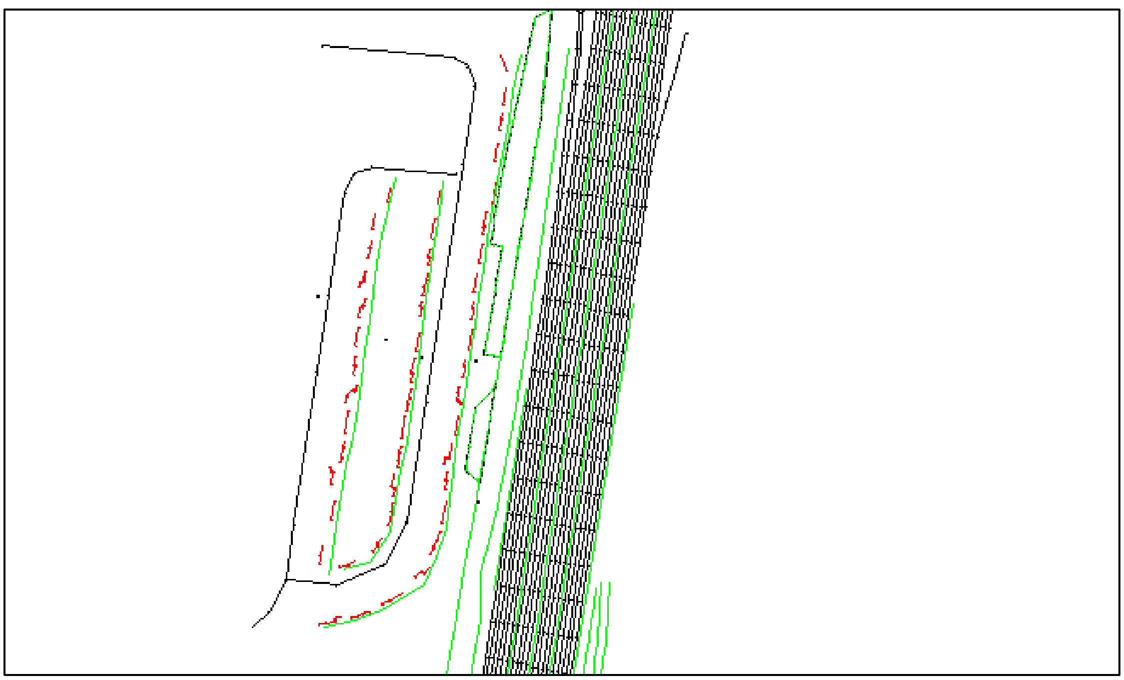
Plan views of the TNM layout for each of the two study sites are displayed in Figure 5 for the YMS study site and Figure 6 for the SL study site. For the YMS study site, specific features modeled in the TNM layout included the school building to the south of the measurement positions and the apartment building to the north. The Livingston Avenue overpass was also modeled as two TNM roadways “on structure” with an embankment defined with terrain lines. A blacktop playground surface immediately to the north of the school building, as well as a baseball diamond infield, were modeled with appropriate ground zones. For the SL study site, separate TNM models were developed to represent the roadside tree zone in two different states (pre-clearing and post-clearing) as well as representation of the residential structures in two different ways (building rows and buildings as barriers). The coordinates of each residential structure in a 120-degree view of all receiver locations were obtained using data from the Franklin County Auditor (XY) and LIDAR points from state-level GIS data (Z and height estimates). For the “buildings as barriers” representation, only the building façade nearest to the freeway was modeled. Additionally, it was determined that use of the first-story height only (including roof) was a better representation than accounting for varying heights (e.g., split level homes).

Selection of specific time periods to be used for TNM validation analysis utilized the following procedures. To minimize the effect associated with unusual traffic fluctuations within a five-minute time block, the ORITE research team decided to utilize a 15-minute time-averaging period for the TNM validation analysis. For the YMS study site, a total of 15 blocks were identified for the “No Barrier” case and 12 blocks were identified for the “With Barrier” case. For the SL study site, 11 blocks were identified for the “Pre-Clearing” case, 8 blocks were identified for the “No Barrier” case, and 8 blocks were identified for the “With Barrier” case. A probability-based model of vehicle classification was developed to estimate traffic flows based on the infrared sensor data set. In total, 54 unique time blocks were modeled in TNM.

Figure 5: Plan View of TNM Layout for Yorktown Middle School (NSA 7) Study Site



[a] TNM Layout with Residential Structures as Building Rows



[b] TNM Layout with Residential Structures as Individual Barrier Objects

Figure 6: Plan View of TNM Layouts for Shady Lane (NSA 2) Study Site

This project utilized a “model-to-monitor” approach to analyze the accuracy of the FHWA TNM traffic model under various conditions. Previous TNM validation studies (e.g., Rochat and Fleming, 2002; 2004) as well as previous studies utilizing the “model-to-monitor” approach (primarily in the air quality analysis discipline) [e.g., U.S. EPA, 1996; Payne-Sturges, et al., 2004; Lupo and Symanski, 2009) were consulted to develop the framework used in this study. The following measures were used:

- Scatter Plot of Measured and Modeled Noise Levels;
- Model Deviation (difference between modeled and measured sound levels);
- Model-to-Monitor Ratio (ratio of modeled to measured data); and
- Percentage of Modeled Data within ± 3.0 dBA of Measured.

The latter measure is selected because it is considered to be the threshold for TNM validation in many states, including work for ODOT (ODOT OES, 2015). The validated TNM model used at the Yorktown Middle School (NSA 7) study site was used to examine the implications of substituting heavy truck volumes with medium truck volumes in TNM at different ratios of substitution. TNM analysis blocks that were classified as "Calm Neutral" meteorological condition (3 blocks for "No Barrier" case, 2 blocks for "With Barrier" case) were used in the substitution analysis since those conditions are most representative of TNM's baseline conditions. The following substitution ratios were analyzed: 1.0, 1.5, 2.0, 2.5, and 3.0; for example, a substitution ratio of 2.0 means that the observed heavy truck volume for a specific TNM analysis block would be multiplied by a factor of 2 and that amount would be added to the observed volume of medium trucks for that analysis block.

RESEARCH FINDINGS AND CONCLUSIONS

Research Summary

This research examined the impacts of traffic noise under various atmospheric conditions, implications for the volume and representation of trucks in traffic modeling, and the impacts on traffic noise attenuation resulting from shielding by building rows and tree zones in the propagation path. A Type II noise barrier project along Interstate 270 in southeastern Columbus, Franklin County, Ohio, was selected for this case study. Traffic noise field studies were carried out at two NSAs located in the section of the project between Livingston Avenue in the south and East Main Street in the north. The Yorktown Middle School (NSA 7) site on the east side of the freeway was the setting for the meteorological and heavy truck analysis tasks. The Shady Lane Neighborhood (NSA 2) site on the west side of the freeway was the setting for the building row and vegetation impacts analysis tasks. Data collection activities occurred in four "waves" accounting for the Pre-Clearing, No Barrier, and With Barrier conditions at the study sites. A total of 2,670 minutes of data were recorded over nine days of field study, including traffic noise, weather conditions, and traffic characteristics for each minute. A comprehensive database of five-minute average A-weighted Leq for traffic noise and corresponding weather and traffic conditions was organized for more detailed analysis. Detailed analysis of the noise database focused on average noise levels under various conditions as well as a multiple regression model to identify the effect of specific traffic and weather variables on measured noise levels. Additionally, a detailed layout of both subject NSAs using the FHWA Traffic Noise Model (TNM) Version 2.5 software program was developed. A total of 54 analysis blocks with length of 15 minutes each were analyzed in TNM. A "model-to-monitor" analysis approach was utilized to compare the modeled noise levels with the measured levels for the same time period. For the Shady Lane Neighborhood (NSA 2) site, separate TNM layouts were developed to represent the neighborhood's residential structures as either a TNM building row object or as separate TNM barrier objects for each structure. The Yorktown Middle School (NSA 7) study site was used to examine the implications of substituting heavy truck volumes with medium truck volumes in TNM at different ratios of substitution including 1.0, 1.5, 2.0, 2.5, and 3.0. The mode accuracy was assessed utilizing a "model-to-monitor" approach which analyzed scatter plots; model deviation (difference between modeled and measured levels); the model-to-monitor ratio; and the percentage of observations modeled within ± 3.0 dBA of the measured level.

Research Findings

The measured noise levels obtained during the field studies carried out for this project were reasonable and consistent with expectations for the context and traffic patterns observed during the study periods. Insertion loss analysis for the noise barrier constructed at the Yorktown Middle School (NSA 7) site indicated that a perceptible noise reduction was achieved at distances within at least 160 feet of the freeway (see Figure 7). Measured noise levels at the Shady Lane Neighborhood (NSA 2) site indicated that there was some noise shielding effect of the residential structures (see Figure 8); this effect was most readily-perceptible behind the first row. The measured noise levels at the first-row backyard and second row front yard locations also indicated that a perceptible reduction in noise was also achieved with the construction of the noise barrier at the Shady Lane Neighborhood site.

Results from the model-to-monitor analysis comparing the TNM-predicted sound levels with the measured sound levels at the Yorktown Middle School (YMS) study site indicated that the model developed by the research team was performing satisfactorily for the "Calm Neutral" atmospheric conditions which are most representative of the conditions modeled in TNM. For the ground-level receiver positions (see Figure 9), 100% of the observations were modeled within ± 3.0 dBA of measured levels and 83% were modeled within ± 1.6 dBA of the measured levels. It is speculated that TNM over-prediction under neutral atmospheric conditions is attributed to factors that cannot be easily controlled within TNM; specifically, complex reflections from median barriers as well as variations in the noise source distribution of heavy and medium trucks in the traffic stream during the measurement periods. The trends of TNM's predictive accuracy under various meteorological conditions were consistent with expectations. Additionally, the "With Barrier" modeling scenario performed well, indicating the continued strong suitability of the software for its primary intended purpose, design of noise abatement (see Figure 10). Additional details of the measured and modeled noise levels for the YMS study site can be viewed in Appendix D, Table 19 through Table 24.

The TNM predicted sound levels at the Shady Lane Neighborhood (SL) study site were also very accurate for the receiver locations with a direct view of the freeway, with the measured levels being predicted to within ± 2.0 dBA for both "Pre-Clearing" and "No Barrier" scenarios. All TNM runs for the SL study site corresponded to a "Calm Lapse" meteorological condition (see Table 25) to ensure that the atmospheric conditions were consistent throughout the study. In general, noise measurements taken during a “Lapse” condition will be lower than those taken under a “Neutral” condition; the “Neutral” condition is assumed in TNM as the program does not explicitly account for meteorological factors in its calculations. Consequently, some over-prediction of these noise levels on the order of 0.5 to 1.5 dBA was anticipated in TNM and this over-prediction was realized in the current study. Prediction of noise levels at receiver locations without a direct view of the freeway (i.e., those locations shielded by building rows) was complicated by complex reflections from the residential structures themselves as well as ground effects from hard surfaces such as local streets or driveways. Modeling the adjacent residential structures as either building rows or noise barriers in TNM produced noticeably different results. The noise barrier representation modeled by the research team produced the most accurate models; this approach was superior to using the TNM building rows object or not representing the residential structures in TNM whatsoever (see Figure 11 for pre-clearing and no barrier cases, Figure 12 for with barrier cases). Overall, trends in the predictive accuracy of TNM were generally as anticipated by the research team, with the model generally over-predicting measured noise levels in the “Pre-Clearing” and “No Barrier” cases and generally under-predicting in the “With Barrier” cases across the two study sites. Additional details of the measured and modeled noise levels for the SL study site can be viewed in Appendix D, Table 25 through Table 30.

Finally, measured noise levels at receiver locations behind two different densities of vegetation yielded useful information about the noise attenuation of roadside tree zones (see Figure 13). In particular, the roadside vegetation (including the more absorptive ground area within the vegetation) provided an additional noise attenuation between 3.0 and 4.0 dBA once the effects of divergence were accounted for. It was also estimated that a tree zone with relatively high density (i.e., no view of the freeway from the measurement position) results in an additional noise reduction of approximately 1.0 dBA as compared to a lower-density location with some views of the freeway.

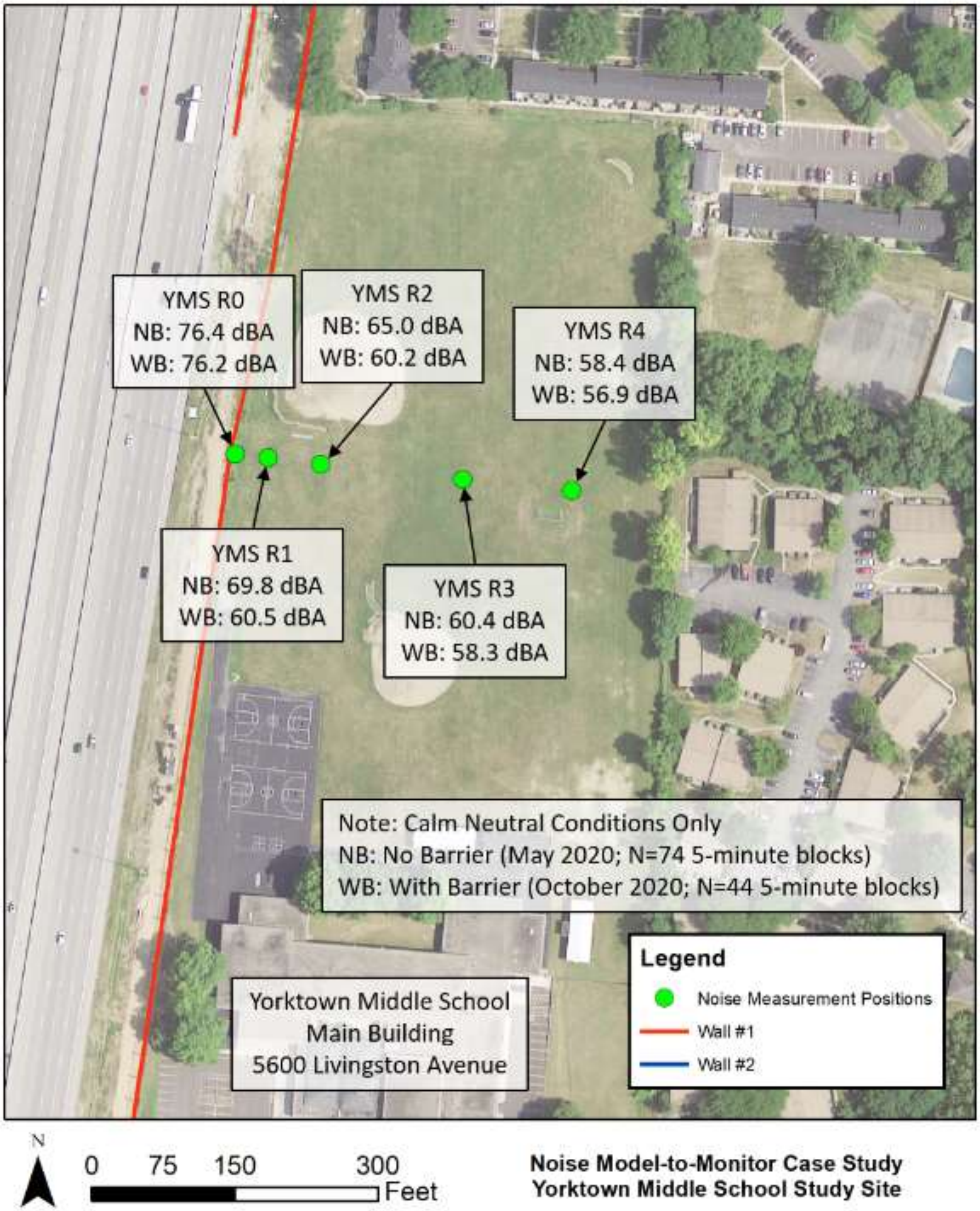


Figure 7: Measured Noise Levels, Yorktown Middle School (NSA 7)

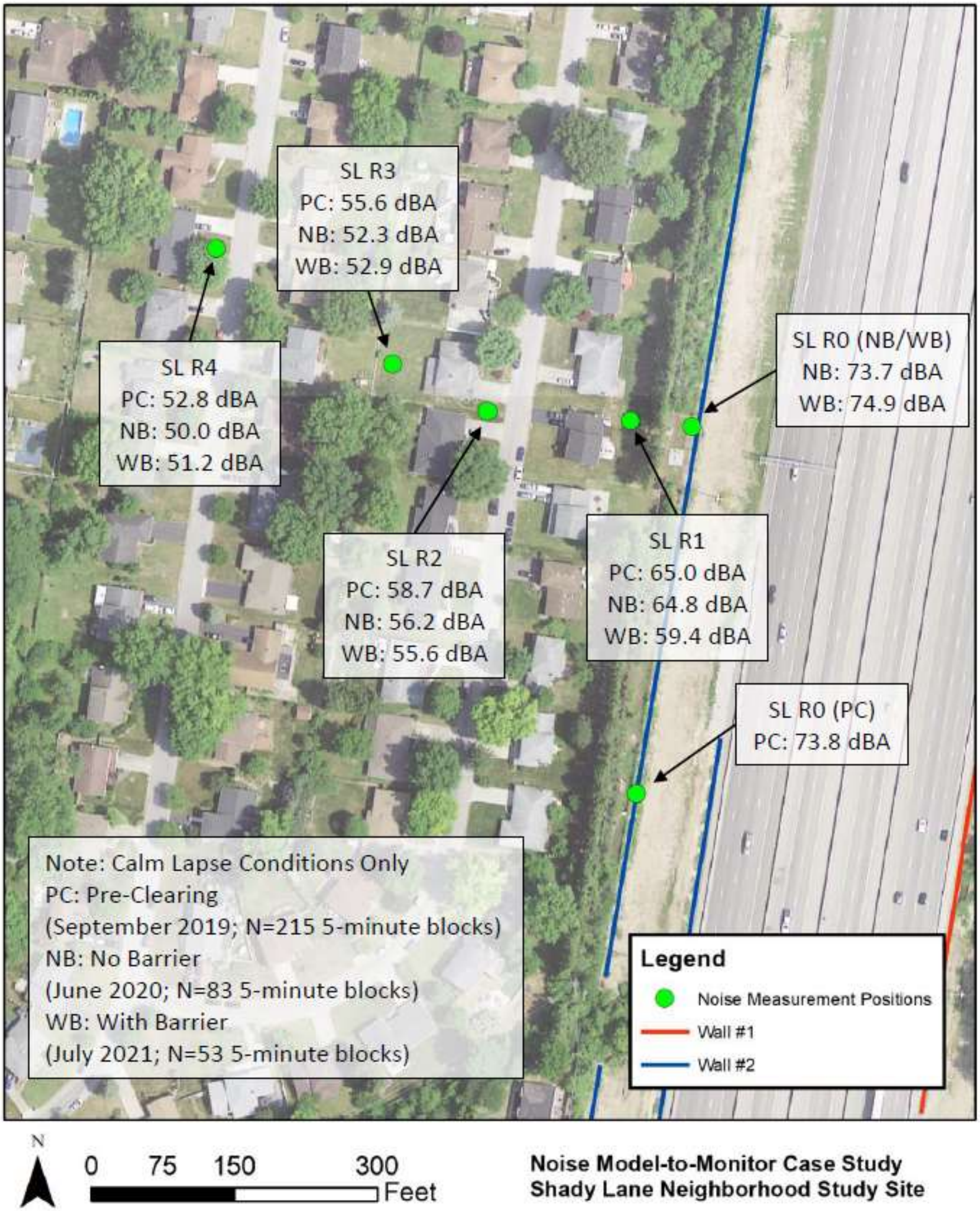


Figure 8: Measured Noise Levels, Shady Lane Neighborhood (NSA 2) Study Site

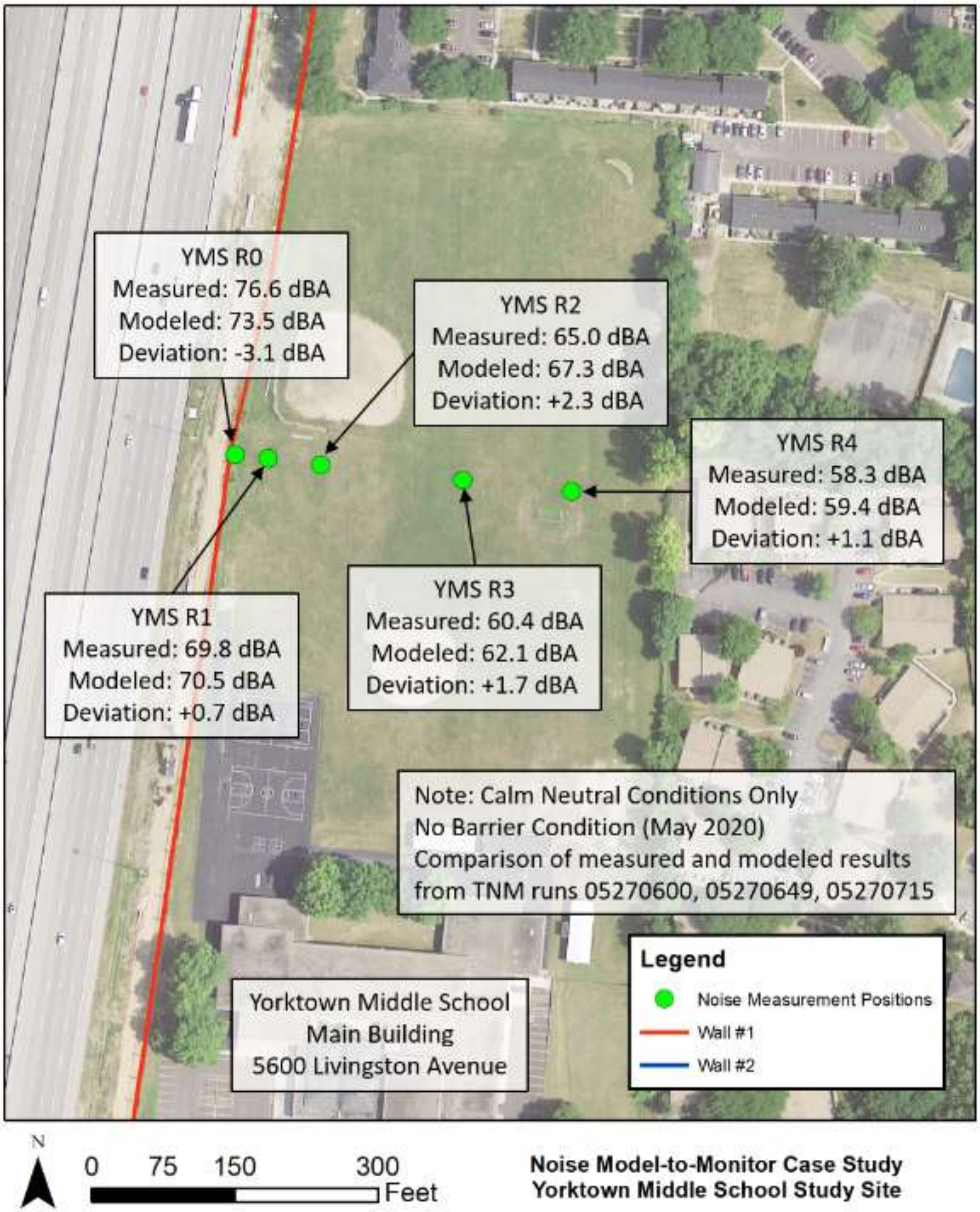


Figure 9: Comparison of Measured and Modeled Noise Levels, Yorktown Middle School (NSA 7), No Barrier Case

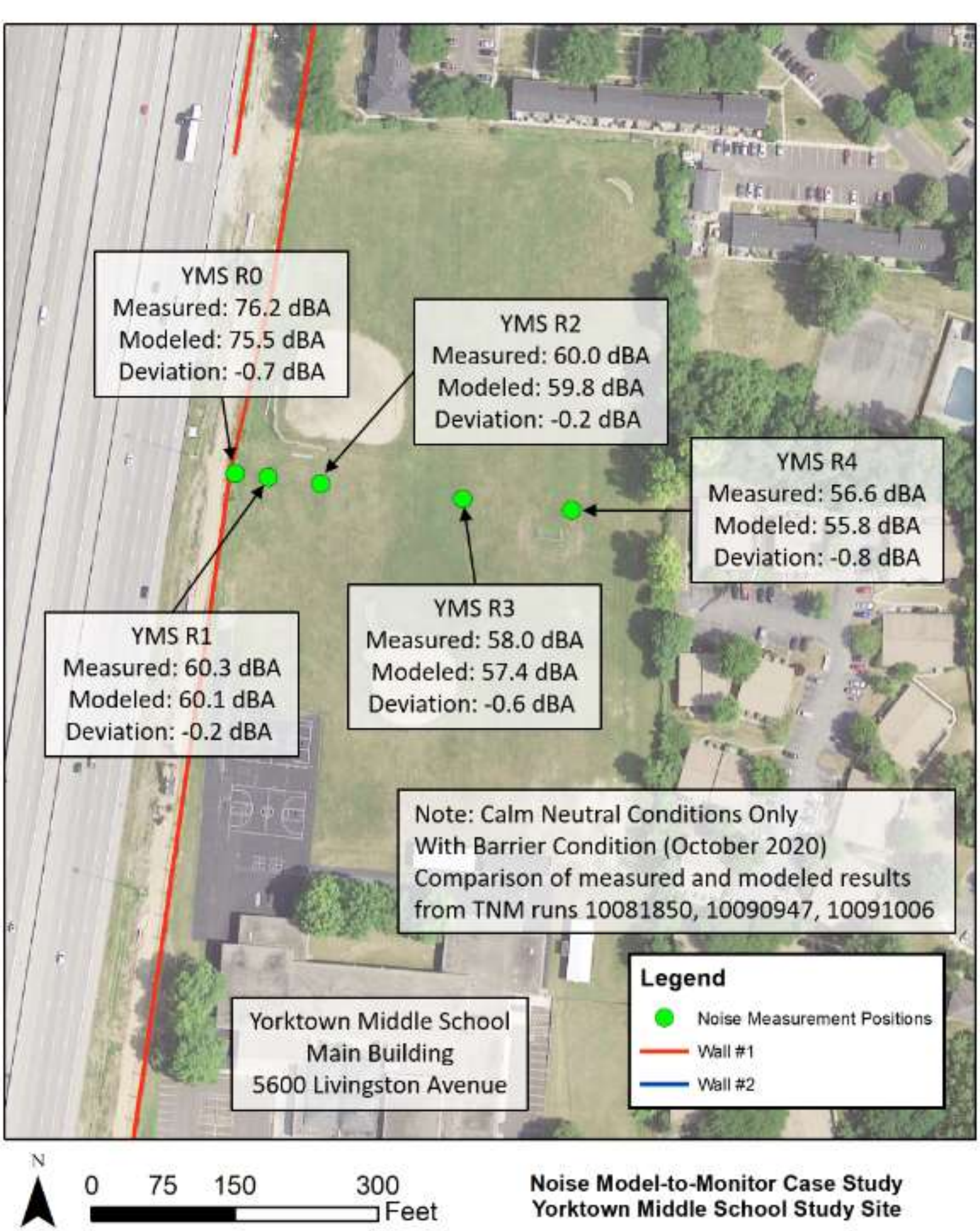


Figure 10: Comparison of Measured and Modeled Noise Levels, Yorktown Middle School (NSA 7), With Barrier Case

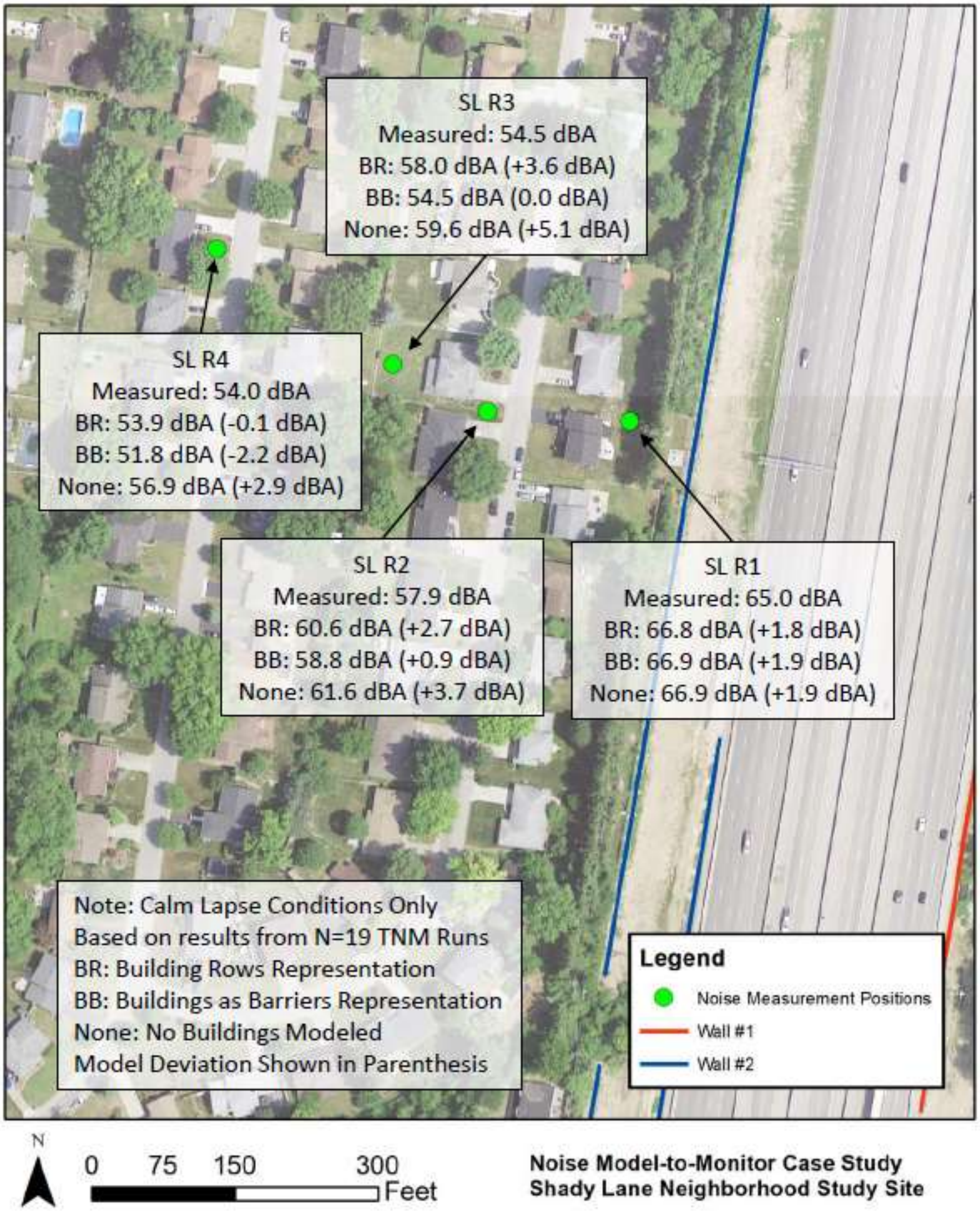


Figure 11: Comparison of Measured and Modeled Noise Levels, Pre-Clearing/No Barrier, Shady Lane Neighborhood (NSA 2)

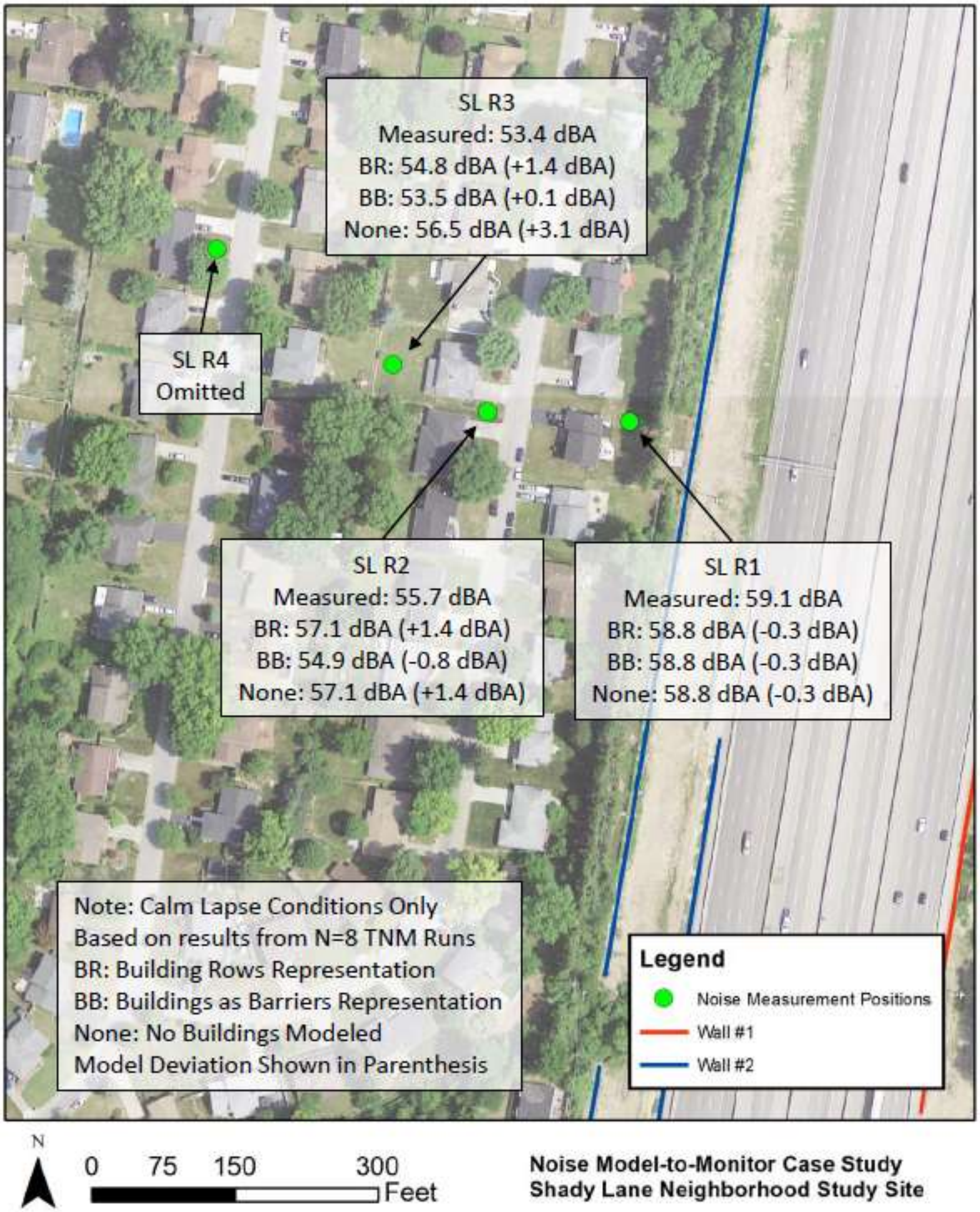


Figure 12: Comparison of Measured and Modeled Noise Levels, With Barrier, Shady Lane Neighborhood (NSA 2)

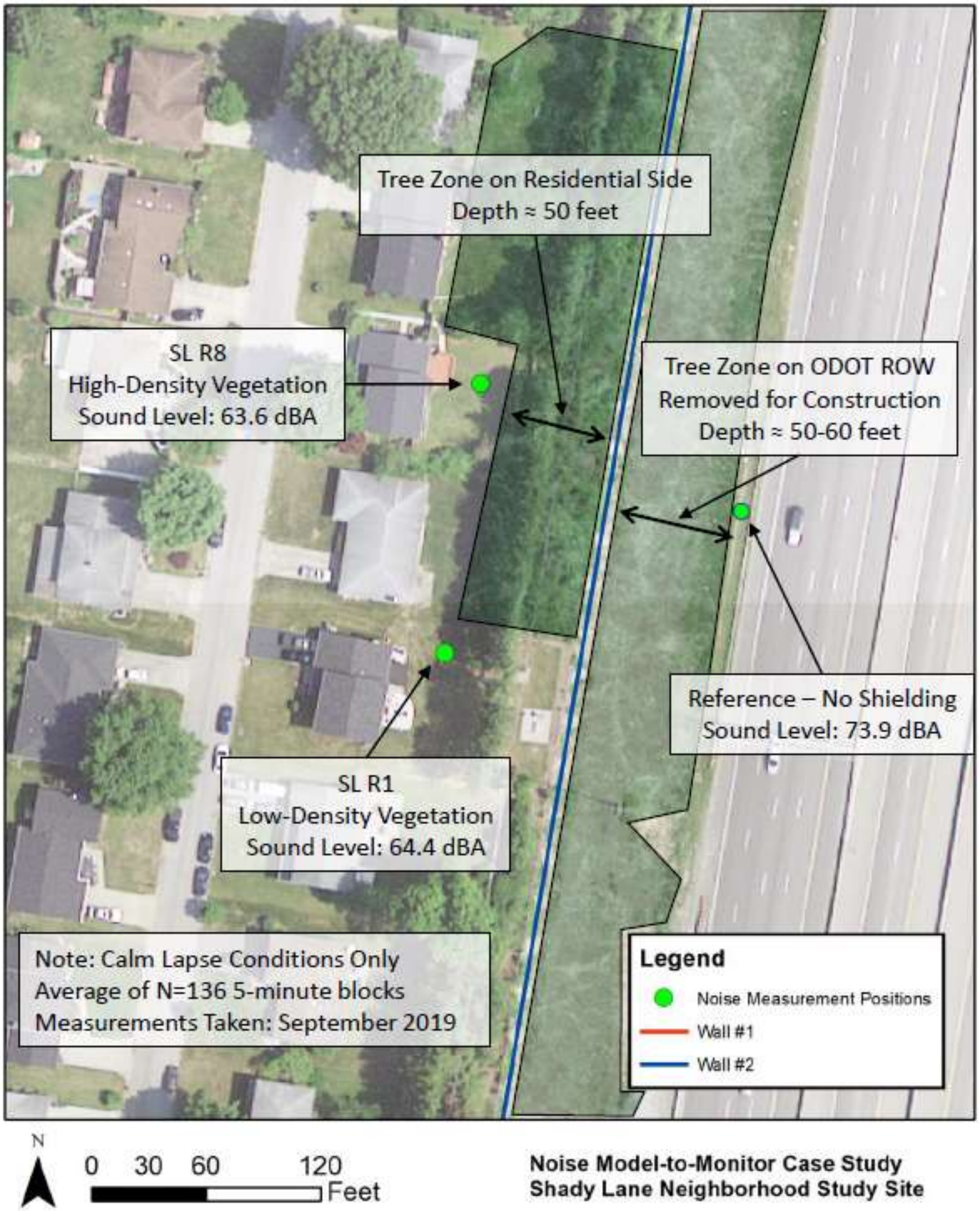


Figure 13: Measured Noise Levels, Shady Lane Neighborhood (NSA 2), Vegetation Study Detail (Pre-Clearing Condition)

Discussion

Based on the data analysis and traffic noise modeling activities undertaken as part of this research study, the research team presents the following key conclusions and discussion of the results, reported in the following sections.

What is the primary factor influencing traffic noise change throughout the day?

The results of this analysis indicated that the measured traffic noise levels are primarily related to the traffic levels on the freeway. As the traffic volume fluctuates throughout the day, so too does the noise that is received at nearby homes and other locations. This finding is verified by the positive correlation between traffic levels and the measured noise levels (see Table 8 and Figure 37 for more details). Variations in the volume and composition of heavy and medium trucks also has a significant impact on traffic noise. However, as the distance from the highway increases, non-highway noise sources are more prevalent (see Figure 38). These findings are consistent with the well-known understanding of the noise impacts of different vehicle types and the propagation effects of traffic noise away from the roadway into adjacent neighborhoods. Vehicle speeds also influence noise, although there was insufficient variation in speeds observed in this study to make a conclusion as to how significant the influence is. As further discussed below, variations in atmospheric conditions also influences noise levels. In particular, traffic noise will be louder if the wind is blowing from the freeway towards the listener's position as well as during sunrise/sunset periods when temperature inversion is occurring.

How does traffic noise change under different atmospheric conditions?

Comparison of the measured sound levels (see Table 7) and a more robust multiple regression model (see Table 8) indicated that measured noise levels were lower under certain atmospheric conditions. In particular, the measured sound levels under the "Lapse" and "Upwind" meteorological conditions were, on average, lower than the measured sound levels under a neutral atmospheric state. The most significant atmospheric conditions affecting traffic noise were identified to be, in order of significance, vector wind speed (+0.4 dBA for every 1 mi/h increase in vector wind speed); cloud cover (+0.6 dBA for overcast conditions); and temperature lapse rate (+3.3 dBA for every 1.0 °C/m (10.3 °F/ft) increase in lapse rate). These findings and the magnitude of the impacts are generally consistent with previous national research on this subject (e.g., HMMH, et al., 2014; FHWA, 2018; Kaliski, et al., 2018).

Is the traffic noise model more accurate if medium trucks are substituted for heavy trucks in TNM?

It has been proposed that the accuracy of TNM output can be improved if the heavy truck volumes observed for the model are added to the medium truck volumes with substitution ratio or volume multiplier applied to the heavy truck volume. This research examined this proposal using the validated TNM model from the Yorktown Middle School (NSA 7) under the meteorological conditions that are most similar to what is included in the TNM calculations. The following substitution ratios were analyzed: 1.0, 1.5, 2.0, 2.5, and 3.0. Results of the heavy-medium truck substitution ratio analysis are presented in Table 15 for the "No Barrier" case and Table 16 for the

"With Barrier" case. The analysis found that the tested substitution ratios did not improve the predictive accuracy of the TNM output in any meaningful way for receiver locations normally impacted by highway traffic noise. For instance, in the No Barrier case, the "optimal" volume multiplier was implied to be approximately 1.0 for receiver locations near the freeway. However, the implied multiplier at the same positions was approximately 3.0 for the With Barrier simulations.

In conclusion, this research finds that a single value for the substitution of heavy trucks with medium trucks is not easily derived and is highly-dependent on shielding and other site-specific conditions. In this case study, the proposed substitution of heavy truck volumes with medium truck volumes in the TNM software with various multipliers applied did not have a significant overall effect at improving the modeled sound levels for either broadband or individual frequency bands. However, all substitution ratios analyzed performed as well if not better than the base model in the YMS no barrier case. Substitution ratios of 2.5 and 3.0 in both cases combined performed as well if not better than the base model in the YMS with barrier case. It is also noted that all substitution ratios examined in this case study validated the model (i.e., predicted measured levels within ±3.0 dBA) except for one 12-foot-height receptor in the "No Barrier" case.

Is the TNM more accurate if residential structures are modeled as individual barriers instead of building row objects?

Regarding the treatment of residential building rows in the TNM software, this study analyzed the implications of modeling these situations utilizing the TNM "building rows" object or modeling each residential structure separately using the TNM noise barrier object. TNM models were developed to accurately reflect the site-specific conditions for all three settings of analysis (Pre-Clearing, No Barrier, and With Barrier). In conclusion, this research finds that modeling each individual residential structure as a separate TNM noise barrier object (single building façade that is closest to the freeway) produces the most accurate modeled noise levels. Of particular interest, the modeled outcomes for the receiver locations behind the first row of homes (R2; 315 feet from the freeway) and the second row of homes (R3; 422 feet from the freeway) were substantially improved with the barrier representation case. For the "With Barrier" analysis case, no substantial differences among the three options for building representation were noted in the model-to-monitor comparison.

What is the impact of roadside vegetation on traffic noise levels?

The existing vegetation at the research site (prior to the start of the noise wall construction project) consisted of a mix of various tree and bush species that are typical of Interstate roadsides in Ohio. Noise measurements collected as part of this study indicated that this vegetation zone generated a perceptible reduction in traffic noise. In particular, the roadside vegetation (including the more absorptive ground area within the vegetation) provided an additional noise attenuation between 3.0 and 4.0 dBA once the effects of divergence were accounted for. It was also estimated that a tree zone with relatively high density (i.e., no view of the freeway from the measurement position) results in an additional noise reduction of approximately 1.0 dBA as compared to a lower-density location with some views of the freeway. The vegetation zone analyzed in this study was approximately 100 feet deep and 30 feet tall. The vegetation zone removed for noise barrier construction was approximately 50 to 60 feet deep. The analysis indicated that the vegetation that existed prior to the start of construction provided a perceptible noise reduction (≈3.0 dBA) while higher-density vegetation provided an additional reduction of ≈1.0 dBA. This reduction is higher than past research results on this topic.

How do the findings of this study compare to the study prepared for the noise wall construction?

The traffic noise analysis study prepared for the case study noise barrier construction project (McCormick Taylor, 2013) was reviewed and the results compared to the findings of the current research study, where applicable. For the YMS study site (see Table 17), the results of the current research study were basically similar to the results of the consultant traffic noise study for the "No Barrier" case, for both measured data and modeled data at comparable distances from the freeway. The model deviation comparing the field-measured and TNM-modeled noise levels was also consistent between the two studies, with the TNM validated noise levels being approximately 2.0 dBA higher than measured noise levels across three comparisons). Additionally, the noise reduction attributed to the noise barrier measured for the current research study was lower than both the consultant model estimates and the estimated reduction from the modeling carried out as part of the current research.

For the SL study site (see Table 18), the measured noise levels for the current study were approximately 4.0 to 5.0 dBA higher than what was measured in the consultant study (pre-construction conditions) even though the traffic was lower in the current study due to the COVID-19 pandemic. However, the modeled noise levels were consistent between the two studies for the pre-construction condition. Additionally, the measured and modeled noise reduction attributed to the first row of residential structures at the SL study site were consistent between the consultant study and the current research study. However, for the "With Barrier" case, the estimated noise reduction attributed to the first row of residential building structures was higher in the consultant study (5.5 dBA) than what was measured by the research team in the current study (3.6 dBA for buildings as barriers representation). This finding is particularly interesting because the consultant study utilized a different approach to modeling the residential structures than what was investigated in the current study. With respect to the noise barrier reductions, the effect of the noise barrier was measured to be approximately 3 dBA higher in the current study as compared with what had been estimated in the consultant study for the first-row backyard location. The effect of the noise barrier for the second-row front yard location was consistent between the measured results of the current study and the estimated noise barrier performance from the consultant traffic noise study.

RECOMMENDATIONS FOR IMPLEMENTATION

Recommendations

Based on the findings and conclusions of this case study, the ORITE research team presents the following recommendations for consideration:

- Recommendation #1: ODOT traffic noise studies should be carried out under calm neutral atmospheric conditions whenever possible.
  This research found that measured traffic noise levels during periods of "Lapse" and "Upwind" meteorological conditions were, on average, lower than the measured sound levels under a neutral atmospheric state. Traffic noise data collection during "Lapse" and "Upwind" periods may result in flawed analyses and inadequate noise abatement recommendations. At a minimum, ODOT OES should outline acceptable ranges of wind and temperature conditions that are permitted for model validation studies and require its traffic noise consultants to verify compliance with those conditions in reporting. It is noted that this recommendation is consistent with FHWA guidance on conducting noise studies.
- Recommendation #2: Substitution of heavy truck volumes with medium truck volumes yielded mixed results as a possible strategy for improving TNM accuracy, based on this case study and the inherent differences in how medium and heavy truck sounds propagate. It is recommended to further investigate TNM predictive accuracy with more research and case studies focusing on this important topic.
  The substitution analysis in this case study was conducted at ODOT's direction based on an internal analysis showing over-predictions present in more than 60 percent of consultant traffic noise studies completed for ODOT in recent years. This case study found that, for the range of substitution ratios examined, the proposed strategy for improving the accuracy of TNM results did not affect the TNM predicted sound levels in a meaningful (i.e., perceptible) way. Additionally, there was no clear value for a substitution ratio that could be applied for both the "No Barrier" and "With Barrier" cases. The difference in the "optimal" multipliers between the No Barrier and With Barrier case underscores the difficulty in attempting to improve the results of the TNM modeling by applying the proposed truck volume substitution approach. If the optimal ratio for the "With Barrier" case (≈3.0 or higher) is applied to the "No Barrier" volumes, the "no build" noise impacts will be overstated, and the resulting noise abatement requirements will be excessive and inappropriate for the situation. On the other hand, it should be noted that all substitution ratios examined in this case study validated the model (i.e., predicted measured levels within ±3.0 dBA) except for one 12-foot-height receptor in the "No Barrier" case. However, if a ratio had to be selected for use in TNM based on this case study, it appears that ratio would be 2.5 or 3.0 (i.e., optimal for both cases combined). It is further recommended that additional studies examining the predictive accuracy of TNM be undertaken and focus on the following parameters: 15%-40% heavy trucks, % heavy trucks with and without vertical

exhaust stacks, % of trucks where actual vertical exhaust stack noise is observed, vehicle speeds, terrain representation (elevations, ground types), and shielding objects (structures, tree zones). ODOT believes TNM appears to perform adequately relative to noise analysis projects with a low truck % because the heavy truck exhaust noise source at 12 ft above the pavement would not typically be a factor because of the low number of heavy trucks. Because this case study involved 12% heavy trucks which is considered neither a low or high truck percentage, TNM did not definitively show overpredicted noise levels in this case study overall. However, ODOT believes if the truck %s are greater than what was in this case study, TNM may overpredict noise levels overall because the heavy truck exhaust noise source in TNM is at 12 ft above the pavement for every heavy truck and would be more prominent in the model coupled with preliminary traffic data showing a high percentage of heavy trucks actually having no vertical stacks, hence, no truck stack noise which means the measured level would understandably be lower than the modeled level. ODOT believes more model-to-monitor case studies should be conducted along freeways with 15%-40% truck %s to determine how TNM would be predicting noise levels in these higher truck % cases.

- Recommendation #3: Traffic noise practitioners should consider modeling each residential structure in noise-sensitive areas as TNM noise barrier objects. This case study found that the most accurate TNM predictions were realized with each residential structure modeled separately as a separate TNM noise barrier object taking the dimensions and position of the building façade that is closest to the freeway being analyzed. Without doing so may cause TNM to overpredict noise levels beyond the first row of homes and potentially predict noise impacts where there are none if the residential structures were modeled as barriers. As noted in the literature review, State DOTs in Arizona, Colorado, and Florida already require this type of modeling for their studies. However, the noise analyst must be aware not to include the noise reduction from the residential buildings as barriers in the reduction from the modeled noise wall.

- Recommendation #4: Traffic noise practitioners should model vegetation zones accurately in instances where the vegetation will remain in place and/or be removed following noise barrier construction. This study found that the roadside vegetation provided a perceptible measured noise reduction and that the modeled noise levels behind the vegetation were adequately modeled using a properly-specified TNM tree zone object. One caveat of this recommendation is that the modeled vegetation should be of sufficient density to block the line of sight between the freeway and the receiver, and that the line-of-sight shielding should be permanent (i.e., coniferous trees or shrubs that will not be affected or removed by the construction of a noise barrier). The vegetation zone analyzed in this study was approximately 100 feet deep and 30 feet tall. The vegetation zone removed for noise barrier construction was approximately 50 to 60 feet deep. The analysis indicated that the vegetation that existed prior to the start of construction provided a perceptible noise reduction (≈3.0 dBA) while higher-density vegetation provided an additional reduction of ≈1.0 dBA. This reduction is higher than past research results on this topic discussed in this report. It is further recommended that State DOTs be made aware of this finding because vegetation removal is a frequent source of noise complaints.

Implementation Plan

To implement the recommendations of this research, the following steps are suggested. For Recommendations #1, #3, and #4, ODOT OES should revise the *ODOT Highway Traffic Noise Analysis Manual* to incorporate the following changes:

- Specify acceptable and unacceptable weather conditions for TNM validation studies to incorporate both wind and temperature gradients;
- Specify requirements for traffic noise analysis studies to properly report compliance with acceptable weather conditions;
- Specify preferences or requirements for utilizing the TNM noise barrier object to represent individual residences or other structures adjacent to the freeway. This should include, at a minimum, recommended guidelines for dimensions and positioning of the modeled elements; and
- Specify requirements for modeling vegetation zones as tree zones in TNM, including the specific conditions for which these zones should be included.

Some State DOTs, as noted in the bibliography, have detailed guidelines for modeling which could be referenced by ODOT to assist with these revisions if desired. With respect to future research studies, it is recommended that ODOT pursue additional investigation on the optimal height of the TNM noise barrier object when it is used to model an individual building. For this study, the height of the longest portion of the structure (i.e., the ground level) was used but the sensitivity of the model results was not tested in detail. Regarding Recommendation #2, it is recognized that there are many viewpoints regarding the representation of large and heavy trucks in the TNM software and how traffic noise analyses should consider these types of vehicles. Future research on this topic should seek to add to a growing body of knowledge on the topic of heavy truck noise emissions and the distribution of source heights with a goal of providing more improved data for traffic noise modeling.

BIBLIOGRAPHY

Arizona Department of Transportation (ADOT) (2017). *Instruction on Using FHWA TNM in Noise Analysis*.

Bajdek, C., Menge, C., Mazur, R.A., Pate, A. and J. Schroeder (2015). *Recommended Best Practices for the Use of the FHWA Traffic Noise Model (TNM)*. Report No. FHWA-HEP-16-018.

Bowlby, W., Williamson, R., Reiter, D., Kaliski, K., Washburn, K., Rochat, J., Meighan, J., Yoerg, K., El-Aassar, A., Knauer, H., Sanchez, G., and D. Barrett (2018). *Field Evaluation of Reflected Noise from a Single Noise Barrier*. Report No. 886, National Cooperative Highway Research Program, Transportation Research Board. https://doi.org/10.17226/25297

Coulson, R. (1996). *Vehicle Noise Source Heights & Sub-Source Spectra*. Florida Atlantic University, Boca Raton, Florida. DOI: https://doi.org/10.1177/0361198196155900102

Chupp, W., A. Hastings, and G. Solman (2020). *Sensitivity Analysis on Highway Noise Level Differences between L_{Aeq} and L_{dn}*. Presented at the 2020 Transportation Research Board Annual Meeting, Washington, D.C.

Donovan, P.R. and C.J. Janello (2017). *Mapping Heavy Vehicle Noise Source Heights for Highway Noise Analysis*. Report No. 842, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. DOI: https://doi.org/10.17226/24704

Donovan, P.R. and B. Rymer (2009). Measurement of Vertical Distribution of Truck Noise Sources during Highway Cruise Pass-Bys by Acoustic Beam Forming. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2123, pp. 145-152. DOI: https://doi.org/10.3141/2123-16

Fan, Y., Zhiyi, B., Zhujun, Z., & Jiani, L. (2010). The Investigation of Noise Attenuation by Plants and the Corresponding Noise-Reducing Spectrum. *Journal of Environmental Health*, Vol. 72, No. 8, pp, 8–15.

Fang, C.-F., & Ling, D.-L. (2003). Investigation of the Noise Reduction Provided by Tree Belts. *Landscape and Urban Planning*, Vol. 63, No. 4, pp. 187–195. https://doi.org/10.1016/S0169-2046(02)00190-1

Fang, C.-F., & Ling, D.-L. (2005). Guidance for noise reduction provided by tree belts. *Landscape and Urban Planning*, Vol. 71, No. 1, pp. 29–34. https://doi.org/10.1016/j.landurbplan.2004.01.005

Fleming, G., A. Rapoza, and C. Lee (1995). *Development of National Reference Energy Mean Emissions Levels for the FHWA Traffic Noise Model (FHWA TNM), Version 1.0*. Report No. FHWA-PD-96-008.

Florida Department of Transportation (FDOT) (2018). *Traffic Noise Modeling and Analysis Practitioners Handbook*.

Gurovich, Y., K. Plotkin, D. Robinson, W. Blake, and P. Donavan (2009). *Acoustic Beamforming: Mapping Sources of Truck Noise*. Report No. 635, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. DOI: https://doi.org/10.17226/14311

Hankard, M., Cerjan, J., & Leasure, J. (2006). *Evaluation of the FHWA Traffic Noise Model (TNM) for Highway Traffic Noise Prediction in the State of Colorado.* Report No. CDOT-2005-21, Colorado Department of Transportation.

Harris, R. A., & Cohn, L. F. (1985). Use of Vegetation for Abatement of Highway Traffic Noise. *Journal of Urban Planning and Development*, Vol. 111, No. 1, pp. 34–48. https://doi.org/10.1061/(ASCE)0733-9488(1985)111:1(34)

Harris Miller Miller & Hansen, Inc., Bowlby & Associates, Inc., Environmental Acoustics, Anderson, G.S. and D.E. Barrett (2014). *Supplemental Guidance on the Application of FHWA's Traffic Noise Model (TNM)*. Report No. 791, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. DOI: https://doi.org/10.17226/22284

Hastings, A. (2007). Heavy Truck Contributions to Highway Traffic Sound Pressure Levels. Presented at the 2007 TRB Noise and Vibration Committee Summer Meeting, San Luis Obispo, California.

Kaliski, K., Haac, R., Brese, D., Duncan, E., Reiter, D., Williamson, R., Pratt, G., Salomons, E., Wayson, R., McDonald, J., Zimmerman, J., Snyder, J., and A. Hastings (2018). *How Weather Affects the Noise You Hear from Highways*. Report No. 882, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. DOI: https://doi.org/10.17226/25226

Karbalaei, S. S., Karimi, E., Naji, H. R., Ghasempoori, S. M., Hosseini, S. M., & Abdollahi, M. (2015). Investigation of the Traffic Noise Attenuation Provided by Roadside Green Belts. *Fluctuation and Noise Letters*, Vol. 14, No. 4, pp. 1550036-1–1550036-9. https://doi.org/10.1142/S0219477515500364

Li, B., Tao, S., Dawson, R.W., Cao, J., and K. Lam (2002). A GIS-Based Road Traffic Noise Prediction Model. *Applied Acoustics*, Vol. 63, No. 6, pp. 679-691. DOI: https://doi.org/10.1016/S0003-682X(01)00066-4.

Lupo, P.J. and E. Symanski (2009). A Comparative Analysis of Modeled and Monitored Ambient Hazardous Air Pollutants in Texas: A Novel Approach Using Concordance Correlation. *Journal of the Air & Waste Management Association*, Vol. 59, No. 11, pp 1278-1286. DOI: https://doi.org/10.3155/1047-3289.59.11.1278

Maleki, K., & Hosseini, S. M. (2011). Investigation of the Effects of Leaves, Branches and Canopies of Trees on Noise Pollution Reduction. *Annals of Environmental Science. Vol*. 5, pp. 13-21.

Martens, M. J. M., & Michelsen, A. (1981). Absorption of acoustic energy by plant leaves. *The Journal of the Acoustical Society of America*, Vol. 69, No. 1, pp. 303–306. https://doi.org/10.1121/1.385313

Menge, C., C. Rossano, G. Anderson, and C. Bajdek (1998). *FHWA Traffic Noise Model, Version 1.0 Technical Manual*. Report No. FHWA-PD-96-010; TNM Version 2.5 Update Sheets, 2004.

McCormick Taylor (2013). *IR-270 Type II Noise Abatement Study* (PID 93359/93360). Prepared for ODOT District 6, Delaware, Ohio, February 2013.

ODOT Office of Environmental Services (OES) (2015). *ODOT Highway Traffic Noise Analysis Manual*. ODOT OES, April 2015. URL: http://www.dot.state.oh.us/Divisions/Planning/Environment/NEPA_policy_issues/NOISE/Pages/NoiseManual.aspx.

Ow, L. F., & Ghosh, S. (2017). Urban cities and road traffic noise: Reduction through vegetation. *Applied Acoustics*, Vol. 120, pp. 15–20. https://doi.org/10.1016/j.apacoust.2017.01.007

Payne-Sturges, D., Burke, T., Breysse, P., Diener-West, M., and T.J. Buckley (2004). Personal Exposure Meets Risk Assessment: A Comparison of Measured and Modeled Exposures and Risks in an Urban Community. *Environmental Health Perspectives*, Vol. 112, No. 5, pp. 589-598. DOI: https://doi.org/10.1289/ehp.6496

Rochat, J.L. and G.G. Fleming (2002). *Validation of FHWA's Traffic Noise Model (TNM): Phase 1*. Report No. FHWA-EP-02-031, August 2002.

Rochat, J.L. and G.G. Fleming (2004). *Addendum to Validation of FHWA's Traffic Noise Model (TNM): Phase 1*. Report No. FHWA-EP-02-031 Addendum, July 2004.

Saurenman, H., Chambers, J., Sutherland, L.C., Bronsdon, R.L. and H. Forschner (2005). *Atmospheric Effects Associated with Highway Noise Propagation*. Final Report 555, Arizona DOT.

U.S. Environmental Protection Agency (EPA) (1996). *Comparison of ASPEN Modeling System Results to Monitored Concentrations*. URL: https://archive.epa.gov/airtoxics/nata/web/html/draft6.html.

U.S. Federal Highway Administration (FHWA) (2004). *FHWA Traffic Noise Model (FHWA TNM), Version 2.5 Look-Up Tables User's Guide*. Report No. FHWA-HEP-05-008. URL: https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25_lookup/. Updated 6/28/2017.

U.S. Federal Highway Administration (FHWA) (2017a). *Summary of Noise Barriers Constructed by December 31, 2016*. URL: https://www.fhwa.dot.gov/environment/noise /noise_barriers/inventory/. Accessed February 20, 2018.

U.S. Federal Highway Administration (FHWA) (2017b). *Traffic Noise Model*. URL: https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/. Updated 6/28/2017.

U.S. Federal Highway Administration (FHWA) (2018). *Noise Measurement Handbook*. Report No. FHWA-HEP-18-065, June 2018.

Van Renterghem, T., Botteldooren, D., & Verheyen, K. (2012). Road traffic noise shielding by vegetation belts of limited depth. *Journal of Sound and Vibration*, Vol. 331 No. 10, pp. 2404–2425. https://doi.org/10.1016/j.jsv.2012.01.006

Van Renterghem, T. (2014). Guidelines for optimizing road traffic noise shielding by non-deep tree belts. *Ecological Engineering*, Vol. 69, pp. 276–286. https://doi.org/10.1016/j.ecoleng.2014.04.029

Van Renterghem, T., Attenborough, K., Maennel, M., Defrance, J., Horoshenkov, K., Kang, J., Bashir, I., Taherzadeh, S., Altreuther, B., Khan, A., Smyrnova, Y., & Yang, H.-S. (2014). Measured light vehicle noise reduction by hedges. *Applied Acoustics*, Vol. 78, pp. 19–27. https://doi.org/10.1016/j.apacoust.2013.10.011

Watts, G., Chinn, L., & Godfrey, N. (1999). The effects of vegetation on the perception of traffic noise. *Applied Acoustics*, Vol. 56, No. 1, pp. 39–56. https://doi.org/10.1016/s0003-682x(98)00019-x

Wayson, R. and W. Bowlby (1990). Atmospheric Effects on Traffic Noise Propagation. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1255, pp. 59-72.

APPENDIX A: LITERATURE REVIEW

Introduction

The objective of the literature review was to identify and synthesize relevant literature on the key topics associated with the research study. The following topics were incorporated in the literature review: 1) meteorological impacts on traffic noise (i.e., temperature inversion, wind, humidity, cloud cover); 2) impact of medium and heavy truck traffic on highway traffic noise and noise barrier performance; 3) noise reduction attributed to building rows near the freeway; 4) noise reduction associated with roadside vegetation; and 5) best practices or other strategies for addressing the above matters in traffic noise modeling. To support the literature review, the ORITE research team examined research studies including NCHRP and State DOT research studies, as well as journal articles and presentations from various technical conferences associated with the traffic noise discipline. Details of the literature review are presented in this Appendix. Additionally, a preliminary analysis of the potential for substitution of heavy trucks with medium trucks in the TNM software is presented based on both literature findings and simulation.

Meteorological Impacts

The propagation of sound can be heavily influenced by atmospheric conditions. As noted in *NCHRP Report 886* (Kaliski, et al., 2018), there are two types of atmospheric effects that are thought to be most influential: absorption of sound waves within the air and the effects of wind and temperature gradients. Absorption of sound waves in air is dependent on both the air temperature and the humidity of the air. Laboratory and field research have established accurate methods for calculating absorption based on temperature and humidity, and the effects are also varied based on the frequency of the sound wave. An example of a predictive model for atmospheric absorption of sound as a function of temperature and humidity is outlined in the standard ISO 9613-1:1993. FHWA (2018) notes that temperature and humidity generally have small effects on measured traffic noise levels at the typical distances analyzed in traffic noise studies, with the impacts of wind and temperature lapse being much more influential at these distances.

The effect of wind and temperature gradients is more complex, but it is generally assumed that sound levels are higher if the receivers are located downwind from the sound source and during periods of temperature inversion (i.e., the temperature is cooler at ground level). For traffic noise analysis, the wind speed is generally analyzed in terms of the vector wind speed with the component perpendicular to the highway being of greatest interest (FHWA, 2018). Research reported by Wayson and Bowlby (1990) found that the effects of vector wind speed and temperature inversion were most notable at distances beyond 120 meters from the highway but had limited impact within 60 meters. A study from the Arizona DOT (Saurenman, et al., 2005) found that the effect of nighttime temperature inversion was shown to increase noise levels between 5 and 8 dB up to 400 meters from the highway. *NCHRP Report 882* (Kaliski, et al., 2018) represents the most recent comprehensive national-level research study on how weather conditions affect noise. This study reported on various weather conditions that affect highway traffic noise levels at different distances from the freeway source. The analysis presented in *NCHRP Report 882* found that, within typical highway traffic noise evaluation distances (500 feet), the effect of weather conditions could be ±6.0 dBA without a noise barrier and between -5.0 and +9.0 dBA with a barrier, depending on barrier geometry. It should be noted that there is limited ability for TNM to address these concerns in the modeling process. However, reference tables are available that provide SHAs with guidance on how sound levels are affected by wind conditions and temperature lapse rate. As part of the research for *NCHRP Report 791*, lookup tables were created to provide guidance on approximate changes in sound levels under various wind and temperature lapse rate under commonly-encountered traffic mix, ground type, and barrier shielding scenarios (Harris Miller Miller & Hansen, Inc., et al., 2014). An example these lookup tables are presented in Figure 14, which displays the estimated sound levels relative to neutral atmospheric conditions for mixed traffic and soft ground, for the with and without Noise Barrier cases.

Automobiles and Trucks, Soft Ground, without Noise Barrier									
Receiver Distance (ft)	Receiver Height (ft)	Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
		Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	–2	–3	3	3	0	–1	0	2
100	5	–3	–4	6	8	0	–1	1	4
200	5	–4	–6	10	12	–1	–2	2	8
400	5	–7	–9	13	14	–2	–4	3	11
800	5	–11	–14	14	15	–4	–8	4	12
1600	5	–16	–21	14	14	–7	–11	4	13
50	15	–1	–1	1	1	0	0	0	1
100	15	–1	–3	2	2	0	–1	1	2
200	15	–3	–5	4	6	–1	–2	1	4
400	15	–5	–8	8	10	–2	–4	3	8
800	15	–8	–12	11	13	–3	–7	4	11
1600	15	–13	–16	12	13	–7	–12	5	12

Automobiles and Trucks, Soft Ground, with Noise Barrier									
Receiver Distance (ft)	Receiver Height (ft)	Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
		Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	–3	–5	8	12	–1	–1	4	9
100	5	–3	–5	7	11	–1	–2	4	10
200	5	–3	–5	6	11	–1	–2	4	11
400	5	–5	–8	5	11	–2	–5	4	13
800	5	–5	–9	5	11	–3	–8	4	16
1600	5	–6	–11	5	9	–5	–12	5	18
50	15	–3	–6	8	12	–1	–1	3	7
100	15	–3	–5	6	10	–1	–2	3	9
200	15	–2	–4	5	9	–1	–2	3	10
400	15	–2	–3	3	8	–1	–3	3	12
800	15	–2	–5	2	6	–2	–6	3	14
1600	15	–2	–8	3	5	–4	–13	4	17

Source: Table 14, Harris Miller Miller & Hansen, Inc., et al. (2014)

Figure 14: A-Weighted Noise Emissions for TNM Average Pavement Type

Heavy Truck Impacts

Overview of Problem

Heavy vehicles (i.e., trucks and buses) are significant contributors to overall traffic noise levels. Noise sources from heavy vehicles include tire-pavement interaction, engine/powertrain noise, and exhaust stack noise. Heavy vehicles are particularly unique in that they have more than four tires, more powerful engines, and an elevated exhaust stack. TNM applies heavy truck noise emissions based on extensive field measurements (Fleming, et al., 1995) and noise source distribution for heavy trucks based on a 1996 study (Coulson, 1996). Discussion of heavy truck noise representation in TNM is provided in detail in the section entitled Medium and Heavy Trucks in TNM. An extensive TNM validation study, including updates for TNM Version 2.5 in 2004, showed that TNM was providing accurate predictions for real highways/traffic mixes both with and without noise barriers (Rochat and Fleming, 2002). As the engine and exhaust characteristics of heavy vehicles have evolved over the past 25 years, there has been some concern that the heavy truck noise as modeled by TNM has not accounted for these changes. Recent research (Donovan and Rymer, 2009; Donovan and Janello, 2017) has demonstrated that the assumed height of the engine and exhaust noise sources from heavy trucks in TNM does not correspond with the actual distribution of these source heights based on field measurements. It was estimated that TNM under-predicted the actual reduction in noise attributed to a barrier by 3 to 6 dB(A), suggesting that the default source height distribution in TNM would result in taller noise barriers being constructed than what was necessary. The results of these studies are summarized in the section Heavy Truck Noise Contribution and Source Distribution Studies, along with discussion of considerations and implications of updating heavy truck source parameters in TNM.

Based on past heavy truck source noise distribution research, there has been discussion in the traffic noise research community about the potential for substituting medium trucks for heavy trucks in TNM, effectively placing the heavy truck upper noise source at a lower position. As part of this research study, the ORITE research team examined the potential for substituting heavy trucks with medium trucks in TNM. A similar concept is already in use for the noise generated by heavy trucks relative to passenger cars, with the assumption of 10 passenger cars being equivalent to 1 heavy truck mentioned in several literature sources (Donovan and Janello, 2017; Chupp, et al., 2020), although it is noted that this substitution ratio is only for comparison purposes and not deployed directly in the TNM inputs. One research study published by Li, et al. (2002) derived an equivalency ratio of automobile to heavy truck noise of approximately 9.12 and a ratio of automobile to medium truck noise of 3.16. Following the same calculations presented in the article, the implied ratio equating medium truck noise with heavy truck noise was estimated to be 2.88; it is noted that the vehicle classifications analyzed in that research are based on definitions used in China and do not necessarily match the TNM vehicle types.

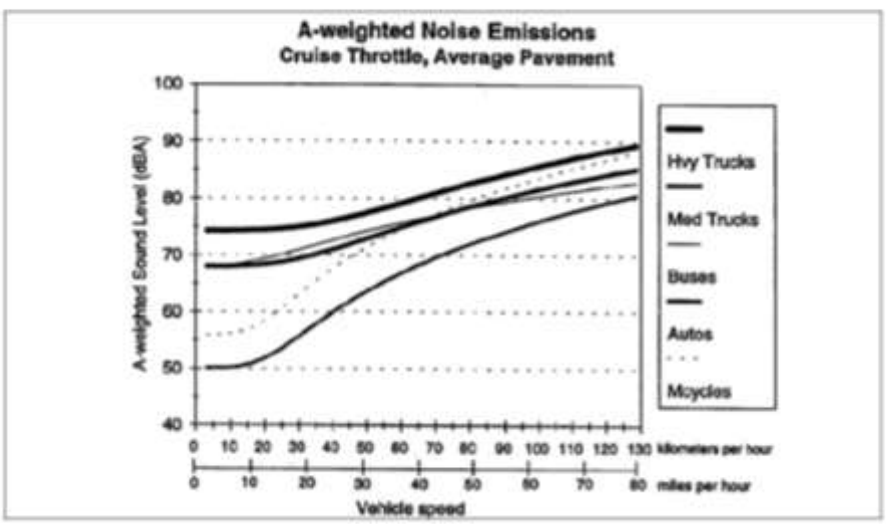
The ORITE research team examined the heavy truck-medium truck substitution question in this study using two approaches. First, a simulation study was conducted to identify the range of plausible values of the proposed substitution ratio. The simulation study is based on original TNM simulations carried out by the research team as well as calculations derived from previously-developed TNM simulations. This simulation study is described in the section Simulation of Medium/Heavy Truck Substitutions. Second, based on the results of the simulation study, the substitution ratios are applied to the TNM models developed for the case study project site for the current research study. The results of that analysis are presented in Appendix D.

Medium and Heavy Trucks in TNM

In 1994 and 1995, the U.S. DOT Volpe National Transportation Systems Center organized and collected vehicle pass-by noise emission data as the basis for the FHWA TNM. The database includes these two vehicle types, among others:

- Medium trucks: all cargo vehicles with two axles and six tires – generally with gross vehicle weight between 4,500 kg (9,900 lb) and 12,000 kg (26,400 lb); and
- Heavy trucks: all cargo vehicles with three or more axles – generally with gross vehicle weight more than 12,000 kg (26,400 lb).

Data were collected for vehicles cruising, accelerating, idling, and for vehicles on grades. In addition, data were obtained for vehicles traveling on different pavement types, including dense-graded asphalt (DGAC), open-graded asphalt (OGAC), and Portland cement concrete (PCC). Figure 15 shows the sound level by vehicle type as a function of speed, at a distance of 15 m (50 ft) from the center of the near travel lane (Menge, et al., 1998; 2004).

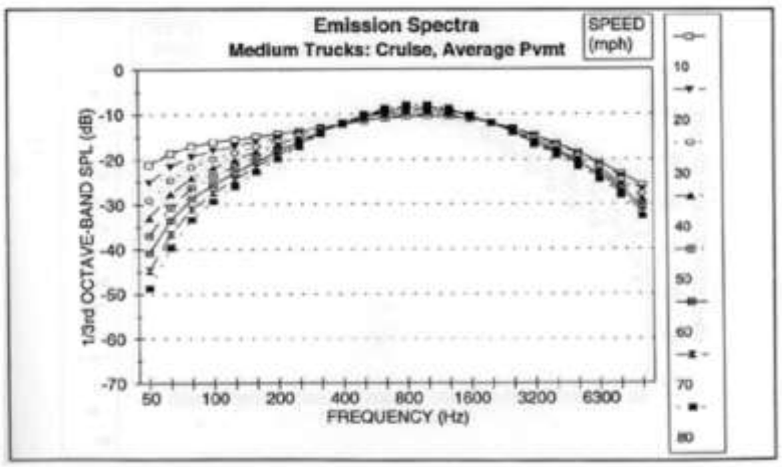


Source: Menge, et al. (1998)

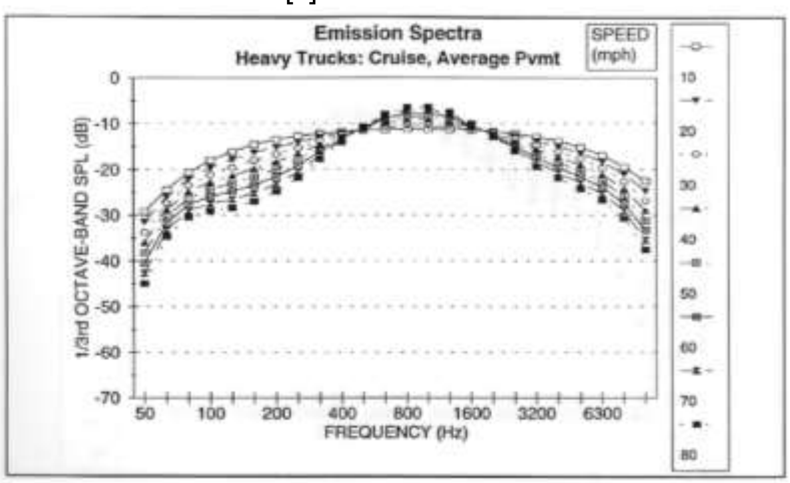
Figure 15: A-Weighted Noise Emissions for TNM Average Pavement Type

For cruise conditions for TNM Average pavement (a combination of DGAC and PCC noise emissions, required for use for noise predictions on projects receiving Federal aid), heavy trucks are about 4 dB louder than medium trucks at most speeds, with slightly greater differences at speeds below about 48 km/h (30 mph). An increase of 4 dB (at highway speeds) would require a volume multiplier of 2.5 to increase medium truck noise by 4 dB at 15 m (50 ft) ($4 = 10*Log_{10}(2.5)$). That multiplier, however, does not account for differences in the medium and heavy truck noise sub-source heights or differences in the spectral content, which influence the effects of sound propagation. As such, the multiplier is not universally applicable, as is demonstrated later in this section. Traveling from the road to sensitive receptors, sound is affected differently at different frequencies. High frequencies are reduced substantially through soft ground effects (further affected by source height) and also some from atmospheric absorption, as well as simple loss of energy (as the sound spreads out) and shielding objects (such as noise barriers). Low frequencies can propagate far distances with little effect other than simple loss of energy and can diffract over the top of shielding objects. The spectral content for medium and heavy trucks is discussed next followed by the noise sub-sources.

Medium truck and heavy truck one-third octave band data are shown in Figure 16 for cruise conditions for TNM Average pavement (Menge, et al., 1998; 2004). Each plot shows the sound level as a function of frequency for speeds ranging from 16 to 129 km/h (10 to 80 mph).



[a] Medium Trucks



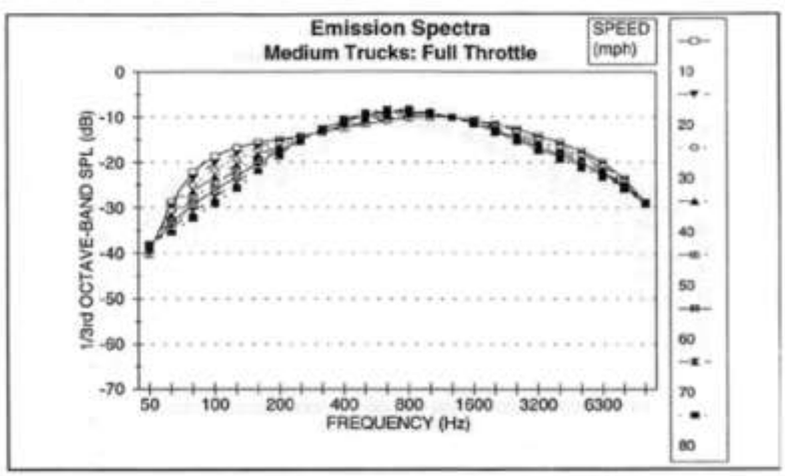
[b] Heavy Trucks

Source: Menge, et al. (1998)

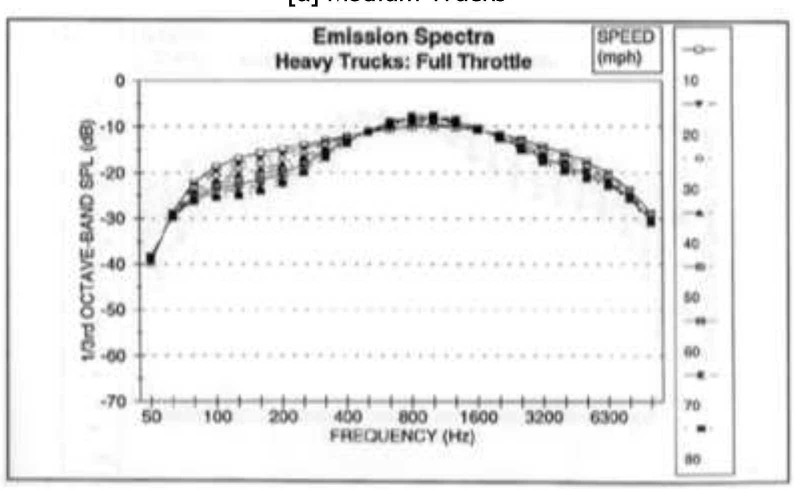
Figure 16: Emissions Spectra for TNM Average Pavement Type

In general, medium truck spectra are flatter across frequencies than spectra for heavy trucks, which tends to peak more around 1000 Hz, particularly at highway speeds. Also, for the cruise conditions, variation in sound level as a function of speed varies by frequency, with variation differing by vehicle type. For medium trucks, low frequencies (< 315 Hz) have the greatest variation by speed, up to 30 dB. At around 1000 Hz, the variation is slight, and at high frequencies (> 3150 Hz), the sound level varies up to about 10 dB by speed. For heavy trucks, sound levels vary by up to about 15 dB in the low and high frequencies and up to about 5 dB around 1000 Hz. Other pavement types show similar trends, although with more variation in high frequencies for medium trucks and less for heavy trucks for the OGAC pavement. In summary for cruise conditions, the two vehicle types have different spectral content variation by speed. Because of these differences in spectra, the sound would be affected differently during sound propagation, by parameters such as ground type and shielding (effects being frequency dependent).

Medium truck and heavy truck one-third octave band data are shown in Figure 17 for full throttle conditions (no distinction by pavement type).



[a] Medium Trucks



[b] Heavy Trucks

Source: Menge, et al. (1998)

Figure 17: Emissions Spectra for TNM Full-Throttle Condition

Full throttle conditions are applied to heavy trucks on an upgrade roadway (grade ≥ 1.5%); they are also applied to both medium trucks and heavy trucks where traffic control devices indicate an acceleration condition. Each plot shows the sound level as a function of frequency for speeds ranging from 16 to 129 km/h (10 to 80 mph). In general, the spectral shapes are very similar, with some differences in the low frequencies, and heavy trucks having a slightly more prominent peak around 1000 Hz. Compared to cruise conditions, full throttle conditions show more low frequency content for both truck types, and these frequencies can contribute more to the broadband sound level over distance and/or with shielding. For the full throttle conditions, variation in sound level as a function of speed varies by frequency with variation differing by vehicle type. Both medium and heavy trucks vary the most at low frequencies. For medium trucks, the most variation is from 63 to 200 Hz with the greatest variation of approximately 11 dB. For heavy trucks, the most variation is from 80 to 315 Hz with the greatest variation of approximately 9 dB. In summary, full throttle spectra also show that the two vehicle types have different spectral content and variation by speed, which can result in the sound having different propagation effects.

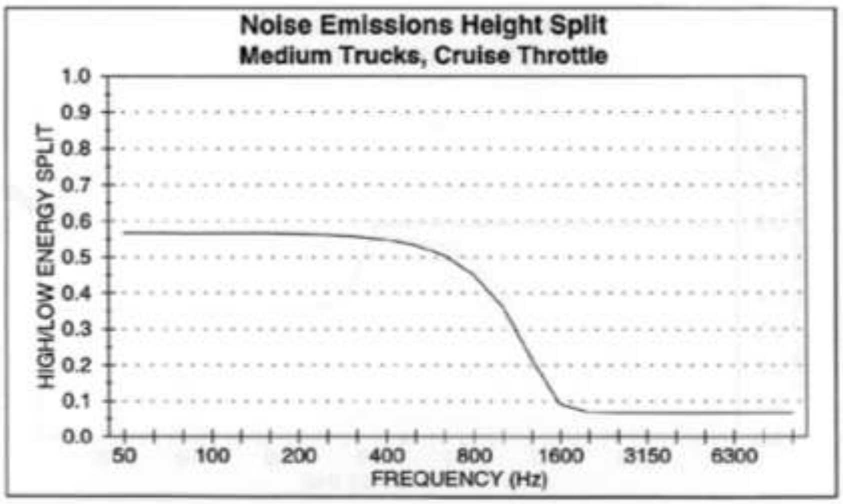
In addition to differences in spectral content, medium trucks and heavy trucks have different noise source locations and distributions. Each vehicle is represented by two noise sub-sources: 1) tire-pavement noise, and 2) engine or exhaust stack. The ratio of sound energy distributed at the lower and upper heights is a function of frequency, vehicle type, and throttle conditions (cruise or full throttle). Table 2 shows the lower and upper sub-source locations by vehicle type and operation condition and the percent distribution for the sound energy.

Table 2: TNM Noise Source Heights and Distributions for Medium and Heavy Trucks

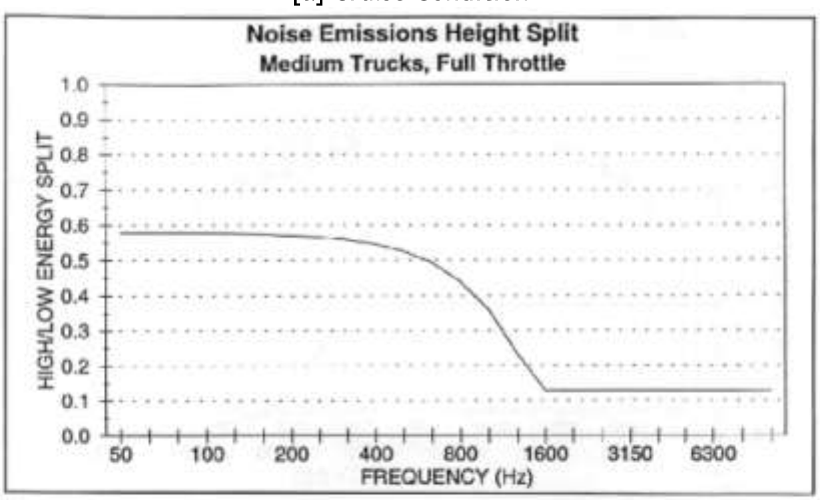
Vehicle type	Lower sub-source height	Upper sub-source height	Operating condition	% Total sound energy at upper sub-source height		
				Low frequencies ≤ 500 Hz	Middle frequencies 500 Hz < f < 2000 Hz	High frequencies ≥ 2000 Hz
Medium truck	0.1 m (0.3 ft) tire-pavement noise	1.5 m (5 ft) engine	Cruise	36 %	Transitions[c]	6 %
Medium truck	0.1 m (0.3 ft) tire-pavement noise	1.5 m (5 ft) engine	Full throttle[a]	37 %	Transitions[c]	11 %
Heavy truck	0.1 m (0.3 ft) tire-pavement noise	3.7 m (12 ft) exhaust stack	Cruise	57 %	Transitions[c]	46 %
Heavy truck	0.1 m (0.3 ft) tire-pavement noise	3.7 m (12 ft) exhaust stack	Full throttle[a,b]	57 %	Transitions[c]	48 %

[a] Applied where user-entered traffic control devices indicate an acceleration condition.
[b] Applied where there is an upgrade roadway (≥ 1.5%).
[c] The percentage transitions from the low frequency % to the high frequency %. See Figure 18 (medium trucks) and Figure 19 (heavy trucks) for the transitions, shown as high sub-source % divided by low sub-source % (figures from TNM Technical Manual and v2.5 update sheets) (Menge, et al., 2004).

Although medium and heavy trucks both use the same lower sub-source height to represent tire-pavement noise, they use different upper sub-source heights: 1.5 m (5 ft) for medium trucks and 3.7 m (12 ft) for heavy trucks. Because of the different upper source locations, sound propagation effects will vary. As an example, if a noise barrier blocks the line of sight to the 1.5 m (5 ft) source but not the 3.7 m (12 ft) source, then medium truck sound will be shielded, with only sound that is diffracted over the barrier at a much-reduced level reaching receivers behind the barrier; for heavy trucks, only the lower sound source will be shielded, while the upper one will propagate directly to the receiver. With about 50% of the sound energy assigned to the upper source, heavy trucks will see only some reduction in sound due to the barrier, mostly for the lower source.

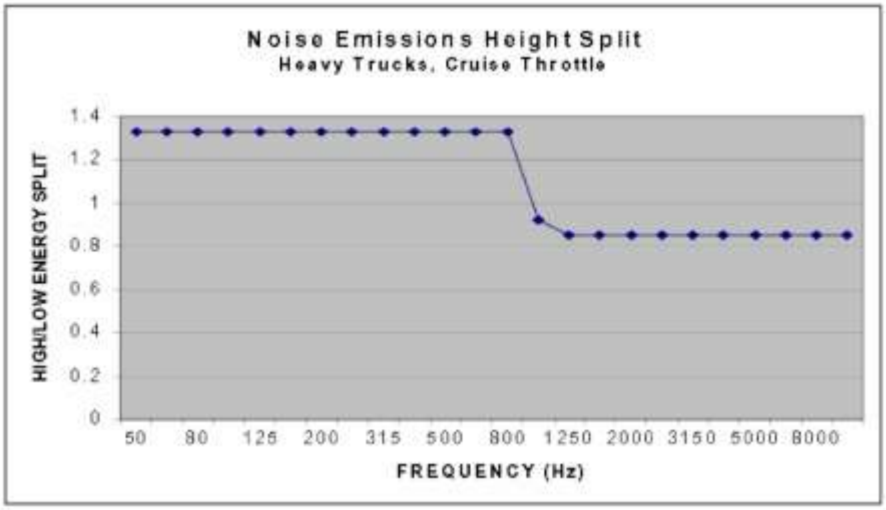


[a] Cruise Condition

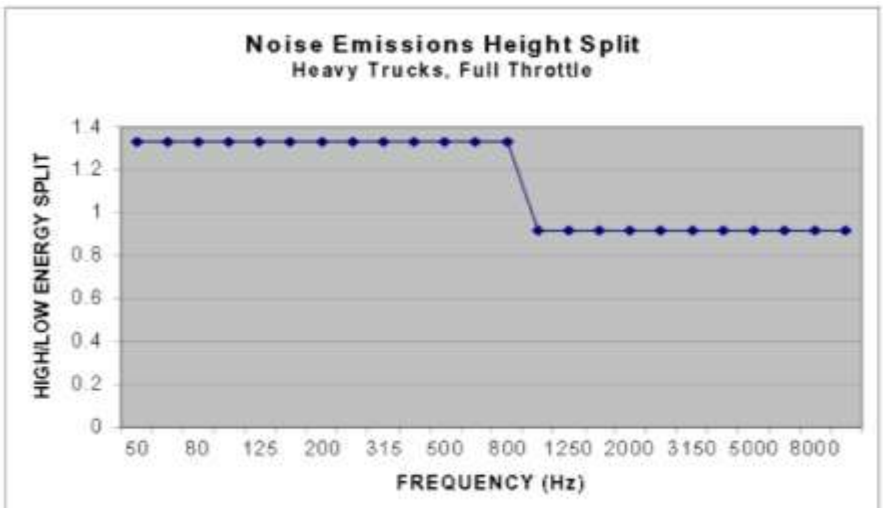


[b] Full-Throttle Condition
Source: Menge, et al. (1998)

Figure 18: High/Low Energy Split for Medium Trucks



[a] Cruise Condition



[b] Full-Throttle Condition
Source: Menge, et al. (1998)

Figure 19: High/Low Energy Split for Heavy Trucks

Heavy Truck Noise Contribution and Source Distribution Studies

To help understand the impact of heavy truck noise on highway noise predictions, we can refer to a study conducted by the Volpe Center by Hastings (2007). This study examined the contribution of heavy truck noise for various highway configurations and parameters. TNM was used varying the following parameters: heavy truck percentage, pavement type, ground type, number of traffic lanes, distance from the roadway, shielding (no barrier and different height barriers), vehicle speed, and site geometry (at-grade and elevated roadways). Depending on the parameters, it was reported that the percentage of heavy trucks at which heavy truck noise dominates over automobile noise ranges from 3.5 to 22.5%. The parameters for which heavy trucks dominate at lower percentages are: two-lane roads, soft ground, far receivers, barriers implemented, elevated roadways, and lower speeds. The parameters for which heavy trucks dominate at higher percentages are: four-lane roads, hard ground, near receivers, no barrier, at-grade roadways, and higher speeds. This information can be used for specific highway cases to help understand when changes to the heavy truck implementation in TNM will impact results. For example, for a case with a noise barrier, only a very small percentage of heavy trucks is required to dominate the traffic noise behind the barrier, so how heavy trucks are implemented (source heights and distribution) can have a substantial impact on predicted sound levels.

To help answer the question about heavy truck noise sources and distribution and if TNM implementation needs to be updated, two studies were conducted as part of the National Cooperative Highway Research Program. In 2009, results for Project 08-56 (Gurovich, et al., 2009) (where an optimized beamforming microphone array was used to study heavy truck noise sources) showed that tire-pavement interaction was the dominant noise source. A small portion of heavy trucks, however, exhibited significant noise generation in the area of the vertical exhaust stack, dominating at low frequencies and elevations around 3.7 m (12 ft), the same height that TNM uses for the upper noise source for heavy trucks. It was found that, for noise prediction modeling purposes, a simple system of two sources, one located near the pavement and another at the exhaust stack elevation, can generally be used for simulating statistical vertical distributions of truck noise sources.

A follow-up NCHRP study (Donovan and Janello, 2017) measured heavy truck noise using a more standard beamforming microphone array. As with the previous study, the researchers found that using two noise sub-sources could adequately represent the profile of heavy truck noise source distribution and yield barrier insertion loss values similar to using more than two sub-sources. The research showed that one source should be located at ground level and the other at 0.1 to 1 m (0.3 to 3 ft) above the ground, range being frequency dependent. The report, however, did discuss that seven out of twenty sites (35%), at which existing traffic heavy truck noise was measured, had 10% or more (up to 28%) heavy trucks with exhaust stack noise. It was mentioned that for most of the heavy trucks, the exhaust stack did not contribute substantially to the broadband sound level (i.e., the tire-pavement noise dominated), and so the height recommendation for the upper sound source appears not to consider the exhaust stack noise. Related to the broadband levels and not to source distribution, the report also states that the heavy truck emission levels are adequately represented in TNM for highway speeds, but additional data for lower speeds are needed. Although the follow-up NCHRP study showed that, on average, a majority of the heavy trucks did not have exhaust stack noise that contributed to the broadband sound level, and the two heavy truck noise sub-sources should be placed at or below 1 m (3 ft), the following needs to be considered:

1. It seems there were enough sites with enough trucks with contributing exhaust stack noise such that exhaust stack noise should be considered in barrier design so as to avoid inadvertent under-prediction of heavy truck noise behind a

barrier. The first NCHRP study (Gurovich, et al., 2009) supports this by placing the upper source at 3.7 m (12 ft).

2. The NCHRP studies were based on one scenario: receivers close to the road and no shielding. Such distribution should apply only to that scenario which is not common for Type I or II noise studies. The method for determining whether or not the exhaust stack noise source contributes to the broadband sound essentially determines how important that noise source is. For the scenario tested, the follow-up study determined that the exhaust stack noise is not important compared to the other sources and so it was eliminated. There are other scenarios, however, where exhaust stack noise is much more important and should therefore not be discounted. One example is the typical Type I or II noise study where the receiver is at farther distances, where low frequency noise dominates; in such cases, the low frequency noise from exhaust stacks likely dominates. Another example is a case where the lower noise source (tire-pavement noise) is shielded (e.g., by a safety barrier or low berm), thus making the upper noise source unshielded and more prominent/important. Knowing the upper source is now important, this would likely change the upper source locations from the ones recommended, 0.1 to 1 m (0.3 to 3 ft, frequency dependent), to ones where the upper source is much higher, likely up to 3.7 m (12 ft). Even if the exhaust stack noise were also shielded, it would be closer to the top of the barrier and likely as or more important than the tire-pavement noise source. Therefore, for implementation in TNM, we need to consider that distribution that does not consider the exhaust stack noise source would likely not provide proper results in typical Type I and Type II studies (at farther distances and with barriers present, when there are trucks with exhaust stacks as part of the highway traffic)[1].
3. Exposure to heavy truck exhaust stack noise is likely to generate community complaints, particularly when tire-pavement noise is greatly reduced due to shielding of that noise source and the exhaust stack noise is not. In that scenario, communities will likely be exposed to intermittent, loud, low-frequency noise that has not be accurately considered in TNM.
4. Because TNM was shown to perform well with its current heavy truck implementation, any changes to source location and/or distribution need to be considered carefully. TNM was optimized to provide the best results possible, and there are other parameters beyond the source location/distribution that affect the diffraction of heavy truck noise over a noise barrier. These other parameters would need to be re-optimized if truck noise sources change position and/or are redistributed. In addition, the architecture for TNM assumes only two sub-source heights for each vehicle type; if one were to place the upper source at varying height depending on frequency (as recommended

[1] Any change in TNM vehicle source heights/distributions needs to be carefully considered for different highway scenarios, whether it is for heavy truck exhaust stacks or heavy or medium truck engine noise, which was also discussed in the 2017 NCHRP report. Failing to consider relative contributions under different scenarios, particularly in cases with shielding, could lead to noise barrier designs that do not protect communities as intended.

in the follow-up NCHRP work), this would require a substantial amount of work in re-coding TNM and would likely require substantial run times once implemented. In summary, although implementation of new heavy truck source locations/distribution is possible, it cannot be accomplished successfully without substantial re-coding, considering source locations/distribution for different site scenarios (e.g., near/far, barrier/no barrier), and re-optimizing based on iterative testing with newer highway traffic data sets to make sure predicted sound levels are still valid.

In contrast to the above discussion, TNM is currently calculating approximately 60% of heavy truck noise at 12 feet height for every heavy truck on every single roadway for every single highway noise project and there is an abundance of evidence that shows this is inaccurate. Ohio DOT believes the following are valid reasons why the way heavy truck noise is currently calculated in TNM should be changed/improved, the current 60% of the heavy truck noise at the stack in the TNM algorithm should be reduced substantially, and/or heavy trucks (HTs) should be modeled as medium trucks (MTs) in TNM2.5:

- Two recent national research reports on heavy truck noise (NCHRP 635 and 842) concluded that the heavy truck noise source is at the tire/pavement interface, not at the 12' truck stack. The current TNM algorithm has over 60% of the heavy truck noise at the stack. The NCHRP Beam Forming research projects show most acoustic energy on heavy trucks is below 3.3 feet. Hence, heavy trucks fall more in line with the TNM algorithm for medium trucks.
- In NCHRP 635 (Acoustic Beamforming: Mapping Sources of Truck Noise), statistical analysis of the vertical distribution of noise sources indicated that for the majority of 63 truck passbys measured at highway speeds on an in-service highway, tire– pavement interaction was the dominant source generating sound close to the pavement. A small proportion of heavy trucks, however, exhibited significant noise generation in the area of the vertical exhaust stack, dominating at low frequencies and elevations around 3.6 m (12 ft). These results are in general agreement with the conclusions of the Caltrans study that used a commercial beamforming microphone array. The two studies provided essentially similar results in terms of sources identified, their relative contributions, and lack of higher elevation sources except in a few cases.
- In NCHRP 842 (Mapping Heavy Vehicle Noise Source Heights for Highway Noise Analysis), tire/pavement noise was the predominant noise source for heavy trucks. Engine/powertrain was a secondary source. Most trucks indicated engine noise; some ground-level noise reflected by the pavement and some typically about 3ft above the pavement through the front wheel well and radiator. Noise from elevated exhaust stacks occurred rarely. 6 trucks out of 1,289 had levels at the stack equal to or greater than at ground level (0.5%). 23 had levels within 5 dBA of ground level (1.8%). 62 had levels within 10 dBA of ground level (4.8%).

- OBSI (On Board Sound Intensity) research and reports show most acoustic energy on heavy trucks is below 3.3 feet. The primary noise source for more than 95% of trucks has been found to be tire-pavement noise, in accordance with Caltrans Quieter Pavement: Acoustic Measurement and Performance Guidance Manual dated February 2018.
- Low berm field measurement research by Ohio DOT in August 2018 showed noise reductions at the back of the berms from the top of berms of 5 - 12 dBA or more. Hence, low berms (3'-6' tall) are substantially effective at reducing noise. TNM assumes that over 60% of the heavy truck exhaust noise is 12 ft above the pavement which appears inaccurate since 4'-6' high berms would not be reducing noise 5 - 12 dBA or more with the current TNM sub-source distributions. Low berm research conducted by Caltrans in 2020 yielded similar results to Ohio's berm study.
- Ohio's noise model validation data shows of 106 noise reports prepared, 419/682 modeled results were higher than the measured result (61%), hence, the model is currently overpredicting noise levels in most cases for all roadway types as a whole. ODOT believes that if the validation data was focused on only freeways, the percentage would be higher than 61%. This makes sense because TNM assumes that over 60% of the heavy truck exhaust noise is 12 ft above the pavement, hence, the modeled result should usually be higher than the measured result, especially when a high truck % is present. This falls in line with the "Mapping Heavy Truck Noise Research" conclusions. ODOT believes TNM appears to perform adequately relative to noise analysis projects with a low truck % because the heavy truck exhaust noise source at 12 ft above the pavement would not typically be a factor because of the low number of heavy trucks. Because this case study involved 12% heavy trucks which is considered neither a low or high truck percentage, TNM did not definitively show overpredicted noise levels in this case study overall. However, ODOT believes if the truck %s are greater than what was in this case study, TNM may overpredict noise levels overall because the heavy truck exhaust noise source in TNM is at 12 ft above the pavement for every heavy truck and would be more prominent in the model coupled with preliminary traffic data showing a high percentage of heavy trucks actually having no vertical stacks, hence, no truck stack noise which means the measured level would understandably be lower than the modeled level. ODOT believes more model-to-monitor case studies should be conducted along freeways with 15%-40% truck %s to determine how TNM would be predicting noise levels in these higher truck % cases.
- Field measured insertion losses are typically > TNM modeled insertion losses. Hence, noise walls are likely being constructed taller than what is necessary because TNM assumes that over 60% of the heavy truck exhaust noise is 12 ft above the pavement. Recent informal heavy truck counts on freeways with and without actual vertical exhaust stacks by several State DOTs revealed that about 17% of all heavy trucks contain at least one vertical exhaust stack.

Hence, 83% of all heavy trucks have no exhaust stacks, hence, no truck stack noise. However, TNM is currently calculating approximately 60% of heavy truck noise at 12 feet above the roadway surface for every heavy truck on every single roadway for every single highway noise project. Of the 17%, it is believed that there is little to no actual truck stack noise observed by the human ear on freeways. In addition, it is unclear what the characteristics of the truck stack noise is in TNM. Truck stack noise should be considered a rare high-frequency noise that is much different than tire-pavement noise. Ohio DOT believes future research should be conducted on this topic to improve heavy truck noise modeling in the TNM software.

- According to Tom Reinhart, Institute Engineer, Powertrain Design and Development Southwest Research Institute, and his Presentation on the Evolution of truck exhaust noise, “truck noise at low speed is dominated by engine radiated noise, and it has been for at least 40 years. At highway speed, the only noise source that matters is tire noise, unless the exhaust system has been modified”.

Simulation of Medium/Heavy Truck Substitutions

The idea has been discussed to use medium trucks as a substitution for heavy trucks in TNM in order to place the upper noise source lower, closer to that recommended in the follow-up NCHRP work for heavy trucks. The inherent differences in medium and heavy trucks in TNM, however, do not support a direct or volume-adjusted substitution. These vehicle types have different spectral content, different noise source locations, and different sound energy distribution for the noise sources. Because of these differences, a direct substitution of medium trucks for heavy trucks can provide inaccurate predicted sound levels. If substituting, a TNM user can adjust the volume of medium trucks to match the same broadband sound level as a result with heavy trucks, however, the adjustment value is site- and receiver-dependent. As previously stated, applying the standard TNM noise emission curves, an increase of 4 dB (at highway speeds) is required to make medium trucks equivalent to heavy trucks at a distance of 15 m (50 ft) from the road. This would require a volume multiplier of 2.5 to increase medium truck noise, but various site characteristics can affect the adjustment value/multiplier, including ground type and shielding objects/terrain. These characteristics influence sound as it propagates, and sound propagation effects are source location- and frequency-dependent. Such a substitution is, therefore, not recommended by the research team.

To help explain the variable and site/receiver-dependent medium truck volume adjustments, a brief simulation study was conducted using TNM. For a real-world highway case with six lanes, paved shoulders, paved median, and heavy trucks isolated to the outer two lanes on each side of the highway, various parameters were modified to show example differences in sound levels. First, the case was run with only the heavy truck traffic, hard soil for the ground next to the road, and with and without a 3 m (10 ft) noise barrier. Then the heavy truck traffic was replaced with medium trucks, first with a volume multiplier of 2.5 as prescribed by broadband levels near the road, then with an optimized volume multiplier [optimized to provide the best results for the 38-72 m (125-250 ft) distances]. This was repeated with a more sound-absorptive ground surface (lawn).

Results for hard soil are shown in Figure 20, and results shown for lawn are shown in Figure 21. The plots show predicted sound levels as a function of distance for each of the cases. First it shows the results for only heavy trucks, then with only medium trucks adjusted with the 2.5 multiplier, then with only the optimized multiplier medium trucks. For each plot, results are shown with no noise barrier (dark/light orange lines) and the 3 m (10 ft) noise barrier (dark/light blue lines). It can be seen that the 2.5 multiplier provides good results (medium truck sound levels match closely with heavy truck sound levels) only at one site: lawn with no barrier; for that site, the optimized multiplier is 2.2, which is very close to 2.5. The other optimized multipliers range from 1.6 to 7.0:

- For hard soil and no barrier, results with the 2.5 multiplier differ from heavy trucks by 1.1-1.5 dB (small variation by distance); optimized (volume x 1.6), results for medium trucks differ very little from heavy trucks (0.0-0.3 dB, small variation by distance).
- For hard soil with a barrier, results with the 2.5 multiplier differ from heavy trucks by 0.6-4.8 dB (large variation by distance); optimized (volume x 5.0), results for medium trucks differ from heavy trucks by 0.1-2.4 dB (some variation by distance).
- For lawn with a barrier, results with the 2.5 multiplier differ from heavy trucks by 1.0-6.2 dB (large variation by distance); optimized (volume x 7.0), results for medium trucks differ from heavy trucks by 0.0-3.5 dB (some variation by distance).

In summary, simulation results demonstrate that there is no simple substitution of heavy trucks with medium trucks. The volume multiplier for medium trucks to match sound levels for heavy trucks varies by site parameters and distance.

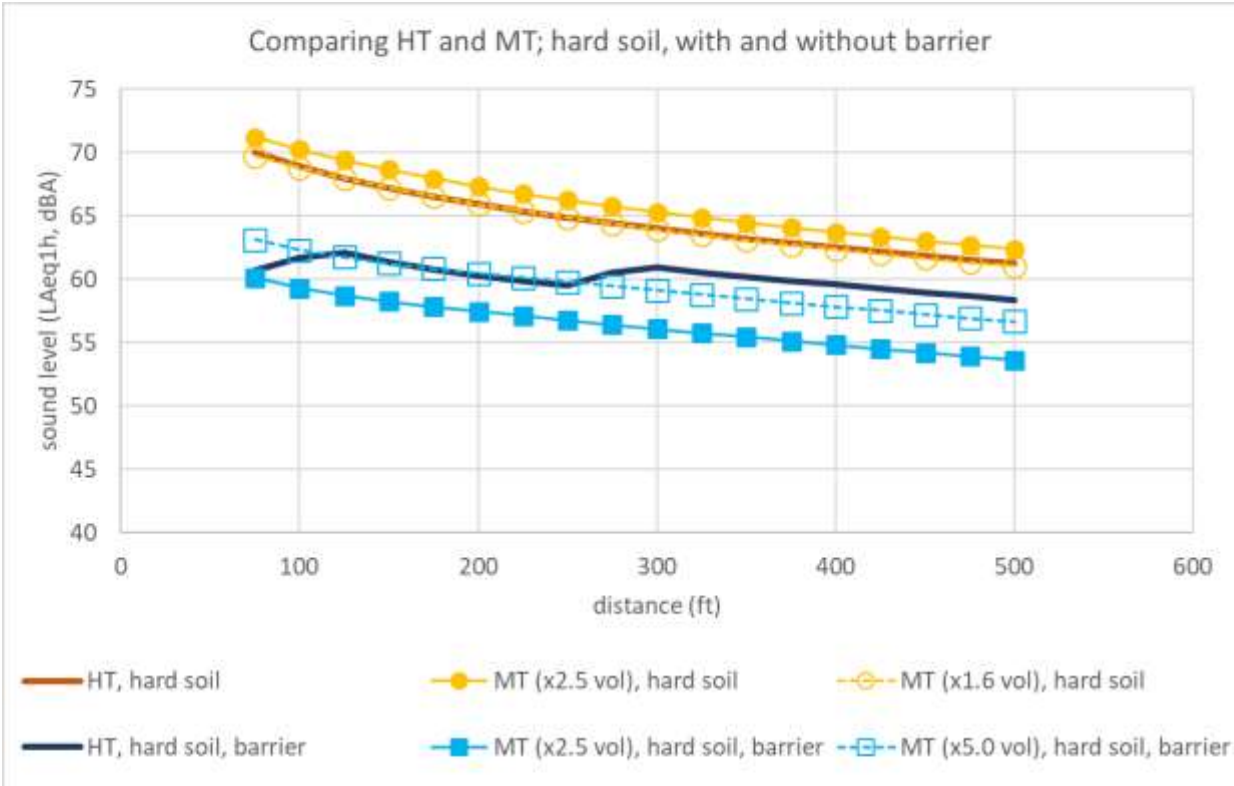


Figure 20: Sound Levels with HT and Volume-Adjusted MT, Hard Soil

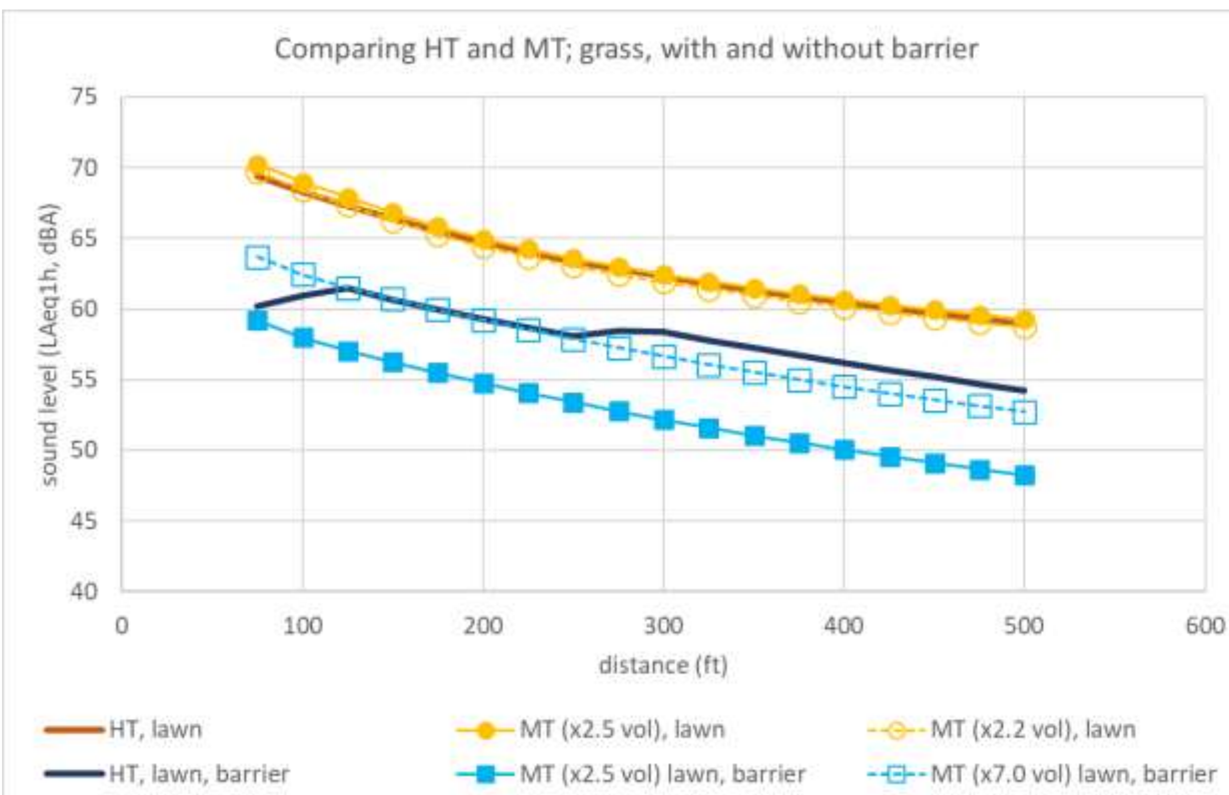
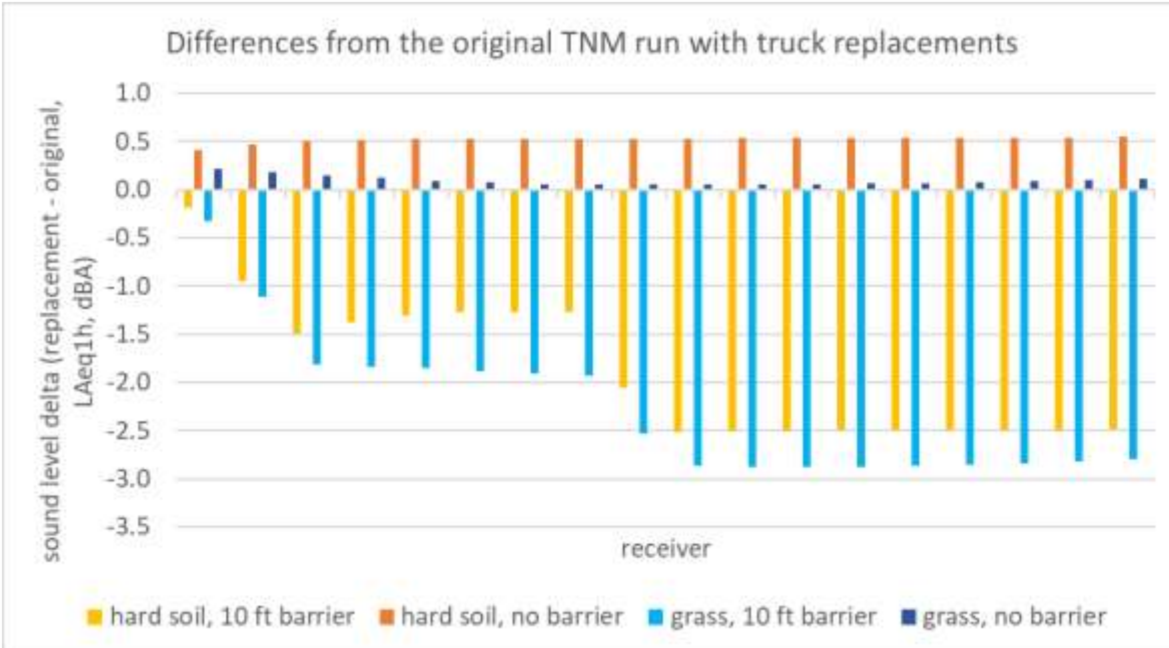


Figure 21: Sound Levels with HT and Volume-Adjusted MT, Lawn

To show the effect of heavy truck replacement on the broadband sound level that includes all traffic, several cases were examined, running TNM first for the case with the original traffic and second for the case with heavy trucks being replaced by medium trucks with a volume multiplier of 2.5. Figure 22 shows the differences for the TNM case described previously (6-lane highway, flat, hard soil, barrier/no barrier). In this TNM case, heavy trucks make up 5% of the total traffic. In can be seen that in the cases with no barrier, for hard soil, the medium truck "equivalent" case generated higher sound levels (~0.5 dB) than the original, although fairly consistent over distance; for lawn, there was very little difference between the heavy truck and medium truck "equivalent" levels. With a 3 m (10 ft) barrier, both the hard soil and grass showed the medium truck "equivalent" predicting levels below that with heavy trucks, with greater differences over distance, and sound level differences ranging from -0.2 to -2.9 dB.

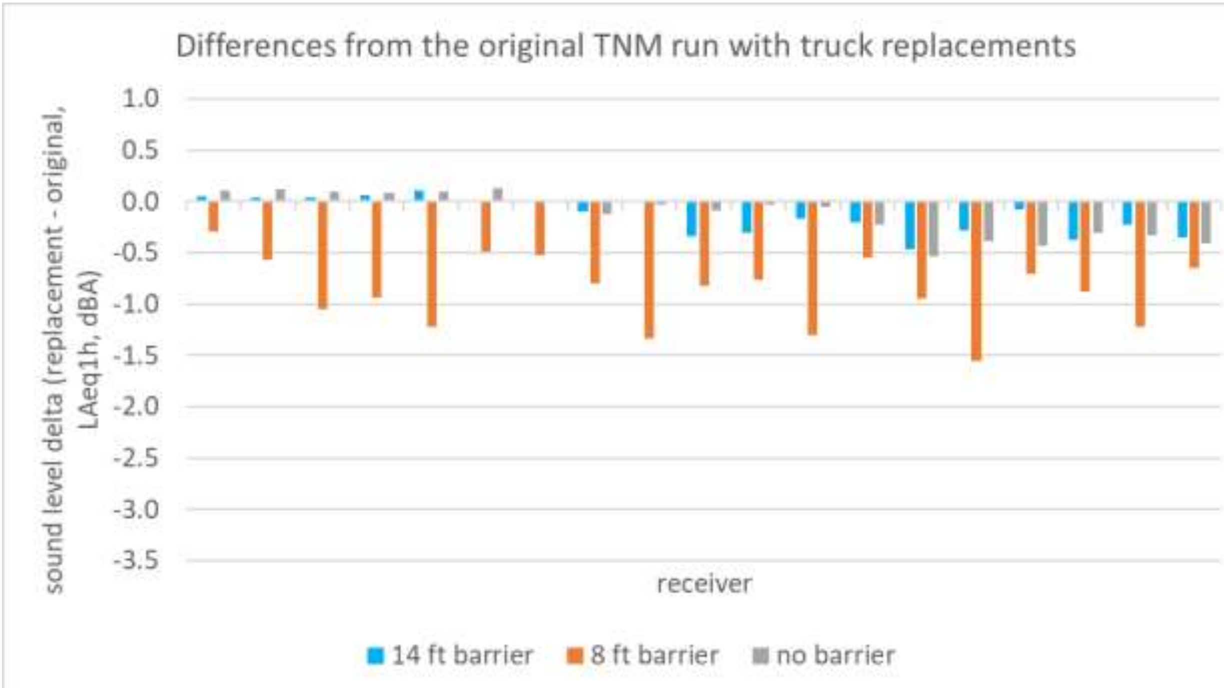
Two more real-world TNM cases were used to show the effect of heavy truck replacement. Figure 23 shows the results for a case with 3% heavy trucks with first, second, and third row receivers adjacent to a four-lane highway that is slightly depressed (run also includes some building rows, lawn as the ground type, and barrier/no barrier). Sound levels were predicted for three cases: with a 4.3 m (14 ft barrier), with a 2.4 m (8 ft) barrier, and with no barrier. It can be seen that the fully shielded [4.3 m (14 ft barrier)] and unshielded (no barrier) cases are fairly similar comparing sound levels with the original traffic and with the medium truck "equivalent." With the 2.4 m (8 ft) barrier, the "equivalent" case has lower sound levels than the original traffic case, ranging from -0.3 to -1.6 dB. Figure 24 shows the results for the last TNM case with 25% heavy trucks, examining sound level over distance at a site with lawn covered undulating terrain, where the line-of-sight is blocked for some of the traffic up/downstream. It can be seen that the medium truck "equivalent" sound levels are higher (0.7 dB) close to the road and vary farther from the road. For the low height receiver, the differences range from -1.7 to -2.3 dB farther from the road and range from +0.4 to -1.3 dB for the high receiver.

The results show that there are meaningful differences in heavy truck and medium truck "equivalent" results when applying a single volume multiplier. That variation is due to site and traffic differences. This suggests that a simple replacement of heavy trucks with medium trucks is not feasible for every possible combination of receiver and TNM inputs that could be encountered by the analyst.



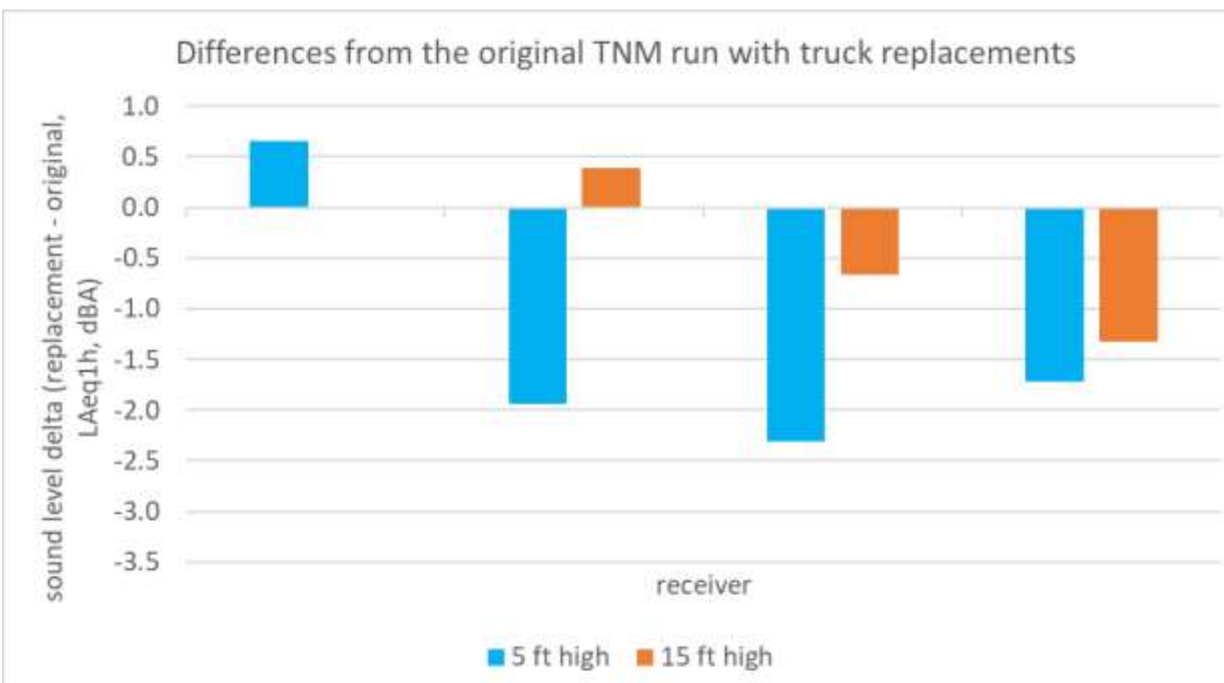
Parameters: 6 Lanes, 5% Heavy Trucks, Flat Roadway

Figure 22: Effect of HT-MT Replacement, Variation from Base Case (2.5x Volume)



Parameters: 4 Lanes, 3% Heavy Trucks, Slightly Depressed Roadway, Lawn

Figure 23: Effect of HT-MT Replacement, Variation from Base Case (2.5x Volume)



Parameters: 4 Lanes, 25% Heavy Trucks, Undulating Terrain, Lawn, No Barrier

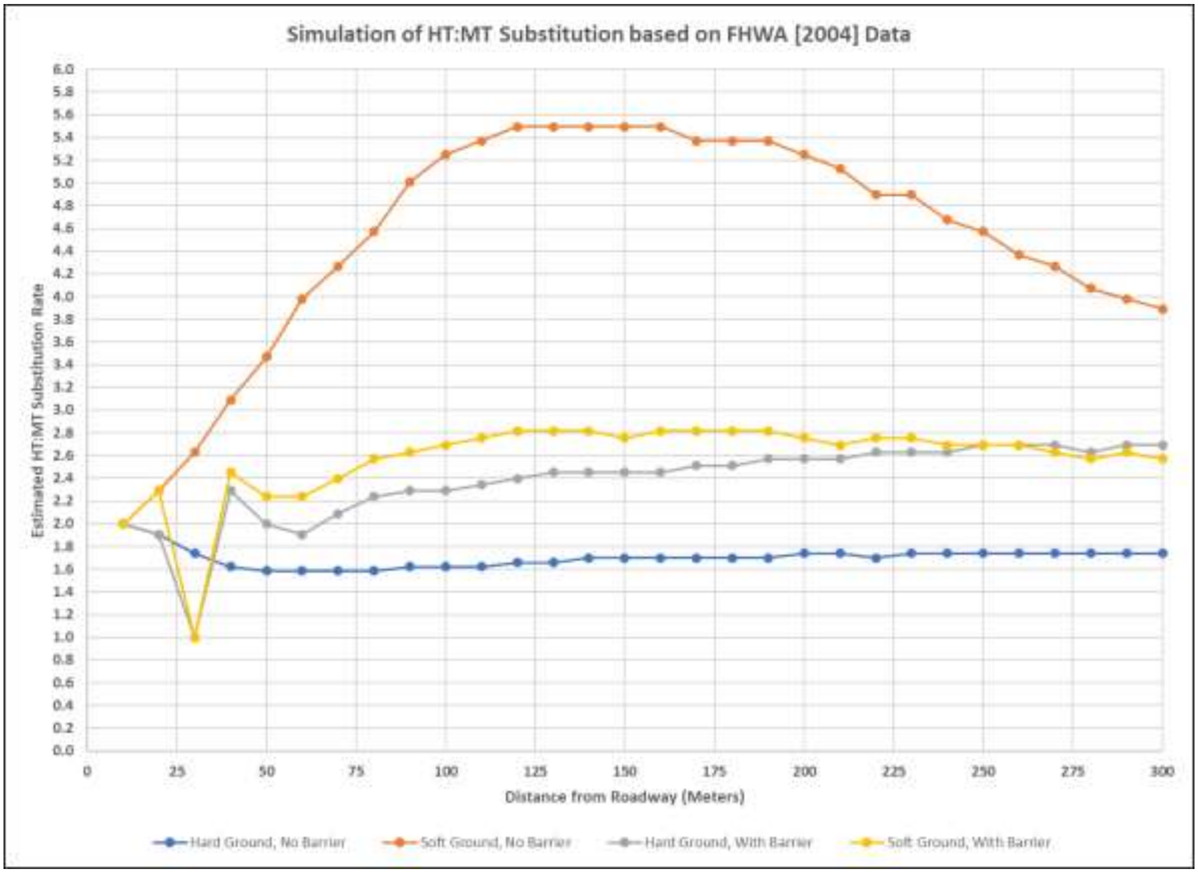
Figure 24: Effect of HT-MT Replacement, Variation from Base Case (2.5x Volume)

Simulation Using FHWA Look-Up Tables Data

A second simulation of potential HT-MT substitution was carried out by the research team using data from the *FHWA Traffic Noise Model (FHWA TNM) Version 2.5 Look-Up Tables* (FHWA, 2004). The original purpose of the look-up tables was to provide state DOTs with guidance on how to carry out a screening-level assessment of potential noise impacts and to determine if a more robust noise analysis would be needed for a specific project. While the use of the look-up tables for that purpose has been superseded, the numerical results are still instructive for the current study. The format of the look-up tables provided a matrix TNM-predicted sound levels for a traffic volume of 1,000 of each TNM vehicle type for an array of receivers under various speed, ground type, and shielding conditions. Comparing the TNM output levels between the medium truck and heavy truck simulation runs allow for a direct calculation of potential equivalency under different conditions.

The results for this simulation indicated that the potential range of values for the substitution of heavy trucks in TNM with medium trucks varied based on the traffic speed, receiver location relative to the highway, ground type, and presence of a noise barrier. For the "No Barrier" case, the average volume multiplier was estimated to be 2.62 for the hard ground surface, with a minimum value of 1.55 and a maximum value of 4.90. For the hard ground surface, the variation in the multiplier was primarily observed with respect to vehicle speeds, with lower speeds indicating a higher multiplier value. Limited variation was noted with respect to receiver distance. For the "No Barrier" case and soft ground surface, the average volume multiplier was 5.20, with a minimum value of 2.00 and maximum value of 7.59. Like the hard ground case, the soft ground surface case yielded the higher values at lower vehicle speeds; however, increasing distance from the highway yielded a parabolic-shaped curve with the highest values being approximately 140 meters from the highway. For the "With Barrier" case, the same trends with respect to traffic speed, receiver location relative to the highway, and ground type were observed. The average volume multipliers were slightly higher for the "With Barrier" case, with an average value of 3.48 for hard ground and 3.22 for soft ground.

A visual representation of the variation in the volume multiplier implied from the FWHA (2004) data set is presented in Figure 25. The data in Figure 25 are drawn from the FHWA (2004) results for both hard and soft ground types and a traffic speed of 100 km/h (≈ 60 mi/h). The "With Barrier" results are based on a barrier with a height of 5 meters (≈ 16.4 ft.) offset 30 meters (≈ 98.4 ft.) from the highway. These values were selected because they are similar to the traffic speed and barrier design specifications for the IR-270 Type II noise barrier project examined in this case study research project. Examining the values reported in Figure 25, it is noted that three out of the four cases have limited variation in the HT-MT substitution rate with distance, although the baseline levels are quite different (as noted previously). The parabolic-shaped relationship of HT-MT substitution rate with distance for the Soft Ground, No Barrier case is also evident in Figure 25, indicating a peak of 5.0-5.5 at a distance 100 to 200 meters from the roadway.



Source: ORITE research team analysis of data from FHWA (2004)
Assumed Parameters: Speed 100 km/h; Barrier Height 5 m; Barrier Offset 30 m
Figure 25: Simulation of HT-MT Substitution based on FHWA (2004) Data

Building Row Impacts

The TNM building row object permits the analyst to account for rows of buildings that are present in the source-receiver propagation path. The TNM building row object inputs include the XYZ coordinate of each segment in the building row, the height of the building row, and the percentage of the building row that consists of structures. The building percentage parameter varies from 20 to 80 percent. If the percentage is over 80 percent, the building row should be modeled as a noise barrier; if the percentage is under 20 percent there is no benefit to including it in the model. Details on how the TNM program calculates the noise reduction attributed to building rows can be found in various TNM reference documents and best practice guidelines (Menge, et al., 1998; 2004; Harris Miller Miller & Hansen, Inc., et al., 2014). Several important points from these references are noted:

- For a single building row object, TNM calculates the 1/3 octave band sound attenuation in a manner similar to a noise barrier and then adjusts this value for the percentage of the row that is shielded by buildings (as measured by the building percentage input parameter).
- For multiple building rows, TNM only calculates the 1/3 octave band attenuations for the most effective building row that interrupts the sound propagation path; the attenuation for other building rows is assumed to be an additional 1.5 dBA per 1/3 octave band for each subsequent row.
- TNM guidance notes that the desired precision for the building row average height is ± 6 feet assuming generally flat terrain between the road and the building row. Additionally, the desired precision for the building row percentage parameter is on the order of ± 10 to 20 percent.
- The noise reduction attributed to building rows in TNM is uniform across the entire length of the building row object; that is to say, the calculation of noise reduction at a receiver behind a building row object is the same no matter where the receiver is placed behind the building row.

As part of the research carried out for *NCHRP Report 791*, a detailed simulation study of the effect of the various building row object inputs was performed (Harris Miller Miller & Hansen, Inc., et al., 2014). The simulation indicated the following:

1) The amount of noise reduction increases as building percentage increases;
2) The effectiveness of the building row in reducing traffic noise decreases as the building row distance from the highway or the distance of the receiver behind the building row increases;
3) Changes in building row heights of less than 5 feet result in a maximum difference of 2 dBA over the simulations tested;
4) The accuracy of the building percentage estimate is more important at higher building percentages (60 to 80 percent);
5) Because of the calculation procedures in the TNM software, the noise reduction attributed to the second and third building rows will vary depending on the position of the building row relative to the freeway and the position of the receiver relative to the building row.

One of the key limitations of the TNM building row object is that the noise attenuation calculated by TNM will be independent of the placement of the receiver relative to the residential structures that comprise the row. For example, if the TNM building row object is used, the calculated noise level at a receiver will be the same if the receiver is located in the backyard of the residence and well-shielded by the structure or if the receiver is located in the gap between two residences. To overcome this issue, some analysts have adopted the practice of using the TNM barrier object to represent residential structures as individual three-sided barrier objects in the TNM layout. The research carried out in *NCHRP Report 791* also examined this approach using TNM case studies from five different real-life highway projects. The findings of the analysis indicated that the buildings as barriers representation generally yielded lower predicted sound levels with the average reduction being 1.5 dBA (range +1 dBA to -5 dBA) with the barrier model. It was concluded that the building as barrier model provided a greater agreement between the measured noise levels and the modeled noise levels for the case study locations (Harris Miller Miller & Hansen, Inc., et al., 2014).

In light of the recent research examining the detailed parameters of the building row object, as well as the potential for representation of residential and other structures as barrier objects in TNM (in lieu of the building row object), some State DOTs have provided guidance on how analysts should approach this problem when constructing noise models. The Colorado DOT, for example, allows for large, single buildings to be modeled as barriers but that strips of residences and commercial buildings should be building rows. The Colorado DOT guidance further notes that the actual height of buildings should be used to develop the average building row height, or that the following heights can be assumed: 15 feet for a one-story house with pitched roof; 25 feet for two stories; and 10 feet per story above two (Hankard Environmental, 2006). Arizona DOT has a similar policy but also permits isolated residential structures to also be modeled as noise barrier objects with three sides (ADOT, 2017). The Florida DOT offers the following guidelines for modeling the height of residential structures within the building row: 10 feet for each story of a building or a mobile home; 12 feet for a single-story home; and 22 feet for a two-story building (FDOT, 2018).

Vegetation Impacts

The TNM software program permits the analyst to input "tree zones" that exist between the highway and receiver locations. To be incorporated into TNM, tree zones should consist of "dense foliage" which is defined as foliage that is sufficiently dense to completely block the view along the propagation path and it is impossible to see even a short distance through the foliage. The noise reduction that is attributed to tree zones varies with the depth of the tree zone along the propagation path and also varies by 1/3 octave band frequency (Menge, et al., 1998; 2004; Harris Miller Miller & Hansen, Inc., et al., 2014). In particular, for tree zones with a depth of less than 10 meters, no attenuation is incorporated in the calculations. However, recent research on TNM best practices (Harris Miller Miller & Hansen, Inc., et al., 2014) found that such "narrow" tree bands should still be included in TNM since there is a longer depth through the tree zone for propagation paths that are at a non-perpendicular angle from the freeway. That same study indicated that an overlaid ground zone is not necessary in order to correctly compute the noise reduction associated with tree zones; however, it is recommended that an overlaid ground zone be used if the ground type within the tree zone is different than the default ground type.

Research on the impacts of vegetation zones on traffic noise reduction is quite extensive, investigating all aspects of the potential noise reduction including the effects of depth, height, species, trunk diameter, canopy state, and even leafing characteristics. An early Dutch study published by Martens (1981) examined three different types of vegetation groups and concluded that the evergreen spruce-fir vegetation group had the highest excess noise attenuation (at least 10 dB per 100 meters at 1.2-meter height) and also concluded that the best attenuation could be achieved with a planting of at least 12 meters in width. Research by Harris and Cohn (1985) found that a narrow belt of vegetation with a depth of approximately 9 feet could yield a noise reduction between 2 and 3 dB, even for vegetation that is planted only for visual screening purposes and without maximum density. The authors also noted that the screening from the vegetation stimulated a non-quantifiable psychological effect of blocking the highway from view, thereby generating the perception of noise reduction. The issue of perception was examined in more detail by Watts, et al. (1999), who examined listener perception at both in-situ vegetation installations near highways and controlled tests using an artificial noise source. The research indicated that listeners were more sensitive to the noise when the source was visually screened versus when no screen was present, even for the same noise levels. It was concluded that the listeners may have had erroneous expectations about how the vegetative screening would function to reduce noise.

One of the most comprehensive studies to date on the noise attenuation of vegetation belts is reported by Fang and Ling (2003). The authors examined noise reduction at 35 different evergreen tree belts in Taiwan and found that the visibility distance of the vegetation belt was the most significant predictor of noise reduction. The visibility distance was measured by walking into the vegetation until no longer visible from the outside, taking the average of three tries at two different locations. Based on the visibility distance, three groups of vegetation types were established with clear distinctions in the noise reductions (per 20 meters of depth) attributed to each type: 1) visibility distance less than 5 meters with excess noise attenuation greater than 6 dBA; 2) visibility distance between 6 and 19 meters with excess noise attenuation between 3.0 and 5.9 dBA; and 3) visibility distances greater than 20 meters with no perceptible excess attenuation (e.g., less than 3 dBA). Follow-up work (Fang and Ling, 2005) developed a multiple-regression model to estimate the noise reduction of six common hedge species (in Taiwan) with various depths and heights. The model indicated that the most effective noise reduction could be achieved when the ratio of noise source height to tree height was between 1:6.6 and 1:3.3 and within a distance of eight times the tree height. Fan, et al. (2010) examined the noise attenuation characteristics of six different evergreen species in various arrangements and concluded that each species had its own distinctive noise-reducing spectrum with a clear distinction between the low frequency and high frequency reductions among the species examined.

An investigation of the noise reduction of nine different greenbelt sites in Northern Iran was reported by Karbalaei, et al. (2015), finding that the maximum reduction of noise was achieved by shrubs and trees of 100 meters width while the mixture of conifers and broad leaves was effective at between 50 and 100 meters in width. Another study from Terhan, Iran, reported by Maleki and Hosseini (2011), examined four different vegetation types and found that the maximum reduction of approximately 19 dBA was achieved at a mixed-vegetation area 100 meters from the sound source. Ow and Ghosh (2017) analyzed various planting densities of roadside vegetation in Singapore and found that traffic noise was reduced by 50% when the density was increased from minimal to moderate density, with no additional reductions realized with further density increases. Additionally, they found that the maximum reduction was found to be between 9 and 11 dBA, the trunk size of the plantings had a significant effect on the noise reduction, and that a depth of at least 10 meters was necessary to be effective.

More recent Dutch research being led by Van Renterghem and colleagues has examined many aspects of the relationship between vegetation characteristics and traffic noise reduction. Van Renterghem, et al. (2012) examined vegetation belts of limited depth and found that significant noise reduction was predicted to occur for tree spacing less than 3 meters and trunk diameter of greater than 0.11 meters. For ground level shrubs with typical above-ground biomass the noise reduction was estimated to be 2 dBA at a maximum. Further work on the effect of hedges (Van Renterghem, et al., 2014) indicated that thick dense hedges could yield an insertion loss between 1.1 and 3.6 dBA with the higher reductions associated with an increased ground effect present in the hedges. Finally, Van Renterghem (2014) provides a useful synthesis of literature on non-deep tree belts including guidelines for optimizing traffic noise shielding for these tree belts. The synthesis indicated that the optimal noise shielding is provided by multiple scattering in the tree trunk layer and the presence of acoustically soft soil ground cover. Additionally, a high biomass density should be provided although the limitations regarding the biological needs of the vegetation should be recognized. Finally, a simulation indicated that a linear relationship exists between excess insertion loss and tree belt depth, ranging from 5 dBA at a 10 meter depth to over 10 dBA at a 30 meter depth.

Regarding how dense trees/vegetation affect noise and if trees can be planted to act as noise barriers, according to FHWA, vegetation, if it is high enough, wide enough, and dense enough that it cannot be seen over or through, can decrease highway traffic noise. A wide strip of trees with very thick undergrowth can lower noise levels. 30 meters of dense vegetation can reduce noise by five decibels. However, it is not feasible to plant enough trees and other vegetation along a highway to achieve such a reduction. Trees and other vegetation can be planted for psychological relief but not to physically lessen noise levels.

Vegetation can decrease highway traffic noise if it is high enough, wide enough, and dense enough that it cannot be seen over or through. A dense stand of vegetation, at least 100 feet thick with very thick undergrowth, is needed to have a noticeable difference in noise levels. However, while trees and other vegetation can act as a visual barrier between resident and the highway, space limitation, and costs make it not feasible to plant enough trees and other vegetation along a highway to achieve a such a noise reduction. According to studies, the removal of limited vegetation does not increase the noise levels discernable to the average human ear.

A study that was completed by the Virginia Research Council back in 2007 looked at the effect of trees on highway noise mitigation. The study concluded that there was minimal noise reduction that could be attributed to the trees. The studies also concluded that in order for a vegetation belt to reduce traffic noise it should be densely planted, with no windows to let noise through. Another study that was completed by the FHWA and CALTRANS concluded that observed noise reductions by vegetation ranged from 0 to 2.7 decibels and averaged 0.9 decibels. A change of 3 decibels or less is not discernable to the average human ear according to FHWA. A study by ODOT in September 2019 in Botkins, Ohio, concluded that a 250’ wide forested area immediately adjacent to an interstate with 2,000 VPH and 33% trucks reduced noise by an average reduction of 3 decibels.

According to research, trimming or removal of shrubs or trees along highways by maintenance or construction does not cause perceptible noise level increases to nearby homes. The sudden visibility of highway traffic previously shielded visually by vegetation, and the possibility of a shift in frequencies, may bring on a renewed awareness of the presence of the traffic noise source.

APPENDIX B: DATA COLLECTION

Case Study Setting

The case study noise wall project that was selected for more detailed analysis in this research study was the PID #93359 (FRA-270-39.68 – Noise Walls) project. The location of the project site was along Interstate 270 on the southeast side of Columbus in Franklin County. The project consisted of the construction of four sets of reflective noise barriers along both sides of Interstate 270 starting at the Livingston Avenue overpass on the southern end of the project and ending at the East Broad Street interchange on the northern end. After a detailed review of the potential Noise Sensitive Areas (NSAs) along the project limits, the research team identified two locations along the section between Livingston Avenue and East Main Street that would serve as the setting for the work. A map showing the location of the selected NSAs is displayed in Figure 26.

Figure 26: Case Study Setting along Interstate 270 in Southeast Columbus

At this location of Interstate 270, there are 12 lanes of highway traffic consisting of four "local" lanes and two "express" lanes in each direction. The local lanes provide service to the interchanges on either end of the segment being analyzed in this project (IR-70 and East Main Street) while the express lanes permit traffic to bypass those interchanges. The pavement surface at this location is a dense-graded asphalt concrete (DGAC) type pavement which is commonly encountered on freeways around the region and state. As indicated by an ODOT permanent count station that is within the project limits, the approximate AADT at this location is 111,600 vehicles per day under pre-COVID pandemic conditions (year 2019) and was approximately 94,750 vehicles per day during the year 2020 as impacted by the COVID pandemic. As noted in Figure 26, the area of NSA 7 at the Yorktown Middle School property was selected for the field studies associated with the meteorological conditions and the heavy truck-medium truck substitution analysis. The area of NSA 2 at the Shady Lane Neighborhood along the west side of the freeway was selected for the building row field study and vegetation impacts field study. Specific details of the setting within each study area are reported in later sections of this appendix.

Additional details of the noise barrier construction project are summarized as follows. The construction project included approximately 265,670 square feet of noise barrier and all necessary ancillary work required such as excavation, guardrail, and restoration. The project was a Type II noise barrier project since no new highway capacity was built. The Type II traffic noise analysis study was completed by the firm of McCormick Taylor (2013) and the design of the noise barrier was completed by the ODOT District 6 design staff. The final design plans for the project were approved in January 2019 and the sale date for the construction contract was in early May 2019. Construction on the project commenced in early November 2019 and the final project was accepted by ODOT in November 2021. Coordination between the research team and both the noise wall contractor and the ODOT District 6 project management was necessary throughout the project to ensure that the research work would not interfere with the progress of the construction. Following standard ODOT designs for roadside noise barriers, ground-mounted barriers followed along the right-of-way line of the freeway while shoulder-mounted barriers were installed at several bridge or culvert locations. The average height of the noise barrier was between 12 and 15 feet depending on the exact location.

Yorktown Middle School (NSA 7) Site

For the meteorological field study and the heavy truck-medium truck substitution analysis, the ORITE research team selected a study site located at the Yorktown Middle School (YMS) property, located at 5600 East Livingston Avenue on the southeast corner of the project limits. The YMS site was contained within the extent of NSA 7 as defined by the consultant traffic noise study for the barrier construction project. A schematic map showing the location of the YMS study area including the location of Interstate 270, the noise measurement locations, key on-site features, and the alignment of the noise barrier is presented in Figure 27. As noted in Figure 27, the wall reference Wall #1A was constructed along the edge of the right-of-way boundary at this location, with a small, overlapped portion of the shoulder-mounted Wall #1B also affecting the study area.

Figure 27: Setting of the Yorktown Middle School (NSA 7) Study Site

As indicated in Figure 27, the research team established a microphone line approximately perpendicular to the freeway at approximately Station 109+00 of Wall #1A of the project. Spacing of the measurement positions along the microphone line was set to approximate the doubling of distance between successive microphone positions away from the highway while also considering the placement arrangement for the other NSA examined in this study. The line was set to be approximately 400 feet away from both the school building to the south and the apartment complex buildings to the north. The open playground and athletic fields north of the school building area was ideal for this type of study providing an open view of the freeway in a free-field environment with limited interference from structures or other reflective surfaces. The ground was relatively flat with a gentle slope (≈ 2 percent) increasing from the right-of-way line to the back of the property. The dominant ground type in the open field was assumed to be a lawn or soft ground type. Some hard ground was present in the sound propagation path in the form of a blacktop playground area and two baseball diamonds with packed dirt infields.

Shady Lane Neighborhood (NSA 2) Site

For the building row and vegetation impacts aspects of the research study, the ORITE research team selected a study site located within the Shady Lane (SL) Neighborhood, a component of NSA 2 as described by the consultant traffic noise study for the barrier construction project. The SL site was located along the west side of the Interstate 270 section immediately to the south of the East Main Street interchange, and just to the north of the YMS study site. A schematic map showing the location of the SL study site including the location of Interstate 270, the noise measurement locations, residential structure locations, and the alignment of the noise barrier is presented in Figure 28. As noted in Figure 28, Wall #2C was constructed along the edge of the right-of-way boundary at this location, with a small, overlapped portion of shoulder-mounted Wall #2B also affecting the study area.

As indicated in Figure 28, microphone placement at the SL study site was approximately perpendicular to Interstate 270 generally aligned with Station 105+75 of Wall #2C of the project. The measurement location closest to the freeway was positioned at approximately this station in the backyard of the first row of homes, with a clear view of the freeway being provided at this location under the “No Barrier” scenario. At each subsequent measurement location further back into the neighborhood, microphones were placed to achieve a target distance from the highway but also to position the measurement units to maximize the shielding provided by the residential structures in each row of buildings. Accordingly, microphone units were aligned with the center of the residential structure the immediate path between the unit and the freeway with units being set back from the structure of interest between 40 and 100 feet. Placement of the microphone units was also dependent on the suitability of the location (e.g., units could not be practically placed in the middle of the local street). The building row parameters were estimated using data from the Franklin County Auditor and aerial imagery. The average building row percentage for the three rows was between 66 and 70 percent while the average height was between 15.5 and 18.6 feet. Additional details of the methods used to derive these values are presented in Appendix D of this report.

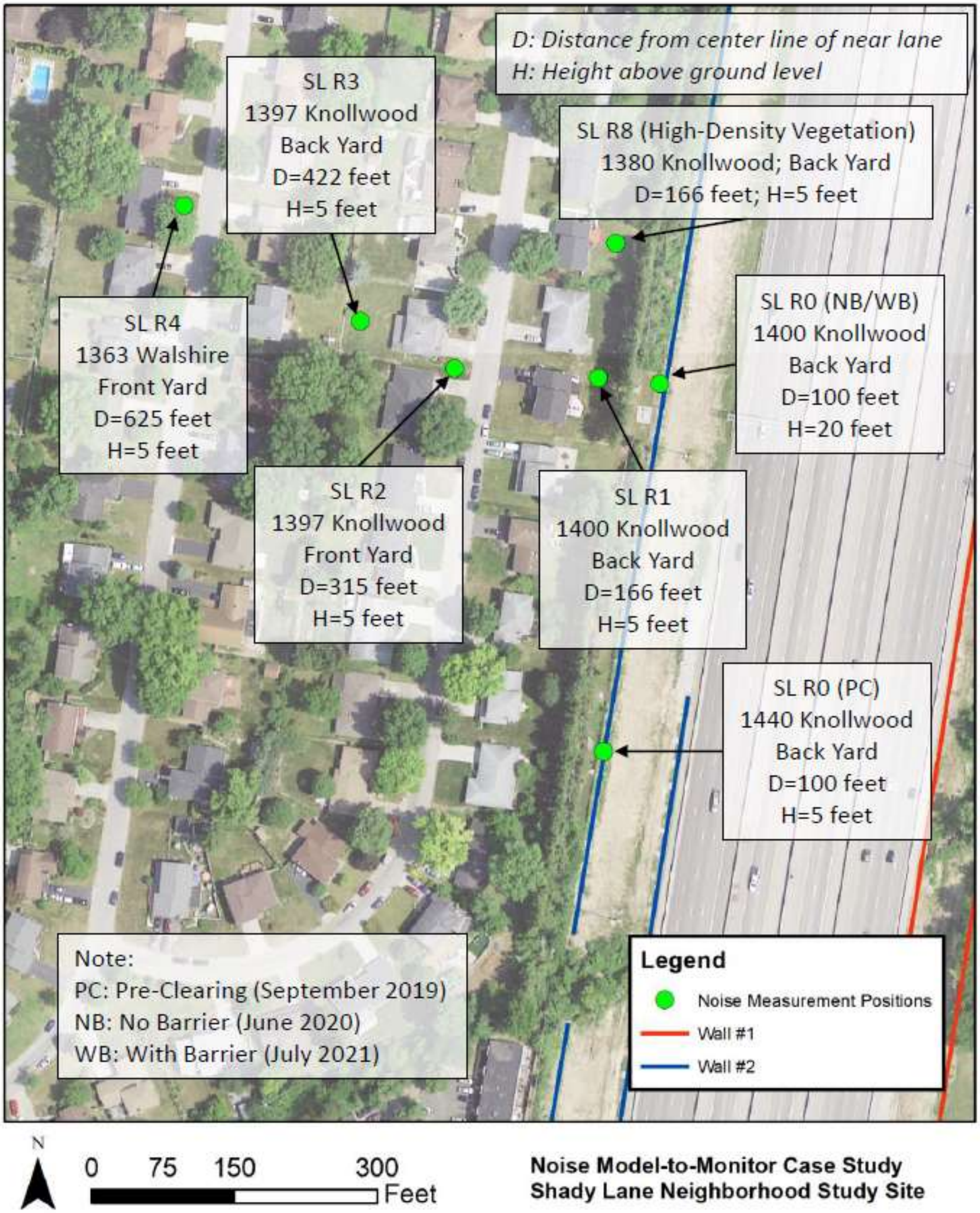


Figure 28: Setting of the Shady Lane Neighborhood (NSA 2) Study Site

The Shady Lane Neighborhood site was an ideal location for the building row and vegetation impacts portion of this research study. First, the arrangement of residential structures within the neighborhood permitted the establishment of three building rows that could be further analyzed using both the field measured data and modeled data from TNM. Second, the site is generally representative of older residential areas that are located adjacent to freeways in Ohio and the Midwest. The residential structures were a mix of single-level, split-level, and two-level homes all constructed in the 1960s. The ground type within the sound propagation path was primarily residential lawns with concrete driveways and two asphalt local streets (Knollwood Drive and Walshire Drive) also present. Vegetation, where present, was relatively older and mature given the age of the development.

In addition to the microphone array setup for studying the building row shielding effect, a special measurement setup was carried out to study the effect of varying density of vegetation on traffic noise reduction. For this study, a measurement unit was placed in the backyard of a different home in the first row of buildings adjacent to the freeway but with higher-density vegetation than what was present at the other site. This setup permitted a close comparison between the higher- and lower-density vegetation settings. Additional details of the vegetation at the SL location are presented in a later section of this appendix.

Details of the microphone unit locations and key positioning dimensions are presented in Table 3 in the next section of this appendix. Images providing additional context for both the YMS and SL study sites are presented in the Data Collection Photos section of this appendix.

Summary of Data Collection Procedures

This section describes the specific procedures and methods used by the ORITE research team in carrying out the field data collection activities at each of the subject NSAs for this research study. Field data collection of traffic noise and related data for this study was carried out in three waves: 1) "pre-clearing" data, collected before any construction activities had started; 2) "no barrier" data, collected after the tree clearing and site preparation had been carried out, but no vertical barrier components installed; and 3) "with barrier" data, collected after barrier construction at the subject NSA. Table 3 presents a summary of the microphone placement for both YMS and SL study sites, including key data on positioning and height.

Data that were collected during the field measurements carried out for this project included traffic noise data, meteorological data, traffic data, and manual observations associated with highway and background noise events. In addition to these data, the research team collected detailed topographic survey data at each study site to support the development of the TNM layouts. Additional details of the data collection procedures are described below.

Table 3: Summary of Key Information on Measurement Locations

Study Area/Mic Reference	Address/Position	Height	Distance from Freeway
Yorktown Middle School (NSA 7)			
• YMS R0 (Reference)	5600 Livingston Avenue	18 feet	75 feet
• YMS R1	5600 Livingston Avenue	5 feet	110 feet
• YMS R2	5600 Livingston Avenue	5 feet	165 feet
• YMS R3	5600 Livingston Avenue	5 feet	315 feet
• YMS R4 *	5600 Livingston Avenue	5 feet	427 feet
Shady Lane Neighborhood (NSA 2)			
• SL R0 (1) (Pre-Clearing)	1440 Knollwood Drive Back Yard	21 feet	100 feet
• SL R0 (2) (No/With Barrier)	1400 Knollwood Drive Back Yard	20 feet	100 feet
• SL R1 (Clear View of Freeway)	1400 Knollwood Drive Back Yard	5 feet	166 feet
• SL R2 (Building Row 1 Shielding)	1397 Knollwood Drive Front Yard	5 feet	315 feet
• SL R3 (Building Row 2 Shielding) *	1397 Knollwood Drive Back Yard	5 feet	422 feet
• SL R4 (Building Row 3 Shielding)	1363 Walshire Drive Front Yard	5 feet	625 feet
• SL R8 (High-Density Vegetation)	1380 Knollwood Drive Back Yard	5 feet	166 feet
* Indicates position of weather unit			

Sound level measurements at each measurement position were obtained using a two-part microphone assembly consisting of a Larson-Davis Model 2560 microphone and attached Larson-Davis Model PRM 828 pre-amplifier connected to a Larson-Davis Model 812 sound level meter (SLM) using a 20 foot microphone extension cable. A digital audio recorder (Sony TASCAM DR-40 or DR-40X) was attached to the output feed of the SLM to capture a recording of the SLM signal. Each assembly (mic/pre-amp and SLM/recorder) was attached to a separate sturdy tripod and the SLM/recorder unit was placed a short distance away from the microphone/pre-amp unit to minimize interference with the recording during routine equipment checks throughout the day. All sound level measurement equipment was laboratory-calibrated prior to starting the field data collection. A hand-held calibration unit (Larson-Davis model CAL200) emitting a calibration tone of 94 dB pure tone at a frequency of 1,000 Hz was used for on-site calibration of the SLM units. Additionally, a one-minute calibration tone was recorded through the SLM into the digital audio recorder for reference to accompany the corresponding traffic noise audio file that was created for each unit. Calibration was set prior to starting daily measurements and checked again at the end of daily measurements; calibration level values were recorded to permit calibration adjustments to be made if necessary. The height of each microphone was set at either 5 feet or at a reference position approximately 5 feet above the noise barrier, as noted in Table 3.

To accompany the sound recording, data on weather conditions and traffic were collected by the research team. Weather data were collected using a ClimaVue 1500 weather station attached to a Campbell Scientific CS-310 data collector that could record temperature, humidity, wind speed, and wind direction in one-minute increments. Temperature levels were collected at heights of 5 and 15 feet above the ground to permit the calculation of the temperature lapse rate. Traffic data were collected using an infrared sensor installed at roadside locations on each side of the freeway. The sensor collected data on the pass-by time, speed, travel lane, and length of each vehicle that passed by the sensor. To supplement the traffic sensor data, video recording of traffic during the measurement periods was obtained to aid in classification for TNM purposes and a radar gun was used for speed checks. Throughout the data collection, the research team recorded details of any loud or unusual noise events that were detected and noted sound levels directly from the SLM units associated with these events. Additionally, events such as wind gusts and noise from background activities were recorded, and routine checks of all equipment were carried out during the data collection periods. Noise from background activities was particularly evident at the SL locations furthest from the freeway including vehicle pass-by traffic on the local streets, grass cutting, air conditioning units, and other human activities. Cloud cover conditions were also noted via manual observation to supplement the weather station data.

The specific data collection periods, study locations, and objectives for each data collection period are described in Table 4. Also noted in Table 4 is a brief statistical summary of the meteorological and traffic conditions encountered during each data collection period.

Table 4: Summary of Data Collection Activities for Research Study

Date	Time	Location	Objective/Scenario # of 5-Minute Analysis Blocks	Summary of Meteorological and Traffic Conditions
9/17/2019	9:00 A.M. to 2:00 P.M.	SL	Building Rows/Pre-Clearing Analysis Blocks = 324	Sunny/Clear; Temp: 69°-77°; Humidity: 57%-80% Wind Condition: Calm (1-2 mi/h) Traffic: 2,244-3,720 veh/hr; 4.7%-13.2% HT
9/19/2019	9:00 A.M. to 2:00 P.M.	SL		Sunny/Clear; Temp: 66°-80°; Humidity: 46%-65% Wind Condition: Calm (< 1 mi/h) Traffic: 2,184-3,660 veh/hr; 4.1%-13.2% HT
9/24/2019	9:00 A.M. to 1:00 P.M.	SL	Vegetation Impacts Analysis Blocks = 136	Sunny/Clear; Temp: 60°-74°; Humidity: 39%-76% Wind Condition: Calm (< 1 mi/h) Traffic: 2,124-3,396 veh/hr; 2.6%-12.9% HT
5/26/2020	2:00 P.M. to 8:00 P.M.	YMS	Meteorological/No Barrier Analysis Blocks = 442	Sunny/Clear; Temp: 85°-90°; Humidity: 29%-38% Wind Condition: Upwind (2-3 mi/h) Traffic: 2,076-3,912 veh/hr; 2.1%-7.0% HT
5/27/2020	6:00 A.M. to 12:00 P.M.	YMS		Overcast; Temp: 70°-80°; Humidity: 53%-69% Wind Condition: Calm (< 1 mi/h) Traffic: 2,028-4,080 veh/hr; 2.7%-10.9% HT
6/1/2020	9:30 A.M. to 1:00 P.M.	SL	Building Rows/No Barrier Analysis Blocks = 155	Sunny/Clear; Temp: 58°-70°; Humidity: 29%-56% Wind Condition: Calm (< 1 mi/h) Traffic: 1,836-3,289 veh/hr; 5.5%-12.8% HT
10/8/2020	2:30 P.M. to 7:30 P.M.	YMS	Meteorological/With Barrier Analysis Blocks = 446	Sunny/Clear; Temp: 62°-72°; Humidity: 30%-50% Wind Condition: Calm (< 1 mi/h) Traffic: 2,220-4,896 veh/hr; 3.6%-11.9% HT
10/9/2020	7:00 A.M. to 12:00 P.M.	YMS		Sunny/Clear; Temp: 45°-70°; Humidity: 45%-90% Wind Condition: Calm (< 1 mi/h) Traffic: 2,713-4,788 veh/hr; 5.1%-11.4% HT
7/23/2021	9:30 A.M. to 1:30 P.M.	SL	Building Rows/With Barrier Analysis Blocks = 223	Light Overcast; Temp: 72°-80°; Humidity: 45%-61% Wind Condition: Calm (1-2 mi/h) Traffic: 2,304-3,972 veh/hr; 3.4%-12.4% HT

Note: Number of analysis blocks indicates number of 5-minute time blocks extracted for traffic noise database analysis.
Traffic data provided for IR-270 for direction of travel closest to study site (NB for YMS; SB for SL)

Summary of Existing Vegetation Review

One of the objectives of this research study was to characterize the extent of the noise reduction that is attributed to the vegetation that existed along the roadside prior to the start of the noise barrier construction project. The SL study area was selected for this work given the extensive vegetation that existed along the freeway in that area. To support the analysis of the noise reduction attributed to the vegetation, the research team completed a comprehensive review of the existing vegetation to include the type/species of plants present along the roadside as well as the depth of vegetation at the various points along the right-of-way. As noted in the literature review discussion, both species and depth have a significant impact on the potential for noise reduction associated with in-situ vegetation. This section presents a summary of the research team's characterization of the vegetation.

The existing vegetation review was carried out in fall 2019 permitting a detailed assessment of the "leaf on" condition of the vegetation. The roadside vegetation included both bushes and various types of trees and was determined to be representative of roadside locations with natural growth. The following tree species were encountered by the research team during the existing vegetation review: black walnut (*Juglans nigra*), crabapple (*Malus*), and Arborvitae (*Thuja occidentalis*) as dominant species with some maple (*Acer saccharum*) and eastern cottonwood (*Populus deltoides*) trees also present. Bush-type plants encountered included wild grape (*Vitis vinifera*), American holly (*Ilex opaca*), and other berry-type plants. The height of the ground-level vegetation extended above the view of the research team and was estimated to be 15 feet above the ground for the highest-density vegetation; most larger and mature trees extended above 50 feet off the ground level.

Guidance on the deployment of tree zones in TNM indicates that the tree zones must have sufficient density to completely block the view along the propagation path between the highway and receiver locations (Harris Miller Miller & Hansen, Inc., et al., 2014). It is also noted from past research that the "visibility depth" of the vegetation can be used as a proxy for the density of the foliage. To characterize the density of the vegetation, the research team examined the extent and depth of the vegetation at various points along the length of the right-of-way which corresponded to the approximate extent of Wall #2C of the noise barrier project. The density of the foliage was relatively high in many locations with an average visibility depth of approximately 20 feet in most places where high-density undergrowth was present, including the location of the SL R8 measurement unit for high-density vegetation. Locations where the trees and undergrowth had been cleared to access roadside features such as light posts had greater visibility back into the neighborhood. Within the right-of-way, the typical depth of the existing vegetation (as measured from the right-of-way boundary back towards the highway) ranged from 40 to 60 feet; in some locations the freeway was completely visible from ground level when viewed at certain angles. This effect was noted at the SL R1 location, which had a partial view of the freeway. Additional context of the existing vegetation can be gleaned from the images presented in Figure 33 and Figure 36 in the following section.

Data Collection Photos

[a] General View, YMS Site, Before Barrier Construction

[b] General View, YMS Site, After Barrier Construction

Source: ORITE research team images.

Figure 29: General View Before and After Barrier Construction, YMS Site

[a] YMS R2 View Without Barrier

[b] YMS R2 View With Barrier

Source: ORITE research team images.

Figure 30: View of YMS R2 Location Before and After Barrier Construction

[a] YMS R4 View Without Barrier

[b] YMS R4 View With Barrier

Source: ORITE research team images.

Figure 31: View of YMS R4 Location Before and After Barrier Construction

[a] SL R0, Pre-Clearing

[b] SL R0, No Barrier/With Barrier
Source: ORITE research team images.

Figure 32: SL R0 Microphone Locations

[a] High-Density Vegetation View (SL R8)

[b] SL R1 No Barrier/Low-Density Vegetation View
Source: ORITE research team images.

Figure 33: Comparison of High-Density (SL R8) and Low-Density (SL R1) Locations

[a] SL R1 With Barrier

[b] SL R2 General View

Source: ORITE research team images.

Figure 34: SL R1 With Barrier and SL R2 Locations

[a] SL R3 General View

[b] SL R4 General View
Source: ORITE research team images.

Figure 35: SL R3 and R4 Locations

[a] View of SL Study Site from Roadside Before Tree Clearing


[b] View of SL Study Site from Roadside Before Noise Barrier Construction
Source: ORITE research team images.

Figure 36: Comparison of Roadside View Before and After Tree Clearing

APPENDIX C: DATA ANALYSIS

Purpose and Objectives

The objective of the data analysis task was to review and process all traffic noise and other data that were obtained in the field studies described in Appendix B. A large database of consisting of measured traffic noise levels, weather condition data, and traffic data (volume and speed) was assembled in one-minute data blocks. Analysis of this database carried out by the ORITE research team provided insight on several key research questions being examined in this case study. This Appendix describes the data processing steps, analysis methods, and key analysis findings.

Data Processing Summary

Processing of the field data was carried out by the ORITE research team following each wave of data collection. Sound level data from each SLM unit and the corresponding WAV file generated by the digital audio recording device were downloaded and a standard file naming convention was established. SLM data were extracted using the Larson-Davis software program "SLM Utility" to output the one-minute Leq for each minute of the analysis periods. Spreadsheet files compiling the one-minute Leq for each microphone location were developed for each date of field data collection. Traffic data were downloaded from the infrared sensor and processed to output data on the time, speed, travel lane, and length for each vehicle passing the measurement site during the data collection periods. One issue that was encountered was that the traffic sensor data provided vehicle lengths and TNM vehicle types are based primarily on axle count and vehicle weight. A video review was undertaken from a sample of representative time periods to determine the classification of each vehicle in the sensor data set. Based on this sample classification, probability-based classification models were developed to determine the likelihood of a vehicle of a certain length being a TNM Automobile, Medium Truck, or Heavy Truck. Separate probability-based models were formulated for the September 2019, May/June 2020, and October 2020 field data collection waves. This manner of classification permitted development of a comprehensive database of traffic noise data to include a larger number of observations with defensible traffic volume and speed data.

Data from the weather station were similarly processed, with one-minute averages for all relevant metrics downloaded from the unit. The temperature lapse rate was calculated in the post-processing stage by taking the difference between the temperature readings at two heights (5 and 15 feet above the ground) and dividing that result by 10 feet. Additionally, the vector wind speed (VWS) for each one-minute block was calculated using the wind speed and wind direction data compiled by the weather station. The temperature lapse and VWS calculations were then merged to create categories of meteorological conditions. Following guidance from FHWA (2018a) and procedures followed in previous national studies (e.g., Bowlby, et al. (2018)), temperature lapse was characterized as lapse (less than -0.1 °C/m), neutral (-0.1 to +0.1 °C/m), or inversion (greater than +0.1 °C/m) while the VWS conditions were upwind (-11 to -2.2 mi/h), calm (-2.2 to +2.2 mi/h), or downwind (+2.2 to +11.0 mi/h). Excessive wind speeds greater than 11 miles per hour were not encountered during the field studies so no time periods were removed from the analysis on that basis.

Event logs were reviewed alongside the SLM data (and listening to the WAV files as appropriate) to identify if noisy or other noted events were unusual or had a significant effect on the resulting one-minute Leq. Minutes that contained unusual or significant noise events were noted in spreadsheets and discarded from further analysis. To aid in the review for unusual noise events, scatter plots were generated comparing minute-by-minute readings for the various microphone unit combinations. Outlier minutes were easily identified based on the variation displayed in the data scatter; this method proved to be particularly useful in identifying unusual noise periods in the SL study area where landscaping or local street vehicle pass-by noise could be present in certain data blocks.

To aid in carrying out the objectives of the research study, the ORITE research team compiled an extensive database of traffic noise levels under various traffic and weather conditions. Development of this database proceeded as follows. Sound level and weather data contained in one-minute data blocks were aggregated into five-minute blocks to minimize variability associated with the minute-to-minute variation in these conditions. Five-minute data blocks were classified based on the dominant meteorological condition for the time block, defined as having the same condition for both temperature lapse and VWS state for at least four out of the five consecutive minutes of the time block. Five dominant meteorological conditions were identified:

- Calm Neutral: VWS ≤ ± 2.2 mi/hr., indicating a wind condition with minimal or no impact on measured noise levels; lapse rate ≤ ± 0.1 °C/m., also indicating minimal or no impact on measured noise levels. It is noted that since TNM does not account for meteorological conditions in the calculations. Thus, the Calm Neutral meteorological condition is most representative of the conditions that correspond to predicted noise levels from TNM.
- Calm Lapse: VWS ≤ ± 2.2 mi/hr., indicating a wind condition with minimal or no impact on measured noise levels; lapse rate < -0.1 °C/m., indicating warmer temperatures closer to ground level and generally resulting in lower noise levels than a neutral atmospheric condition.
- Upwind Lapse: VWS < -2.2 mi/hr., indicating wind predominantly blowing from the measurement point toward the freeway and generally resulting in lower noise levels than a calm wind condition; lapse rate < -0.1 °C/m., indicating warmer temperatures closer to ground level and generally resulting in lower noise levels than a neutral atmospheric condition.
- Downwind Lapse: VWS > +2.2 mi/hr., indicating wind predominantly blowing toward the measurement point from the freeway and generally resulting in higher noise levels than a calm wind condition; lapse rate < -0.1 °C/m., indicating warmer temperatures closer to ground level and generally resulting in lower noise levels than a neutral atmospheric condition.
- Calm Inversion: VWS ≤ ± 2.2 mi/hr., indicating a wind condition with minimal or no impact on measured noise levels; lapse rate > +0.1 °C/m., indicating

cooler temperatures closer to ground level and generally resulting in higher noise levels than a neutral atmospheric condition.

The five-minute data blocks were formed on a "rolling" basis meaning that each individual minute of data could be included in up to five separate blocks. Minutes that were determined to be invalid based on unusual noise were also discarded from the database development; this included both unusual highway noise (e.g., loud vehicles) or abnormal conditions affecting all microphone locations at the site (e.g., flock of loud birds flying overhead). Some five-minute blocks were discarded because there was an inadequate sample size for a given meteorological condition. A summary of the data blocks available for each study site, analysis condition, and meteorological condition is presented in Table 5.

Table 5: Summary of Five-Minute Data Blocks in Noise Database

Location/Objective	Total Blocks	Dominant Meteorological Condition				
		Calm Lapse	Calm Neutral	Calm Inversion	Upwind Lapse	Downwind Lapse
SL/Pre-Clearing	324	324				
SL/Vegetation	136	136				
YMS/No Barrier	442	271	80	0	91	0
SL/No Barrier	155	155				
YMS/With Barrier	446	308	72	28	0	38
SL/With Barrier	223	223				

For the YMS study site, it is noted from Table 5 that the wind condition for the "No Barrier" scenario was primarily upwind (VWS toward the highway) while the downwind condition (VWS toward the microphones) was dominant during the "With Barrier" scenario. The implication for this is that the effect of the upwind and downwind VWS states could not be analyzed for both the "No Barrier" and "With Barrier" cases. For the SL study site, the database was limited to only five-minute periods that matched the "Calm Lapse" condition since the objectives for that study location were not related to the weather conditions. To maximize the available number of data blocks for analysis at the SL study location, five-minute blocks where non-traffic noise or local street pass-by traffic was noted were retained in initial database development. These blocks would then be omitted from analyses where data obtained from the specific affected microphone locations were being examined.

Analysis Methods

This section describes the calculation procedures utilized to estimate the sound level differences between the various conditions analyzed. The noise barrier insertion loss is defined as the difference in the sound level at a receptor location with and without the presence of a noise barrier, assuming no change in the sound level of the source. There are three methods (described in (FHWA, 2018a) for the calculation of insertion loss: 1) Direct Measurement of sound levels Before and After construction; 2) Indirect Measured utilizing measured sound levels before construction and modeled noise levels after construction; and 3) Indirect Predicted utilizing modeled sound levels for both Before and After conditions. For this research study, the "Direct Measurement" method was utilized as the ORITE research team had access to the exact same measurement locations both prior to and after noise barrier construction at the case study sites. The noise barrier insertion loss is calculated using the following formula derived from (FHWA, 2018a):

$$IL_i = (L_{Aref} + L_{edge} - L_{Arec}) - (L_{Bref} - L_{Brec})$$

Where:

- IL_i is the insertion loss at receiver location (i);
- L_{Bref} and L_{Aref} are, respectively, the Before and After sound levels at the reference microphone location, set according to FHWA guidelines;
- L_{edge} is the reflections/edge-diffraction bias adjustment; and
- L_{Brec} and L_{Acre} are, respectively, the Before and After sound levels at the i^{th} receiver location.

Following the above equation, the resulting IL will be a positive number if the barrier is reducing sound levels at the analyzed receptor location. FHWA guidance suggests a bias adjustment of -0.5 dBA, which accounts for a slight increase in noise levels at the reference microphone location after barrier construction due to reflections from the sides of large semi-trailers and diffraction of sound waves over the top edge of the noise barrier. Examining the data collected at the YMS location for the current case study indicated that the suggested value of -0.5 dBA was appropriate for use in this study. The insertion loss equation described above can be extended to permit comparison between the average sound levels at the same receiver location (i) under any two different conditions (e.g., neutral or lapse atmospheric conditions). Two analysis conditions are defined: Baseline, consisting of the “control” condition (e.g., calm wind condition), and Analysis, consisting of the variable of interest (e.g., upwind condition). The following modification to the above equation is used to calculate the difference between the two conditions:

$$\Delta SL_i = (L_{Bref} - L_{Brec}) - (L_{Aref} - L_{Arec})$$

Where:

- ΔSL_i is the change in measured sound levels at receiver location (i);
- L_{Bref} and L_{Aref} are, respectively, the Baseline and Analysis condition sound levels at the reference microphone location; and
- L_{Brec} and L_{Arec} are, respectively, the Baseline and Analysis condition sound levels at the i^{th} receiver location.

Following the above equation, the ΔSL will be positive if the Analysis condition results in higher noise levels than the Baseline condition and negative if the Analysis condition sound levels are lower than the Baseline condition. It is noted that both above equations can be utilized for properly calculated broadband sound levels (e.g., A-weighted) of any time-averaged duration as well as the sound levels for specific frequency bands where such data are available.

Due to the meteorological conditions present at the study sites during the field measurements (see Table 5) and the methods used by the research team to compile the traffic noise database, the following limitations are noted within the analysis:

- The impact of VWS condition (downwind, calm, or upwind) in relation to the presence of a barrier could not be analyzed due to the dominant wind conditions being different between the two barrier scenarios.
- The effect of temperature inversion (e.g., temperature lapse rate greater than +0.1 °C/m) could not be analyzed for the "No Barrier" condition since no inversion periods were noted during this part of the field study.
- The dominant meteorological condition in the broader study area is Calm Lapse; accordingly, this condition was selected as the default condition for the analysis of building row noise reduction and vegetation impacts. The effect of other meteorological conditions on the noise reduction attributed to building rows and vegetation was not examined.

Database Analysis Results

Noise Barrier Impacts

The impact of the noise barrier, as measured by the noise barrier insertion loss, was analyzed for the YMS study site (Wall #1A). The calculation procedures for insertion loss utilized the "Direct Measurement" method as described by FHWA (2018a) as outlined previously, including the reflection/edge diffraction bias adjustment of 0.5 dBA. Table 6 presents the estimated insertion loss for the Calm Neutral and Calm Lapse meteorological conditions. It is noted that these two meteorological conditions were the only two conditions for which an adequate sample of measured data was available for both the "No Barrier" and "With Barrier" conditions. For the receiver location closest to the freeway (R1 at 105 feet), the insertion loss was estimated to be 8.6 dBA under the Calm Neutral atmospheric condition. The noise barrier insertion loss decreased with increasing distance from the freeway, an expected result. Noise barrier insertion loss was lower at all four microphone positions for the Calm Lapse atmospheric condition, also an expected result since the Calm Lapse condition yielded lower measured noise levels at the 5-foot heights relative to the reference position.

Table 6: Noise Barrier Insertion Loss, YMS All Receivers

Receptor Location	Calm Neutral			Calm Lapse		
	No Barrier (n=74)	With Barrier (n=44)	Insertion Loss	No Barrier (n=250)	With Barrier (n=285)	Insertion Loss
Reference	76.4	76.2	N/A	76.0	77	N/A
R1 (105 ft.)	69.8	60.5	8.6	68.3	61.5	7.5
R2 (160 ft.)	65.0	60.2	4.1	63.6	61.6	2.7
R3 (315 ft.)	60.4	58.3	1.4	59.3	59.7	0.0
R4 (425 ft.)	58.4	56.9	0.8	57.5	58.3	-0.4

Meteorological Impacts

The noise impacts of the following meteorological conditions were examined in this case study: temperature, humidity, dewpoint, temperature lapse rate, wind speed, wind direction, vector wind speed, and cloud cover. The meteorological impacts were analyzed using the YMS study site under the "No Barrier" scenario, which eliminates the presence of the barrier as a confounding factor in the analysis. Table 7 reports the average sound levels at each YMS microphone location for the “No Barrier” scenario under Calm Neutral, Calm Lapse, and Upwind Lapse conditions. On average, the Lapse condition had an effect of reducing the average noise levels by approximately 0.8 dBA across the four microphone positions, with a slightly decreasing effect with increasing distance. The Upwind condition yielded an additional decrease of approximately 1.2 dBA on average across the four positions. The net effect of Lapse and Upwind conditions combined (far right column of Table 7) resulted in an average reduction of 2.0 dBA compared to the Calm Neutral condition. These findings are expected and consistent with expectations. It is noted that the magnitude of both effects (Lapse and Upwind) decreases with increasing distance from the highway. This result does not agree with the results presented in NCHRP Report 791 (Harris Miller Miller & Hansen, Inc., et al., 2014), which note that the meteorological effects are more profound with greater distance from the highway. It is speculated that, in the case of the YMS study site, the large stand of mature trees and topographic changes along the eastern edge of the YMS property resulted in a shielding effect that minimized these effects at the furthest receiver points.

Table 7: Lapse and Upwind Impacts, YMS No Barrier Case

Receptor Location	Calm Neutral (CN) (n=74)	Calm Lapse (CL) (n=250)	Upwind Lapse (UL) (n=71)	ΔSL (CL)	ΔSL (UL)	ΔSL (CL+UL)
Reference	76.4	76.0	75.0	N/A	N/A	N/A
R1 (105 ft.)	69.8	68.3	65.9	-1.1	-1.4	-2.5
R2 (160 ft.)	65.0	63.6	61.3	-1.0	-1.3	-2.3
R3 (315 ft.)	60.4	59.3	57.5	-0.7	-0.8	-1.5
R4 (425 ft.)	58.4	57.5	55.2	-0.5	-1.3	-1.8

To further investigate the effect of meteorological conditions on traffic noise, a multiple regression model was developed using the YMS study site “No Barrier” scenario data set. The final model (presented in Table 8) predicts the sound level as a function of microphone distance from the highway (logarithmic transformed), three meteorological conditions (vector wind speed, temperature lapse rate, and cloud cover), and traffic flow for each of three TNM vehicle classifications (auto, medium truck, and heavy truck). Model variables tested but not included in the final model were temperature, humidity, dewpoint, wind speed, wind direction, and average traffic speed. However, some of those variables were incorporated in other ways (e.g., vector wind speed accounts for both wind speed and wind direction).

All variables were significant at the $\alpha = 0.05$ level or better and the model R-squared was 0.956, indicating an outstanding model fit. The parameter for the receiver distance from the freeway incorporated a logarithmic transformation due to the anticipated behavior of sound waves spreading. The distance parameter in the final model implies a noise reduction of approximately 2.3 dBA per doubling of distance (rule of thumb is 3.0 dBA), an acceptable result. Examining the meteorological variables, the parameter values indicate an increase of VWS of 1 mi/h yields an 0.41 dBA increase in sound level; an increase of 1.0 °C/m of temperature lapse rate yields a 3.3 dBA increase in sound level; and an overcast sky condition will result in sound levels that are approximately 0.6 dBA higher than clear skies, on average. These findings are all generally consistent with expectations for how these weather conditions impact traffic noise in the free-field environment.

Table 8: Details of Multiple Regression Model, YMS No Barrier Case

Variable Description	Estimate	Standard Error	T-Ratio	P-Value
Intercept	101.104	0.308844	327.36	<.0001
LOG (Distance from Freeway (Feet))	-7.602	4.28E-02	-177.50	<.0001
Average Vector Wind Speed (mi/h)	0.413	0.025727	16.05	<.0001
Temperature Lapse Rate (°C/m)	3.330	0.25585	13.00	<.0001
Cloud Cover (= Overcast)	0.591	0.042033	14.05	<.0001
Traffic Flow Auto (veh/h)	0.000527	8.67E-05	6.08	<.0001
Traffic Flow Medium Truck (veh/h)	0.00360	0.001574	2.29	0.0222
Traffic Flow Heavy Truck (veh/h)	0.00521	0.000673	7.74	<.0001
Model R-Squared = 0.956; N = 1,580				

Heavy and Medium Truck Impacts

The impact of medium and heavy truck traffic volumes on noise levels was also examined at the YMS study site under the "No Barrier" scenario. A scatter plot showing the relationship between the measured Leq for each of the YMS measurement positions and the total truck volume (hourly flow for MT plus HT) is presented in Figure 37. Examining Figure 37 there is a clear positive linear relationship between the noise and truck volumes, although more "scatter" in the data is observed as the distance from the highway increases. The correlation between measured traffic noise and truck hourly flow was approximately 0.762 for the reference microphone position and between 0.493 and 0.573 for the four five-foot microphone positions.

The multiple regression model developed for the meteorological conditions (see Table 8) can also be parsed to determine the assumed substitution ratio for the various combination of TNM vehicle types analyzed. In particular, the ratio of the different model parameters that correspond to the vehicle classifications represent a potential substitution ratio for the three pairs of vehicle types. Accordingly, the following substitution ratios are estimated:

Ratio of AU to HT: 0.000527 ÷ 0.00521 = 9.887

Ratio of AU to MT: 0.000527 ÷ 0.00360 = 6.837

Ratio of MT to HT: 0.00521 ÷ 0.00360 = 1.446

The implied ratio for Auto to Heavy Trucks from the current study is consistent with previous literature which assumes a value of 10 for this ratio (Li, et al., 2002; Donovan and Janello, 2017; Chupp, et al., 2020). The implied ratio of Medium Trucks to Heavy Trucks is also similar to the ratio presented by Li, et al. (2002) although the implied Medium Trucks to Heavy Trucks ratios are not consistent.

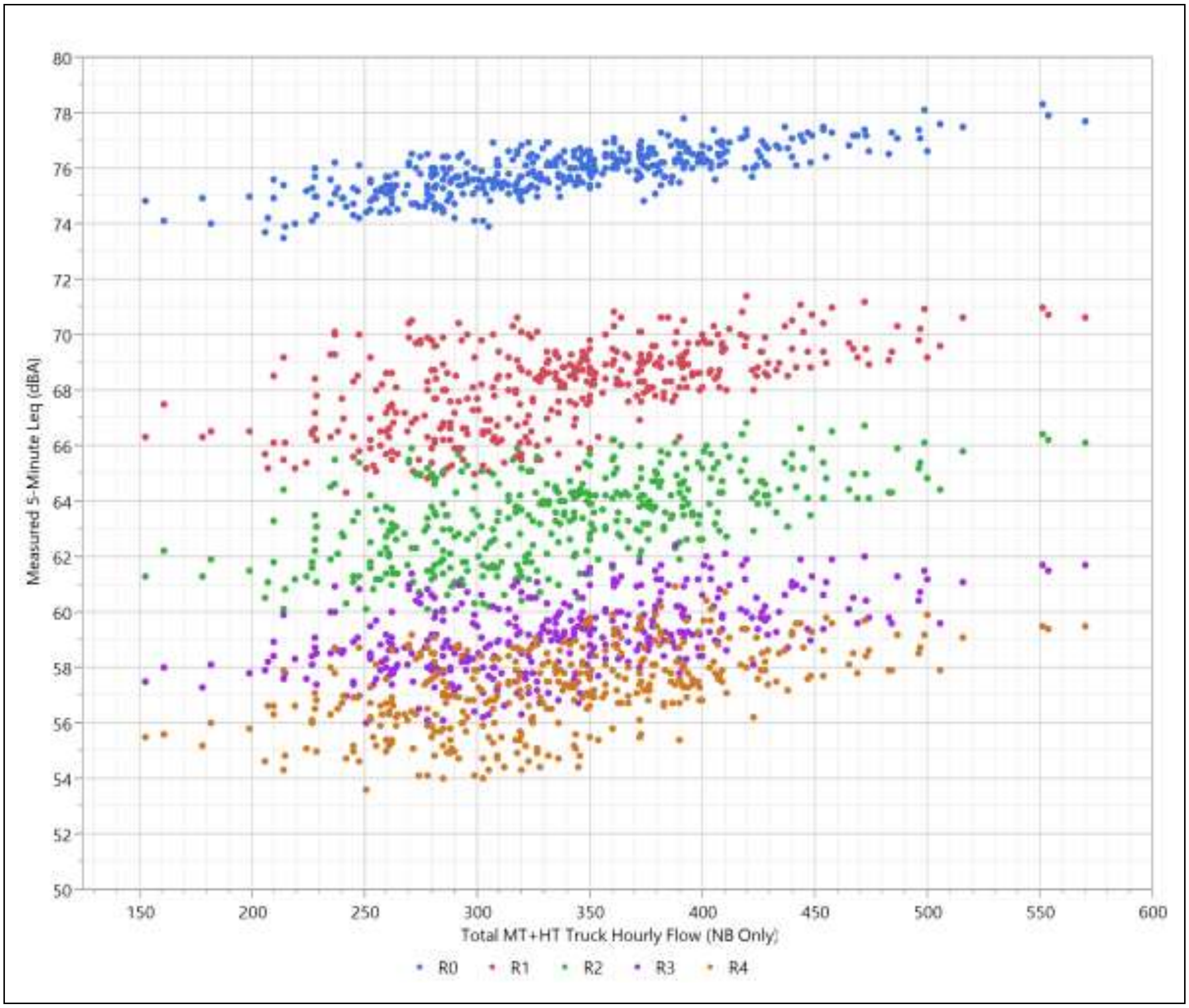


Figure 37: Scatter Plot of Measured Sound Levels and Truck Volumes, YMS NB

Building Row Impacts

The Shady Lane Neighborhood (SL) site was used to analyze the impact of building rows on traffic noise propagation. The average measured 5-minute Leq at each measurement position over the course of the field measurement periods is reported in Figure 38 with the three analysis scenarios (Pre-Clearing, No Barrier, and With Barrier) reported separately along the Y-axis of the chart. As noted in Figure 38, the noise levels measured at the closest two positions (R0 and R1) display similar trends while the positions deeper into the neighborhood are subject to exposure from both very loud highway events and also activities in the neighborhood such as lawn mowers or pass-by traffic on local streets. It is also noted in Figure 38 that there is a clear and distinctive gap or drop-off in sound levels between R1 and R2 (first row of homes); a similar distinctive drop-off, although smaller in magnitude, can be discerned in the second row (between R2 and R3). However, for the third row of homes (between R3 and R4) the sound level drop-off is less distinctive, and, in some cases, there is almost no difference between the sound levels at the two locations.

Numerical analysis of the noise reduction between successive building rows in the SL study site is presented in Table 9 (Row 1), Table 10 (Row 2), and Table 11 (Row 3). The noise reduction is reported as the ΔSL in each table. The ΔSL for each building row was calculated with receiver-specific noise interference removed; for example, a vehicle pass-by affecting the R4 location would not necessarily affect the valid calculation of the drop-off in noise between R2 and R3. To provide additional context, the "Excess ΔSL" is also reported as the difference between the measured ΔSL and the expected noise reduction from geometric spreading (equal to ten times the log of the ratio of the distances of each receiver from the highway). It is noted that there are also ground effects (including both soft ground of residential lawns and hard ground of the local roadways) and minor diffraction across various elevation changes also affecting the propagation path through the building rows, so the entire ΔSL excess may not be fully-attributed to the presence of the residential structures. Nevertheless, the ΔSL excess provides a good approximation of the impact of the buildings. The average ΔSL excess for each building row is reported as follows:

Row 1: +1.1 to +5.5 dBA

Row 2: +1.4 to +2.6 dBA

Row 3: +0.6 to +1.5 dBA

Based on the measurements and calculations carried out for this case study, the noise reduction attributed to building rows in the SL neighborhood was only discernable for the first row of buildings and was lower than the assumed threshold of hearing for the other two rows. For both Row 1 and Row 2, the excess noise reduction was higher in the "No Barrier" scenario as compared to the "Pre-Clearing" scenario. For the "With Barrier" scenario, the excess noise reduction attributed to the building rows was approximately +1.1 to +1.5 dBA for all three rows. Probably the most interesting finding from the measurements at the SL study site is that the third row of buildings provide no perceptible reduction in traffic noise across all three scenarios examined. This may be due to the offset nature of the buildings and gaps between the buildings providing a skewed angle view of the highway from the R4 location, particularly in the "No Barrier" condition. Additionally, the R4 location is subject to significant background (i.e., non-highway) noise from many locations.

Table 9: Summary of Building Row Noise Reductions, SL First Row

Analysis Scenario	Receiver Location (Distance)	L(Reference)	L(Receiver)	ΔSL	ΔSL (Excess)
Pre-Clearing	R1 (166)	73.8	65.0	+6.1	+3.3
	R2 (315)		58.9		
No Barrier	R1 (166)	73.7	64.8	+8.3	+5.5
	R2 (315)		56.5		
With Barrier	R1 (166)	74.9	59.4	+3.9	+1.1
	R2 (315)		55.5		

Table 10: Summary of Building Row Noise Reductions, SL Second Row

Analysis Scenario	Receiver Location (Distance)	L(Reference)	L(Receiver)	ΔSL	ΔSL (Excess)
Pre-Clearing	R2 (315)	73.8	58.7	+3.1	+1.8
	R3 (422)		55.6		
No Barrier	R2 (315)	73.6	56.2	+3.9	+2.6
	R3 (422)		52.3		
With Barrier	R2 (315)	74.9	55.6	+2.7	+1.4
	R3 (422)		52.9		

Table 11: Summary of Building Row Noise Reductions, SL Third Row

Analysis Scenario	Receiver Location (Distance)	L(Reference)	L(Receiver)	ΔSL	ΔSL (Excess)
Pre-Clearing	R3 (422)	73.7	55.6	+2.8	+1.1
	R4 (625)		52.8		
No Barrier	R3 (422)	73.8	52.3	+2.3	+0.6
	R4 (625)		50.0		
With Barrier	R3 (422)	75.5	54.4	+3.2	+1.5
	R4 (625)		51.2		

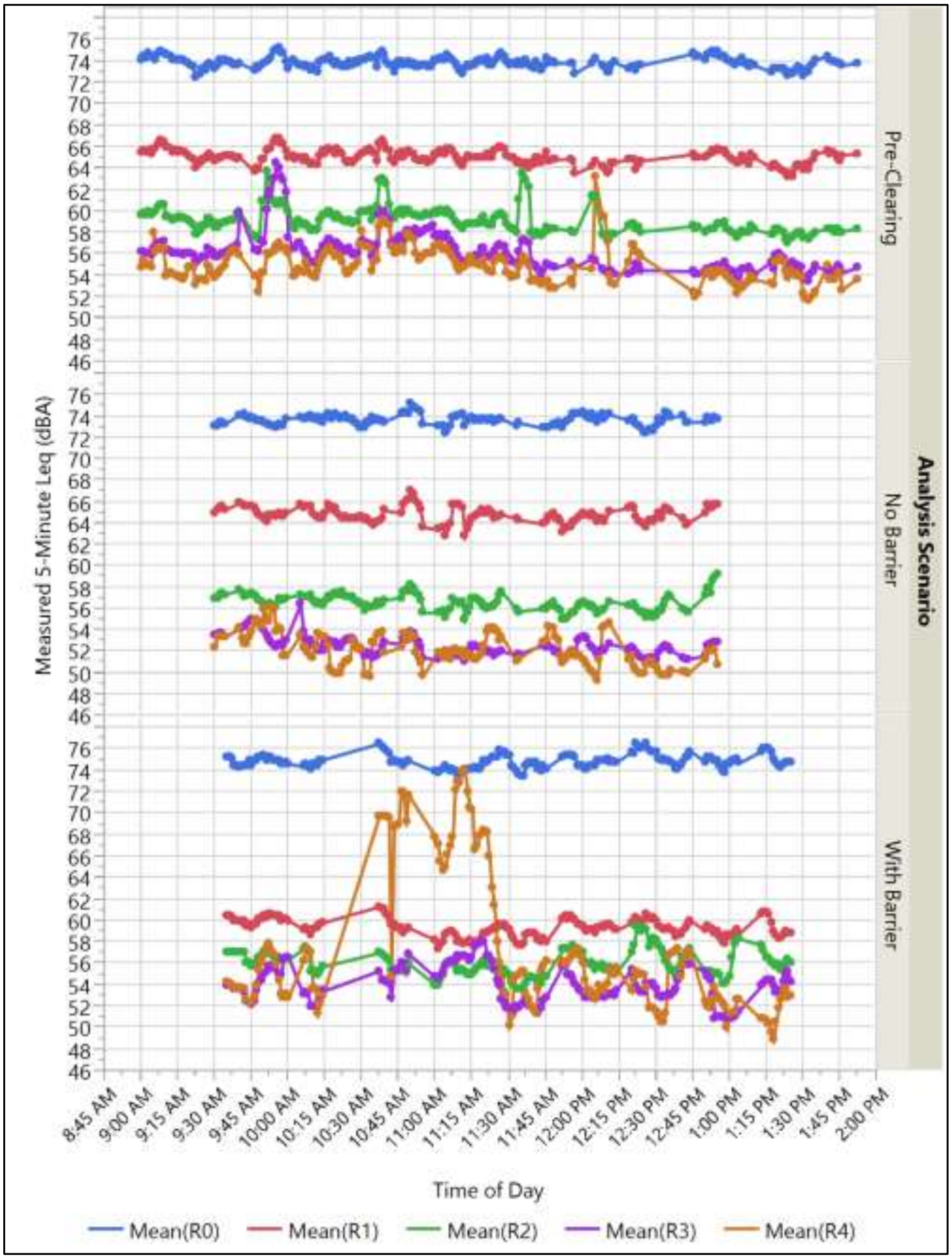


Figure 38: Measured Sound Levels by Time of Day, SL All Receiver Locations

Vegetation Impacts

To analyze the impact of roadside vegetation on traffic noise reduction, the ORITE research team deployed a special one-day field measurement study focusing on the backyard of the first row of homes in the SL study area. This field study took place in September 2019 prior to the start of tree clearing for the noise wall construction project as well as prior to the leaves falling off the trees for the autumn season. Measurement positions were established at the location designated R1 and a second location designated R8. The R1 location was assumed to be representative of a low-density vegetation state with a partial view of the freeway when viewed from certain angles while standing at the microphone position. The R8 location, on the other hand, represented high-density vegetation and there were no views of the freeway available from any point at the microphone position. The location of R8 was in the backyard of the second home directly to the north of the R1 location approximately 160 feet to the north. Comparison of these views are presented in Figure 33 for reference. The approximate depth of the vegetation at the R1 location was 50-60 feet (all within ODOT right-of-way) and the depth at the R8 location was approximately 100 feet (including some trees on the residential side of the right-of-way boundary). For reference purposes, a second pair of microphones were positioned approximately 40 feet from the centerline of the far outside lane of the freeway directly aligned with the corresponding backyard measurement positions.

The noise reduction impacts of the roadside vegetation were calculated as follows. Five-minute data blocks were extracted from the one-minute data blocks using the process previously described. Only blocks with the Calm Lapse meteorological condition were included; however, no unusual freeway noises were eliminated since all receiver locations would be similarly affected by these events. No unusual events at the specific measurement positions R1 and R8 were noted for removal. This process resulted in a total of 136 five-minute blocks available for further analysis. There was a strong correlation noted ($r = 0.986$) in the average five-minute Leq levels between the two microphone locations nearest to the freeway and thus it was determined that the traffic noise conditions were similar between the two positions. The measured traffic noise levels at each position was as follows:

Measured Noise at Highway (Reference) Location = 73.9 dBA

Measured Noise at Low-Density Position = 64.4 dBA

Measured Noise at High-Density Position = 63.6 dBA

Taking the average reduction between the backyard microphone locations and their corresponding freeway microphone locations, as well as comparing the two backyard microphone locations directly, provided insight into the noise reduction attributed to the higher-density foliage. The following results were obtained:

Noise Reduction at Low-Density Position = 9.5 dBA

Noise Reduction at High-Density Position = 10.3 dBA

Difference in Noise Levels between High and Low Density = 0.8 dBA

Assuming a noise reduction of approximately 6 dBA due to geometric spreading (≈ 3 dBA for doubling of distance two times between 40 and 166 feet), the excess noise reduction attributed to the presence of roadside vegetation is estimated to be between 3.0 and 4.0 dBA depending on the density of the vegetation. Noting that the threshold of human hearing is assumed to be approximately 3.0 dBA, it is concluded that the presence of vegetation creates a perceptible difference in traffic noise. The higher-density vegetation is estimated to provide an additional 0.8 dBA reduction compared to a lower-density vegetation state with a partial view of the freeway.

These conclusions should be considered with some caveats. First, it is noted that the noise reduction between the highway and the measurement positions was also influenced by the presence of the absorptive soft ground of the residential lawns and the grassy area of the roadside between the highway and tree line, as well as the attenuation effects associated with the ground cover within the tree zones. However, these effects should be minimal and would be present at other areas where tree zones are present between the freeway and the first row of residences. Second, it is noted that the estimated noise reduction attributed to roadside vegetation includes vegetation on the ODOT right-of-way as well as vegetation in the backyard of the first row of homes on the private property. For a typical noise wall project, only vegetation within the ODOT right-of-way would be cleared. However, in the instance of the R1 low-density measurement position, the entirety of the trees shielding the receiver position from the freeway were cleared for the construction project. Consequently, even when considering a partial loss of soft-ground attenuation due to construction activities along the ODOT right-of-way, it is likely that a perceptible difference in sound levels was achieved with the existing vegetation.

APPENDIX D: FHWA TNM ANALYSIS

TNM Model Development

The ORITE research team developed detailed models of each of the two study sites using the FHWA Traffic Noise Model (TNM) version 2.5 software package (FHWA, 2017b). All best practices and recommended procedures for TNM layout development (Harris Miller Miller & Hansen, Inc., et al., 2014; Bajdek, et al., 2015) were utilized in the model creation. This section describes the TNM model development and key details of the critical objects in the TNM layout.

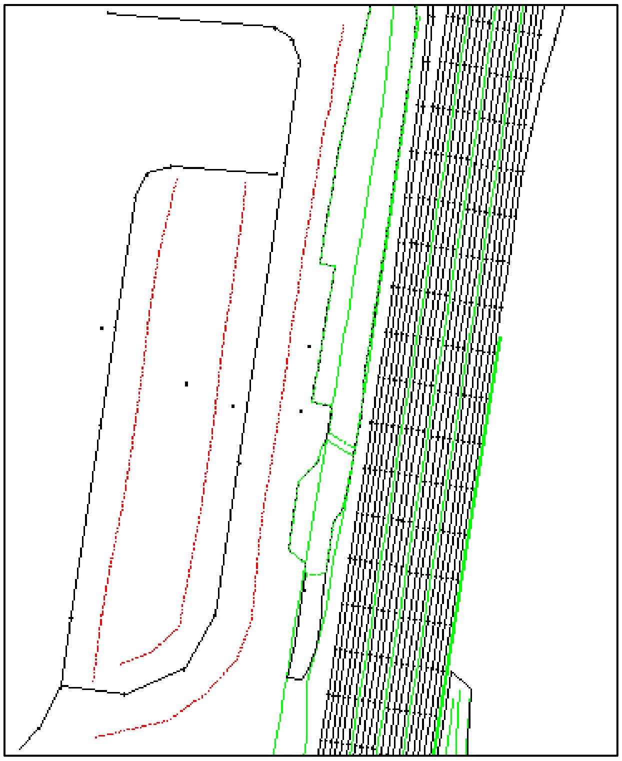
All roadway lanes along Interstate 270, six in each direction, were modeled as individual TNM roadway objects with a length of roadway extending at least 1,500 feet beyond the receiver lines both north and south of the study area. The roadway centerline was established using coordinates based on the State Plane Coordinate System Ohio South Zone estimated from the noise barrier construction plans. The shoulders were also modeled as roadway objects to ensure correct propagation over those hard surfaces. The widths of all travel lanes and shoulders were estimated from aerial imagery. All roadway objects were overlapped by 0.2 feet to ensure that there were no small gaps of default ground type (lawn) present between roadway lanes. All roadway objects were modeled as dense-graded asphalt concrete (DGAC) pavement type since the modeling objective was validation rather than noise barrier design. Median barriers between the “local” and “express” lanes were modeled as three closely-spaced terrain lines. Terrain lines were also used to define ditches and other terrain changes along the propagation path. Ground zones were established in locations along the shoulder where natural ground had been disturbed during the tree clearing and barrier construction process. Three closely-spaced terrain lines were also used to model two portable concrete barrier (PCB) installations that were present during measurements taken during times when the construction project was active (although measurements were not taken when work was in the area, the PCB was present to protect bridges in the area). Precise coordinates of all microphone positions as well as other features were obtained using high-precision GPS equipment supplied by the ORITE research team. Elevations of TNM objects not obtained using GPS equipment were estimated from design plans, area benchmarks, or on-site measurements with manual devices. The coordinates and height of the noise barriers were estimated using data from the ODOT construction plans.

For the YMS study site, specific site features modeled in the TNM layout included the school building to the south of the measurement positions and the apartment building to the north. The Livingston Avenue overpass was also modeled as two TNM roadway objects “on structure” with an embankment defined with terrain lines. A blacktop playground surface immediately to the north of the school building, as well as a baseball diamond infield, were modeled with appropriate ground zones.

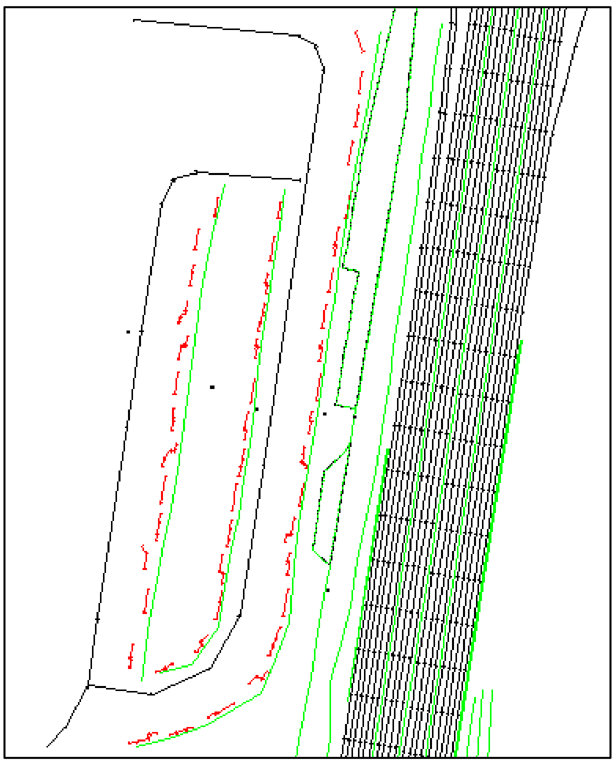
Figure 39 displays the plan view for the YMS study site TNM layout.

Figure 39: TNM Layout for YMS (NSA 7) Study Site

For the SL study site, the ORITE research team had to develop a TNM model to incorporate the roadside tree zone in two different states (pre-clearing and post-clearing), representation of the residential structures in two different ways (building rows and buildings as barriers), and other propagation path elements such as the local streets. The roadside tree zone coordinates were estimated using the ODOT design plans with field checks to verify specific dimensions. A tree zone height of 30 feet was assumed; limited variation in the results were noted with varying tree zone heights in model development. A ground zone consisting of the TNM “field grass” ground cover type was overlaid with the tree zone to provide a better representation of the ground absorption within the vegetated area. The coordinates of each residential structure in a 120-degree view of all receiver locations were obtained using data from the Franklin County Auditor (XY) and LIDAR points from state-level GIS data (Z and height estimates). Coordinates of the approximate location along following the center of the roofline and roughly centered between each residence were used to establish the XY coordinates for each of the building rows while the Z coordinate was taken as the average ground level of each adjoining property. The height of each structure as obtained from LIDAR data was used to develop a weighted average height of the building row. The building percentage was estimated by taking the total length of the first story of each residence divided by the total frontage of each parcel. For the “buildings as barriers” representation, only the building façade nearest to the freeway was modeled. Additionally, it was determined that use of the first-story height only (including roof) was a better representation than accounting for varying heights (e.g., split level homes). Figure 40 displays the plan view for the SL study site TNM layout, showing the building row representation and the “buildings as barriers” representation.



[a] TNM Layout for “Building Rows” Representation



[b] TNM Layout for “Buildings as Barriers” Representation

Figure 40: TNM Layout for SL (NSA 2) Study Site

A summary of the building row information is presented in Table 12 below.

Table 12: Details of Building Rows, SL Study Site

Building Row	Description	Total Length (Feet)	First-Floor Building Length (Feet)	Building Percentage	Number/Type of Residences	Average Height
1	Knollwood Drive East Side	1,700	1,185	70%	21 Total 4 One-Story 8 Split-Level 9 Two-Story	17.0 Feet
2	Knollwood Drive West Side	1,164	778	67%	14 Total 4 One-Story 10 Split-Level	15.5 Feet
3	Walshire Drive East Side	1,077	710	66%	13 Total 2 One-Story 6 Split-Level 5 Two-Story	18.4 Feet

Selection of specific time periods to be used for TNM validation analysis utilized the following procedures. To minimize the effect associated with unusual traffic fluctuations within a five-minute time block, the ORITE research team decided to utilize a 15-minute time-averaging period for the TNM validation study. The one-minute data set was reviewed to identify 15-minute blocks with at least 10-12 minutes of similar meteorological condition. Time blocks with significant external or background noises were omitted from the selection process as well. For the YMS study site, a total of 15 blocks were identified for the "No Barrier" case and 12 blocks were identified for the "With Barrier" case. For the SL study site, 11 blocks were identified for the "Pre-Clearing" case, 8 blocks were identified for the "No Barrier" case, and 8 blocks were identified for the "With Barrier" case. Each 15-minute block was given an 8-digit reference code corresponding to the month, date, and start time of the block (expressed in 24-hour time). For example, the block 09170910 was September 17, 2019 with a start time of 9:10 A.M. It is noted that there was no overlap between study sites and dates so there was no need to define TNM blocks in any other manner. Traffic volume and speed data from the sensor data set was summarized for each TNM time block by lane and for three TNM vehicle types (Auto, Medium Truck, and Heavy Truck). Motorcycles, if detected, were included in the modeled traffic; very few buses were noted in the traffic stream during the TNM blocks and thus were omitted from the model runs. To aid in streamlining the TNM calculations, the average speed of all vehicles in a specific lane was assumed to be the speed for the Automobile and Motorcycle vehicles while the truck speeds were estimated to be 6 mi/h less than the average. The reduced speed for trucks was verified using field-measured speeds indicating that approximate difference.

The average TNM calculation run time was approximately 8-10 minutes for individual model runs at the YMS location (with and without barrier) as well as the SL building rows representation case. The SL "building as barrier" representation case had a significantly longer calculation time of approximately 45-55 minutes per run.

Model-to-Monitor Analysis Methods

This project utilized a “model-to-monitor” approach to analyze the accuracy of the FHWA TNM traffic model under various conditions. There are numerous studies that have examined the performance of FHWA TNM utilizing specific metrics such as the deviation between the modeled and measured noise levels or the absolute value of the deviation between modeled and measured levels (e.g., Rochat and Fleming, 2002; 2004). Following these studies, the “model deviation” for this study was calculated by subtracting the measured sound level from the modeled sound level for the specific analysis time block and receiver location of interest. Using this format, a positive value indicates that FHWA TNM model output results in an over-prediction of the sound levels while a negative value indicates under-prediction. It is noted that a calculated model deviation within ± 3.0 dBA is considered adequate for the purposes of model validation for Ohio DOT traffic noise studies (ODOT OES, 2015). The absolute value of the model deviation may also be used to ensure that values that are equal in magnitude but opposite in sign do not yield an average value of zero, in turn leading to the incorrect conclusion of no deviation. However, for the purposes of analyzing FHWA TNM model accuracy, the sign of the model deviation may be a useful indication of over-prediction or under-prediction, as appropriate, for different vector wind speed conditions (upwind, calm, or downwind). The “model deviation” statistic was also utilized when evaluating the implications of substituting heavy truck volumes with medium truck volumes in TNM at different ratios of substitution. The validated TNM model used at the Yorktown Middle School (NSA 7) study site was used for this portion of the analysis. TNM analysis blocks that were classified as “Calm Neutral” meteorological condition (3 blocks for “No Barrier” case, 2 blocks for “With Barrier” case) were used in the substitution analysis since those conditions are most representative of TNM’s baseline conditions. The following substitution ratios were analyzed: 1.0, 1.5, 2.0, 2.5, and 3.0; for example, a substitution ratio of 2.0 means that the observed heavy truck volume for a specific TNM analysis block would be multiplied by a factor of 2 and that amount would be added to the observed volume of medium trucks for that analysis block.

In addition to the model deviation calculation, a scatter plot of all modeled and measured values for each combination of analysis time block and receiver location can be developed. For scatter plots, the measured sound levels are reported on the X-axis while the corresponding modeled sound levels are reported on the Y-axis. Following this format, data points for which the model is over-predicting are found in the top left portion of the scatter plot while points that are under-predicted are on the bottom right portion. From the scatter plot, a linear regression line can be fit to the data indicating the average deviation of the entire data set as compared to a line of constant slope (i.e., the line of Y = X). The preferred outcome is to have most of the points on the scatter plot closely grouped around this line.

The “model-to-monitor” approach has been used primarily in the air quality realm to compare the performance of EPA air quality modeling software relative to monitored levels of different pollutants (e.g., U.S. EPA, 1996; Payne-Sturges, et al., 2004; Lupo and Symanski, 2009). Two important metrics that are used in the air quality field to make conclusions about model accuracy under different conditions are

1) the median of model-to-monitor ratios (e.g., the modeled value divided by the measured value) and 2) the percentage of observations for which the model is within a certain percentage or a given order of magnitude of the measured value. The research team could not locate any studies in the highway traffic noise analysis literature that utilized these metrics for model analysis. However, given their application in other model-to-monitor analysis disciplines, these metrics were also examined in the current study.

Model-to-Monitor Analysis Results, YMS Study Site

Details of the model-to-monitor (M2M) analysis results for the Yorktown Middle School (NSA 7) site are presented in this section. Data tables and exhibits that correspond to the analysis results are presented herein. Numerical results for the measured and modeled sound levels, and other relevant data from the model-to-monitor analysis, are also summarized in tabular form at the end of this appendix.

Discussion of M2M Analysis Results: YMS Study Site

Scatter plots comparing the measured and TNM modeled sound levels for the YMS location are presented in Figure 41 (No Barrier) and Figure 42 (With Barrier). Box plots showing the model-to-monitor ratio for both analysis cases at the YMS study site are displayed in Figure 43. To interpret the scatter plots, it is noted that the top left half of the plot represents a model over-prediction while the bottom right half represents a model under-prediction of the sound levels. Table 13 presents the numerical values for the average model deviation, median model-to-monitor ratio, and the percentage of observations that are within 3 dBA of the measured levels for the five microphone positions, various meteorological conditions, and three levels of truck traffic. From these exhibits, the following conclusions are noted:

- For the No Barrier scenario, the modeled sound levels at the reference microphone location R0 are consistently lower than measured by approximately 2.3 dBA across all meteorological conditions. Sound levels at the 5-foot height measurement positions are overpredicted by the noise model, between 2.3 and 4.0 dBA higher on average.
- Greater scatter in the measured sound level data is noted with increasing distance from the highway (this effect is most clearly displayed in Figure 43).
- For the Calm Neutral meteorological case, the average model deviation is approximately +0.5 dBA indicating a good fit. Additionally, 100% of the modeled data points under the Calm Neutral condition are within 3 dBA of the measured data. It is noted that the TNM software is based on the Calm Neutral condition with no options to account for wind or temperature lapse in the calculations. This is a useful finding that indicates the model setup and methods used to process the traffic data are valid for this case study.
- For the Calm Lapse and Upwind Lapse, a positive deviation between the modeled and measured data is noted, indicating that the model is over-predicting sound levels under these conditions. In particular, the model deviation for the Upwind Lapse condition was approximately +3.5 dBA on

average; such a deviation would be unacceptable for model validation if FHWA and ODOT guidelines are followed. This result is expected as both Lapse and Upwind conditions are expected to reduce sound levels relative to a Calm Neutral atmosphere.

- Performance of the TNM model for the YMS “With Barrier” case was superior to the model performance under the “No Barrier” case across all comparison metrics. As indicated by the tighter clustering of points surrounding the line of modeled = measured, a greater agreement was realized across the board with the barrier present. The average model deviation indicated a slight under-prediction of sound levels ranging from -0.43 dBA at the reference location to -1.9 dBA at the furthest location from the highway. Additionally, 100% of modeled points were within ±3.0 dBA of the measured levels.
- Performance of the TNM model improved as the percentage of trucks increased. It is speculated that this result is a function of the traffic flow being more intermittent during the “No Barrier” measurements, which took place in May 2020 during the COVID-19 pandemic. The quality and distribution of the traffic flow was more typical of the average conditions during the “With Barrier” measurements, which took place in October 2020.

The practical implication for the above findings is that the TNM software is performing in a satisfactory manner for traffic noise prediction under Calm Neutral atmospheric conditions if sufficient details and model development best practices are used. Additionally, the model performance for the With Barrier case was quite good, which is expected given that the primary function of the software is to analyze potential noise barriers and earthen berms for highway project noise mitigation.

M2M Scatter Plot: YMS No Barrier

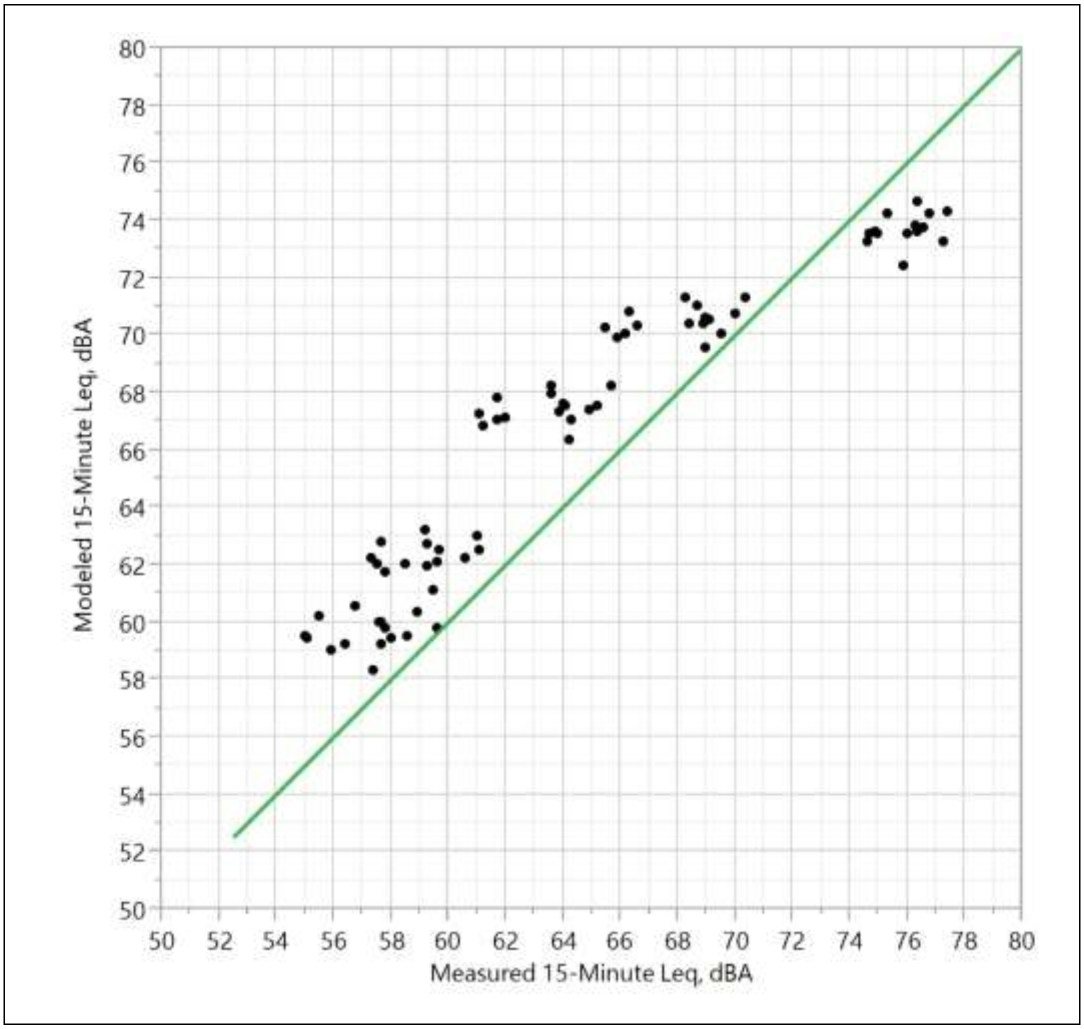


Figure 41: Comparison of Modeled and Measured Sound Levels, YMS No Barrier

M2M Scatter Plot: YMS With Barrier

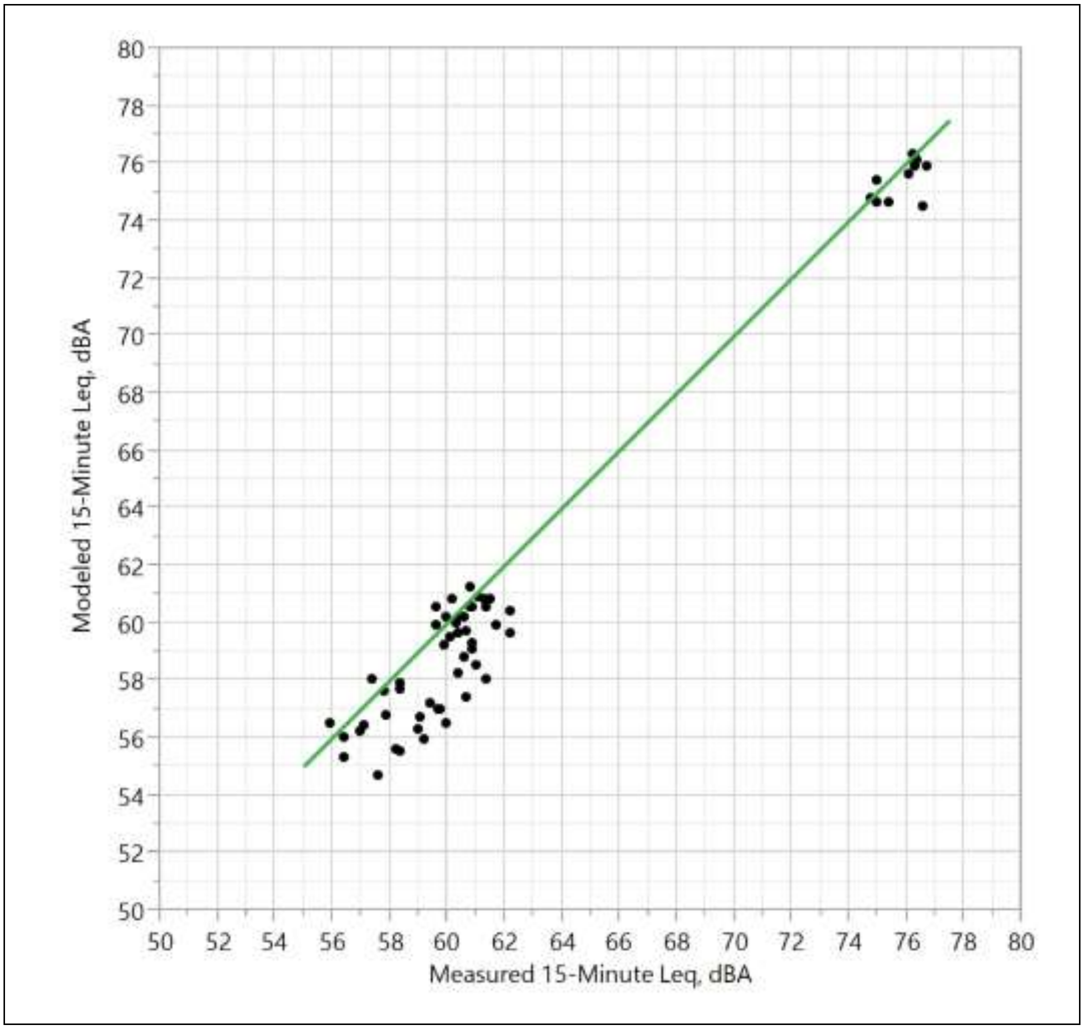
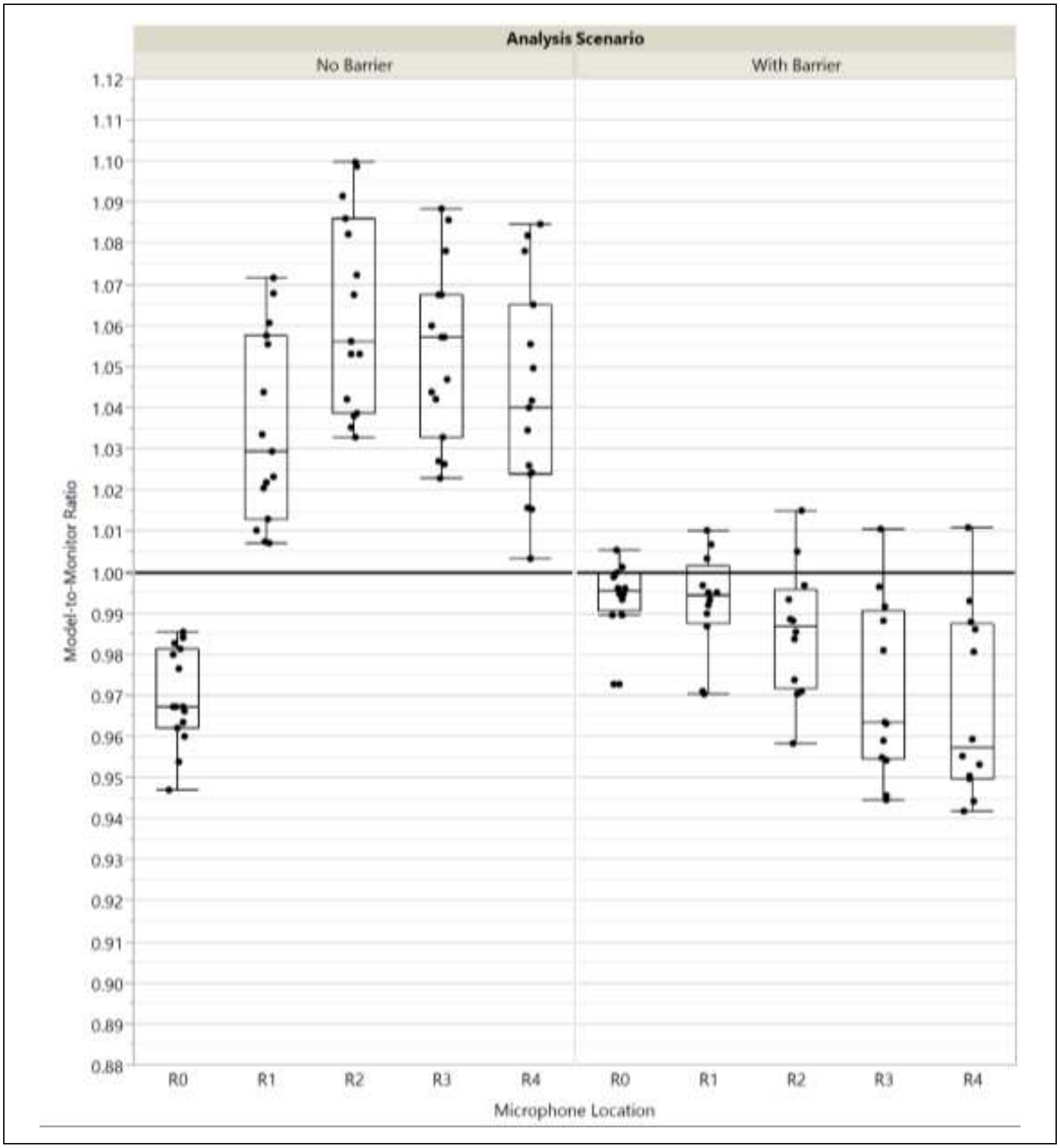


Figure 42: Comparison of Modeled and Measured Sound Levels, YMS With Barrier

M2M Ratio Plot: YMS by Microphone Location



Note: Model-to-monitor ratio of 1.0 indicates Modeled Noise Level = Measured Noise Level

Figure 43: Model-to-Monitor Ratio for YMS All Locations by Barrier Scenario

M2M Comparison Statistics, YMS Study Site

Table 13: Model-to-Monitor Comparison Statistics, YMS Study Site

	No Barrier (N=75)			With Barrier (N=60)		
	Average Model Deviation	Median Model-to-Monitor Ratio	Percent of Observations ± 3.0 dBA	Average Model Deviation	Median Model-to-Monitor Ratio	Percent of Observations ± 3.0 dBA
All Data	**+1.909**	**1.038**	**47/75 (62.7%)**	**-1.082**	**0.988**	**60/60 (100%)**
Microphone Location: R0	-2.320	0.970	15/15 (100%)	-0.433	0.995	12/12 (100%)
Microphone Location: R1	+2.340	1.035	10/15 (66.7%)	-0.458	0.994	12/12 (100%)
Microphone Location: R2	+3.973	1.063	5/15 (33.3%)	-0.875	0.987	12/12 (100%)
Microphone Location: R3	+3.147	1.054	7/15 (46.7%)	-1.742	0.963	12/12 (100%)
Microphone Location: R4	+2.407	1.043	10/15 (66.7%)	-1.900	0.957	12/12 (100%)
Met Condition: Calm Neutral	+0.527	1.010	15/15 (100%)	-0.427	0.993	15/15 (100%)
Met Condition: Calm Lapse	+1.630	1.028	28/40 (70.0%)	-1.130	0.987	30/30 (100%)
Met Condition: Upwind Lapse	+3.505	1.059	4/20 (20.0%)	N/A	N/A	N/A
Met Condition: Downwind Lapse	N/A	N/A	N/A	-1.250	0.980	10/10 (100%)
Met Condition: Calm Inversion	N/A	N/A	N/A	-1.800	0.970	5/5 (100%)
Truck Level: Low (< 7%)	+2.535	1.056	18/40 (45.0%)	N/A	N/A	N/A
Truck Level: Medium (7-10%)	+1.194	1.029	29/35 (64.4%)	-1.915	0.970	20/20 (100%)
Truck Level: High (> 10%)	N/A	N/A	N/A	-0.500	0.992	40/40 (100%)

Model-to-Monitor Analysis Results, SL Study Site

Details of the model-to-monitor (M2M) analysis results for the Shady Lane Neighborhood (NSA 2) site are presented in this section. Data tables and exhibits that correspond to the analysis results are presented herein. Numerical results for the measured and modeled sound levels, and other relevant data from the model-to-monitor analysis, are also summarized in tabular form at the end of this appendix.

Discussion of M2M Analysis Results: SL Study Site

The objective of the analysis for the SL study site was to determine if the TNM building row object or buildings modeled as TNM barrier objects was a better representation of the measured sound level data. Scatter plots comparing the measured and TNM modeled sound levels for the SL location are presented in Figure 44 (Building Row case), Figure 45 (Buildings as Barriers case), and Figure 46 (Buildings Not Modeled case). Box plots showing the model-to-monitor ratio for the three analysis cases are displayed in Figure 47. To interpret the scatter plots, it is noted that the top left half of the plot represents a model over-prediction while the bottom right half represents a model under-prediction of the sound levels. Table 14 presents the numerical values for the average model deviation, median model-to-monitor ratio, and the percentage of observations within 3 dBA of the measured levels for the five microphone positions and each analysis case. From these exhibits, it is evident that the "buildings as barriers" representation has a better overall model performance than the "building rows" representation, across all three model-to-monitor comparison metrics examined. Of particular interest, the model-to-monitor comparisons for the receiver locations behind the first row (R2) and the second row (R3) are substantially improved with the barrier representation case. The model performance behind the third row (R4) is better if the building row model is used; however, with this location being more than 600 feet from the freeway, the measured noise is subject to both highway and non-highway noise sources. Both options for representation of buildings adjacent to the freeway produced superior model results when compared with the option of omitting these structures from any aspect of the TNM layout. For the "With Barrier" analysis case, no substantial differences among the three options for building representation were noted in the model-to-monitor comparison. This finding is consistent with the measured results presented in Appendix C, indicating that the shielding from building rows has a limited impact for noise reduction in the circumstances where the noise barrier is present.

M2M Scatter Plot: SL Building Rows (BR) Model

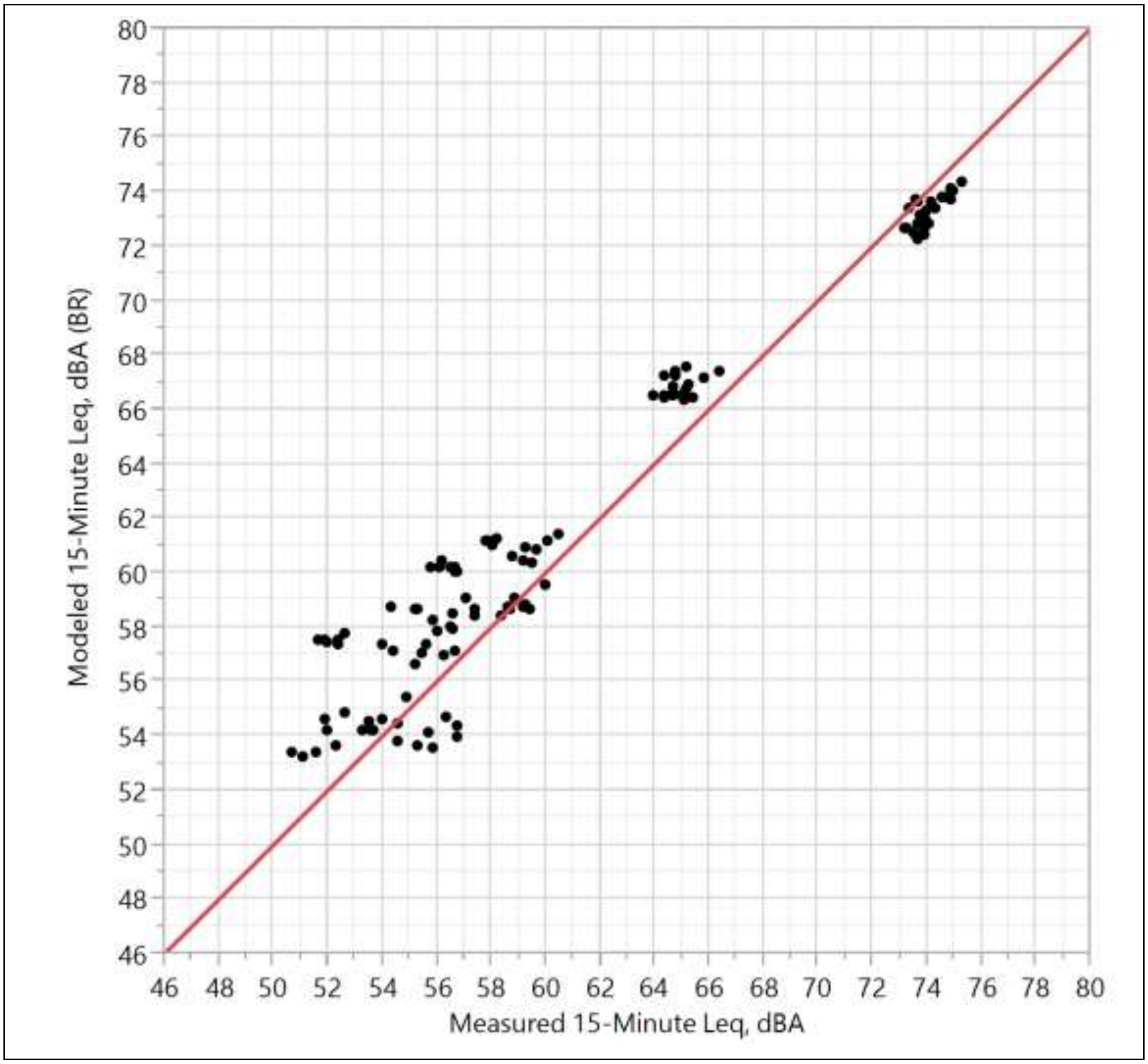


Figure 44: Comparison of Modeled and Measured Sound Levels, SL BR Model

M2M Scatter Plot: SL Buildings as Barriers (BB) Model

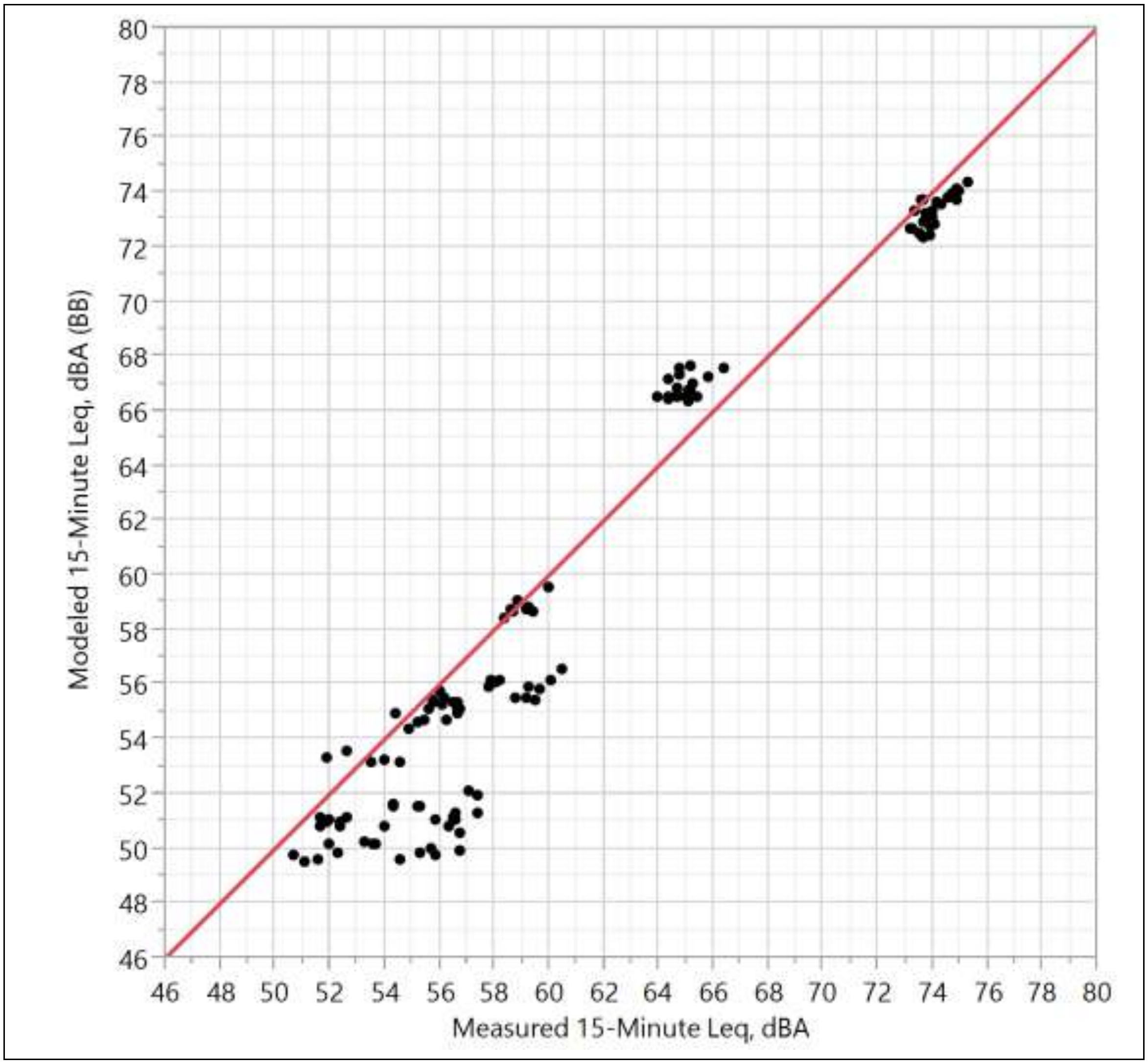


Figure 45: Comparison of Modeled and Measured Sound Levels, SL BB Model

M2M Scatter Plot: SL No Buildings (NM) Model

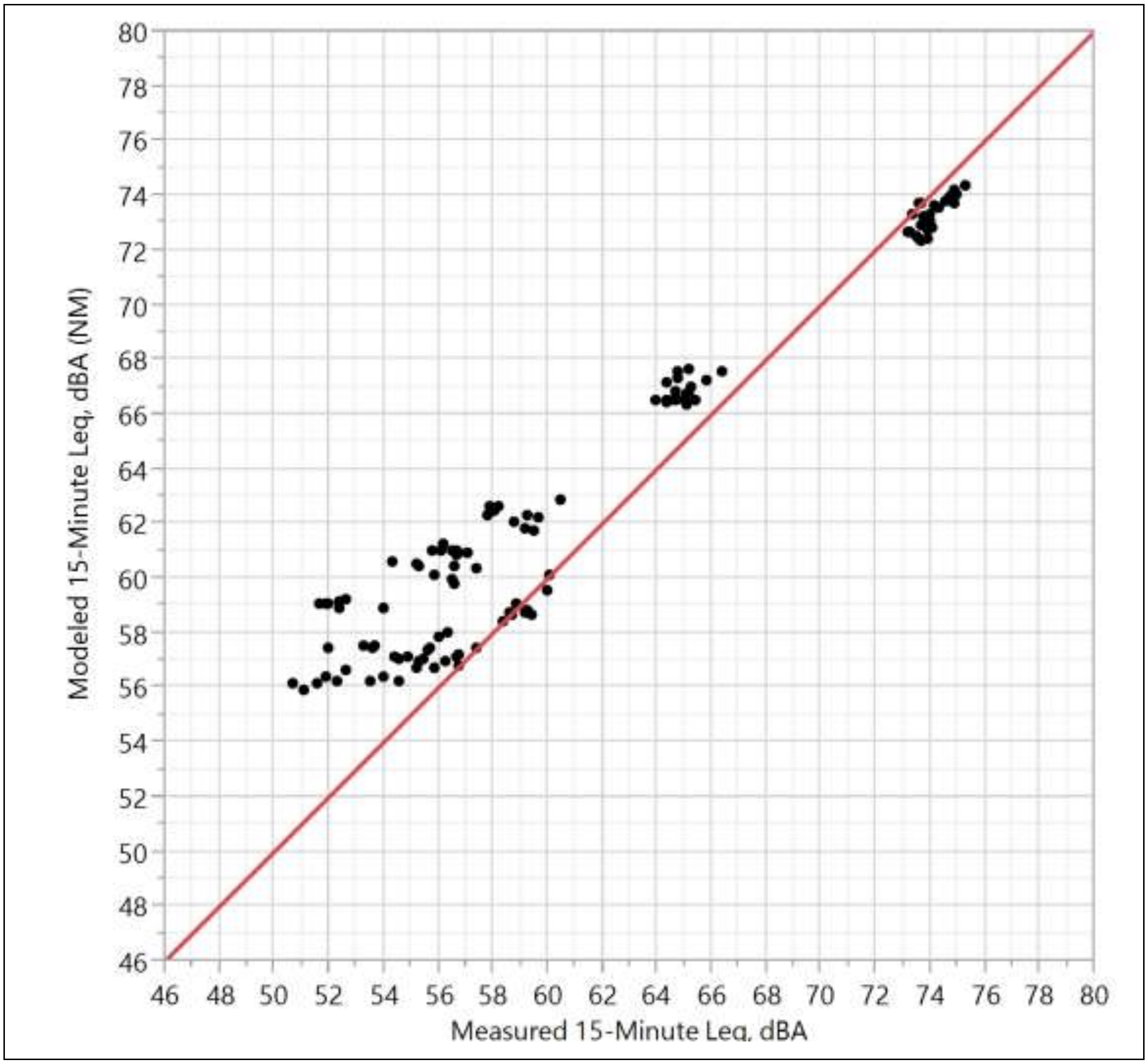
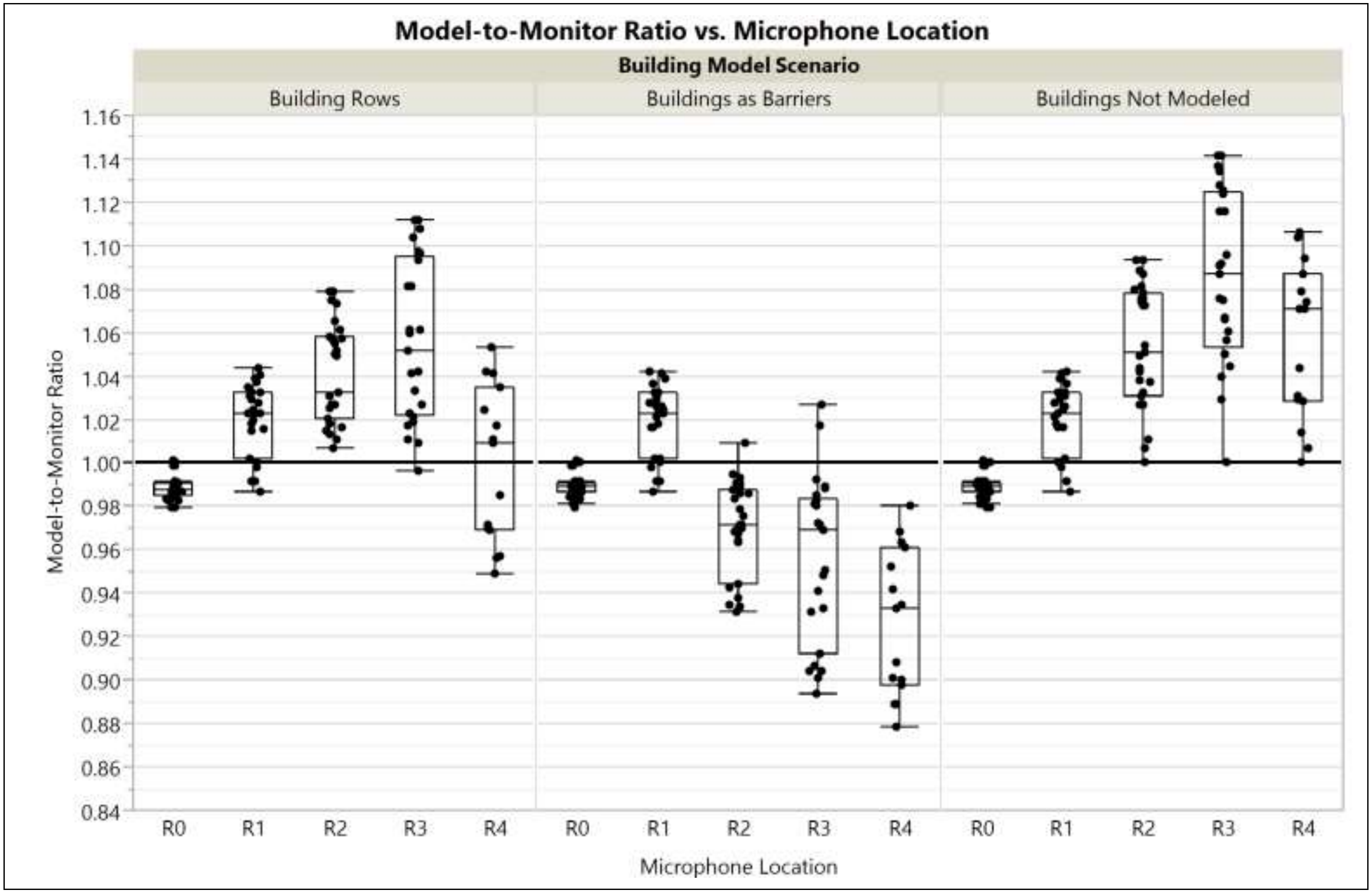


Figure 46: Comparison of Modeled and Measured Sound Levels, SL NM Model

M2M Ratio Plot: SL by Microphone Location



Note: Model-to-monitor ratio of 1.0 indicates Modeled Noise Level = Measured Noise Level

Figure 47: Model-to-Monitor Ratio for SL All Locations by Modeling Scenario

M2M Comparison Statistics, SL Study Site

Table 14: Model-to-Monitor Comparison Statistics, SL Study Site

	Building Rows			**Buildings as Barriers**			**Buildings Not Modeled**		
	Average Model Deviation	**Median Model-to-Monitor Ratio**	**Percent of Observations ± 3.0 dBA**	**Average Model Deviation**	**Median Model-to-Monitor Ratio**	**Percent of Observations ± 3.0 dBA**	**Average Model Deviation**	**Median Model-to-Monitor Ratio**	**Percent of Observations ± 3.0 dBA**
All Data	**1.199**	**1.020**	**99/121 (73%)**	**-1.335**	**0.986**	**94/121 (70%)**	**+2.089**	**1.031**	**81/121 (67%)**
Pre-Clearing	+0.916	1.018	49/55 (89%)	-2.264	0.950	29/55 (53%)	+2.138	1.038	37/55 (67%)
No Barrier	+2.389	1.040	20/36 (56%)	-0.567	0.983	35/36 (97%)	+3.214	1.060	16/36 (44%)
With Barrier	+0.290	1.001	30/30 (100%)	-0.553	0.989	30/30 (100%)	+0.650	1.002	28/30 (93%)
Microphone Location: R0	-0.870	0.988	27/27 (100%)	-0.841	0.989	27/27 (100%)	-0.837	0.989	27/27 (100%)
Microphone Location: R1	+1.204	1.023	27/27 (100%)	+1.233	1.028	27/27 (100%)	+1.233	1.023	27/27 (100%)
Microphone Location: R2	+2.341	1.032	17/27 (47%)	-1.800	1.021	20/27 (100%)	+3.063	1.051	14/27 (52%)
Microphone Location: R3	+2.976	1.052	13/25 (37%)	-2.524	0.998	15/25 (60%)	+4.604	1.087	6/25 (24%)
Microphone Location: R4	-0.100	1.009	15/15 (100%)	-4.027	0.972	5/15 (33%)	+2.953	1.071	7/15 (47%)

TNM Analysis Results: Heavy/Medium Truck Substitution

Another objective of this project was to examine the performance of the validated TNM model if the heavy truck volumes observed for the model are added to the medium truck volumes with substitution ratio or volume multiplier applied to the heavy truck volume. The validated TNM model used at the Yorktown Middle School (NSA 7) study site was used for this analysis. The following substitution ratios were analyzed: 1.0, 1.5, 2.0, 2.5, and 3.0; for example, a substitution ratio of 2.0 means that the observed heavy truck volume for a specific TNM analysis block would be multiplied by a factor of 2 and that amount would be added to the observed volume of medium trucks for that analysis block. Results of the heavy-medium truck substitution ratio analysis are presented in Table 15 for the "No Barrier" case and Table 16 for the "With Barrier" case. Also presented in these tables is the implied "Optimal" substitution ratio based on the results from the simulated ratios.

Table 15: Analysis of Heavy-Medium Truck Substitution Ratios, YMS No Barrier

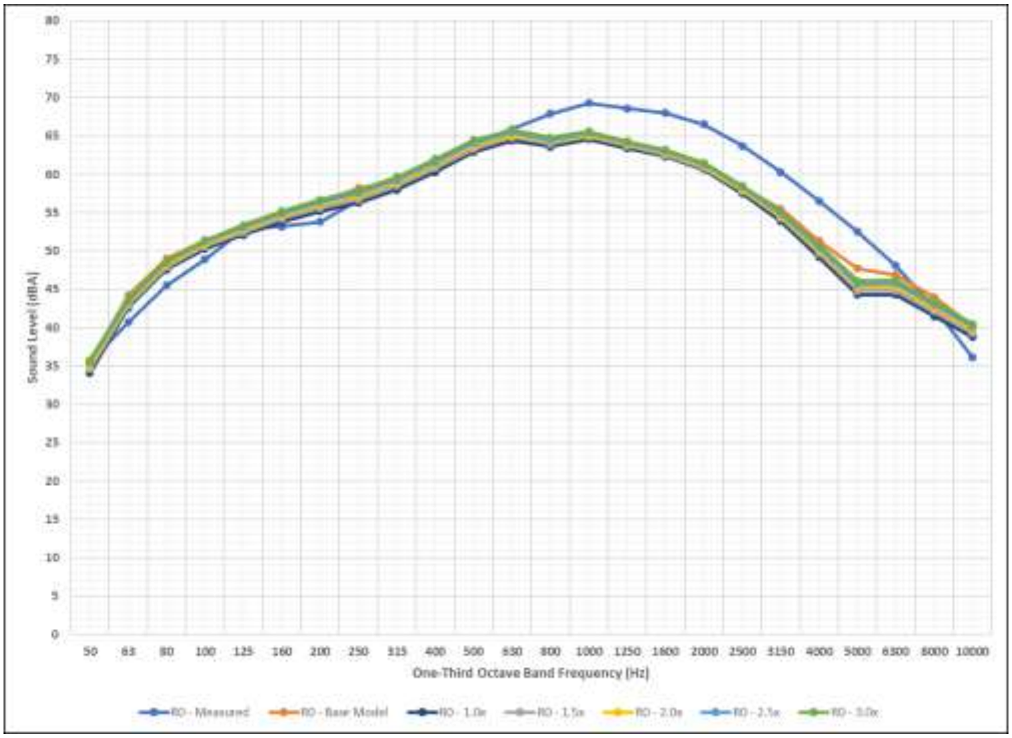
	Measured or Modeled Sound Level (Model Deviation)				
	R0	R1	R2	R3	R4
Measured	76.6	69.8	65.0	60.4	58.3
Base Model	73.5 (-3.1)	70.5 (+0.7)	67.3 (+2.3)	62.1 (+1.7)	59.4 (+1.1)
Ratio = 1.0	72.8 (-3.8)	69.6 (-0.2)	66.2 (+1.2)	60.4 (0.0)	57.3 (-1.0)
Ratio = 1.5	73.1 (-3.5)	70.0 (+0.2)	66.6 (+1.6)	60.7 (+0.3)	57.7 (-0.6)
Ratio = 2.0	73.4 (-3.2)	70.3 (+0.5)	66.9 (+1.9)	61.1 (+0.7)	58.1 (-0.2)
Ratio = 2.5	73.7 (-2.9)	70.5 (+0.7)	67.2 (+2.2)	61.4 (+1.0)	58.5 (+0.2)
Ratio = 3.0	74.0 (-2.6)	70.8 (+1.0)	67.4 (+2.4)	61.7 (+1.3)	58.7 (+0.4)
"Optimal"	> 3.0	≈ 1.25	< 1.0	≈ 1.0	≈ 2.25

Table 16: Analysis of Heavy-Medium Truck Substitution Ratios, YMS With Barrier

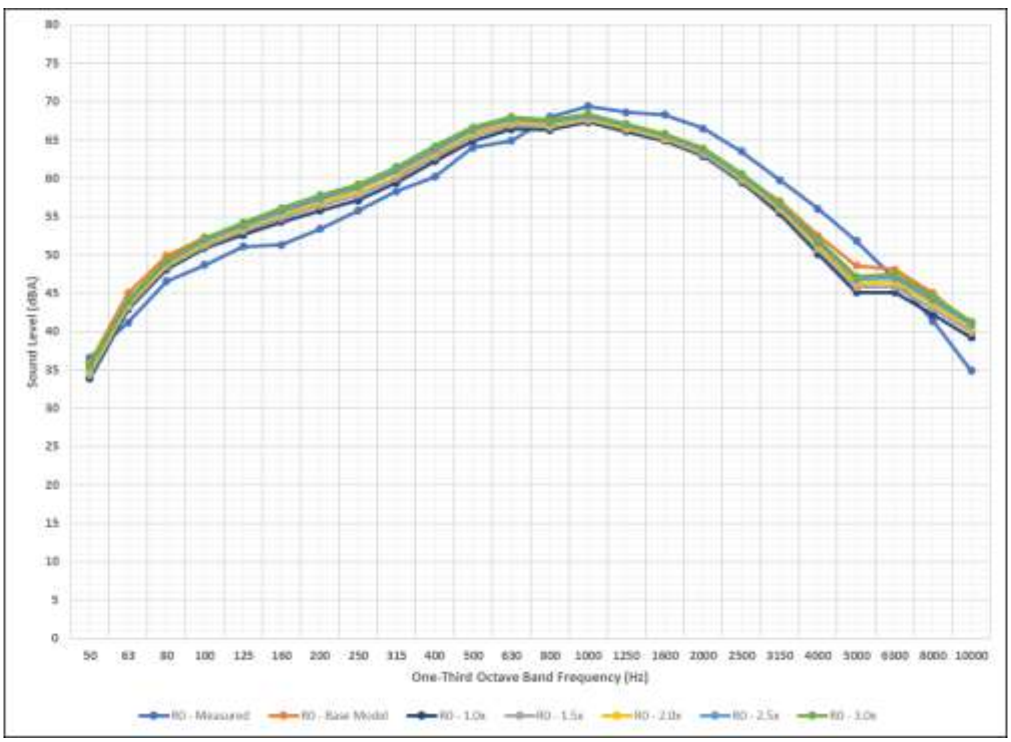
	Measured or Modeled Sound Level (Model Deviation)				
	R0	R1	R2	R3	R4
Measured	76.2	60.3	60.0	58.0	56.6
Base Model	75.5 (-0.7)	60.1 (-0.2)	59.8 (-0.2)	57.4 (-0.6)	55.8 (-0.8)
Ratio = 1.0	74.7 (-1.5)	58.9 (-1.4)	58.5 (-1.5)	55.7 (-2.3)	54 (-2.6)
Ratio = 1.5	75.1 (-1.1)	59.4 (-0.9)	58.9 (-1.1)	56.1 (-1.9)	54.4 (-2.2)
Ratio = 2.0	75.4 (-0.8)	59.8 (-0.5)	59.3 (-0.7)	56.5 (-1.5)	54.8 (-1.8)
Ratio = 2.5	75.7 (-0.5)	60.1 (-0.2)	59.7 (-0.3)	56.9 (-1.1)	55.2 (-1.4)
Ratio = 3.0	76.0 (-0.2)	60.5 (+0.2)	60.0 (0.0)	57.2 (-0.8)	55.5 (-1.1)
"Optimal"	> 3.0	≈ 2.75	≈ 3.0	> 3.0	> 3.0

Referring to the results presented in Table 15, the tested multipliers do not improve the predictive accuracy of the model in any meaningful way with the exception of the location furthest from the highway (R4). In the YMS "No Barrier" case, with the exception of R0, it is unclear why the levels under ratios 1.0, 1.5, 2.0 and 2.5 are higher than the base model levels after eliminating the high truck exhaust stack noise. It is suspected that variations in the model validation are due to factors outside of TNM's control. This would include complex reflections from the multiple median barriers as well as variations in the composition of MT and HT on the freeway at the time. Examining the results in Table 16, it is evident that a volume multiplier that is approximately greater than or equal to 3.0 may provide a better match between the measured and modeled broadband sound levels, although it is noted that the overall model performance is quite satisfactory using the traditional approach with no volume adjustments. The difference in the "optimal" multipliers between the No Barrier and With Barrier case underscores the difficulty in attempting to improve the results of the TNM modeling by applying the proposed truck volume substitution approach. In particular, if the optimal ratio for the "With Barrier" case (≈3.0 or higher) is applied to the "No Barrier" volumes, the "no build" noise impacts would almost certainly be overstated, and the resulting recommended noise barrier height would be taller than necessary.

To provide additional context for the discussion surrounding the potential for substitution of heavy truck volumes with medium truck volumes at various substitution ratios, the measured and modeled (base case and simulated substitution ratios) sound levels at different one-third octave band frequency levels were analyzed. These comparisons are presented in Figure 48 through Figure 52. For the reference microphone (R0) location (Figure 48), the measured noise levels are higher than the modeled levels in the higher frequency ranges (above 1,000 Hz) but the modeled levels are a good match for the measured levels below 1,000 Hz. For all of the 5-foot height microphones, there is a noticeable difference in the measured and modeled sound levels in the range between 200 and 800 Hz in both the No Barrier and With Barrier cases. Additionally, for the With Barrier cases, the measured sound levels at the higher frequency bands are higher than the modeled levels for the ground-level receiver locations. These discrepancies are reasonably expected due to sound wave behavior that is not modeled in TNM (e.g., reflections from median barriers), minor discrepancies between the TNM vehicle types and the characteristics of the vehicles for which the noise was actually measured, and complex reflections from the ground or other propagation path features. It is noted, however, from the results presented in Figure 48 through Figure 52, it is evident that the proposed substitution of heavy truck volumes with medium truck volumes in the TNM software with various multipliers applied do not have a significant effect overall at improving the modeled sound levels for either broadband or individual frequency bands.

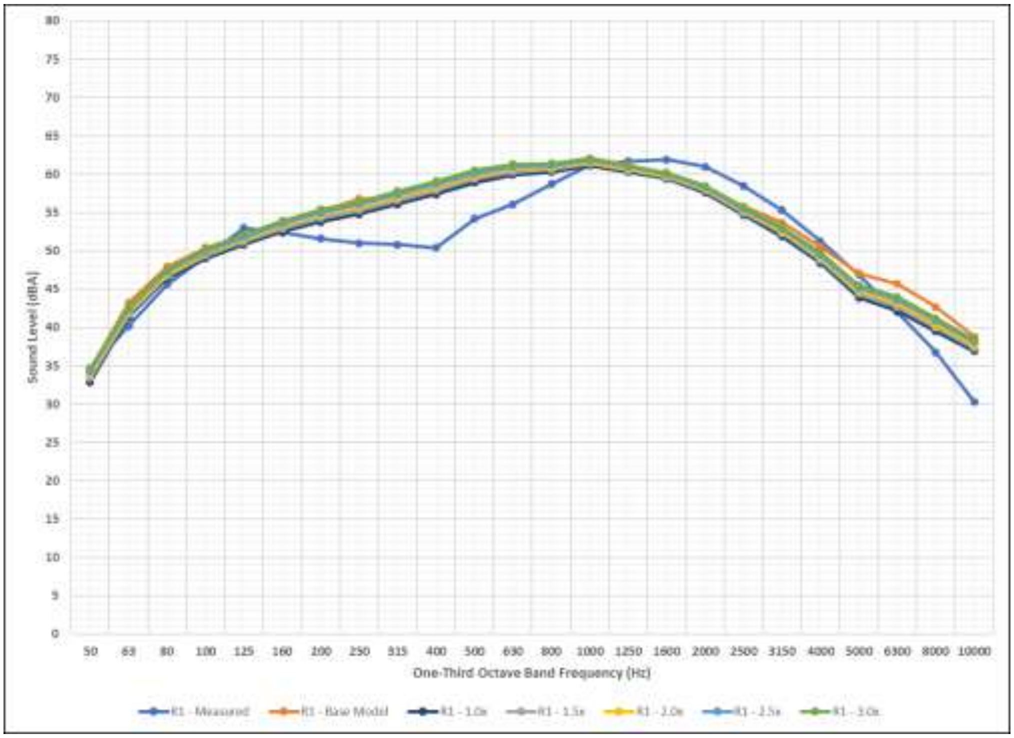


[a] YMS R0 No Barrier (TNM Blocks: 05270600, 05270649, 05270715)

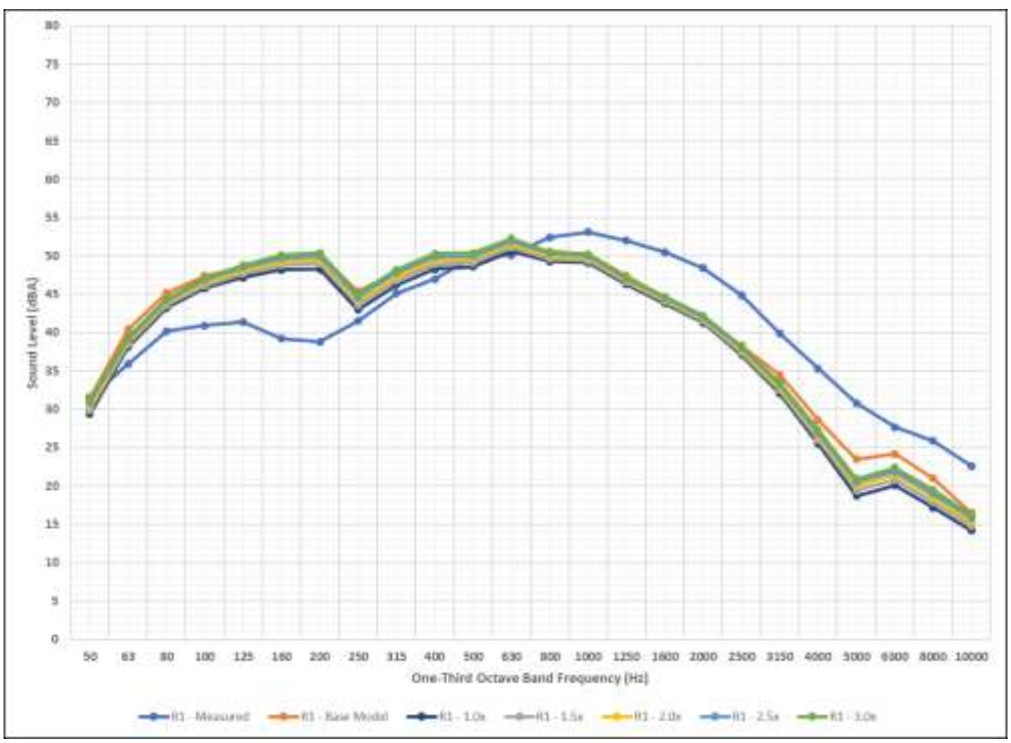


[b] YMS R0 With Barrier (TNM Blocks: 10090947, 10091006)

Figure 48: Comparison of HT:MT Ratios, YMS R0 Location

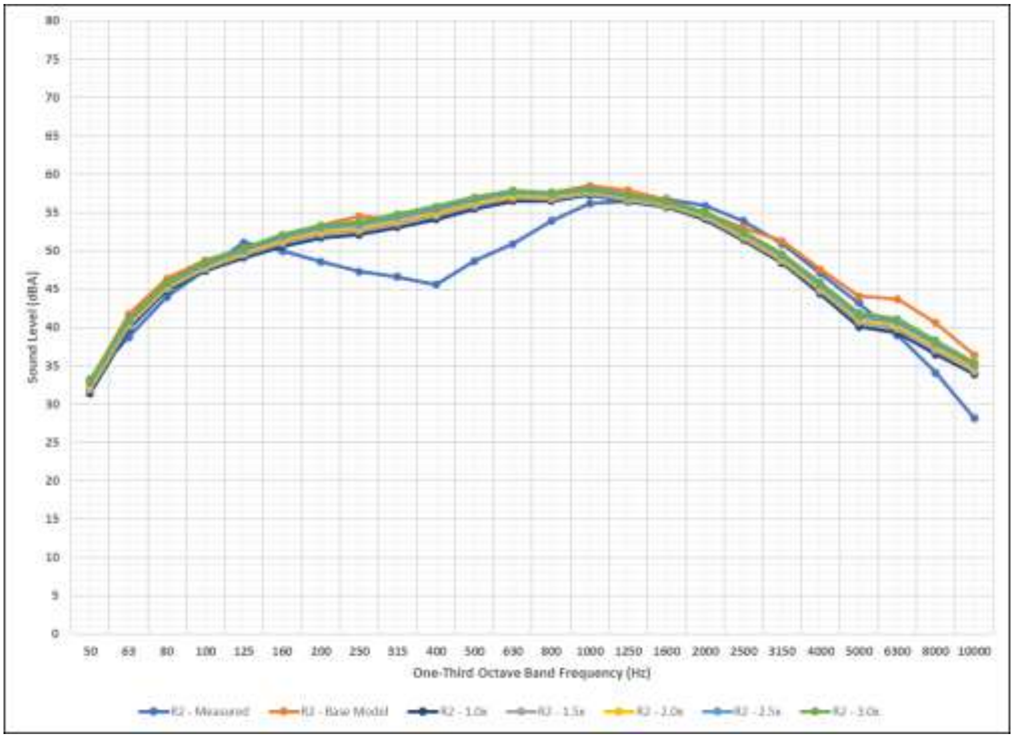


[a] YMS R1 No Barrier (TNM Blocks: 05270600, 05270649, 05270715)

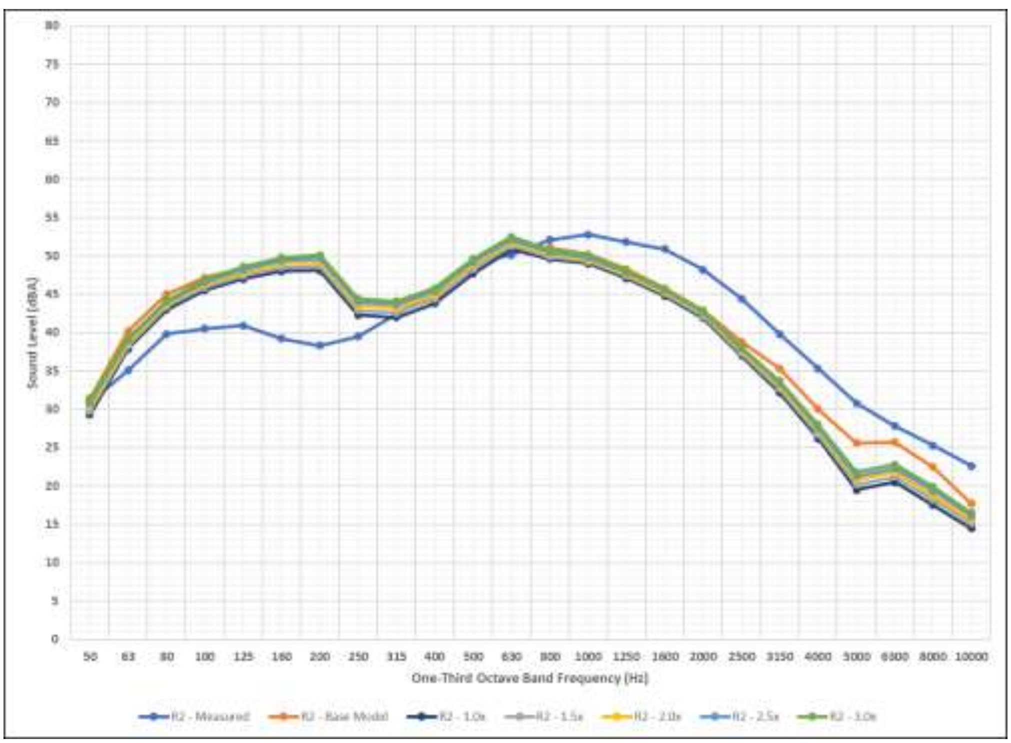


[b] YMS R1 With Barrier (TNM Blocks: 10090947, 10091006)

Figure 49: Comparison of HT:MT Ratios, YMS R1 Location

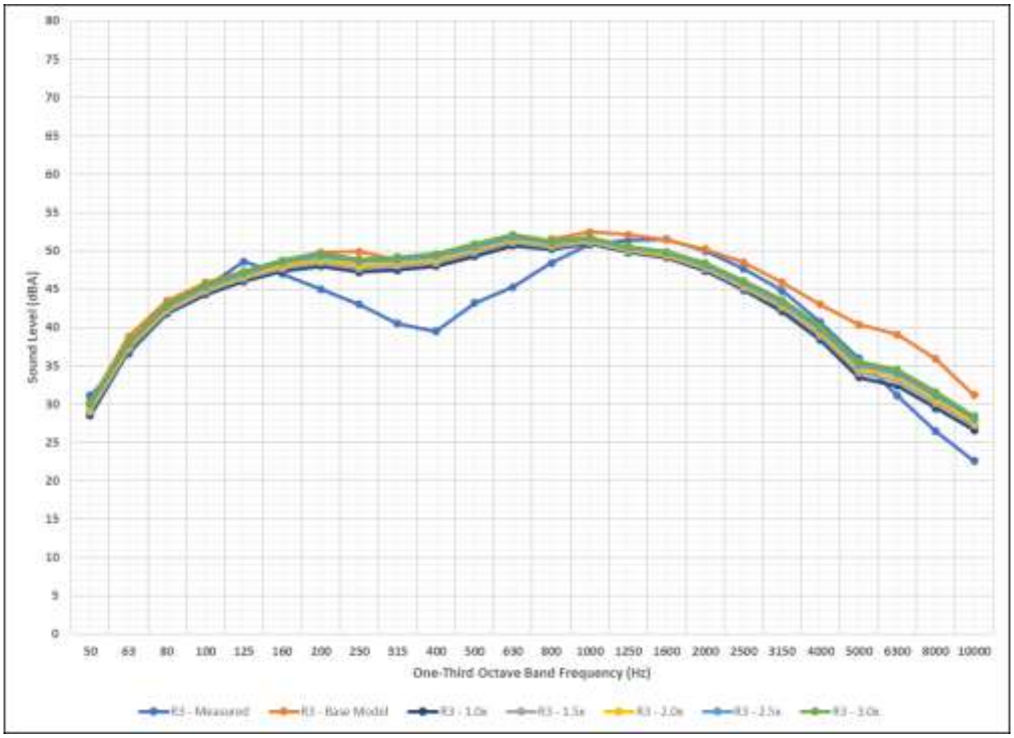


[a] YMS R2 No Barrier (TNM Blocks: 05270600, 05270649, 05270715)

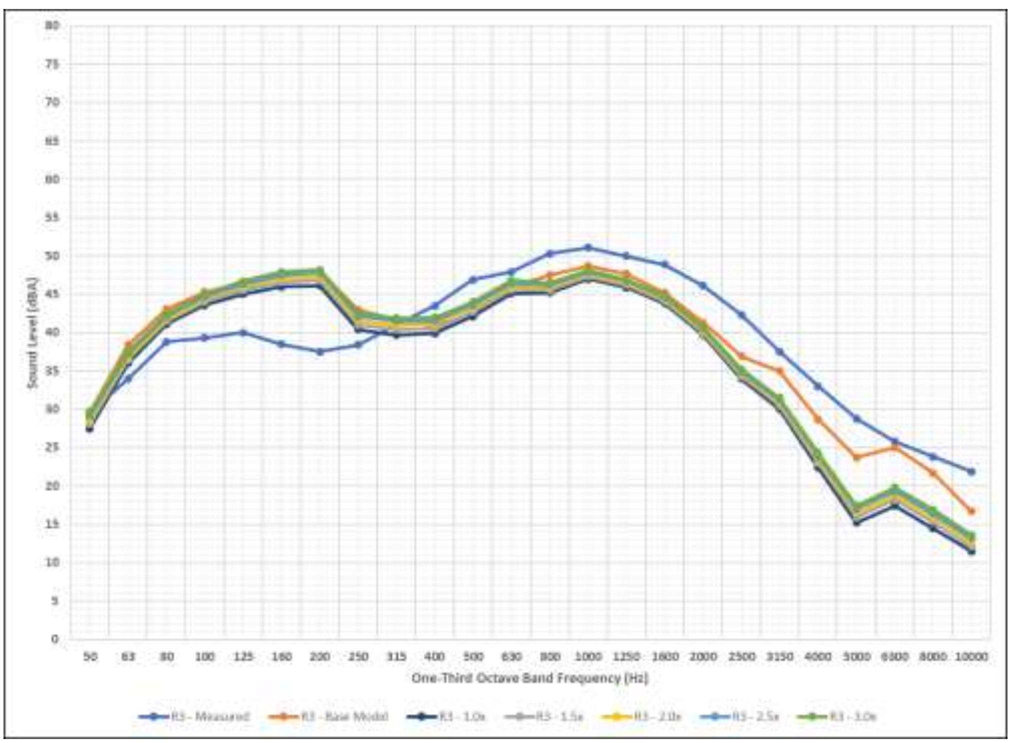


[b] YMS R2 With Barrier (TNM Blocks: 10090947, 10091006)

Figure 50: Comparison of HT:MT Ratios, YMS R2 Location

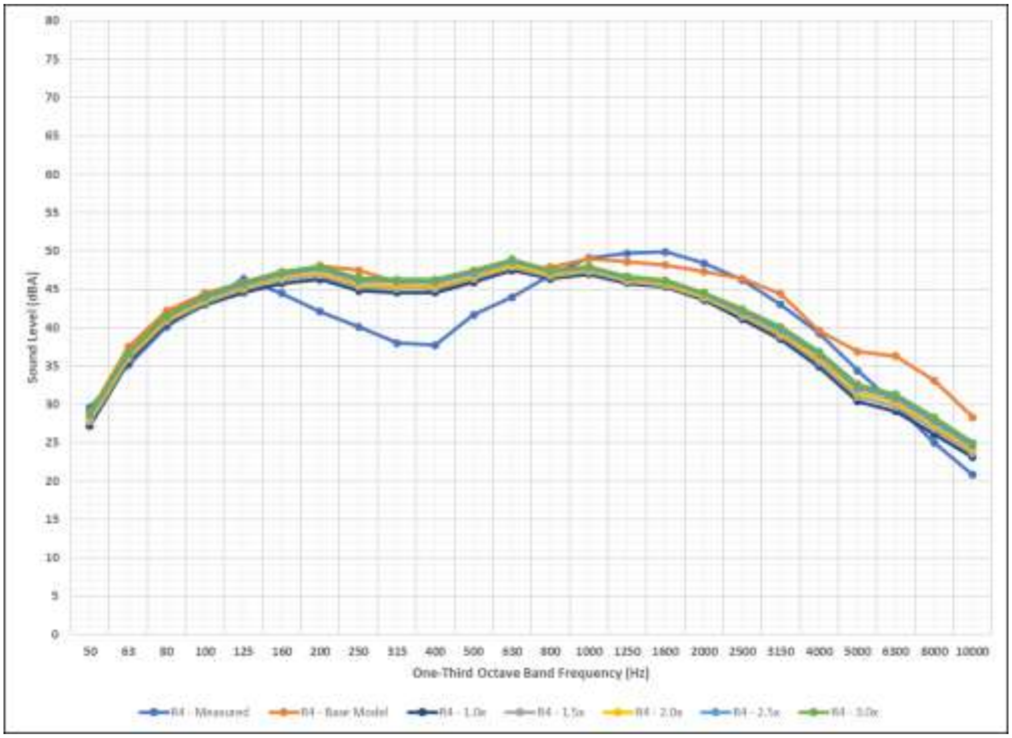


[a] YMS R3 No Barrier (TNM Blocks: 05270600, 05270649, 05270715)

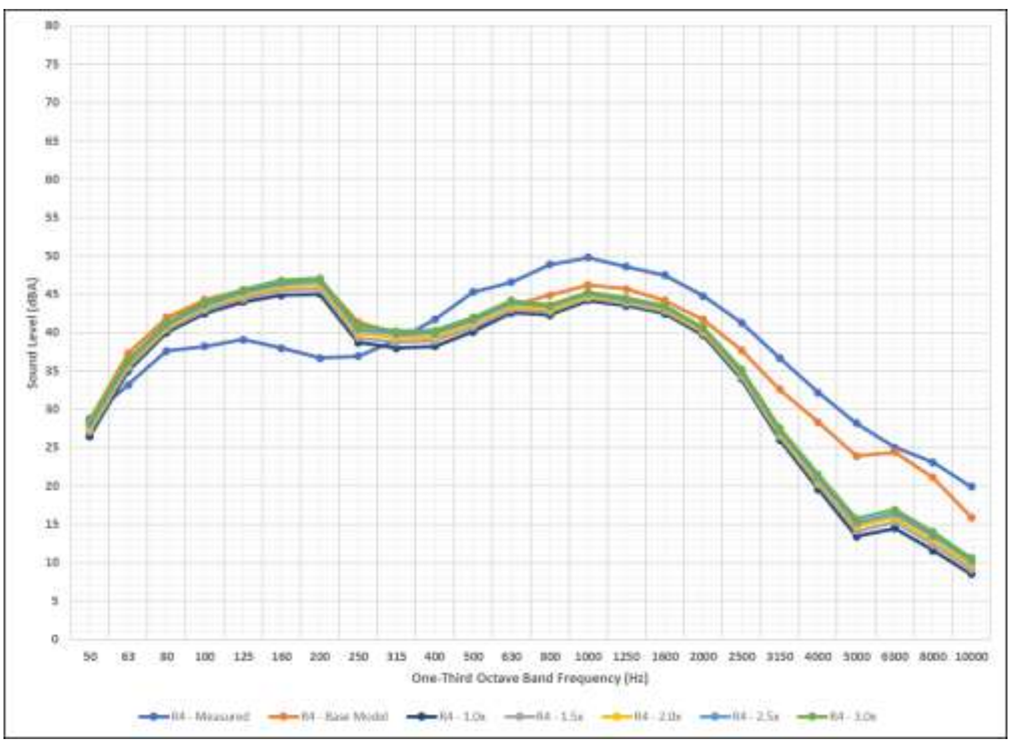


[b] YMS R3 With Barrier (TNM Blocks: 10090947, 10091006)

Figure 51: Comparison of HT:MT Ratios, YMS R3 Location



[a] YMS R4 No Barrier (TNM Blocks: 05270600, 05270649, 05270715)



[b] YMS R4 With Barrier (TNM Blocks: 10090947, 10091006)

Figure 52: Comparison of HT:MT Ratios, YMS R4 Location

Comparison with Consultant Traffic Noise Study

All ODOT noise barrier projects are required to be based on a detailed traffic noise analysis and modeling study carried out by a consultant that is prequalified for this type of work. The traffic noise analysis study prepared for the case study noise barrier construction project (McCormick Taylor, 2013) was reviewed and the results compared to the findings of the current research study, where applicable. These comparisons are presented in Table 17 for the YMS study site and Table 18 for the SL study site. For the YMS study site, the results of the current research study were basically similar to the results of the consultant traffic noise study for the "No Barrier" case, for both measured data and modeled data at comparable distances from the freeway. The model deviation comparing the field-measured and TNM-modeled noise levels was also consistent between the two studies, with the TNM validated noise levels being approximately 2.0 dBA higher than measured noise levels across three comparisons). However, for the "With Barrier" case, the noise reduction attributed to the noise barrier measured for the current research study was lower than both the consultant model estimates and the estimated reduction from the modeling carried out as part of the current research.

For the SL study site, the measured noise levels for the current study were approximately 4.0 to 5.0 dBA higher than what was measured in the consultant study (pre-construction conditions) even though the traffic was lower in the current study due to the COVID-19 pandemic. However, the modeled noise levels were consistent between the two studies for the pre-construction condition. Additionally, the measured and modeled shielding effect of the first row of residential structures at the SL study site was consistent between the consultant study and the current research study for the pre-construction condition. However, for the "With Barrier" case, the estimated noise reduction attributed to the first row of residential building structures was higher in the consultant study (5.5 dBA) than what was measured by the research team in the current study (3.6 dBA for buildings as barriers representation). This finding is particularly interesting because the consultant study utilized a different approach to modeling the residential structures than what was investigated in the current study. With respect to the noise barrier reductions, the effect of the noise barrier was measured to be approximately 3 dBA higher in the current study as compared with what had been estimated in the consultant study for the first-row backyard location. The effect of the noise barrier for the second-row front yard location was consistent between the measured results of the current study and the estimated noise barrier performance from the consultant traffic noise study.

Appendix D Data Tables and Figures

Comparison with Consultant Traffic Noise Study

Table 17: Comparison of Current Study and Consultant Study, YMS Study Site

		Current Study	Consultant Study	Comments
Measurement Details	**Dates**	NB: 5/26/20 and 5/27/20 WB: 10/8/20 and 10/9/20	8/7/2012	
	Day(s) of Week	NB: Thursday/Friday WB: Thursday/Friday	Tuesday	
	Time(s) of Day	6:00 A.M. to 12:00 P.M. 2:00 P.M. to 8:00 P.M.	5:05 to 5:15 P.M.	
Traffic Conditions (Northbound IR-270)	**Total (NB)**	Average: 3,141 veh/hr	1,798 veh/hr	Current Study Higher
	HT (NB)	Average: 199 veh/hr (6.3%)	69 veh/hr (3.8%)	
	Total (WB)	Average: 2,866 veh/hr	5,526 veh/hr	Design Year Traffic for Consultant Study*
	HT (WB)	Average: 222 veh/hr (7.7%)	87 veh/hr (1.6%)	
Receptor Details	**Location**	Locations YMS R2/R3	NSA 7 Location R19	
	Distance from Freeway	R2: 165 Feet R3: 315 Feet	255 Feet	
	Average Leq (Measured, NB)	R2: 65.0 dBA R3: 60.4 dBA	63.5 dBA	Results Similar
	Average Leq (Modeled, NB)	R2: 67.3 dBA R3: 62.1 dBA	Validated: 65.4 dBA Design Year: 68.2 dBA	Results Similar
	Average Leq (Measured, WB)	R2: 60.0 dBA R3: 58.0 dBA	N/A	
	Average Leq (Modeled, WB)	R2: 59.8 dBA R3: 57.4 dBA	Design Year: 61.7 dBA (Height 14 feet)	No Direct Comparison
Noise Barrier Reduction	**Measured (WB)**	R2: 5.0 dBA R3: 2.3 dBA	N/A	
	Modeled (WB)	R2: 7.6 dBA R3: 4.7 dBA	6.5 dBA	Results Similar
Note: NB = No Barrier; WB = With Barrier;				
*Traffic conditions for consultant study correspond to validation traffic levels (NB) and design year traffic levels (WB).				

Table 18: Comparison of Current Study and Consultant Study, SL Study Site

		Current Study	Consultant Study	Comments
Measurement Details	Dates	PC: 9/17/19 and 9/19/19 WB: 7/23/21	8/7/12	
	Day(s) of Week	PC: Tuesday/Thursday WB: Friday	Tuesday	
	Time(s) of Day	9:00 A.M. to 2:00 P.M.	4:15 - 4:30 P.M.	
Traffic Conditions (Southbound IR-270)	SB Total (PC)	Average: 2,826 veh/hr	4,144 veh/hr	Validation Traffic for Consultant Study*
	SB HT (PC)	Average: 226 veh/hr (8.0%)	92 veh/hr (2.2%)	
	SB Total (WB)	Average: 3,219 veh/hr	6,222 veh/hr	Design Year Traffic for Consultant Study*
	SB HT (WB)	Average: 231 veh/hr (7.2%)	99 veh/hr (1.6%)	
First Row Details	Location	1400 Knollwood (R1)	1392 Knollwood (R9)	
	Average Leq (Measured, PC)	65.2 dBA	60.4 dBA	Model Deviations Similar
	Average Leq (Modeled, PC)	67.0 dBA	Validated: 62.4 dBA Design Year: 67.8 dBA	
	Average Leq (Measured, WB)	59.1 dBA	N/A	No Direct Comparison
	Average Leq (Modeled, WB)	58.5 dBA	62.0 dBA	
Second Row Details	Location	1397 Knollwood (R2)	1385 Knollwood (R8)	
	Average Leq (Measured, PC)	59.0 dBA	55.2 dBA	Model Deviations Similar
	Average Leq (Modeled, PC)	BR: 60.9 dBA; BB: 59.4 dBA	Validated: 56.7 dBA Design Year: 60.5 dBA	
	Average Leq (Measured, WB)	55.7 dBA	N/A	No Direct Comparison
	Average Leq (Modeled, WB)	BR: 57.1 dBA; BB: 54.9 dBA	56.5 dBA	
First Row Noise Reduction	Measured (PC)	6.2 dBA	5.2 dBA	Results Similar
	Modeled (PC)	BR: 6.1 dBA; BB: 7.6 dBA	Validated: 5.7 dBA Design Year: 7.3 dBA	
	Measured (WB)	3.4 dBA	N/A	Consultant Study Higher
	Modeled (WB)	BR: 1.4 dBA; BB: 3.6 dBA	5.5 dBA	
Noise Barrier Reduction (First Row Backyard)	Measured (WB)	6.1 dBA	N/A	Current Study Higher
	Modeled (WB)	8.5 dBA	5.8 dBA	
Noise Barrier Reduction (Second Row Front Yard)	Measured (WB)	3.3 dBA	N/A	Results Similar
	Modeled (WB)	BR: 3.8 dBA; BB: 4.5 dBA	4.0 dBA	

Note: PC = Pre-Clearing; WB = With Barrier; BR = Building Rows; BB = Buildings as Barriers

*Traffic conditions for consultant study correspond to validation traffic levels (PC) and design year traffic levels (WB). Modeled traffic noise levels for consultant study based on TNM model data provided in noise barrier design tables with residential structures in the first row of homes modeled as a nearly-enclosed four-sided TNM building row object with a 20% building percentage. Additional rows were not modeled.

Data Tables: Measured and Modeled Sound Levels

Table 19: TNM Analysis Blocks and Meteorological Conditions, YMS Study Site

Block	Scenario	Date	Time	Duration	Met Condition	Temperature	RH	Wind Condition	Vector Wind Speed
5270600	NB	9/19/2019	6:00 AM	15 Minutes	Calm Neutral	71°	65%	Calm	1.0-2.0 mi/h
5270649	NB	9/19/2019	6:49 AM	15 Minutes	Calm Neutral	70°; 67%)	67%	Calm	1.0-2.0 mi/h
5270715	NB	9/19/2019	7:15 AM	15 Minutes	Calm Neutral	70°; 68%)	68%	Calm	1.0-2.0 mi/h
5270805	NB	9/19/2019	8:05 AM	15 Minutes	Calm Lapse	71°; 68%)	68%	Calm	1.0-2.0 mi/h
5270837	NB	9/19/2019	8:37 AM	15 Minutes	Calm Lapse	72°; 68%)	68%	Calm	1.0-2.0 mi/h
5270940	NB	9/19/2019	9:40 AM	15 Minutes	Calm Lapse	74°; 66%)	66%	Calm	1.0-2.0 mi/h
5271029	NB	9/19/2019	10:29 AM	15 Minutes	Calm Lapse	77°; 60%)	60%	Calm	< 1.0 mi/h
5271105	NB	9/19/2019	11:05 AM	15 Minutes	Calm Lapse	77°; 58%)	58%	Calm	< 1.0 mi/h
5271125	NB	9/19/2019	11:25 AM	15 Minutes	Calm Lapse	79°; 57%)	57%	Calm	< 1.0 mi/h
5261524	NB	9/17/2019	3:24 PM	15 Minutes	Calm Lapse	88°; 43%)	43%	Calm	1.0-2.0 mi/h
5261558	NB	9/17/2019	3:58 PM	15 Minutes	Upwind Lapse	88°; 39%)	39%	Upwind	2.0-5.0 mi/h
5261629	NB	6/1/2020	4:29 PM	15 Minutes	Upwind Lapse	89°; 37%)	37%	Upwind	2.0-5.0 mi/h
5261712	NB	6/1/2020	5:12 PM	15 Minutes	Upwind Lapse	89°; 33%)	33%	Upwind	2.0-5.0 mi/h
5261754	NB	6/1/2020	5:54 PM	15 Minutes	Upwind Lapse	90°; 32%)	32%	Upwind	2.0-5.0 mi/h
5261809	NB	6/1/2020	6:09 PM	15 Minutes	Calm Lapse	88°; 32%)	32%	Calm	1.0-2.0 mi/h
10090947	WB	6/1/2020	9:47 AM	15 Minutes	Calm Neutral	59°; 62%)	62%	Calm	< 1.0 mi/h
10091006	WB	6/1/2020	10:06 AM	15 Minutes	Calm Neutral	60°; 61%)	61%	Calm	< 1.0 mi/h
10091045	WB	6/1/2020	10:45 AM	15 Minutes	Calm Lapse	64°; 55%)	55%	Calm	< 1.0 mi/h
10091104	WB	6/1/2020	11:04 AM	15 Minutes	Calm Lapse	66°; 52%)	52%	Calm	< 1.0 mi/h
10081440	WB	7/23/2021	2:40 PM	15 Minutes	Downwind Lapse	68°; 36%)	36%	Downwind	2.0-5.0 mi/h
10081506	WB	7/23/2021	3:06 PM	15 Minutes	Downwind Lapse	70°; 35%)	35%	Downwind	2.0-5.0 mi/h
10081648	WB	7/23/2021	4:48 PM	15 Minutes	Calm Lapse	71°; 32%)	32%	Calm	< 1.0 mi/h
10081707	WB	7/23/2021	5:07 PM	15 Minutes	Calm Lapse	71°; 33%)	33%	Calm	< 1.0 mi/h
10081753	WB	7/23/2021	5:53 PM	15 Minutes	Calm Lapse	70°; 33%)	33%	Calm	< 1.0 mi/h
10081821	WB	7/23/2021	6:21 PM	15 Minutes	Calm Lapse	70°; 32%)	32%	Calm	< 1.0 mi/h
10081850	WB	7/23/2021	6:50 PM	15 Minutes	Calm Neutral	66°; 40%)	40%	Calm	< 1.0 mi/h
10081915	WB	7/23/2021	7:15 PM	15 Minutes	Calm Inversion	63°; 48%)	48%	Calm	< 1.0 mi/h

Table 20: Measured and Modeled Sound Levels: YMS R0 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Modeled	Deviation	M/M Ratio
5270600	NB	Calm Neutral (71°; 65%)	75.9	72.4	-3.5	0.954
5270649	NB	Calm Neutral (70°; 67%)	76.6	73.7	-2.9	0.962
5270715	NB	Calm Neutral (70°; 68%)	77.4	74.3	-3.1	0.960
5270805	NB	Calm Lapse (71°; 68%)	76.4	73.6	-2.8	0.963
5270837	NB	Calm Lapse (72°; 68%)	76.8	74.2	-2.6	0.966
5270940	NB	Calm Lapse (74°; 66%)	76.3	73.8	-2.5	0.967
5271029	NB	Calm Lapse (77°; 60%)	76.0	73.5	-2.5	0.967
5271105	NB	Calm Lapse (77°; 58%)	77.3	73.2	-4.1	0.947
5271125	NB	Calm Lapse (79°; 57%)	76.0	73.5	-2.5	0.967
5261524	NB	Calm Lapse (88°; 43%)	76.4	74.6	-1.8	0.976
5261558	NB	Upwind Lapse (88°; 39%)	74.7	73.5	-1.2	0.984
5261629	NB	Upwind Lapse (89°; 37%)	74.9	73.6	-1.3	0.983
5261712	NB	Upwind Lapse (89°; 33%)	75.3	74.2	-1.1	0.985
5261754	NB	Upwind Lapse (90°; 32%)	74.6	73.2	-1.4	0.981
5261809	NB	Calm Lapse (88°; 32%)	75.0	73.5	-1.5	0.980
10090947	WB	Calm Neutral (59°; 62%)	76.3	76.0	-0.3	0.995
10091006	WB	Calm Neutral (60°; 61%)	76.1	75.6	-0.5	0.994
10091045	WB	Calm Lapse (64°; 55%)	76.3	76.2	-0.1	0.998
10091104	WB	Calm Lapse (66°; 52%)	76.7	75.9	-0.8	0.990
10081440	WB	Downwind Lapse (68°; 36%)	76.4	76.1	-0.3	0.997
10081506	WB	Downwind Lapse (70°; 35%)	76.2	76.3	+0.1	1.002
10081648	WB	Calm Lapse (71°; 32%)	76.6	74.5	-2.1	0.973
10081707	WB	Calm Lapse (71°; 33%)	76.3	75.9	-0.4	0.995
10081753	WB	Calm Lapse (70°; 33%)	75.4	74.6	-0.8	0.989
10081821	WB	Calm Lapse (70°; 32%)	75.0	75.4	+0.4	1.005
10081850	WB	Calm Neutral (66°; 40%)	74.8	74.8	0.0	1.000
10081915	WB	Calm Inversion (63°; 48%)	75.0	74.6	-0.4	0.995
Note: NB = No Barrier; WB = With Barrier						

Table 21: Measured and Modeled Sound Levels: YMS R1 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Modeled	Deviation	M/M Ratio
5270600	NB	Calm Neutral (71°; 65%)	69.0	69.5	+0.5	1.007
5270649	NB	Calm Neutral (70°; 67%)	70.0	70.7	+0.7	1.010
5270715	NB	Calm Neutral (70°; 68%)	70.4	71.3	+0.9	1.013
5270805	NB	Calm Lapse (71°; 68%)	69.1	70.5	+1.4	1.020
5270837	NB	Calm Lapse (72°; 68%)	68.7	71.0	+2.3	1.033
5270940	NB	Calm Lapse (74°; 66%)	69.0	70.6	+1.6	1.023
5271029	NB	Calm Lapse (77°; 60%)	68.9	70.4	+1.5	1.022
5271105	NB	Calm Lapse (77°; 58%)	69.5	70.0	+0.5	1.007
5271125	NB	Calm Lapse (79°; 57%)	68.4	70.4	+2.0	1.029
5261524	NB	Calm Lapse (88°; 43%)	68.3	71.3	+3.0	1.044
5261558	NB	Upwind Lapse (88°; 39%)	66.2	70.0	+3.8	1.057
5261629	NB	Upwind Lapse (89°; 37%)	65.5	70.2	+4.7	1.072
5261712	NB	Upwind Lapse (89°; 33%)	66.3	70.8	+4.5	1.068
5261754	NB	Upwind Lapse (90°; 32%)	65.9	69.9	+4.0	1.061
5261809	NB	Calm Lapse (88°; 32%)	66.6	70.3	+3.7	1.056
10090947	WB	Calm Neutral (59°; 62%)	60.8	60.5	-0.3	0.995
10091006	WB	Calm Neutral (60°; 61%)	60.0	60.2	+0.2	1.003
10091045	WB	Calm Lapse (64°; 55%)	60.2	60.8	+0.6	1.010
10091104	WB	Calm Lapse (66°; 52%)	60.9	60.5	-0.4	0.993
10081440	WB	Downwind Lapse (68°; 36%)	61.3	60.8	-0.5	0.991
10081506	WB	Downwind Lapse (70°; 35%)	60.8	61.2	+0.4	1.006
10081648	WB	Calm Lapse (71°; 32%)	61.7	59.9	-1.8	0.971
10081707	WB	Calm Lapse (71°; 33%)	61.1	60.9	-0.2	0.996
10081753	WB	Calm Lapse (70°; 33%)	60.4	59.6	-0.8	0.987
10081821	WB	Calm Lapse (70°; 32%)	60.3	60.0	-0.3	0.995
10081850	WB	Calm Neutral (66°; 40%)	60.1	59.5	-0.6	0.990
10081915	WB	Calm Inversion (63°; 48%)	60.9	59.1	-1.8	0.970
Note: NB = No Barrier; WB = With Barrier						

Table 22: Measured and Modeled Sound Levels: YMS R2 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Modeled	Deviation	M/M Ratio
5270600	NB	Calm Neutral (71°; 65%)	64.2	66.3	+2.1	1.033
5270649	NB	Calm Neutral (70°; 67%)	65.2	67.5	+2.3	1.035
5270715	NB	Calm Neutral (70°; 68%)	65.7	68.2	+2.5	1.038
5270805	NB	Calm Lapse (71°; 68%)	64.1	67.5	+3.4	1.053
5270837	NB	Calm Lapse (72°; 68%)	63.6	67.9	+4.3	1.068
5270940	NB	Calm Lapse (74°; 66%)	64.0	67.6	+3.6	1.056
5271029	NB	Calm Lapse (77°; 60%)	64.9	67.4	+2.5	1.039
5271105	NB	Calm Lapse (77°; 58%)	64.3	67.0	+2.7	1.042
5271125	NB	Calm Lapse (79°; 57%)	63.9	67.3	+3.4	1.053
5261524	NB	Calm Lapse (88°; 43%)	63.6	68.2	+4.6	1.072
5261558	NB	Upwind Lapse (88°; 39%)	61.7	67.0	+5.3	1.086
5261629	NB	Upwind Lapse (89°; 37%)	61.1	67.2	+6.1	1.100
5261712	NB	Upwind Lapse (89°; 33%)	61.7	67.8	+6.1	1.099
5261754	NB	Upwind Lapse (90°; 32%)	61.2	66.8	+5.6	1.092
5261809	NB	Calm Lapse (88°; 32%)	62.0	67.1	+5.1	1.082
10090947	WB	Calm Neutral (59°; 62%)	60.4	60.2	-0.2	0.996
10091006	WB	Calm Neutral (60°; 61%)	59.6	59.9	+0.3	1.004
10091045	WB	Calm Lapse (64°; 55%)	59.6	60.5	+0.9	1.015
10091104	WB	Calm Lapse (66°; 52%)	60.6	60.2	-0.4	0.993
10081440	WB	Downwind Lapse (68°; 36%)	62.2	60.4	-1.8	0.972
10081506	WB	Downwind Lapse (70°; 35%)	61.5	60.8	-0.7	0.989
10081648	WB	Calm Lapse (71°; 32%)	62.2	59.6	-2.6	0.959
10081707	WB	Calm Lapse (71°; 33%)	61.4	60.5	-0.9	0.985
10081753	WB	Calm Lapse (70°; 33%)	60.9	59.3	-1.6	0.973
10081821	WB	Calm Lapse (70°; 32%)	60.7	59.7	-1.0	0.983
10081850	WB	Calm Neutral (66°; 40%)	59.9	59.2	-0.7	0.988
10081915	WB	Calm Inversion (63°; 48%)	60.6	58.8	-1.8	0.971
Note: NB = No Barrier; WB = With Barrier						

Table 23: Measured and Modeled Sound Levels: YMS R3 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Modeled	Deviation	M/M Ratio
5270600	NB	Calm Neutral (71°; 65%)	59.5	61.1	+1.6	1.027
5270649	NB	Calm Neutral (70°; 67%)	60.6	62.2	+1.6	1.026
5270715	NB	Calm Neutral (70°; 68%)	61.0	63.0	+2.0	1.033
5270805	NB	Calm Lapse (71°; 68%)	59.7	62.5	+2.8	1.047
5270837	NB	Calm Lapse (72°; 68%)	59.3	62.7	+3.4	1.057
5270940	NB	Calm Lapse (74°; 66%)	59.3	62.7	+3.4	1.057
5271029	NB	Calm Lapse (77°; 60%)	61.1	62.5	+1.4	1.023
5271105	NB	Calm Lapse (77°; 58%)	59.3	61.9	+2.6	1.044
5271125	NB	Calm Lapse (79°; 57%)	59.6	62.1	+2.5	1.042
5261524	NB	Calm Lapse (88°; 43%)	59.2	63.2	+4.0	1.068
5261558	NB	Upwind Lapse (88°; 39%)	57.5	62.0	+4.5	1.078
5261629	NB	Upwind Lapse (89°; 37%)	57.3	62.2	+4.9	1.086
5261712	NB	Upwind Lapse (89°; 33%)	57.7	62.8	+5.1	1.088
5261754	NB	Upwind Lapse (90°; 32%)	57.8	61.7	+3.9	1.067
5261809	NB	Calm Lapse (88°; 32%)	58.5	62.0	+3.5	1.060
10090947	WB	Calm Neutral (59°; 62%)	58.4	57.7	-0.7	0.988
10091006	WB	Calm Neutral (60°; 61%)	57.8	57.6	-0.2	0.996
10091045	WB	Calm Lapse (64°; 55%)	57.4	58.0	+0.6	1.011
10091104	WB	Calm Lapse (66°; 52%)	58.4	57.9	-0.5	0.992
10081440	WB	Downwind Lapse (68°; 36%)	61.4	58.0	-3.4	0.944
10081506	WB	Downwind Lapse (70°; 35%)	61.0	58.5	-2.5	0.960
10081648	WB	Calm Lapse (71°; 32%)	60.7	57.4	-3.3	0.945
10081707	WB	Calm Lapse (71°; 33%)	60.4	58.2	-2.2	0.963
10081753	WB	Calm Lapse (70°; 33%)	59.7	57.0	-2.7	0.955
10081821	WB	Calm Lapse (70°; 32%)	59.4	57.2	-2.2	0.963
10081850	WB	Calm Neutral (66°; 40%)	57.9	56.8	-1.1	0.981
10081915	WB	Calm Inversion (63°; 48%)	59.0	56.3	-2.7	0.955
Note: NB = No Barrier; WB = With Barrier						

Table 24: Measured and Modeled Sound Levels: YMS R4 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Modeled	Deviation	M/M Ratio
5270600	NB	Calm Neutral (71°; 65%)	57.4	58.3	+0.9	1.016
5270649	NB	Calm Neutral (70°; 67%)	58.6	59.5	+0.9	1.015
5270715	NB	Calm Neutral (70°; 68%)	58.9	60.3	+1.4	1.024
5270805	NB	Calm Lapse (71°; 68%)	57.8	59.8	+2.0	1.035
5270837	NB	Calm Lapse (72°; 68%)	57.6	60.0	+2.4	1.042
5270940	NB	Calm Lapse (74°; 66%)	57.7	60.0	+2.3	1.040
5271029	NB	Calm Lapse (77°; 60%)	59.6	59.8	+0.2	1.003
5271105	NB	Calm Lapse (77°; 58%)	57.7	59.2	+1.5	1.026
5271125	NB	Calm Lapse (79°; 57%)	58.0	59.4	+1.4	1.024
5261524	NB	Calm Lapse (88°; 43%)	56.8	60.5	+3.7	1.065
5261558	NB	Upwind Lapse (88°; 39%)	55.1	59.4	+4.3	1.078
5261629	NB	Upwind Lapse (89°; 37%)	55.0	59.5	+4.5	1.082
5261712	NB	Upwind Lapse (89°; 33%)	55.5	60.2	+4.7	1.085
5261754	NB	Upwind Lapse (90°; 32%)	55.9	59.0	+3.1	1.055
5261809	NB	Calm Lapse (88°; 32%)	56.4	59.2	+2.8	1.050
10090947	WB	Calm Neutral (59°; 62%)	57.0	56.2	-0.8	0.986
10091006	WB	Calm Neutral (60°; 61%)	56.4	56.0	-0.4	0.993
10091045	WB	Calm Lapse (64°; 55%)	55.9	56.5	+0.6	1.010
10091104	WB	Calm Lapse (66°; 52%)	57.1	56.4	-0.7	0.988
10081440	WB	Downwind Lapse (68°; 36%)	60.0	56.5	-3.5	0.942
10081506	WB	Downwind Lapse (70°; 35%)	59.8	57.0	-2.8	0.954
10081648	WB	Calm Lapse (71°; 32%)	59.2	55.9	-3.3	0.944
10081707	WB	Calm Lapse (71°; 33%)	59.1	56.7	-2.4	0.959
10081753	WB	Calm Lapse (70°; 33%)	58.4	55.5	-2.9	0.951
10081821	WB	Calm Lapse (70°; 32%)	58.2	55.6	-2.6	0.955
10081850	WB	Calm Neutral (66°; 40%)	56.4	55.3	-1.1	0.980
10081915	WB	Calm Inversion (63°; 48%)	57.6	54.7	-2.9	0.950
Note: NB = No Barrier; WB = With Barrier						

Table 25: TNM Analysis Blocks and Meteorological Conditions, SL Study Site

Block	Scenario	Date	Time	Duration	Met Condition	Temperature	RH	Wind Condition	Vector Wind Speed
9190907	PC	9/19/2019	9:07 AM	15 Minutes	Calm Lapse	67°	62%	Calm	< 1.0 mi/h
9190927	PC	9/19/2019	9:27 AM	15 Minutes	Calm Lapse	68°	60%	Calm	< 1.0 mi/h
9191006	PC	9/19/2019	10:06 AM	15 Minutes	Calm Lapse	71°	56%	Calm	< 1.0 mi/h
9191021	PC	9/19/2019	10:21 AM	15 Minutes	Calm Lapse	72°	55%	Calm	< 1.0 mi/h
9191042	PC	9/19/2019	10:42 AM	15 Minutes	Calm Lapse	74°	53%	Calm	< 1.0 mi/h
9191103	PC	9/19/2019	11:03 AM	15 Minutes	Calm Lapse	74°	52%	Calm	< 1.0 mi/h
9191123	PC	9/19/2019	11:23 AM	15 Minutes	Calm Lapse	75°	51%	Calm	< 1.0 mi/h
9191254	PC	9/19/2019	12:54 PM	15 Minutes	Calm Lapse	78°	48%	Calm	< 1.0 mi/h
9191327	PC	9/19/2019	1:27 PM	15 Minutes	Calm Lapse	80°	47%	Calm	< 1.0 mi/h
9170910	PC	9/17/2019	9:10 AM	15 Minutes	Calm Lapse	71°	75%	Calm	< 1.0 mi/h
9170930	PC	9/17/2019	9:30 AM	15 Minutes	Calm Lapse	71°	72%	Calm	< 1.0 mi/h
6010943	NB	6/1/2020	9:43 AM	15 Minutes	Calm Lapse	60°	52%	Calm	< 1.0 mi/h
6011023	NB	6/1/2020	10:23 AM	15 Minutes	Calm Lapse	62°	45%	Calm	< 1.0 mi/h
6011049	NB	6/1/2020	10:49 AM	15 Minutes	Calm Lapse	64°	43%	Calm	< 1.0 mi/h
6011104	NB	6/1/2020	11:04 AM	15 Minutes	Calm Lapse	64°	40%	Calm	1.0-2.0 mi/h
6011120	NB	6/1/2020	11:20 AM	15 Minutes	Calm Lapse	65°	37%	Calm	< 1.0 mi/h
6011144	NB	6/1/2020	11:44 AM	15 Minutes	Calm Lapse	66°	35%	Calm	1.0-2.0 mi/h
6011200	NB	6/1/2020	12:00 PM	15 Minutes	Calm Lapse	67°	35%	Calm	< 1.0 mi/h
6011220	NB	6/1/2020	12:20 PM	15 Minutes	Calm Lapse	68°	32%	Calm	< 1.0 mi/h
7231037	WB	7/23/2021	10:37 AM	15 Minutes	Calm Lapse	75°	51%	Calm	< 1.0 mi/h
7231100	WB	7/23/2021	11:00 AM	15 Minutes	Calm Lapse	77°	51%	Calm	< 1.0 mi/h
7231115	WB	7/23/2021	11:15 AM	15 Minutes	Calm Lapse	77°	50%	Calm	1.0-2.0 mi/h
7231130	WB	7/23/2021	11:30 AM	15 Minutes	Calm Lapse	77°	50%	Calm	1.0-2.0 mi/h
7231145	WB	7/23/2021	11:45 AM	15 Minutes	Calm Lapse	78°	49%	Calm	1.0-2.0 mi/h
7231205	WB	7/23/2021	12:05 PM	15 Minutes	Calm Lapse	78°	49%	Calm	< 1.0 mi/h
7231230	WB	7/23/2021	12:30 PM	15 Minutes	Calm Lapse	78°	47%	Calm	1.0-2.0 mi/h
7231251	WB	7/23/2021	12:51 PM	15 Minutes	Calm Lapse	78°	49%	Calm	1.0-2.0 mi/h

Table 26: Measured and Modeled Sound Levels: SL R0 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Building Rows		Buildings as Barriers		Buildings Not Modeled	
				Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)
9190907	PC	Calm Lapse (67°; 62%)	74.7	73.8	-0.9 (0.988)	73.8	-0.9 (0.989)	73.9	-0.8 (0.989)
9190927	PC	Calm Lapse (68°; 60%)	74.3	73.4	-0.9 (0.988)	73.5	-0.8 (0.989)	73.5	-0.8 (0.989)
9191006	PC	Calm Lapse (71°; 56%)	73.7	72.8	-0.9 (0.988)	72.9	-0.8 (0.989)	72.9	-0.8 (0.989)
9191021	PC	Calm Lapse (72°; 55%)	73.9	72.6	-1.3 (0.982)	72.7	-1.2 (0.984)	72.7	-1.2 (0.984)
9191042	PC	Calm Lapse (74°; 53%)	73.8	73.1	-0.7 (0.991)	73.2	-0.6 (0.992)	73.2	-0.6 (0.992)
9191103	PC	Calm Lapse (74°; 52%)	73.9	73.1	-0.8 (0.989)	73.2	-0.7 (0.991)	73.2	-0.7 (0.991)
9191123	PC	Calm Lapse (75°; 51%)	74.0	72.9	-1.1 (0.985)	73.0	-1.0 (0.987)	73.0	-1.0 (0.986)
9191254	PC	Calm Lapse (78°; 48%)	74.2	73.6	-0.6 (0.992)	73.7	-0.5 (0.993)	73.6	-0.6 (0.992)
9191327	PC	Calm Lapse (80°; 47%)	73.6	73.7	+0.1 (1.001)	73.8	+0.2 (1.002)	73.7	+0.1 (1.001)
9170910	PC	Calm Lapse (71°; 75%)	73.7	73.6	-0.1 (0.999)	73.7	0.0 (1.000)	73.7	0.0 (1.000)
9170930	PC	Calm Lapse (71°; 72%)	73.4	73.4	0.0 (1.000)	73.3	-0.1 (0.999)	73.3	-0.1 (0.999)
6010943	NB	Calm Lapse (60°; 52%)	73.6	72.4	-1.2 (0.984)	72.4	-1.2 (0.984)	72.4	-1.2 (0.984)
6011023	NB	Calm Lapse (62°; 45%)	73.7	72.2	-1.5 (0.980)	72.2	-1.5 (0.980)	72.3	-1.4 (0.981)
6011049	NB	Calm Lapse (64°; 43%)	73.9	72.4	-1.5 (0.980)	72.4	-1.5 (0.980)	72.4	-1.5 (0.980)
6011104	NB	Calm Lapse (64°; 40%)	73.5	72.5	-1.0 (0.986)	72.5	-1.0 (0.986)	72.5	-1.0 (0.986)
6011120	NB	Calm Lapse (65°; 37%)	73.5	72.5	-1.0 (0.986)	72.5	-1.0 (0.986)	72.5	-1.0 (0.986)
6011144	NB	Calm Lapse (66°; 35%)	73.3	72.6	-0.7 (0.990)	72.6	-0.7 (0.990)	72.6	-0.7 (0.990)
6011200	NB	Calm Lapse (67°; 35%)	74.1	72.8	-1.3 (0.982)	72.8	-1.3 (0.982)	72.8	-1.3 (0.982)
6011220	NB	Calm Lapse (68°; 32%)	73.2	72.6	-0.6 (0.992)	72.6	-0.6 (0.992)	72.6	-0.6 (0.992)
7231037	WB	Calm Lapse (75°; 51%)	75.3	74.3	-1.0 (0.986)	74.3	-1.0 (0.986)	74.3	-1.0 (0.986)
7231100	WB	Calm Lapse (77°; 51%)	74.0	73.3	-0.7 (0.990)	73.3	-0.7 (0.990)	73.3	-0.7 (0.990)
7231115	WB	Calm Lapse (77°; 50%)	74.8	73.8	-1.0 (0.987)	73.8	-1.0 (0.987)	73.8	-1.0 (0.987)
7231130	WB	Calm Lapse (77°; 50%)	74.6	73.8	-0.8 (0.990)	73.8	-0.8 (0.990)	73.8	-0.8 (0.990)
7231145	WB	Calm Lapse (78°; 49%)	74.9	73.7	-1.2 (0.984)	73.7	-1.2 (0.984)	73.7	-1.2 (0.984)
7231205	WB	Calm Lapse (78°; 49%)	74.8	73.8	-1.0 (0.987)	73.8	-1.0 (0.987)	73.8	-1.0 (0.987)
7231230	WB	Calm Lapse (78°; 47%)	75.0	74.0	-1.0 (0.986)	74.0	-1.0 (0.986)	74.0	-1.0 (0.986)
7231251	WB	Calm Lapse (78°; 49%)	74.9	74.1	-0.8 (0.990)	74.1	-0.8 (0.990)	74.2	-0.7 (0.991)
Note: PC = Pre-Clearing; NB = No Barrier; WB = With Barrier									

Table 27: Measured and Modeled Sound Levels: SL R1 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Building Rows		Buildings as Barriers		Buildings Not Modeled	
				Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)
9190907	PC	Calm Lapse (67°; 62%)	66.4	67.4	+1.0 (1.015)	67.4	+1.0 (1.016)	67.5	+1.1 (1.017)
9190927	PC	Calm Lapse (68°; 60%)	65.8	67.1	+1.3 (1.020)	67.1	+1.3 (1.020)	67.2	+1.4 (1.021)
9191006	PC	Calm Lapse (71°; 56%)	65.1	66.6	+1.5 (1.023)	66.7	+1.6 (1.024)	66.7	+1.6 (1.025)
9191021	PC	Calm Lapse (72°; 55%)	65.4	66.4	+1.0 (1.015)	66.5	+1.1 (1.017)	66.5	+1.1 (1.017)
9191042	PC	Calm Lapse (74°; 53%)	65.3	66.9	+1.6 (1.025)	67.0	+1.7 (1.026)	67.0	+1.7 (1.026)
9191103	PC	Calm Lapse (74°; 52%)	65.3	66.9	+1.6 (1.025)	67.0	+1.7 (1.026)	67.0	+1.7 (1.026)
9191123	PC	Calm Lapse (75°; 51%)	65.2	66.7	+1.5 (1.023)	66.8	+1.6 (1.024)	66.7	+1.5 (1.023)
9191254	PC	Calm Lapse (78°; 48%)	65.2	67.5	+2.3 (1.035)	67.6	+2.4 (1.037)	67.6	+2.4 (1.037)
9191327	PC	Calm Lapse (80°; 47%)	64.8	67.4	+2.6 (1.040)	67.5	+2.7 (1.042)	67.5	+2.7 (1.042)
9170910	PC	Calm Lapse (71°; 75%)	64.8	67.2	+2.4 (1.037)	67.3	+2.5 (1.039)	67.3	+2.5 (1.039)
9170930	PC	Calm Lapse (71°; 72%)	64.4	67.2	+2.8 (1.043)	67.1	+2.7 (1.042)	67.1	+2.7 (1.042)
6010943	NB	Calm Lapse (60°; 52%)	65.1	66.3	+1.2 (1.018)	66.3	+1.2 (1.018)	66.3	+1.2 (1.018)
6011023	NB	Calm Lapse (62°; 45%)	64.4	66.4	+2.0 (1.031)	66.4	+2.0 (1.031)	66.4	+2.0 (1.031)
6011049	NB	Calm Lapse (64°; 43%)	65.0	66.5	+1.5 (1.023)	66.5	+1.5 (1.023)	66.5	+1.5 (1.023)
6011104	NB	Calm Lapse (64°; 40%)	64.4	66.5	+2.1 (1.033)	66.5	+2.1 (1.033)	66.5	+2.1 (1.033)
6011120	NB	Calm Lapse (65°; 37%)	64.7	66.6	+1.9 (1.029)	66.6	+1.9 (1.029)	66.6	+1.9 (1.029)
6011144	NB	Calm Lapse (66°; 35%)	64.0	66.5	+2.5 (1.039)	66.5	+2.5 (1.039)	66.5	+2.5 (1.039)
6011200	NB	Calm Lapse (67°; 35%)	64.7	66.8	+2.1 (1.032)	66.8	+2.1 (1.032)	66.8	+2.1 (1.032)
6011220	NB	Calm Lapse (68°; 32%)	64.7	66.5	+1.8 (1.028)	66.5	+1.8 (1.028)	66.5	+1.8 (1.028)
7231037	WB	Calm Lapse (75°; 51%)	60.0	59.5	-0.5 (0.991)	59.5	-0.5 (0.991)	59.5	-0.5 (0.991)
7231100	WB	Calm Lapse (77°; 51%)	58.4	58.4	0.0 (1.000)	58.4	0.0 (1.000)	58.4	0.0 (1.000)
7231115	WB	Calm Lapse (77°; 50%)	58.7	58.6	-0.1 (0.998)	58.6	-0.1 (0.998)	58.6	-0.1 (0.998)
7231130	WB	Calm Lapse (77°; 50%)	58.6	58.7	+0.1 (1.002)	58.7	+0.1 (1.002)	58.7	+0.1 (1.002)
7231145	WB	Calm Lapse (78°; 49%)	59.4	58.6	-0.8 (0.987)	58.6	-0.8 (0.987)	58.6	-0.8 (0.987)
7231205	WB	Calm Lapse (78°; 49%)	59.2	58.7	-0.5 (0.992)	58.7	-0.5 (0.992)	58.7	-0.5 (0.992)
7231230	WB	Calm Lapse (78°; 47%)	59.3	58.8	-0.5 (0.991)	58.8	-0.5 (0.991)	58.8	-0.5 (0.991)
7231251	WB	Calm Lapse (78°; 49%)	58.9	59.0	+0.1 (1.001)	59.0	+0.1 (1.001)	59.0	+0.1 (1.001)
Note: PC = Pre-Clearing; NB = No Barrier; WB = With Barrier									

Table 28: Measured and Modeled Sound Levels: SL R2 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Building Rows		Buildings as Barriers		Buildings Not Modeled	
				Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)
9190907	PC	Calm Lapse (67°; 62%)	60.5	61.4	+0.9 (1.015)	59.8	-0.7 (0.989)	62.8	+2.3 (1.038)
9190927	PC	Calm Lapse (68°; 60%)	60.1	61.1	+1.0 (1.017)	59.6	-0.5 (0.991)	60.1	0.0 (1.000)
9191006	PC	Calm Lapse (71°; 56%)	59.2	60.4	+1.2 (1.020)	59.0	-0.2 (0.996)	61.8	+2.6 (1.044)
9191021	PC	Calm Lapse (72°; 55%)	59.5	60.3	+0.8 (1.013)	58.9	-0.6 (0.990)	61.7	+2.2 (1.037)
9191042	PC	Calm Lapse (74°; 53%)	59.7	60.8	+1.1 (1.018)	59.4	-0.3 (0.995)	62.2	+2.5 (1.042)
9191103	PC	Calm Lapse (74°; 52%)	59.3	60.9	+1.6 (1.027)	59.4	+0.1 (1.002)	62.3	+3.0 (1.051)
9191123	PC	Calm Lapse (75°; 51%)	58.8	60.6	+1.8 (1.031)	59.1	+0.3 (1.006)	62.0	+3.2 (1.054)
9191254	PC	Calm Lapse (78°; 48%)	58.2	61.2	+3.0 (1.052)	59.8	+1.6 (1.028)	62.6	+4.4 (1.076)
9191327	PC	Calm Lapse (80°; 47%)	57.9	61.1	+3.2 (1.055)	59.8	+1.9 (1.033)	62.6	+4.7 (1.081)
9170910	PC	Calm Lapse (71°; 75%)	58.1	61.0	+2.9 (1.050)	59.5	+1.4 (1.024)	62.4	+4.3 (1.074)
9170930	PC	Calm Lapse (71°; 72%)	57.8	61.1	+3.3 (1.057)	59.5	+1.7 (1.029)	62.3	+4.5 (1.078)
6010943	NB	Calm Lapse (60°; 52%)	56.8	60.0	+3.2 (1.056)	57.8	+1.0 (1.018)	60.9	+4.1 (1.072)
6011023	NB	Calm Lapse (62°; 45%)	56.7	60.0	+3.3 (1.058)	57.8	+1.1 (1.019)	60.8	+4.1 (1.072)
6011049	NB	Calm Lapse (64°; 43%)	56.7	60.2	+3.5 (1.062)	57.9	+1.2 (1.021)	61.0	+4.3 (1.076)
6011104	NB	Calm Lapse (64°; 40%)	56.1	60.2	+4.1 (1.073)	57.9	+1.8 (1.032)	61.0	+4.9 (1.087)
6011120	NB	Calm Lapse (65°; 37%)	56.5	60.2	+3.7 (1.065)	57.9	+1.4 (1.025)	61.0	+4.5 (1.080)
6011144	NB	Calm Lapse (66°; 35%)	55.8	60.2	+4.4 (1.079)	57.9	+2.1 (1.038)	61.0	+5.2 (1.093)
6011200	NB	Calm Lapse (67°; 35%)	56.2	60.4	+4.2 (1.075)	58.1	+1.9 (1.034)	61.2	+5.0 (1.089)
6011220	NB	Calm Lapse (68°; 32%)	55.8	60.2	+4.4 (1.079)	58.0	+2.2 (1.039)	61.0	+5.2 (1.093)
7231037	WB	Calm Lapse (75°; 51%)	56.0	57.8	+1.8 (1.032)	55.7	-0.3 (0.995)	57.8	+1.8 (1.032)
7231100	WB	Calm Lapse (77°; 51%)	55.2	56.6	+1.4 (1.026)	54.6	-0.6 (0.989)	56.7	+1.5 (1.028)
7231115	WB	Calm Lapse (77°; 50%)	55.5	57.0	+1.5 (1.027)	54.7	-0.8 (0.986)	57.0	+1.5 (1.027)
7231130	WB	Calm Lapse (77°; 50%)	54.4	57.1	+2.7 (1.049)	54.9	+0.5 (1.009)	57.1	+2.7 (1.049)
7231145	WB	Calm Lapse (78°; 49%)	56.3	56.9	+0.6 (1.010)	54.7	-1.6 (0.971)	56.9	+0.6 (1.010)
7231205	WB	Calm Lapse (78°; 49%)	55.5	57.0	+1.5 (1.027)	54.7	-0.8 (0.986)	57.0	+1.5 (1.027)
7231230	WB	Calm Lapse (78°; 47%)	56.7	57.1	+0.4 (1.006)	54.9	-1.8 (0.968)	57.1	+0.4 (1.006)
7231251	WB	Calm Lapse (78°; 49%)	55.6	57.3	+1.7 (1.031)	55.1	-0.5 (0.991)	57.3	+1.7 (1.031)
Note: PC = Pre-Clearing; NB = No Barrier; WB = With Barrier									

Table 29: Measured and Modeled Sound Levels: SL R3 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Building Rows		Buildings as Barriers		Buildings Not Modeled	
				Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)
9190907	PC	Calm Lapse (67°; 62%)	57.1	59.0	+1.9 (1.033)	55.5	-1.6 (0.973)	60.9	+3.8 (1.067)
9190927	PC	Calm Lapse (68°; 60%)	57.4	58.6	+1.2 (1.021)	55.3	-2.1 (0.963)	57.4	+0.0 (1.000)
9191006	PC	Calm Lapse (71°; 56%)	56.5	58.0	+1.5 (1.027)	54.7	-1.8 (0.967)	59.9	+3.4 (1.060)
9191021	PC	Calm Lapse (72°; 55%)	56.6	57.9	+1.3 (1.023)	54.6	-2.0 (0.964)	59.8	+3.2 (1.057)
9191042	PC	Calm Lapse (74°; 53%)	57.4	58.4	+1.0 (1.017)	55.0	-2.4 (0.958)	60.3	+2.9 (1.051)
9191103	PC	Calm Lapse (74°; 52%)	56.6	58.5	+1.9 (1.034)	55.1	-1.5 (0.973)	60.4	+3.8 (1.067)
9191123	PC	Calm Lapse (75°; 51%)	55.9	58.2	+2.3 (1.041)	54.7	-1.2 (0.979)	60.1	+4.2 (1.075)
9191254	PC	Calm Lapse (78°; 48%)	54.3	58.7	+4.4 (1.081)	55.3	+1.0 (1.019)	60.6	+6.3 (1.116)
9191327	PC	Calm Lapse (80°; 47%)	54.3	58.7	+4.4 (1.081)	55.3	+1.0 (1.019)	60.6	+6.3 (1.116)
9170910	PC	Calm Lapse (71°; 75%)	55.2	58.6	+3.4 (1.062)	55.1	-0.1 (0.998)	60.5	+5.3 (1.096)
9170930	PC	Calm Lapse (71°; 72%)	55.3	58.6	+3.3 (1.060)	55.1	-0.2 (0.996)	60.4	+5.1 (1.092)
6010943	NB	Calm Lapse (60°; 52%)	54.0	57.3	+3.3 (1.061)	53.6	-0.4 (0.993)	58.9	+4.9 (1.091)
6011023	NB	Calm Lapse (62°; 45%)	52.4	57.3	+4.9 (1.094)	53.6	+1.2 (1.023)	58.9	+6.5 (1.124)
6011049	NB	Calm Lapse (64°; 43%)	52.4	57.5	+5.1 (1.097)	53.8	+1.4 (1.027)	59.1	+6.7 (1.128)
6011104	NB	Calm Lapse (64°; 40%)	51.7	57.5	+5.8 (1.112)	53.7	+2.0 (1.039)	59.0	+7.3 (1.141)
6011120	NB	Calm Lapse (65°; 37%)	51.9	57.5	+5.6 (1.108)	53.8	+1.9 (1.037)	59.0	+7.1 (1.137)
6011144	NB	Calm Lapse (66°; 35%)	52.0	57.4	+5.4 (1.104)	53.8	+1.8 (1.035)	59.0	+7.0 (1.135)
6011200	NB	Calm Lapse (67°; 35%)	52.6	57.7	+5.1 (1.097)	53.9	+1.3 (1.025)	59.2	+6.6 (1.125)
6011220	NB	Calm Lapse (68°; 32%)	51.7	57.5	+5.8 (1.112)	53.9	+2.2 (1.043)	59.0	+7.3 (1.141)
7231037	WB	Calm Lapse (75°; 51%)	54.9	55.4	+0.5 (1.008)	54.3	-0.6 (0.988)	57.1	+2.2 (1.039)
7231100*	WB	Calm Lapse (77°; 51%)	55.8	54.2	-1.6 (0.972)	53.0	-2.8 (0.950)	55.9	+0.1 (1.002)
7231115*	WB	Calm Lapse (77°; 50%)	56.6	54.5	-2.1 (0.963)	53.1	-3.5 (0.938)	56.3	-0.3 (0.995)
7231130	WB	Calm Lapse (77°; 50%)	51.9	54.6	+2.7 (1.052)	53.3	+1.4 (1.027)	56.4	+4.5 (1.087)
7231145	WB	Calm Lapse (78°; 49%)	54.6	54.4	-0.2 (0.996)	53.1	-1.5 (0.973)	56.2	+1.6 (1.029)
7231205	WB	Calm Lapse (78°; 49%)	53.5	54.5	+1.0 (1.019)	53.1	-0.4 (0.993)	56.2	+2.7 (1.050)
7231230	WB	Calm Lapse (78°; 47%)	54.0	54.6	+0.6 (1.012)	53.2	-0.8 (0.986)	56.4	+2.4 (1.045)
7231251	WB	Calm Lapse (78°; 49%)	52.6	54.8	+2.2 (1.041)	53.5	+0.9 (1.016)	56.6	+4.0 (1.075)
Note: * Indicates results omitted from model-to-monitor analysis. PC = Pre-Clearing; NB = No Barrier; WB = With Barrier									

Table 30: Measured and Modeled Sound Levels: SL R4 Receiver Location

Block	Scenario	Met Condition (Temperature; RH%)	Measured	Building Rows		Buildings as Barriers		Buildings Not Modeled	
				Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)	Modeled	Deviation (M/M Ratio)
9190907	PC	Calm Lapse (67°; 62%)	56.4	54.7	-1.7 (0.970)	52.6	-3.8 (0.932)	58.0	+1.6 (1.028)
9190927	PC	Calm Lapse (68°; 60%)	56.8	54.3	-2.5 (0.956)	52.3	-4.5 (0.921)	56.8	0.0 (1.000)
9191006	PC	Calm Lapse (71°; 56%)	55.3	53.6	-1.7 (0.969)	51.6	-3.7 (0.934)	56.9	+1.6 (1.029)
9191021	PC	Calm Lapse (72°; 55%)	55.9	53.5	-2.4 (0.957)	51.5	-4.4 (0.922)	56.7	+0.8 (1.014)
9191042	PC	Calm Lapse (74°; 53%)	56.8	53.9	-2.9 (0.949)	51.9	-4.9 (0.914)	57.2	+0.4 (1.007)
9191103	PC	Calm Lapse (74°; 52%)	55.7	54.1	-1.6 (0.971)	52.0	-3.7 (0.934)	57.4	+1.7 (1.031)
9191123	PC	Calm Lapse (75°; 51%)	54.6	53.8	-0.8 (0.985)	51.6	-3.0 (0.946)	57.0	+2.4 (1.044)
9191254	PC	Calm Lapse (78°; 48%)	53.7	54.2	+0.5 (1.009)	52.2	-1.5 (0.972)	57.5	+3.8 (1.071)
9191327	PC	Calm Lapse (80°; 47%)	53.3	54.2	+0.9 (1.017)	52.2	-1.1 (0.980)	57.5	+4.2 (1.079)
9170910	PC	Calm Lapse (71°; 75%)	52.0	54.2	+2.2 (1.042)	52.0	0.0 (1.000)	57.4	+5.4 (1.104)
9170930	PC	Calm Lapse (71°; 72%)	53.6	54.2	+0.6 (1.011)	52.1	-1.5 (0.972)	57.4	+3.8 (1.071)
6010943*	NB	Calm Lapse (60°; 52%)	54.7	53.3	-1.4 (0.974)	51.1	-3.6 (0.934)	56.0	+1.3 (1.024)
6011023	NB	Calm Lapse (62°; 45%)	51.1	53.2	+2.1 (1.041)	51.0	-0.1 (0.998)	55.9	+4.8 (1.094)
6011049	NB	Calm Lapse (64°; 43%)	51.6	53.4	+1.8 (1.035)	51.2	-0.4 (0.992)	56.1	+4.5 (1.087)
6011104*	NB	Calm Lapse (64°; 40%)	51.8	53.4	+1.6 (1.031)	51.1	-0.7 (0.986)	56.1	+4.3 (1.083)
6011120*	NB	Calm Lapse (65°; 37%)	53.2	53.4	+0.2 (1.004)	51.2	-2.0 (0.962)	56.0	+2.8 (1.053)
6011144*	NB	Calm Lapse (66°; 35%)	52.6	53.4	+0.8 (1.015)	51.2	-1.4 (0.973)	56.1	+3.5 (1.067)
6011200	NB	Calm Lapse (67°; 35%)	52.3	53.6	+1.3 (1.025)	51.3	-1.0 (0.981)	56.2	+3.9 (1.075)
6011220	NB	Calm Lapse (68°; 32%)	50.7	53.4	+2.7 (1.053)	51.3	+0.6 (1.012)	56.1	+5.4 (1.107)
7231037*	WB	Calm Lapse (75°; 51%)	69.3	52.7	-16.6 (0.761)	52.9	-16.4 (0.764)	55.9	-13.4 (0.807)
7231100*	WB	Calm Lapse (77°; 51%)	69.9	51.5	-18.4 (0.737)	51.7	-18.2 (0.74)	54.7	-15.2 (0.783)
7231115*	WB	Calm Lapse (77°; 50%)	67.9	51.9	-16.0 (0.764)	51.8	-16.1 (0.763)	55.0	-12.9 (0.81)
7231130*	WB	Calm Lapse (77°; 50%)	52.9	52.0	-0.9 (0.982)	51.9	-1.0 (0.980)	55.1	+2.2 (1.041)
7231145*	WB	Calm Lapse (78°; 49%)	56.5	51.7	-4.8 (0.915)	51.7	-4.8 (0.915)	54.9	-1.6 (0.972)
7231205*	WB	Calm Lapse (78°; 49%)	54.3	51.8	-2.5 (0.954)	51.8	-2.5 (0.954)	55.0	+0.7 (1.013)
7231230*	WB	Calm Lapse (78°; 47%)	54.8	51.9	-2.9 (0.947)	51.9	-2.9 (0.947)	55.1	+0.3 (1.006)
7231251*	WB	Calm Lapse (78°; 49%)	52.0	52.2	+0.2 (1.004)	52.1	+0.1 (1.002)	55.3	+3.3 (1.063)
Note: * Indicates results omitted from model-to-monitor analysis. PC = Pre-Clearing; NB = No Barrier; WB = With Barrier									