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RESEARCH REPORT

EFFECTIVENESS OF SHORT SOLID BARRIERS TO REDUCE NOISE GENERATED BY DIFFERENT TYPES OF HIGHWAY VEHICLES

OLUDARE OWOLABI, D.Sc, P.E (PRINCIPAL INVESTIGATOR)
EMMA BUTTERFIELD (INDUSTRY EXPERT)
MEHDI SHOKOUHIAN, PhD (Co-PI)
PELUMI ABIODUM (RESEARCH ASSOCIATE)
CORNELIUS DAARKO (RESEARCH ASSOCIATE)
CHICHEDO DURU (RESEARCH ASSOCIATE)

MORGAN STATE UNIVERSITY & RSG

FINAL REPORT

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16. Abstract: Tall highway noise barriers have served as an effective noise abatement strategy. However, it comes with the high cost and limited adoption in diverse environments. The purpose of this study was to investigate the feasibility and reasonableness of short safety barriers as a highway noise abatement strategy. Through purposeful selection, five out of ten potential sites with pre-existing short concrete barriers around Maryland highways were investigated. At-grade and elevated roadways with short concrete barriers were included in the study. Sound level meters were used to measure the sound at different distances from the nearest roadway. Traffic counts and speed were gathered concurrently. The study adopted seven distinct sound propagation models. These models included custom models created for the California Department of Transportation (Caltrans) and the Traffic Noise Model (TNM) versions 2.5 and 3.2. The results indicated that, in some conditions, short noise barriers— generally 2.5 to 3 feet tall—can markedly diminish noise levels. These barriers achieved noise reductions of 3 to 5 decibels (dB) for at-grade roadways at typical residential setbacks from highways. Noise reductions of up to 9 dB were observed in scenarios involving elevated highways. This suggests that shorter solid barriers may be nearly as effective as taller ones in some situations. The research identified discrepancies between empirical data and prevalent models like TNM 2.5 forecasts, highlighting the necessity for model improvements and supplementary observations. Short concrete barriers can be feasible and reasonable as they can provide 3 to 5 dB of reduction.

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ACRONYMS AND ABBREVIATIONS

FHWA: Federal Highway Administration

TNM: Traffic Noise Model

MDOT SHA: Maryland Department of Transportation State Highway Administration

US DOT: United States Department of Transportation

EXECUTIVE SUMMARY

One enduring environmental problem is noise pollution, particularly for areas near highways. Serious health problems like sleep disruptions, cardiovascular disorders, and cognitive loss have all been related to exposure to traffic noise. Highway noise barriers are an essential strategy for Maryland to address this issue. More research on the viability and efficacy of shorter noise barriers is required due to their cost-effectiveness, which may have the twin benefits of reducing noise pollution and enhancing road safety. The purpose of this study was to determine how well short concrete barriers work to reduce noise from passing cars. The goal was to give the (State Highway Administration) information so they could determine if these barriers could be utilized to reduce traffic noise. The research team used both theoretical noise models and field measurements to do a thorough investigation at several sites in Maryland. Sites were chosen according to a set of standards, such as the kind of roadway, the height of the barrier, and the lack of structures that would interfere. At-grade and elevated roadways with short concrete barriers were included in the study. Sound level meters were used to measure the sound at different distances from the nearest roadway. Traffic counts and speeds were gathered concurrently. The team assessed the short barriers' ability to reduce noise using seven distinct sound propagation models. These models included custom models created for the California Department of Transportation (Caltrans) and the Traffic Noise Model (TNM) versions 2.5 and 3.2. The modeling took into consideration a few variables, including traffic patterns, elevation, and ground type. The aim was to evaluate the noise reduction effectiveness of the short concrete barriers and compare the obtained findings with the noise modeling tools' predictions. The findings suggested that, under some circumstances, short noise barriers—typically measuring 2.5 to 3 feet in height—can significantly reduce noise. These barriers provided noise reductions of 3 to 5 decibels (dB) for at-grade roadways at standard residential setbacks from highways. There were noise reductions of up to 9 dB in situations involving elevated roadways. This implies that short solid barriers may be almost as effective as taller ones under some circumstances. The study also found differences between field data and common models such as TNM 2.5 projections, underscoring the need for model enhancements and additional measurements. TNM 2.5 occasionally underestimated the efficacy of short solid barriers, especially for elevated roads. These differences were addressed by modifications to TNM 3.2 and additional unique modeling techniques.

CHAPTER ONE

INTRODUCTION

1.1 Background and Study Overview

One of the prominent environmental persistent challenges is noise pollution. There has been heightened concern, especially as the health and environmental impact continue to become major and persistent public health concerns. Communities that are adjacent to highways, or those who live near heavily used roads, have been reported to experience adverse effects on their health among of which are prominently sleep disturbance, cardiovascular diseases, and depreciating cognitive performance (Basner & McGuire, 2018). The effects of vehicle traffic noise on the heart have been thoroughly researched for many years. To determine an exposure-response association between road traffic noise exposure and the prevalence of hypertension, a meta-analysis based on 24 research papers were conducted by Van Kempen & Babisch, (2012). The findings found an odds ratio of 1.034 per 5 dB increase in $L_{Aeq,16h}$, within the 45 - 74 dBA range, without a threshold value. Chronic sleep disturbance is a significant public health concern, with environmental noise exposure being a major adverse consequence (World Health Organization & others, 2011).

To alleviate these effects, one of the foremost steps taken overtime has been the installation of noise barriers by the state's Department of Transportation (DOT). Noise barriers are structures built along highways to reduce traffic noise by blocking or redirecting sound waves from vehicles. The key characteristics of the noise barriers lie in the material make up, design, its effectiveness, and the location where it was placed. Noise barriers reduce noise through absorption, deflection, or refraction at near and far distant resident 5 to 10 dB depending on the height, length, and shape of the barrier (Figure 1.1). The material makeup of the barrier can be concrete, metal, wood, composite materials, or emerging materials (sustainable use of waste materials) (Fredianelli et al., 2019; Laxmi et al., 2022).

Common factors affecting noise barriers' acoustic performance include material properties, geometrical considerations, ground surface properties, and metrological conditions (Garai & Guidorzi, 2015; Lodico, 2020, 2023). Studies have extensively examined the prominence and best practices with the design and geometry of noise barriers (Conter & Haider, 2008; Watts, 2000). Absorbing surfaces are crucial as they reduce the reflection of sound energy by the barrier.

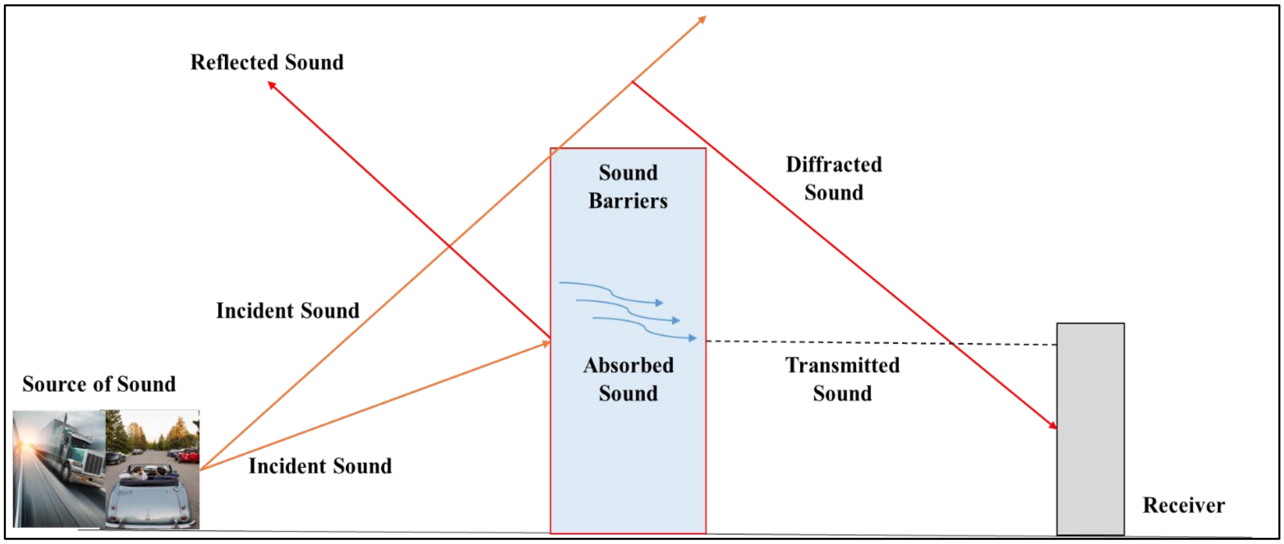

Figure 1.1: *Mechanism of Noise Barrier Performance (Laxmi et al., 2022)*

Thirty reflection measurements were conducted on various noise barrier structures and modifications by Sipari et al., (2017). The single reflection/absorption value of the studied barriers at 200-5000 Hz ranged between 4-10 dB, with no significant deviation observed at 200-2000 Hz. However, their study did not consider any identified acoustically hard surfaces. The ground type, whether hard, concrete, or forest ground, has an influence on the noise barriers performance (Laxmi et al., 2022). When the source of sound is located on the ground, it creates either constructive or destructive interference.

Different barrier materials perform differently in terms of acoustics, durability, cost, and aesthetics. Reflective and absorptive materials are the two broad categories that are currently being investigated and deployed for noise attenuation (Kesten et al., 2020; Laxmi et al., 2022). Reflective barriers reflect sound energy away from the receivers adjacent to the roadway but may increase noise levels for those on the opposite side. Improvement depends on site conditions, barrier height, and building nature (Jiang & Kang, 2016). Continuous reflection can cause a closed canyon-like situation, increasing noise by 3-6 dB at the receiver. Open housing residential areas can see a 1-3% increase in noise levels from traffic (Laxmi et al., 2022). Reflecting barriers are made from various materials, among which are concrete, metals, glass, plastic, masonry blocks, and other transparent materials. Absorptive barriers can reduce the sound reflected by diffusing sound waves through reflection phenomena. The addition of absorptive materials, such as concrete, cement-fix wood, impure metals, ceramics, and composites, around the edges of barriers can significantly reduce sound reflections and diffraction from the upper borders of walls (Laxmi et al., 2022).

The level of improvement varies depending on site conditions, barrier height, and the nature of the surrounding buildings. While noise barriers effectively mitigate the environmental impacts of motorways, their design must balance both acoustic performance and visual aesthetics. Innovations in material selection and barrier design have the potential to increase their effectiveness; however, landscape integration and aesthetic considerations are crucial for community acceptance and overall success (Jiang & Kang, 2016).

1.2 Problem Statement

Urbanization is rapidly increasing. This has led to the construction of more buildings near highways and expressways, increasing the number of people affected by noise pollution. However, these buildings potentially act as barriers, reducing residents' exposure to noise pollution (Alberola et al., 2005; Lodico, 2020). Aside from that, noise barriers adjacent to the roadway is one noise abatement strategy that is frequently used during highway projects. However, one of the major constraints is the cost of these tall barriers, often exceeding $1.3 million per mile in Maryland (Ibili et al., 2022; Oludare et al., 2019). As such, their high cost is a significant driver of overall project costs for the Maryland Department of Transportation (MDOT) and other state agencies. The Washington State Department of Transportation estimates the current construction cost of a noise wall to be $51.61 per square foot, which translates into a fourteen-foot-high wall (typically) costing about $3.9 million per mile (Washington State Department of Transportation, 2023).

To reduce the cost of noise abatement, state transportation agencies have started to evaluate short concrete barriers, to serve the dual purpose of improving driving safety as well as abating traffic noise. Short noise walls may also be more feasible to construct than taller sound walls due to reduced site constraints. Extensive noise modeling is required to determine the feasibility of abatement choices. In the past, the Federal Highway Administration (FHWA) only accepted the use of its Traffic Noise Model (TNM 2.5) for all federally funded projects. However, recent studies carried out by Ohio Department of Transportation (ODOT) and California Department of Transportation (Caltrans), the measured insertion loss of short barriers was greater than the insertion loss that would be expected based on TNM 2.5 modeling results (Lodico, 2023). The major reason attributed to discrepancy in the TNM 2.5 results, and the measured insertion loss, is due to some identified errors in the TNM software and the noise source heights of different highway vehicles. Due to technological advancement, recent versions of highway trucks have reduced exhaust noise to the point of near inaudibility as well as the lowering of the acoustic center of the noise source closer to the pavement surface (Cubick & Rochat, 2022). Lodico (2023) observed in her study that TNM 2.5 was shown to underpredict the insertion losses of short barriers along elevated highway alignments and behind a short berm. It was also observed that with alternative SoundPLAN modelling methods, results improved by 3.1 to 3.5 dB compared to TNM 2.5.

Before statewide adoption and implementation of short barriers as a noise abatement strategy for traffic noise, it is vital to evaluate their effectiveness and appropriateness. Other noise abatement strategies including berms and tall noise barriers have been researched and found effective but can be costly and are often highway project driven. This report presents the findings to help the state to evaluate existing utilization of short concrete barrier methodologies for mitigating traffic noise by providing a literature review, developing guidelines for field evaluation, conducting noise measurements, and model the insertion loss using different methodologies.

1.3 Research Objectives

The initial construction cost of barriers has led to considerable interest by local transportation agencies and the Federal Highway Administration (FHWA) in finding less costly alternatives, such as short noise barriers. Many agencies have found that the utilization of short concrete safety barriers as a noise mitigation strategy is highly beneficial. Additional research is needed to see if short noise barriers can satisfy the FHWA noise requirements and meet the Noise Reduction Design Goal (NRDG) (Noise Barrier Acceptance Criteria Analysis Publication

No. FHWA-HEP- 16-017).

The primary objective of this study is to evaluate the effectiveness of short concrete noise barriers in mitigating noise impacts. This report will serve as a guide for SHA to assess the applicability of short concrete barriers at appropriate locations as an alternative to traditional taller concrete sound barriers. To achieve the overall aim of the study, this report seeks to present the findings:

1. Review of relevant research, methodologies, tools, and technologies that have been used in evaluating short concrete noise barriers as noise abatement;
2. Development of best measurement practices around existing short concrete barriers;
3. Conduct noise measurements of concrete barrier insertion loss based on industry standard and in accordance with FHWA Noise Measurement Handbook (2018);
4. Model the noise transmission around short concrete barriers in order to validate traffic noise model and predict insertion losses of short barriers;
5. Determine insertion losses around existing short concrete barriers; and
6. Examine the feasibility, benefited noise reduction, cost reasonableness, and Noise Reduction Design Goals (NRDGs).

The results presented in this research will assist SHA to justify decisions and to achieve the highest return value on noise mitigation strategy by optimizing the choice of the barrier height.

1.4 Deliverables

The deliverables for this project and the sections of this report where these deliverables can be found is follows:

1. Summary of literature review on the existing methodologies and tools to evaluate the effectiveness of short noise barriers. See Chapter 2 of this report.
2. Guidelines for the evaluation of the effectiveness of the noise barrier and details about the sites as well as noise measurement work plan. See Chapter 3 of this report as well as the appendix for the noise measurement work plan.
3. Field data results, noise prediction models and evaluation results of the effectiveness of the noise barriers. See Chapter 4 of this report as well as the appendix.
4. Final report.

1.5 Organization of Report

This report is organized into five chapters. After this introductory chapter, Chapter 2 presents a comprehensive literature review on the existing methodologies and tools to evaluate the effectiveness of short noise barriers. Chapter 3 describes the methodology used for field measurements, data collection, and noise modeling. Chapter 4 provides the results from the field measurements, noise modeling, and all analysis carried out in this study. Finally, Chapter 5 summarizes all research findings and conclusions.

CHAPTER TWO

LITERATURE REVIEW

This section provides details of the review of utilization of short noise barriers, the methodology utilized for evaluation, the modeling techniques, and discusses states that are considering the adoption and a few proprietary products.

A state of the practice survey of the State Department of Transportation's (DOTs), with respect to the adoption and implementation of short noise barriers, was conducted. In conducting the review, a variety of library database collections were utilized as well as the review of State DOTs that have adopted the noise abatement strategy**.** Published research related to the measure of effectiveness of short noise concrete barriers was also reviewed. It is pertinent to note that effectiveness ratings are based primarily on insertion loss, benefited noise reduction, and cost reasonableness are not considered as part of effectiveness rating.

The literature review also focused on prior work that has included developing comprehensive guidelines or standards. Leveraging on our previous network of highway noise practitioners from the executed SHA project on Highway Geometrics and Noise Abatement research, a detailed survey was conducted with State DOTs and noise practitioners.

Background information was reviewed regarding research, methodologies, tools, and technologies that have been used in evaluating the possibility of utilizing short concrete noise barriers as a noise abatement strategy with a view of developing comprehensive guidelines or standards, including their weaknesses, strengths of existing technology, and examples where improvements can be made. Additionally, since realistic modelling is a precursor to accurately determining the feasibility of abatement choices, another review with a view to determining the best modeling technique that can realistically model the insertion loss of short concrete noise barriers was conducted. All these requirements will assist in closing the existing knowledge gap and providing comprehensive guidelines to evaluate the abatement system based on actual field performance.

2.1 Review of the Utilization of Short Noise Barriers as a Noise Abatement Strategy

Koussa et al., (2013), evaluated the acoustic performance of conventional and low height gabions noise barriers (about 40 inches [1m] tall) by using both numerical and experimental approaches.

Their results found that low height gabions noise barriers resulted in insertion losses of about 8 dB at locations behind the barrier. Jolibois et al., (2015), performed in situ measurements to determine the acoustic performance of a low height noise barrier (38 inches [0.95m] tall) with an inverted L- shaped assembly of pressed wood boards covered on the source with fibrous absorbing material along a tramway. This barrier provided an average noise reduction of more than 10 dB for the trams closest to the barrier. Similarly, Radsten-Ekman et al., (2011) evaluated the acoustic properties of a one-meter-high (40 inches) vegetated noise barrier along a roadway.

The barrier was made of a metallic structure, filled with a substrate on which 40 plants per square meter were grown on both sides. Acoustic measurements were conducted along the vegetated noise barrier. A questionnaire survey was also administered to the pedestrians walking behind the barrier. Results showed that the barrier reduced the traffic sound level by 5 dB. Song et al., (2022) similarly evaluated the acoustic performance of near-rail low-height noise barriers (about 40 inches [1m] tall) installed on suburban railway bridges by utilizing a finite element numerical procedure that takes into consideration wheel-rail noise and structure-borne noise of the bridge. The model was verified by field tests. Based on the numerical analysis results, it was found that both the near-rail low-height noise barrier and conventional vertical noise barrier had good acoustic performance. The acoustic performance of the near-rail low-height noise barrier gradually improves, but the improvement rate gradually slows down as the height of the noise barrier increases. Their study revealed that the noise reduction of both the inverted L-shaped and Y-shaped near-rail low-height barriers were better than that of the vertical one (L and Y-shaped insertion losses ranged from about 7 to 11 dB, while the vertical barrier had an insertion loss from 7 to 9.5 dB). Furthermore, the noise reduction effects of the inverted L-shaped near-rail low-height noise barrier were slightly better than the Y-shaped one. Table 2.1 shows the summary of the review of the utilization of short noise barriers as a noise abatement strategy, while Figure 2.1 reveals the graphical depiction of the relationship between types of short noise barriers and their insertion loss.

Table 2.1: *Summary of Review of the Utilization of Short Noise Barriers as a Noise Abatement Strategy*

Author	Description	Methodology	Results
Koussa et al., 2013	Evaluation of the acoustic performance of conventional and low height gabions noise barriers along a two-lane rigid pavement road.	Numerical simulations using boundary element method (BEM) and experimental approach using in-situ test in accordance with the European CEN/TS 1793-5:2003 Standard as well as scale model measurements.	Effectiveness of 1m high noise gabions barrier with an 8 dB insertion loss. BEM simulations results showed good agreement when validated with scale model measurements. Gabions barriers that are originally used as retaining structures or hydraulic protections, can be used as effective noise barriers.
Jolibois et al., 2015	In situ measurements to determine the acoustic performance of a low height noise barrier (less than one meter high) with an inverted L-shaped assembly of pressed wood boards covered on the source with fibrous absorbing material along a tramway.	Field measurements along a tramway utilizing full-scale protype L-shaped noise barrier prototype (approximately 1 meter high). Comparison of field measurements with the boundary element method (BEM) simulations.	The barrier provided an average attenuation of more than 10 dB for close trams, and of more than 5 dB for far trams. Attenuation becomes more efficient with complex shapes or more efficient sound absorbing materials. BEM calculations yield good results when compared with field measurements.
Radsten-Ekman et al., 2011	Evaluation of the acoustic property of a one-meter-high	The barrier was made of a metallic structure, filled with a substrate on which 40 plants per square meter were	The barrier reduced the sound pressure level with about 5 dB (LA_{eq}), at sitting height (1.2 meters), 3.5 meters from the roadside. Survey

	vegetated noise barrier along a roadway	grown on both sides. Field acoustic measurements and questionnaire study administered to pedestrians.	results suggested that the barrier made the sound environment better but not good.
Song et al., 2022	Evaluation of the acoustic performance of near-rail low-height noise barriers installed on suburban railway bridges.	Finite element numerical procedure that takes into consideration wheel-rail noise and structure-borne noise of the bridge which was verified by field test.	The noise reduction of both the inverted L-shaped and Y-shaped near-rail low-height near-rail low-height noise were better than that of the vertical one (L and Y-shaped insertion loss ranging from about 7 to 11dB and the vertical barrier insertion loss ranging from 7 to 9.5 dB. Further, the noise reduction of the inverted L-shaped near-rail low-height noise barrier were slightly better than the Y-shaped one.
Park & Koh, 2020	Prediction and field tests of railway noise and effects of a low-height noise barrier	Field measurements and the Schell 03 2012 model.	The noise reduction of the 0.74 meters tall concrete barrier placed at a distance of 1.78 meters from the rail track axis was 6dB on average with a mean difference of 2.5 dB between the predicted and measured values.
Kim, 2006	Effects of median barriers on highway noise levels	Traffic noise using the latest FHWA Traffic Noise Model, TNM version 2.5.	Traffic noise levels were reduced by up to 4.3 dB with median barrier from 1.8 meters to 3meters in height.

Zaets, 2021	Influence of estimation of the inclination angle of the top of the noise protection barrier on its efficiency.	Finite Element method created in the COMSOL Multiphysics software environment	. Results revealed that with an increase in sound in the 500 Hz frequency band, the efficiency of the barriers reaches its maximum values at different heights along the angles of 45-75°, while maximum efficiency was observed at 16.3 feet (5 meters) from the position of the sound source.
Karimi & Younesian, 2014	The performance of T-shape and Y shape inclined noise barriers in railway noise mitigation.	Numerical simulation implemented in SoundPLAN through the ray tracing technique.	Inclination angle was found to play a significant role in the amount of noise mitigation for elevated receptors, with up to 7 dB of additional noise reduction occurring at receivers located 10 m above ground level.
Cubick & Rochat, 2022	Solid safety barriers as a highway traffic noise reduction strategy	Federal Highway Administration Traffic Noise Model (TNM) predicted noise level reductions, attributable to solid safety barriers (height from 30 inches to 70 inches (0.76 meters to 1.8 meters), were developed for research scenarios in locations with both hard soil and lawn ground types.	Between 3dB and 5dB of noise reduction was found at sites within a few hundred feet of the roadway.
Lodico, 2023	Development and evaluation of modeling methods for their	Five modeling methods utilizing TNM implemented in SoundPLAN were	The result of the research showed that approximately 3 to 5 dB of noise reduction

	ability to accurately calculate the performance of short barriers in reducing traffic noise at the roadside.	developed, and these candidate modeling methods were then compared under numerous theoretical scenarios and validated using five real-world highway scenarios.	can be realized at traditional setback of residences at-grade highway alignments from a short concrete safety barrier. In situations where the highway alignment is elevated, this noise reduction increases to as much as 10 to 15 dB from a short safety barrier.
Sperry et al., 2023	Examination of how heavy truck noise is shielded by low-height roadside solid safety barriers (SSBs).	Field measurements of the maximum sound level (L_{max}) of individual heavy truck pass-by events at two representative locations in Ohio were obtained at a position where a low-height SSB was present as well as at a nearby unshielded position.	A perceptible reduction in the pass-by event L_{max} (between 3 and 5 dB) was realized for locations behind the SSBs. For events where the exhaust source was shielded by the SSB, the noise reduction was higher for the 42 inches (1.1m) tall SSB, but no difference was found for sites with 32 inch (0.8m) tall SSBs.
Wijnant et al, 2021 [15]	A FEM/Kirchhoff-Helmholtz integral model for noise diffractors on low height noise barriers	The finite element/Helmholtz integral model is used to calculate the scattered acoustic field in the proximity of the distractor allowing for noise sources at larger distances from the diffractor.	A large reduction of the model size and reduced calculations. Insertion loss of different barrier heights and larger distances from the source were obtained.
van der Eerden et al., 2021	Comparison of the in-situ measurement for a 1.1meter-high diffracting Whiswall and a 1.1 meters barrier with the	A numerical parabolic equation method (PE) was coupled to the FEM model to obtain the numerical results	A diffracting system on a 1.1m high WHIS Wall compared to a 1.1-meter-high meter barrier led to about a 3.5 dB additional insertion. The WHIS wall with the diffractor

	results of a numerical finite element model (FEM)		reduces noise by 7 to 9 dB while leaving the view intact. It combines diffraction with a low, custom made, absorbent substructure.
Oldham & Egan, 2015	Utilization of the boundary element method for a parametric investigation of the performance of highway noise barriers with multi-edge tops and different acoustic treatment.	Boundary Element Method.	Results showed that with a reflective edge located on the source side of a barrier at very short source to barrier distances and/or high barriers was found to result in a negative value of relative insertion loss, which is based upon resonances in the gap between the additional edge and the barrier postulated.
Ding et al., 2011	Estimating the Effect of Semi-Transparent Low-Height Road Traffic Noise Barriers with Ultra Weak Variational Formulation	The Ultra Weak Variational Formulation (UWVF) method is utilized to extend the case of propagation through a porous medium while the Zwicker and Kosten rigid-frame porous medium model is used to model sound propagation through the porous barrier.	The insertion loss ranged from 5 dB up to 13 dB, when considering all barriers, lane choices, vehicle types, and vehicle speeds.

Park et al. (2020) calculated the noise reduction of a 0.74m (30 inches) low height noise concrete barrier placed at 70 inches (1.78 meters) from the rail track axis. The barrier noise reduction was calculated to be 6 dB on average, with a mean difference of 2.5 dB between the predicted and measured values. Kim (2006), using TNM 2.0, evaluated the insertion loss of median barriers in reducing highway noise. Results showed that insertion loss increased by up to 4.3 dB with median barriers ranging in height from 6 feet (1.8 meters) to 10 feet (3 meters).

Zaets (2021) investigated the effect of different angles of inclination of the top portion of a sound barrier on its acoustic performance using finite element model created in the Comsol Multiphysics software environment. This study considered the influence of the inclination angle of the top part of the barrier on the sound field around the barrier from various locations of sound sources in a wide frequency range. Results revealed that with an increase in sound in the 500 Hz frequency band, the efficiency of the barriers reaches its maximum value at different heights along the angles of 45 - 75°, while maximum efficiency was observed at 16.3 feet (5 meters) from the position of the sound source. At 49.2 feet (15 meters) between the barrier and the sound source, the influence of the inclination angle becomes less pronounced even for the octave band with geometric mean frequency of 31 Hz.

Subsequently, concluding that as the distance between the sound source and the barrier increases, the effect of the inclination angle of the top part of the barrier on its effectiveness decreases. However, he opined that the use of barriers with an inclined portion leads to a shift in the center of mass of the barrier, which necessitates the use of more powerful struts and an increase in the requirements for the bearing capacity of foundations. Karimi & Younesian, (2014) opined that noise attenuation efficiency is a function of geometric correlation between the source, barrier, receiver, frequency, and type of sound source. Their numerical simulation was implemented in SoundPLAN, using the ray tracing technique capability, to study the performance of T-shape and Y-shape inclined noise barriers in railway noise mitigation. They performed 36 tests with four different frequencies, three barrier locations, and three various speeds (1.5 m/s, 1.8m/s and 2.35 m/s, respectively). Their results showed that inclination angles can play a significant role in noise mitigation level in high elevations, up to 7 dB of additional noise reduction may occur at receivers located 32.8 feet (10 meters) above the ground.

2.2 Relevant Research, Methodologies, Tools, and Technologies that have been used in Evaluating the Reasonableness and Feasibility of the Noise Abatement Strategy

Cubick & Rochat, (2022), investigated the effect of solid safety barriers for sites at a variety of distances from a highway for both city streets and freeways of various widths using the Federal Highway Administration Traffic Noise Model (TNM). TNM predicted noise level reductions, attributable to solid safety barriers, were developed for research scenarios in locations with both hard soil and lawn ground types. The findings are presented in Figure 2.1. Results showed a readily perceptible and sometimes substantial noise reduction (between 3 dB and 5 dB) at sites within a few hundred feet of the roadway.

Lodico (2023) developed and evaluated modeling methods for their ability to accurately calculate the performance of short barriers in reducing traffic noise at the roadside. Five modeling methods were selected, and these candidate modeling methods were then compared under numerous theoretical scenarios and validated using five real-world highway scenarios. The research described the development of modeling methods to best calculate the insertion loss of solid safety barriers ranging in height from 30 inches to 70 inches (0.76 meters to 1.8 meters). The result of the study showed that approximately 3 to 5 dB of noise reduction can be realized at traditional setbacks of residences at-grade highway alignments from a short concrete safety barrier. In situations where the highway alignment is elevated, this noise reduction increases to as much as 10 to 15 dB from a short safety barrier. These noise reductions would be considered readily noticeable and, in some cases, would meet the feasibility and design goal criteria identified under FHWA criteria.

Sperry et al., (2023) examined how heavy truck noise is shielded by low-height roadside solid safety barriers (SSBs). Measurements of the maximum sound level (L_{max}) of individual heavy truck pass-by events at two representative locations in Ohio were obtained at a position where a low-height SSB was present as well as at a nearby unshielded position. The results indicated that a perceptible reduction in the pass-by event L_{max} (between 3 and 5 dB) was realized for locations behind the SSBs. Variations in the measured noise reduction were associated with the line-of-sight shielding between various truck noise sources and the receiver positions.

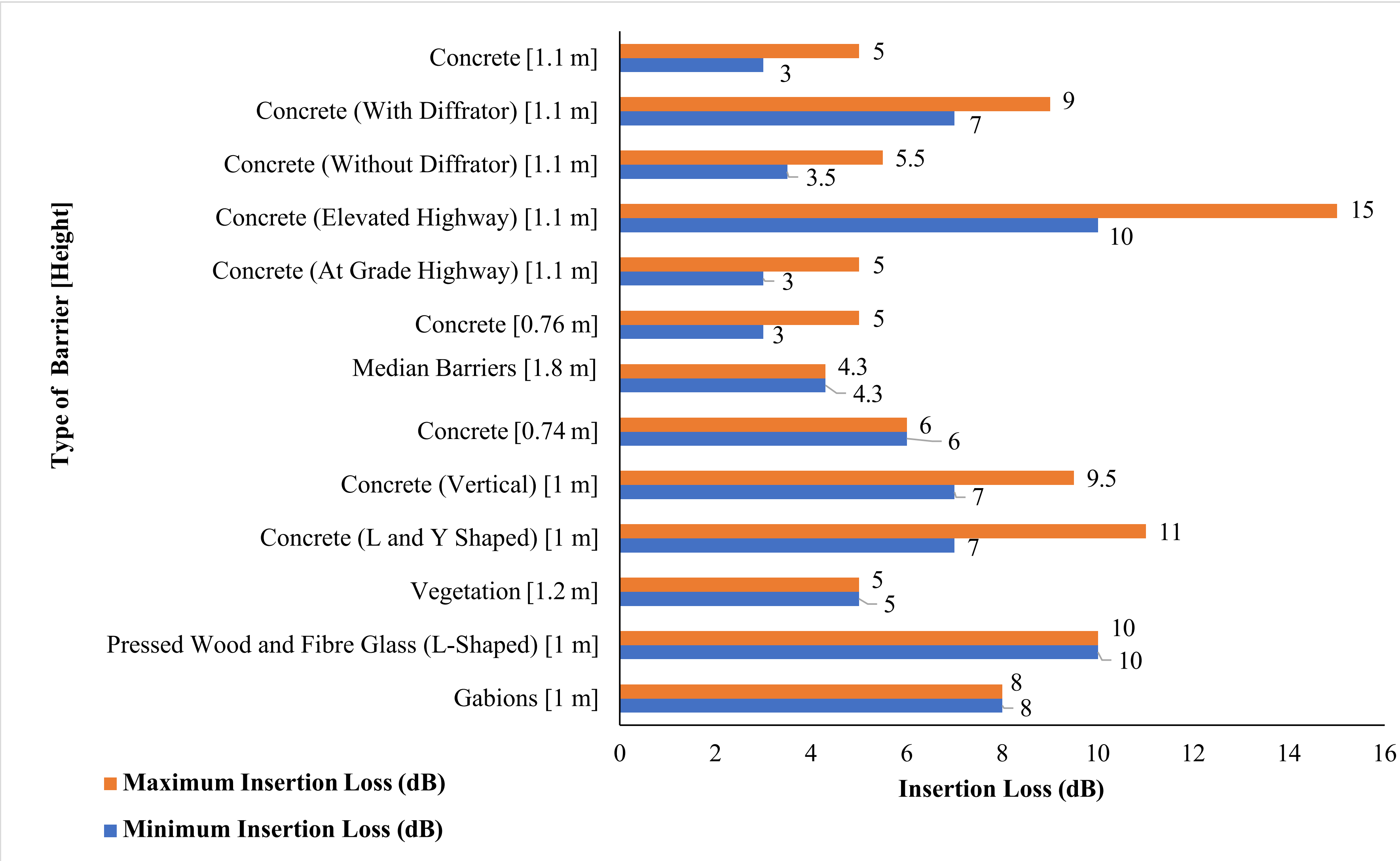

Figure 2.1: *Graphical Representation of Summary of Review of Short Barrier Types and Variation of Insertion Loss*

For events in which the exhaust source was shielded by the SSB, the measured noise reductions were higher at the site with the 1.1-meter tall SSB, although there was no difference for the site with the shorter (0.8 meter) SSB. It is recommended that analysts consider the potential for noise reduction associated with low-height SSBs in locations where such barriers are expected to be permanent.

Noise diffractors are a novel way to reduce traffic noise. They bend noise in an upward direction, as opposed to blocking or absorbing noise, creating a shadow zone of reduced noise levels behind the diffractor. Wijnant et al., (2021) described a finite element/Kirchhoff- Helmholtz integral model for a diffractor mounted on a low height noise barrier. The finite element model is used to calculate the scattered acoustic field in the proximity of the distractor, allowing for noise sources at larger distances from the diffractor. The research established a database of reduction values for a large number of evaluation distances for various source distances, source heights and barrier heights. van der Eerden et al., (2021) compared in-situ measurements for a 1.1-meter-high diffracting Whiswall and a 1.1 m barrier with the results of a numerical finite element model (FEM). To enhance the accuracy of the model a numerical parabolic equation method (PE) was coupled to the FEM model and a representative downwind condition was considered. The results at longer distance (up to 305 meters (1000 feet)) were used to design an engineering method for the enhanced barrier effect that can be used in standard noise calculation models, such as the Dutch national calculation model (SRM2) or the ISO 9613-2 standard.

2.3. Various Modeling Techniques that can Realistically Model the Insertion Loss of Short Concrete Noise Barrier.

As stated earlier, the feasibility of utilizing short solid barriers as an abatement strategy is beginning to be of interest to States DOTs due to the high cost of tall noise barriers. As improved modeling techniques continue to emerge that will enable state agencies to accurately predict the noise reduction of shorter barriers, this noise reduction strategy may become more popular as it will give DOTs additional options for situations where tall barriers may not be feasible. Few researchers have reported on the evaluation of short solid barriers as a noise abatement strategy. Lodico (2023) concluded from the results of the detailed research on traffic noise modeling of short safety barriers as follows:

1. With improved modeling methods, short solid sound walls apart from improving safety may be an option to provide some noise reduction to communities.
2. TNM 2.5 was shown to underpredict the insertion losses of short barriers along elevated roadways as well as overpredicting insertion losses of short barriers at distant locations along at-grade roadways.
3. The integration of TNM 2.5 algorithms in SoundPLAN improved the predictions by 2.7 dB for five real-world highway simulations.
4. The alteration of TNM 2.5 implemented in SoundPLAN to utilize upper sub source heights closer to the pavement surface further improved the predictions.
5. In order to be acoustically effective, short sound walls must be constructed with solid materials with a minimum surface weight of 4 pounds per square without a gap at the base or in the face of the wall.
6. TNM 3.1 had 1.3 dB improvement from TNM 2.5, however results are 1.3 to 2.2 dB better with implementation into SoundPLAN.

Oldham & Egan, (2015), utilized the boundary element method for a parametric investigation of the performance of highway noise barriers with multi-edge tops and different acoustic treatments. Other parameters investigated included source to barrier distance, the receiver to barrier distance, barrier height, the length of the additional edge and the gap between the additional edges, and the face of the barrier. Results showed that a reflective edge located on the source side of a barrier at very short source to barrier distances and/or high barriers had a negative value of relative insertion loss, which is based upon resonances in the gap between the additional edge and the barrier postulated.

2.4. Proprietary Short Noise Barrier System with its Reasonableness and Feasibility

Wijnant et al., (2021), opined that noise diffractors are a novel way to reduce traffic noise, as opposed to blocking or absorbing noise, diffractors bend noise in an upward direction, creating a shadow zone of reduced noise levels behind the diffractor. Subsequently, Wijnant et al. (2021) and van der Eerden et al. (2021) validated with effective modeling and noise measurements that placing a diffracting system on a 1.1 meter high WHIS Wall compared to a 1.1 meter high meter barrier will lead to about a 3.5 dB additional intersection. The WHIS wall with the diffractor reduces noise by 7 to 9 dB while leaving the view intact. It combines diffraction with a low, custom made, absorbent substructure (Figure 2.2). The noise reduction is similar to a 3-meter conventional noise barrier, even though the WHIS wall is only 1-meter tall (4 Silence, 2020).

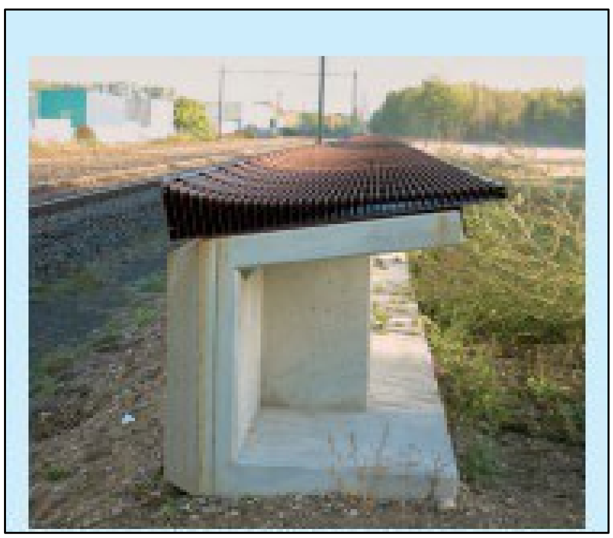

Figure 2.2. *The 1-meter WHIS Wall with Diffractor (Source: 4 Silence 2020)*

2.5 Review of the State of the Practice Survey of DOTs with Respect to the Adoption and Implementation of Short Noise Barriers

In an effort to consider the feasibility of the adoption of short noise barriers as a noise abatement strategy, Ohio Department of Transportation (ODOT) conducted a comprehensive in-state field study that revealed the effectiveness of short berms in abating highway noise (Burton et al., 2016). The study equally revealed that many of the small height earth berms of less than 6 foot (1.8 meters) provided noise reduction much greater than 5 dB. Along with the same objective, the California Department of Transportation (Caltrans) study revealed a reduction of 10 to 12 dB at distances of 90 feet (27.4 meters) and 130 feet (39.6 meters) behind short, earthen berms (Lodico, 2023). Additionally, the study revealed that the replacement of a 3 foot (0.9 meters) tall solid concrete safety barrier at the edge of a highway bridge deck with a steel railing resulted in numerous noise complaints (Rymer, 2020). Iowa DOT equally has been exploiting alternative abatement strategies, one of their studied cases revealed that a standard low-height berm (8 foot [2.4 meters] tall) provided an estimated noise reduction value of 6 dBA (NCHRP 25-57, 2022). Details of other states that have implemented other noise abatement strategies such as the use of Standard Low-Height noise berms are contained in the National Cooperative Highway Research Program (NCHRP) 25-57 (2022). In one of the Arizona DOT projects, when a taller sound wall was suggested to replace an already existing low berm, the neighborhood chose to maintain the modest berm as it is (NCHRP 25-57, 2022). Lodico, (2023) equally conducted a survey of five real-world highway noise measurement locations in the United States.

2.6 Survey Assessment and Data from Field Professionals

2.6.1 Survey Overview

This study designed and administered questionnaires to capture responses from professionals in noise abatement from U.S. DOTs. The objective of the survey was to gather state practices on the utilization of short solid safety barriers as noise abatement. The survey was distributed to the participants at the 2023 Noise Conference at Grand Rapids in May 2023, as well as to noise practitioners across all U.S. State agencies. Twelve responses were received. Data from the survey was analyzed and was used in developing guidelines on the utilization of short solid safety barriers as noise abatement. The survey instrument is shown in Appendix A. The results of the survey are shown in Appendix B. Further analysis and discussion of the results are presented in Chapter 4 of this report.

2.6.2 Target Audience

This survey conducted by Morgan State University included audiences from various U.S. DOTs and engineering firms involved in noise barrier design and construction. This research was more interested in responses from various State DOTs with their firsthand experience on the utilization of short solid safety barriers as noise abatement. The list of state DOTs that participated in this survey are as follows:

- Oregon State Department of Transportation (ODOT)
- Nevada State Department of Transportation (NDOT)
- Ohio Department of Transportation (ODOT)
- Washington Department of Transportation (WDOT)
- Illinois Department of Transportation (IDOT)
- Montana Department of Transportation (MODOT)
- Maryland State Department of Transportation (MDOT)
- Virginia State Department of Transportation (VDOT)

The list of engineering firms involved in noise abatement who participated in this survey are as follows:

- USAF
- Acoustical Design and Consulting LLC
- Mecanum Inc Canada

- Phoenix Noise and Vibration

The survey contains three sections:

- Section 1 includes questions on responder's information;
- Section 2 asks about the utilization of short concrete barrier as noise abatement; and
- Section 3 gathers additional comments.

2.7 Conclusions from the Literature Review

Literature indicates that short concrete barriers (0.762 meters (30 inches) to 1.778 meters (70 inches) placed close to the roadway have the potential to abate highway noise and their performance can be further improved by installing diffractors at the top of the barriers or by varying the top shapes of the barrier. Many short barrier systems have been implemented including classical wall-type barriers, gabions, and complex-shaped barriers. The insertion losses of these barrier systems typically ranged from 5 dB to 10 dB, depending on the barrier height, noise source characteristics, and receiver location. Previous research also showed that approximately 3 to 5 dB of noise reduction can be realized at traditional setbacks of residences at-grade highway alignments from a short concrete safety barrier. In situations where the highway alignment is elevated, this noise reduction may increase to as much as 10 to 15 dB from a short safety barrier. For roadways with higher percentages of heavy trucks and the events in which the exhaust source was shielded by the short solid barrier (SSB), the measured noise reductions were higher at the site with the 1.0 meters tall SSB, although there was no difference for the site with the shorter 0.8m. It was also noted in the review that noise diffractors are a novel way to reduce traffic noise, as they bend noise in an upward direction, as opposed to blocking or absorbing noise, thereby creating a shadow zone of reduced noise levels behind the diffractor. Modelling techniques that had been utilized include finite element/Kirchhoff- Helmholtz integral model, boundary element method (BEM), numerical simulation implemented in SoundPLAN through the ray tracing technique, and the alteration of TNM 2.5 implemented in SoundPLAN. All these modelling techniques have their limitations depending on the various scenarios where they were implemented.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

This section outlines the data collection process, which includes measuring traffic volume, speed, and noise levels, as well as noise modeling using the Traffic Noise Model (TNM). The research methodology follows the guidelines from the Federal Highway Administration (FHWA) Noise Measurement Handbook (FHWA, 2018) and the Mayland State Highway Administration (SHA, 2020) Highway Noise Abatement Planning and Engineering Guidelines. Several sites with short solid concrete barriers were provided by SHA and investigated based on specific criteria that were carefully reviewed to represent the best scenarios. Initially, these sites were screened using online aerial imagery to ensure they met the required criteria. It is to be noted that the best scenario for a study like this would be an investigation using noise measurements pre- and post-construction of short concrete barriers. The methodology described in this chapter is to offer a replacement strategy for the best scenario described earlier. The limitations and future considerations are provided at the end of this chapter.

3.1 Criteria for Selection of Potential Sites

The available online aerial imagery and panoramic views of the short solid barriers available in the State of Maryland were provided by SHA, which were screened, and the following criteria were utilized to select candidate sites for the noise measurements.

- Roadway should be at-grade or elevated above surrounding ground.
- Roadway must have a short safety barrier at the edge-of-shoulder (EOS)
- Short barriers must extend at least 400 feet in each direction from monitoring sites.
- The site must extend back to at least 150 feet from highway.
- There should be no road inconsistencies, for example a sharp curve or incline or significant pavement joints, etc.
- There should be no other interfering structures (tall barriers, houses, etc.) between the road and the measurement locations.
- Monitoring sites are accessible (field staff will likely need to walk some distance carrying field equipment)
- Monitoring equipment can be set up at site (so, not a marsh, for example)
- Preference is given to sites where simultaneous measurements can be made with and without the short barrier.
- Preference is given to sites where line-of-sight exists between measurement locations and highways.
- There are no extraneous noise sources such as other roadways or mechanical equipment, barking dogs, etc.
- Variation in roadway functional classification and pavement types.

After a thorough review of Google Earth files containing aerial imagery and panoramic views of the short barriers, thirteen candidate sites were selected for further study. Ideal site candidates are where a short solid barrier was located along only a portion of the roadway, with comparable site conditions existing both behind the barrier and along the portion of the road without a barrier. There were five of these sites that could potentially include measurements both with and without short barriers.

3.2 Reconnaissance and Final Site Selection

Final site selection was conducted through a reconnaissance that took fourteen (14) days to complete. The reconnaissance entailed a detailed site visit at each of the nine preliminary site, 10 sites were agreed on for further consideration. Table 1 shows the characteristics of all the nine sites finally selected.

Table 3.1: *Potential Noise Measurement Sites with their Characteristics*

Site Name	Site1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Latitude Coordinates	38.8003000	38.8846614	38.9180834	39.2025846	39.2352780	39.1397220	39.2941670	39.38805600	39.0269440
Longitude Coor.	-76.9030000	-76.8440303	-76.9411487	-77.2682378	-77.2875000	-77.2116670	-76.7902780	-77.45305600	-76.4436110
Location	Old Branch Ave, Camp Springs, MD 20748 (Property at 6516 Old Branch Avenue)	Capitol Beltway Capital Heights Maryland (before exit 15, NB, Largo Maryland	Us-50, New York Ave	Dwight D Eisenhower Hwy Germantown Maryland (I-270)	Washington National Pike, Clarksburg, MD (i-270) (before Comus road)	I-270, Gaithersburg, Maryland (around exit 10)	8074 Baltimore National Pike (US-40) Ellicott City, Maryland 21043	5671 US-340/15 Fredrick, Maryland	757 E College Pkwy Annapolis, Maryland
County	Prince George	Prince George	Prince George	Montgomery	Montgomery	Montgomery	Howard	Fredrick	Anne Arundel
Roadway Type	At grade	Elevated	Elevated	At grade	Elevated	At grade	At grade	Elevated	At Grade
Number of Lanes	4	4	3	3	3	2	2	2	3
Functional Classification	Arterial	Freeway	Arterial	Freeway	Freeway	Freeway	Arterial	Arterial	Arterial
Posted Speed Limit	55	55	45	55	55	55	45-55	45-55	44-55
Pavement type	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt	Asphalt
Barrier Type	Short Concrete	Short Concrete	Short solid Mansory wall	Short Concrete	Short Concrete	Short Concrete	Short Concrete	Short Concrete	Short Concrete with steel blades/guiderails
Possibility of simultaneous measurements for both barrier and non-barrier condition	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes on US 301
Roadway direction, where barrier is present	N and S	N	N and S	N	N	N	N and S, Barrier is in the median	N and S	Between US301 Westbound and E College Parkway
Possibility for measurement on both sides of location	No, Only on the South bound as North bound is the Andrews Airforce base	No	Yes	No	No	No	Yes	Yes	No on US301 westbound
Forested	One side Yes and Other Side No	Yes	Yes	Yes	Yes	Yes	South Side not Forested, North Side Yes	Sound Bound not forested, North Bound forested	No
Require Right of way access on private property	Yes	No	No	Yes	Yes	Yes	Yes for the North Side	Yes	Yes

Post-reconnaissance findings indicated that out of the ten (10) surveyed sites, only five met the condition where roadway characteristics were similar for both the barrier and non-barrier sections. The remaining five sites were to serve as barrier condition only. An additional site was added to the site location, making it a total of ten sites which were discovered during the reconnaissance. During reconnaissance, five out of the ten sites were dropped due to on-site measurement challenges, leaving three sites with both barrier and no-barrier conditions and two sites with only barrier conditions, resulting in a total of five sites for the study as shown in Figure 3.1.

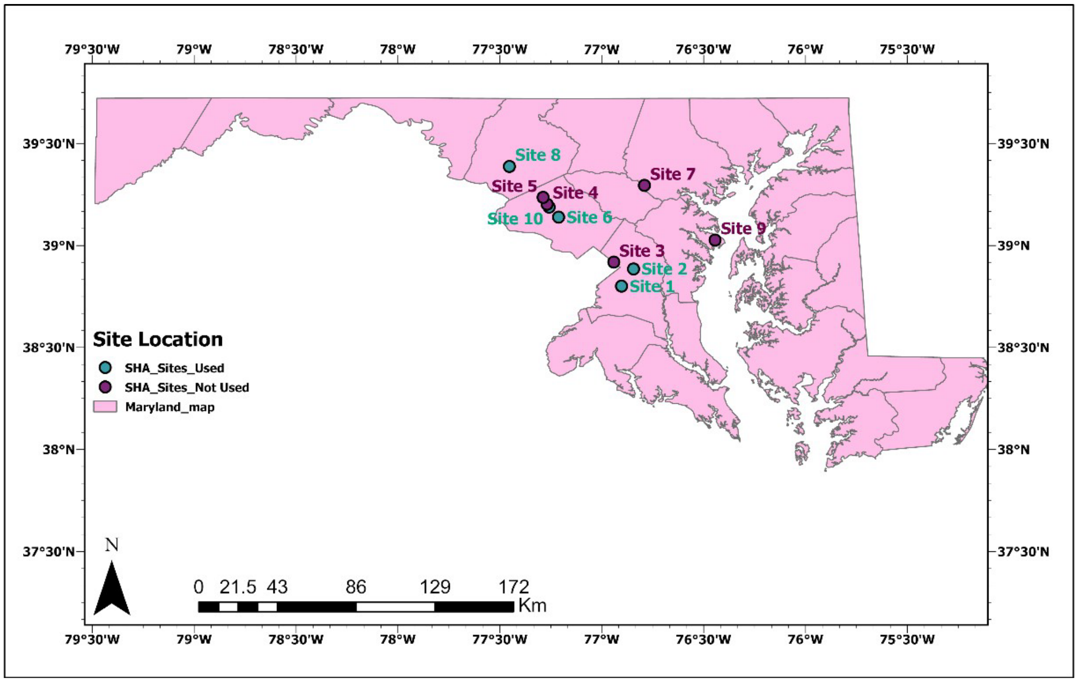

Figure 3.1: *Study Area Map Showing the Sites Location*

3.3 Data Collection

3.3.1 Measurement Procedures

At sites where barrier and no-barrier conditions have similar roadway characteristics, noise measurements were made simultaneously at the barrier site and no-barrier site. The remaining sites that do not fulfil these comparable site conditions, noise measurements were done only behind the barrier portion. The noise measurements were done for a period of one hour and during near free flow traffic conditions. Field monitoring included two to four sound monitoring units, located at distances of 25 feet, 50 feet, 75 feet, and other appropriate distances from the center of the near lane of travel, given site constraints. The sound level meter was set at a height of five (5) feet. Measurements were made following FHWA, Highway Traffic Noise: Analysis Abatement Guidance and the SHA Highway Noise Abatement Planning and Engineering Guidelines. Traffic volume and speeds, as well as temperature and wind conditions, were documented. Weather data, including temperature and average and gust wind speeds, were measured using an Onset HOBO anemometer. Traffic volumes were captured using a video camera to facilitate manual counting of the traffic volumes in the lab. Traffic speed was captured intermittently in real time using a radar gun. Based on ease of accessibility, Site 1 was selected for use of the acoustic camera. The acoustic camera is an OptiNav BeamformX Acoustic Array System with the SIG ACAM 120 having a frequency response from 60 Hz to 15 kHz. The system has an array of 40 digital microphones that are sampled simultaneously with 24-bit resolution, thus providing accurate phase and amplitude measurements for beamforming and other digital processing algorithms.

3.3.2 Traffic Noise Measurement

To calculate noise received from highway traffic for the purpose of this study, an American National Standards Institute/International Electrotechnical Commission (ANSI/IEC) Class 1 sound level meters were used to monitor sound pressure levels. Sound level measurements were conducted using the Larson Davis Level Model 831 Sound Level Meters (SLM). The meters were set to log 1/3 octave band sound levels once each second. The sound data was downloaded, processed, and summarized into hourly LA_{eq}.

Before field deployment, the SLMs were calibrated and ensured to have a tolerable margin of errors. Within a specified range of the calibration level, the level that corresponds to the calibration sound pressure level must be found. The maximum discrepancy was -0.5 dB and sound level meters were calibrated before and after each measurement.

3.4 Sites Description

The overall monitoring sites characteristics are as presented in Table 3.2

Table 3.2: *Monitoring Site Characteristics*

Site	Condition	Distances (ft)	Road Condition	Pavement Type
1	Barrier	25,50,75,100	At Grade	Asphalt
1	No Barrier	25,50	At Grade	Asphalt
2	Barrier	25,50	Elevated	Asphalt
2	No Barrier	25,50	At Grade	Asphalt
6	Barrier	25,50,75,100	Elevated	Asphalt
8	Barrier	25,50	Elevated	Asphalt
8	No Barrier	25,50	Elevated	Asphalt
10	Barrier	25,50,75	Elevated	Asphalt

3.4.1 Site 1:

Site 1 is situated at 6516 Old Branch Avenue in Camp Springs, MD, 20748. The roadway consists of three lanes in each direction. Measurements were taken for both barrier and no barrier conditions, with the 3-foot short safety concrete barrier. Sound levels were recorded at three locations for the barrier condition, positioned at distances of 50 feet, 75 feet, and 100 feet from the barrier. At no-barrier condition, measurements were taken at two distances: 50 feet and 75 feet. Data collection occurred twice during midday hours: the first session was from 12:30 pm to 1:30 pm, and the second session was from

2:15 pm to 3:17 pm. The sound level meter was placed 5 feet above ground level at each location. Traffic speed was recorded at one-minute intervals over ten minutes, with the average minimum and maximum vehicle speeds being 24 mph and 50 mph, respectively. Simultaneously with the noise measurements, traffic counts and volumes were collected in both travel directions using manual counting and a video camera. The collected traffic volume data were analyzed and classified according to Federal Highway Administration (FHWA) guidelines. Refer to Table 3.3 and Table 3.4 for detailed traffic volume and vehicle classification information.

Table 3.3: *Traffic Volume and Vehicle Classification Along - Old Branch Avenue – Set 1*

Vehicle Class	Number of Vehicles (10 mins)	Hourly Volume (NB)	Number of Vehicles (10 mins)	Hourly Volume (SB)
Cars	9,52	5,712	1,008	6,048
Medium Truck	24	144	30	180
Heavy Truck	15	90	20	120
Buses	10	60	14	84
Motorcycle	0	0	0	0
Total	1,001	6,006	1,072	6,432

Table 3.4: *Traffic volume and vehicle classification along - Old Branch Avenue – Set 2*

Vehicle Class	Number of Vehicles (10 mins)	Hourly Volume (NB)	Number of Vehicles (10 mins)	Hourly Volume (SB)
Cars	552	3,312	508	3,048
Medium Truck	17	102	16	96
Heavy Truck	12	72	10	60
Buses	10	60	1	6
Motorcycle	0	0	1	6
Total	591	3,546	536	3,216

Figure 3.2 shows the monitoring locations - behind the short concrete wall under the barrier condition at Site 1. Figure 3.3 shows the monitoring locations under the no-barrier condition for Site 1. a cross-section of the roadway at Site 1 and shows the receiver distances for the no-barrier condition.

Figure 3.2: *Site 1 – Barrier Monitoring Location*

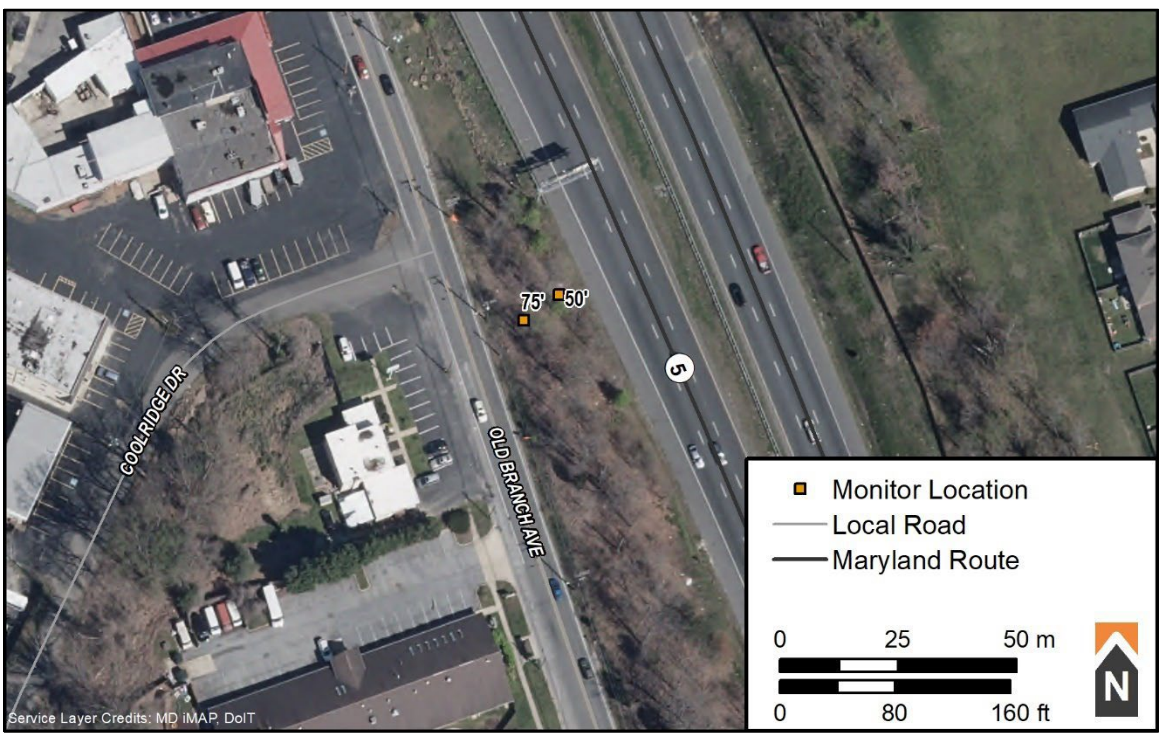

Figure 3.3: *Site 1 – No Barrier Monitoring Location*

3.4.2 Site 2

Site 2 is located on the Capitol Beltway in Capitol Heights, MD, just before Exit 15 in the northbound direction towards Largo, MD. The roadway consists of four lanes in both northbound and southbound directions. Measurements were taken in the northbound direction. Sound pressure levels were collected at two receiver distances for both barrier and no-barrier conditions. The short concrete barrier at this site is a height of 3 feet. Data collection occurred during evening hours, from 4:27 pm and 5:27 pm. At the time of measurement, the temperature was 59°F, wind speed was 7 mph, and the relative humidity was 48%. SLM microphones were placed 5 feet above ground level, and sound levels were recorded at each receiver location for a one-hour period. Traffic speed was recorded at one-minute intervals over ten minutes, with the average minimum and maximum vehicle speeds being 24 mph and 50 mph, respectively. Traffic volume was collected simultaneously with the sound level measurements. Both manual counting and video recording were used to capture traffic volume in both directions of travel. Refer to Table 3.5 for detailed traffic volume and vehicle classification information according to FHWA standards.

Table 3.5: *Traffic Volume and Vehicle Classification for Site 2*

Vehicle Class	Number of Vehicles (NB) (10 mins)	Hourly Volume (NB)	Number of Vehicles (SB) (10 mins)	Hourly Volume (SB)
Cars	909	5,454	896	5,376
Medium Truck	30	180	26	156
Heavy Truck	39	234	24	144
Buses	30	180	22	132
Motorcycle	1	6	0	0
Total	1,009	6,054	968	5,808

Figure 3.4 shows the monitoring locations behind the short concrete wall for Site 2. Figure 3.5 shows the monitoring location under the no-barrier condition for Site 2.

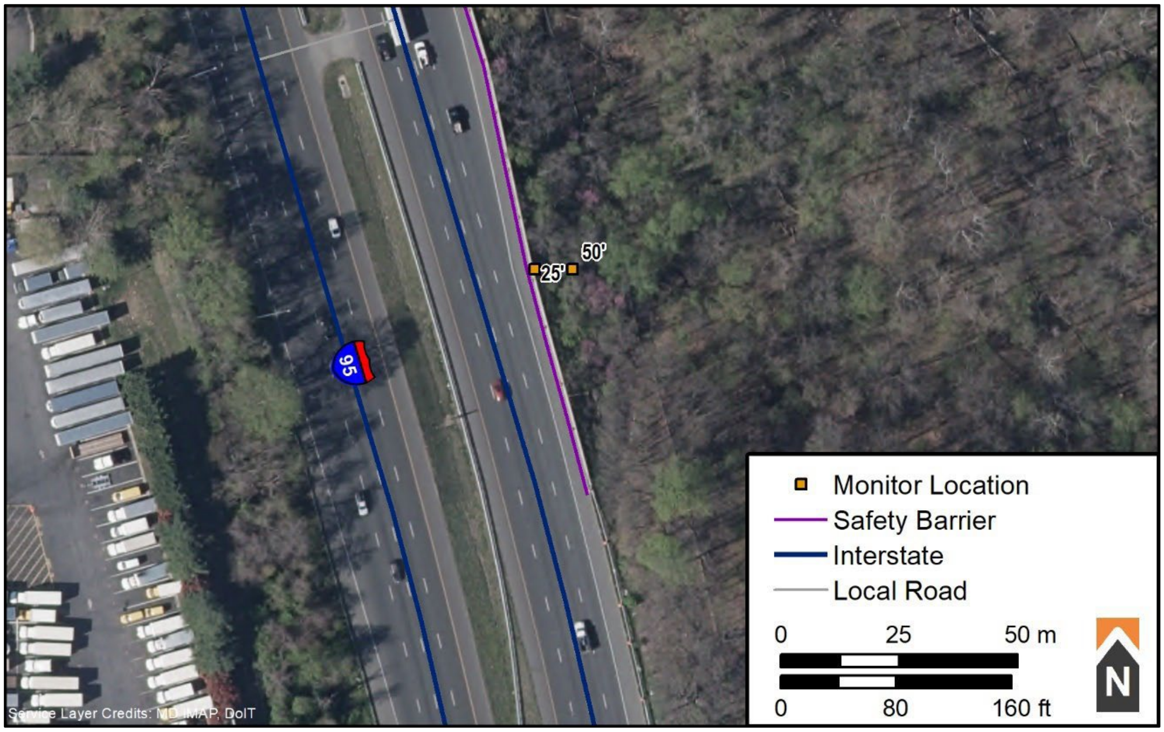

Figure 3.4: *Site 2 –Barrier Monitoring Location*

Figure 3.5: *Site 2 – No Barrier Monitoring Location*

3.4.3 Site 3

Site 3 is located at US-50, New York Ave. Noise measurements were not conducted at this site because it is situated on the boundary between Maryland and Washington, D.C., and permission to access the property for measurements was not obtained. Figure 3.6 provides the aerial and street views of the site.

3.4.4 Site 4

Site 4 is located at I-495 in Bethesda, MD. Noise measurements were not feasible at this site due to inaccessibility. Figure 3.7 shows the aerial and street views of the site.

Figure 3.6: *Aerial and Street View of Site 3*

Figure 3.7: *Aerial and Street View of Site 4*

3.4.5 Site 5

Site 5 is located at I-495 in Bethesda, MD. Noise measurements were not feasible at this site due to inaccessibility. Figure 3.8 shows the aerial and street views of the site.

Figure 3.8: *Aerial and Street View of Site 5*

3.4.6. Site 6

Site 6 is located along I-270 near Exit 10 in Gaithersburg, MD. The site features four northbound lanes, three lane on-ramp lanes, and four southbound lanes. The closest roadway to the sound level meter is a three-lane on-ramp. Measurements were taken only for the barrier condition, with the short concrete barrier standing at a height of 3 feet. Sound levels were collected at four receiver distances: 25 feet, 50 feet, 75 feet, and 100 feet. Data collection occurred during the morning hours between 11:50 AM and 12:50 PM, with temperature, wind speed and relative humidity recorded at 66°F, 7 mph, and 59% respectively. Sound level meters were placed 5 feet above ground level, and sound levels were recorded at each receiver location for one hour. Traffic speed was recorded at one-minute intervals over ten minutes, with average minimum and maximum vehicle speeds being 41 mph and 73 mph respectively. Traffic volume was also collected simultaneously with the sound level measurements. Both manual counting and video recording were used to capture traffic volume in both travel directions. Refer to Table 3.6 for detailed traffic volume and vehicle classification information according to FHWA standards. Figure 3.9 shows the monitoring locations behind the short concrete wall for Site 6.

Table 3.6: *Traffic Volume and Vehicle Classification for Site 6*

Vehicle Class	**Number of Vehicles (NB) (20 mins)**	**Hourly Volume (NB)**	**Number of Vehicles (SB) (20 mins)**	**Hourly Volume (SB)**
Cars	1,775	5,325	1,374	4,122
Medium Truck	77	231	38	114
Heavy Truck	109	327	42	126
Buses	73	219	39	117
Motorcycle	0	0	0	0
Total	1,113	6,102	1,493	4,479

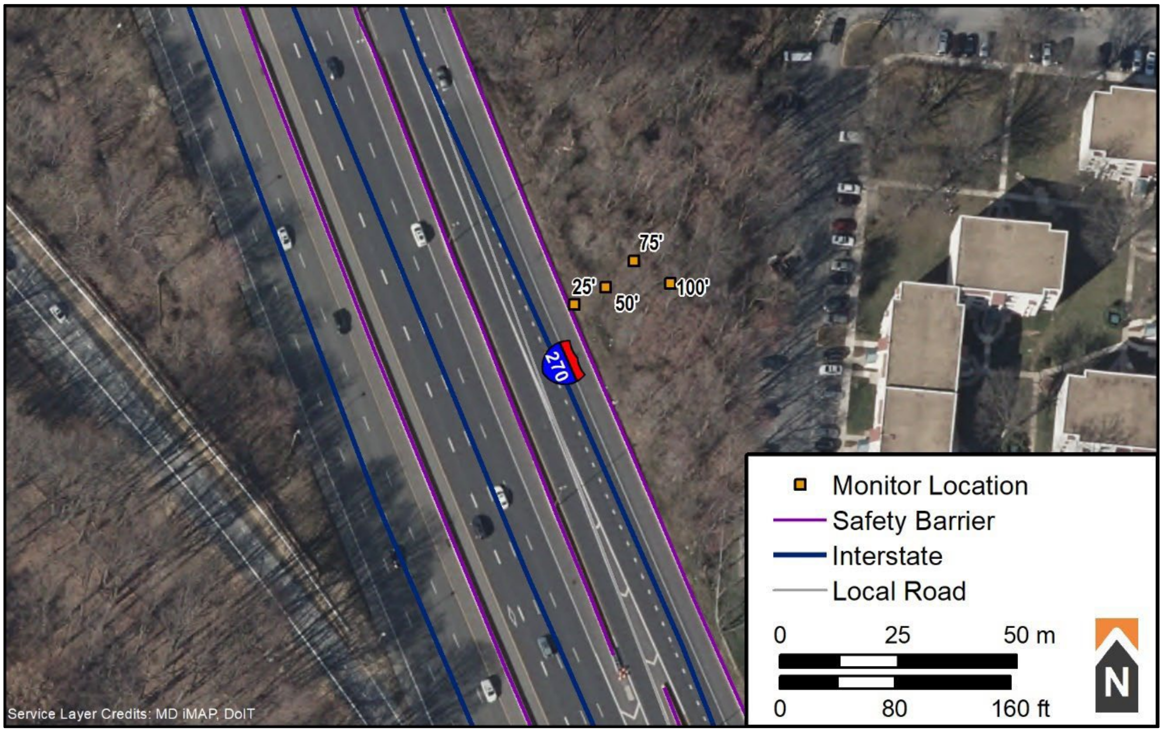

Figure 3.9: *Site 6 –Barrier Monitoring Location*

3.4.7 Site 7

Site 7 is situated at 8074 Baltimore National Pike in Ellicott City, MD. Although noise measurements were attempted at this site, they were nullified due to the barrier's placement between two roadways. This positioning made it challenging to obtain accurate measurements on one side of the roadway without interference from traffic on the other side. Figure 3.10 provides the aerial and street views of Site 7.

Figure 3.10: *Aerial and Street View of Site 7*

3.4.8 Site 8

Site 8 is situated along Ranier Dr in Frederick, MD. This site features two-lane roadways moving in the eastbound and westbound directions, and measurements were conducted for both barrier and no-barrier conditions.

On the eastbound roadway where measurements were taken for the barrier condition, there were two lanes and a single on-ramp lane due to an exit located just after the barrier. Conversely, at the point of no-barrier, there were two lanes. On the westbound roadway, the number of lanes was three at the point of no-barrier and changed to two at the barrier condition due to a merge on the roadway. The short concrete barrier at this site stands at a height of 3 feet.

Sound levels were collected at two receiver distances, 25 feet and 50 feet, simultaneously at both the barrier and no-barrier conditions. Data collection occurred during the evening hours, from 4:20 PM to 5:30 PM, with temperature, wind speed and relative humidity recorded at 48°F, 4 mph, and 60% respectively. Sound level meters were positioned 5 feet above ground level, and sound levels were recorded at each receiver for a one-hour period.

Traffic speed was recorded at one-minute intervals over ten minutes, with average minimum and maximum vehicle speeds measured at 54 mph and 80 mph, respectively.

Traffic volume was also collected simultaneously with the sound level measurements using both manual counting and video recording techniques. Refer to Table 3.7 for detailed traffic volume and vehicle classification information according to FHWA standards.

Table 3.7: Traffic Volume and Vehicle Classification Along Ranier Dr, Frederick, MD

Vehicle Class	**Number of Vehicles (EB) (20 mins)**	**Hourly Volume (EB)**	**Number of Vehicles (WB) (20 mins)**	**Hourly Volume (WB)**
Cars	602	1,806	645	1,935
Medium Truck	11	33	21	63
Heavy Truck	17	51	22	66
Buses	5	15	8	24
Motorcycle	0	0	0	0
Total	635	1,905	696	2,088

Figure 3.11 shows a map of the roadway at Site 8, illustrating the monitoring locations distances behind the short concrete wall under the barrier condition. Figure 3.12 presents a cross-section of the roadway at Site 8, showing the monitoring locations under no-barrier condition.

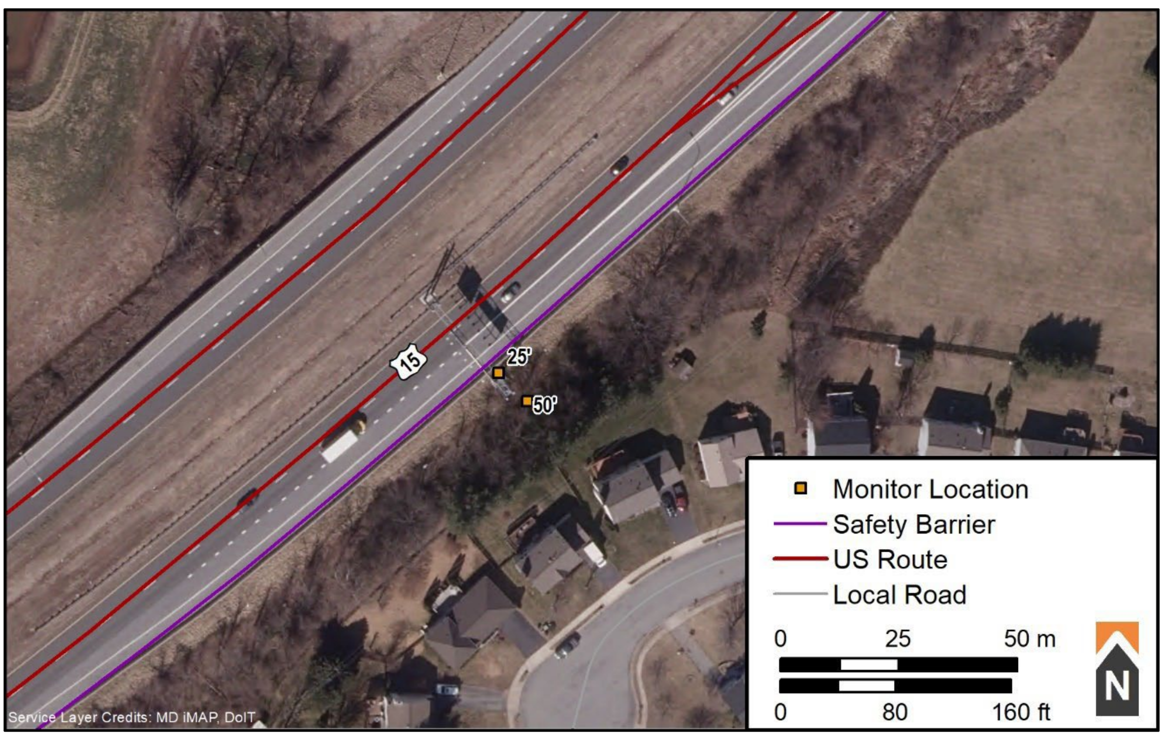

Figure 3.11: *Site 8 –Barrier Monitoring Location*

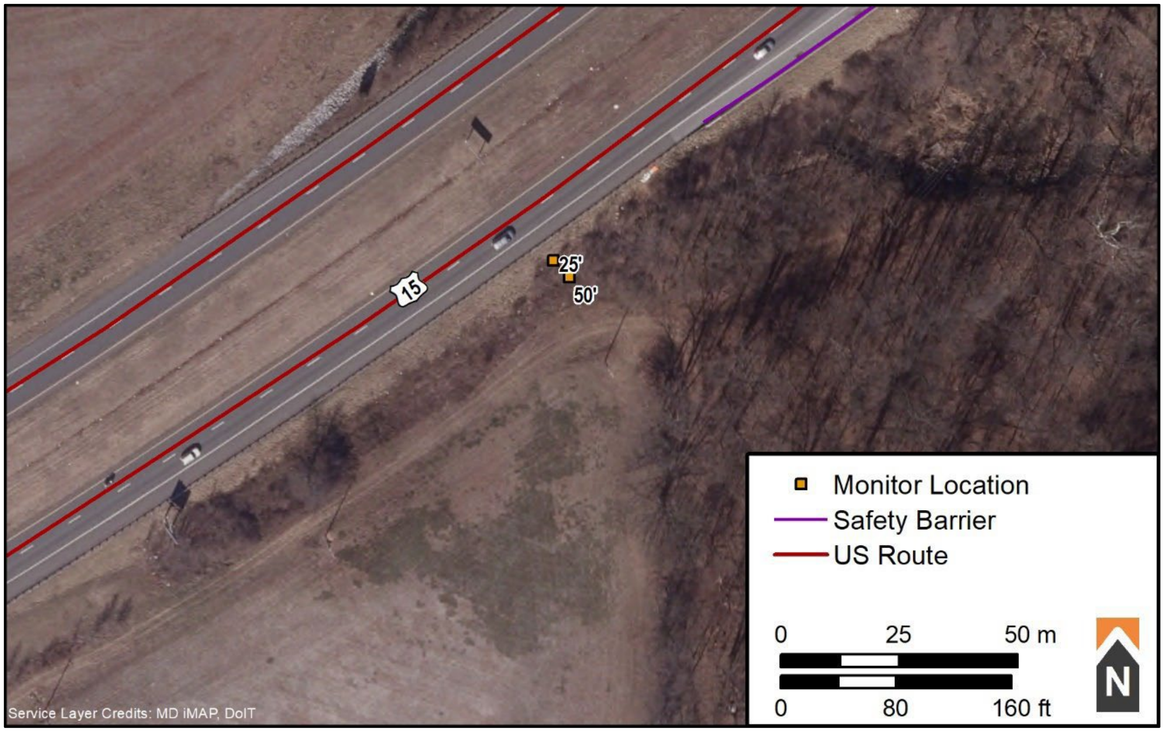

Figure 3.12: *Site 8 –No-Barrier Monitoring Location*

3.4.9 Site 9

Site 9 is situated on I-83 in Baltimore, MD. Noise measurements were not feasible at this site due to the presence of two-way traffic on the roadway where the barrier was located. It would have been challenging to obtain a full hour of noise measurement without interference from vehicles moving in the opposite direction. Figure 3.13 provides the aerial and street views of Site 9.

Figure 3.13: *Aerial and Street View of Site 9*

3.4.10 Site 10

Site 10 is located on Washington National Pike in Germantown, MD. This site features two roadways moving northbound and southbound, with measurements conducted for barrier conditions only. Both roadways have four lanes, and the short concrete barrier stands at a height of 3 feet.

Sound levels were collected at three receiver distances: 25 feet, 50 feet, and 75 feet. Data collection took place during the afternoon hours for two hours, from 12:55 p.m. to 2:00 p.m. Sound level meters were positioned 5 feet above ground level, and sound levels were recorded at each receiver for a one-hour period.

Traffic speed was recorded at one-minute intervals over ten minutes, with average minimum and maximum vehicle speeds measured at 42 mph and 73 mph, respectively, with temperature, wind speed, and relative humidity recorded at 41°F, 9 mph, and 55% respectively. Simultaneously with the sound level measurements, traffic volume data were collected. Manual counting and video recording techniques were used to capture traffic volume in both directions of travel. Refer to Table 3.8 for detailed traffic volume and vehicle classification information according to FHWA standards. Figure 3.14 shows map of the roadway along with the monitoring locations behind the short concrete wall at the barrier condition for Site 10.

Table 3.8: *Traffic Volume and Vehicle Classification for Site 10*

Vehicle Class	Number of Vehicles (SB) (56 mins)	Hourly Volume (SB)	Number of Vehicles (NB) (56 mins)	Hourly Volume (NB)
Cars	2,965	3,177	3,485	3,734
Medium Truck	96	103	112	120
Heavy Truck	146	156	272	291
Buses	66	71	60	64
Motorcycle	0	0	0	0
Total	3,273	6,780	3,929	4,208

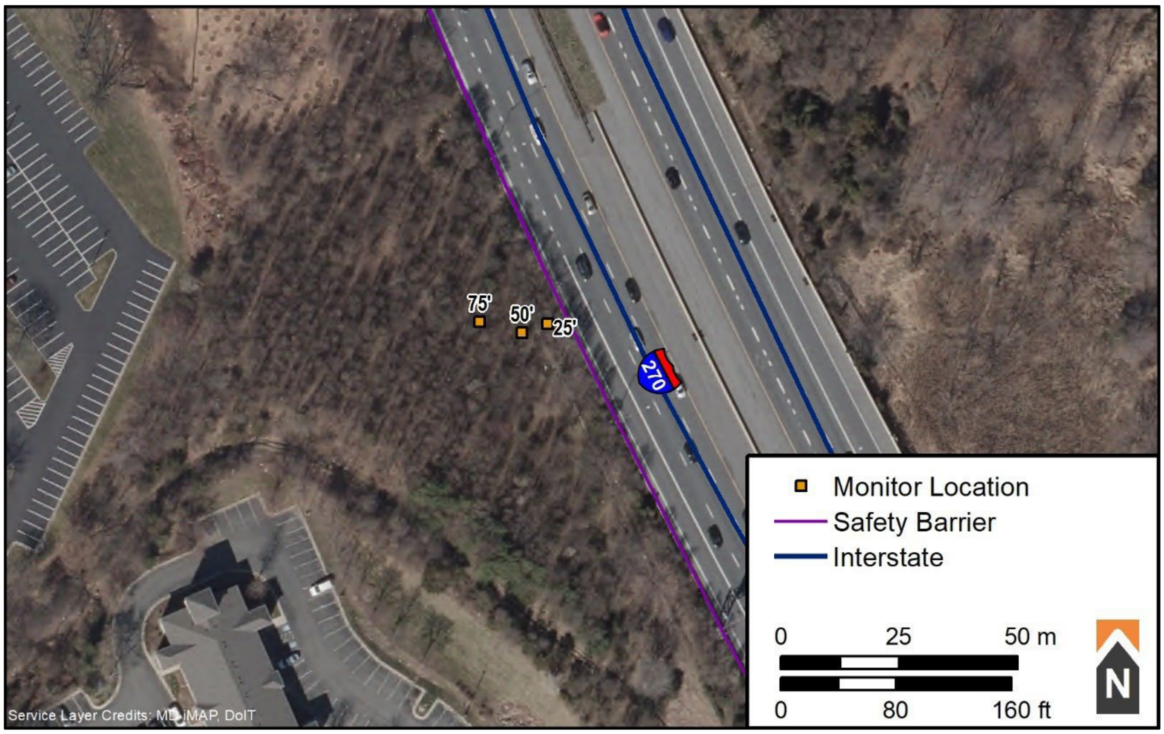

Figure 3.14: *Site 10 –Barrier Monitoring Location*

3.5 Sound Propagation Models

This research adopted seven (7) sound propagation models. They are the Traffic Noise Model v2.5 and v3.2 (i.e TNM 2.5 and TNM 3.2), as well as four modeling techniques found in a similar study for the for the California Department of Transportation (Caltrans). A summary of the modeling methods described in this paper is shown in Table 3.9. Further discussion of the development and selection of modeling methods is available in the Caltrans Project Memo (Lodico, 2023).

Models 1 and 6 are direct uses of the TNM 2.5 and TNM 3.2 software, respectively. Models 2, 3, 4, and 5 utilize the SoundPLAN implementation of TNM 2.5, including the SoundPLAN "Bug Fix," which fixes five errors in TNM 2.5 that were identified by the SoundPLAN developers in 2007. Model 7 does not include the bug fix implemented for Model 2. Table 3.8

describes the different models and their source heights and the respective multipliers for lower, upper heavy trucks, and upper other vehicles.[1]

[1] The five identified errors an error in the ground impedance calculation, an error with path differences over short barriers, an error in the insertion loss calculation, an error in the calculation of multiple barriers, and calculating propagation in two dimensions instead of three dimensions.

Table 3.9: *Summary of Modeling Methods*

		Source Height			**Multiplier For Source Height**		
Model Number	**Implementation Software**	**Lower**	**Upper, Heavy Trucks**	**Upper, Other Vehicle Types**	**Lower**	**Upper Heavy Truck**	**Upper, Other Vehicle Types**
1	TNM 2.5	0 feet	12 feet	5 feet	0 feet (A)	12 feet (C)	5 feet (B)
2	SoundPLAN1[a]	0 feet	12 feet	5 feet	0 feet (A)	12 feet (C)	5 feet (B)
3	SoundPLAN1[a]	0 feet	2.3 feet	0.33 feet	0 feet (A)	0 feet (A)	0 feet (A)
4	SoundPLAN1[a]	0 feet	3 feet	0.33 feet	0 feet (A)	0 feet (A)	0 feet (A)
5	SoundPLAN1[a]	0 feet	3 feet	0.33 feet	0 feet (A)	5 feet (B)	0 feet (A)
6	TNM 3.2	0 feet	12 feet	5 feet	0 feet (A)	12 feet (C)	5 feet (B)
7	SoundPLAN1[b]	0 feet	12 feet	5 feet	0 feet (A)	12 feet (C)	5 feet (B)

[a] *Includes use of the SoundPLAN "Bug Fix" for TNM 2.5.*

[b] *Did not use of the SoundPLAN "Bug Fix" for TNM 2.5.*

Models 3, 4, and 5 vary the upper sub-source heights and multipliers to match the NCHRP Report 842 results. The different noise source heights were facilitated through use of a code, provided by the SoundPLAN development team, allowing for the alteration of TNM source heights and energy distributions in TNM implemented within the SoundPLAN software package. The code also allowed for the alteration of the Multiplier, *m*, that is used in TNM to correct for ground effects in the TNM software. The TNM software does not allow for the alterations of source heights, distributions, or Multipliers. The Multipliers are indicated with a capital letter (A, B, or C), which is used to indicate the Multiplier type throughout the remainder of this report. Further discussion of the development and selection of modeling methods is available in the Caltrans Project Memo. Figure 3.15 describes the symbology within the TNM 2.5 cross-sections.

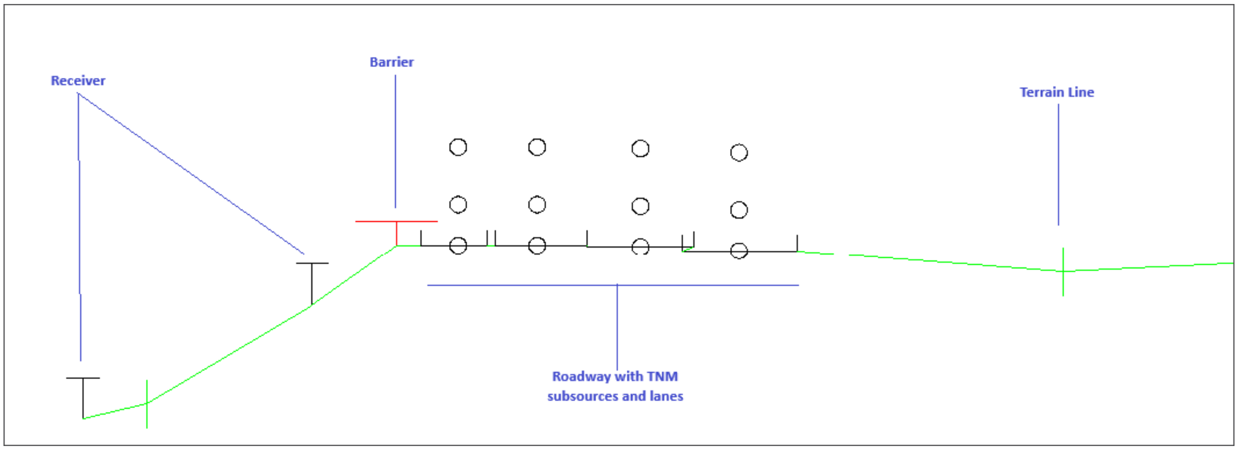

Figure 3.15: *TNM 2.5 Geometry Symbology*

Models 1 and 6 are direct uses of the TNM 2.5 and TNM 3.2 software, respectively. Models 2, 3, 4, and 5 utilize the SoundPLAN implementation of TNM 2.5, including the SoundPLAN "Bug Fix," which fixes five errors in TNM 2.5 that were identified by the SoundPLAN developers in 2007 (Koussa et al., 2013). Model 7 is similar to Model 2 but implemented without the "Bug Fixes" in SoundPLAN. Models 3, 4, and 5 vary the upper sub-source heights and multipliers to match the NCHRP Report 842 results (FHWA, 2011). The different noise source heights were facilitated through use of a code, provided by the SoundPLAN development team, allowing for the alteration of TNM source heights and energy distributions in TNM implemented within the SoundPLAN software package. The code also allowed for the alteration of the Multiplier, *m*, that is used in TNM to correct ground effects in the TNM software (USDOT FHWA, 2010). The TNM software does not allow for the alterations of source heights, distributions, or Multipliers.

3.6 Model Traffic Summary

Table 3.10 summarizes the total traffic volume for each roadway direction, vehicle classification percentage, and speed. For modeling, the traffic was further split per lane based on the traffic counts conducted on the site. Each lane was counted for 10 to 20 minutes then extrapolated to an hourly traffic volume for use in the modeling as is seen in Tables 3.2 – 3.7 and the summary presented in Table 3.9. Overall, in the count data, all trucks made up three to ten percent of the total traffic, with one to seven percent heavy trucks. Sites 6 and Site 10 had a higher average heavy truck percentage at 4% and 6%, respectively. Sites 1 and 8 had the lowest proportion of total trucks to all traffic. Site 1 also had the highest volume of total vehicles and Site 8 had the lowest. Average vehicle speeds ranged from 48 to 67 miles per hour.

Table 3.10: *Modeled Traffic Input Summary*

Site	Roadway	Direction	Total Hourly Vehicles	Vehicle Percentage Medium Truck	Heavy Truck	Bus	Motorcycle	Speed (AVG)
Site 1 - Set A	MD Rt. 5	SB	6066	2%	1%	1%	1%	60
Site 1 - Set A	MD Rt. 5	NB	6516	3%	2%	1%	1%	60
Site 1 - Set B	MD Rt. 5	SB	6444	3%	2%	0%	0%	51
Site 1 - Set B	MD Rt. 5	NB	7212	3%	2%	2%	2%	51
Site 2	I-95	NB	6054	3%	4%	3%	0%	48
Site 2	I-95	SB	5808	3%	2%	2%	0%	48
Site 6	I-270	NB	6102	4%	5%	4%	0%	57
Site 6	I-270	SB	4479	3%	3%	3%	0%	57
Site 8	US Rt. 15	EB	1905	2%	3%	1%	0%	67
Site 8	US Rt. 15	WB	2088	3%	3%	1%	0%	67
Site 10	I-270	NB	4210	3%	7%	1%	0%	57
Site 10	I-270	SB	3507	3%	4%	2%	0%	57

3.7 Traffic Model Inputs

The sound propagation modeling applied herein accounts for factors such as propagation over different ground types (pavement and soft ground), roadway elevation, shielding effects from local terrain and structures, traffic speed, and hourly traffic volume. The model inputs were the same for all seven modeling methods: TNM 2.5, TNM 3.2 and the four Caltrans modeling methods.

Six-inch resolution aerial imagery from MD iMAP, Maryland's Geographic Information System (GIS) database and Esri software was used to create the existing roadway and geometry configurations. A DEM (digital elevation model) was used to add elevations to the model. The elevation for each site was derived from their respective counties DEM in feet from the MD iMAP service.

CHAPTER FOUR

RESULTS AND DISCUSSION

This Chapter summarizes the results, which include the model validation and barrier insertion loss, of the sound propagation modeling using the six methodologies described in Section 3.5. It also extends theoretical modeling from prior research to include TNM 3.2.

4.1 Theoretical Modeling

Two theoretical scenarios, mirroring monitored sites, were evaluated using TNM 3.2 to compare with previous research that assessed TNM 2.5 and four Caltrans modeling methods. The scenarios include an at-grade and an elevated roadway, each with a 42-inch barrier and a 4-lane alignment, featuring 10% trucks and 90% light vehicles. The insertion loss results using the six models, as detailed in Section 3.2, for both the at-grade and elevated roadways are illustrated in Figures 4.1 and 4.2, respectively.

As shown in Figure 4.1 for the at-grade scenario, TNM 3.2 produces similar insertion loss values to TNM 2.5 at the 25-foot receptor distance (within 1 dB) and aligns closely (within 1 dB) with TNM implemented in SoundPLAN (Model 2) and the NCHRP height-based models (Models 3, 4, and 5). This consistency suggests that the corrections included in TNM 3.2 enhance the results compared to TNM 2.5 for at-grade cases. The calculated insertion losses using TNM 3.2 decrease with distance from the barrier, consistent with existing literature.

For the elevated scenario depicted in Figure 4.2, TNM 3.2 results were within 1 dB of TNM 2.5, showing insertion losses of less than 4 dB across all distances, which do not decrease with distance, contrary to literature. The NCHRP height-based models (Models 3, 4, and 5) provided significantly higher insertion loss values compared to TNM 2.5 and TNM 3.2 for the elevated scenario. TNM implemented in SoundPLAN (Model 2) showed insertion losses trending with, but 3 to 5 dB lower than, the NCHRP height-based models, yet considerably higher than TNM 2.5 and TNM 3.2. These findings indicate that the corrections in TNM 3.2 do not improve results over TNM 2.5 for elevated cases.

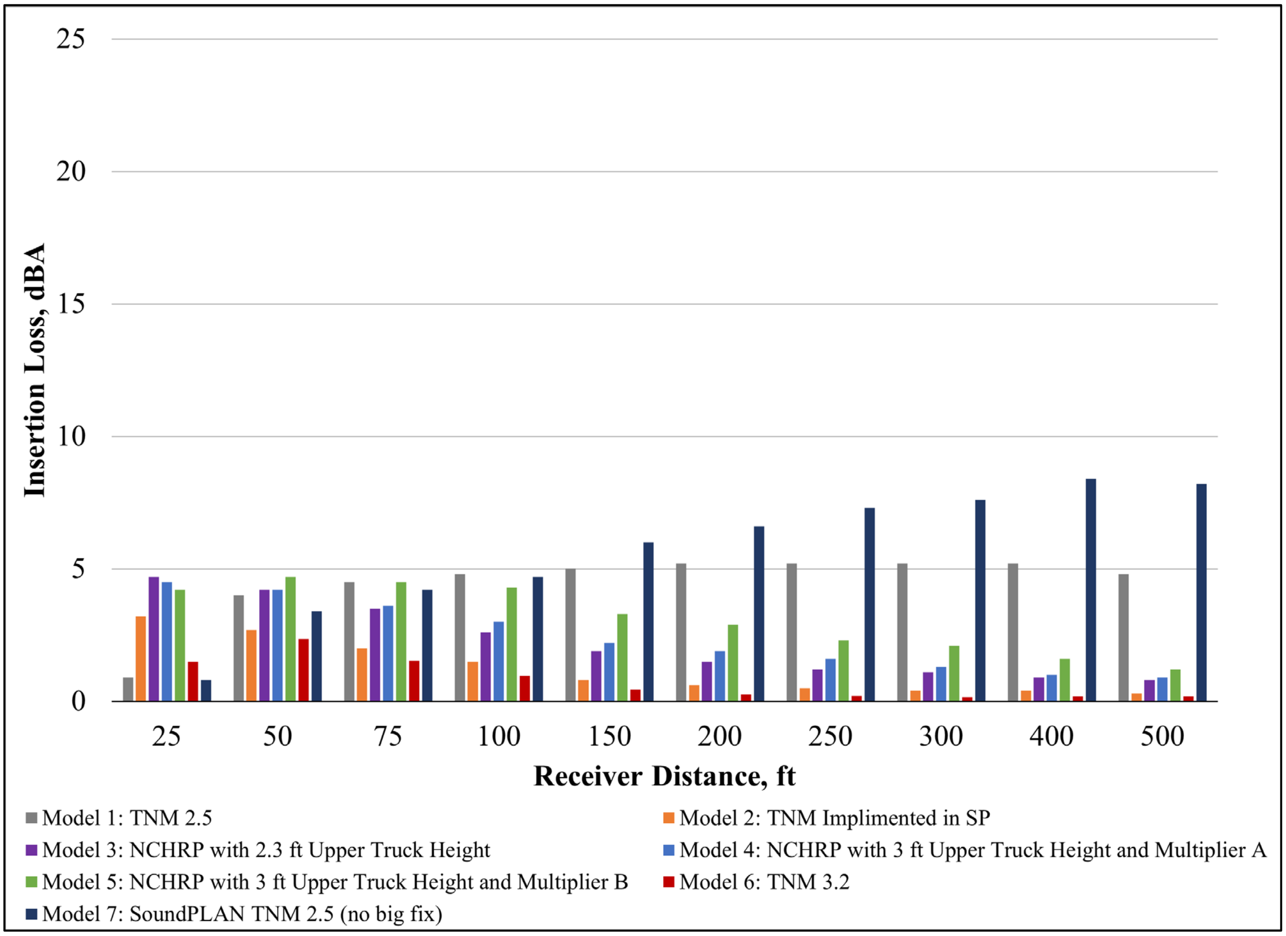

Figure 4.1: *Insertion Loss for At-Grade 4-Lane Highway with 42-Inch Barrier*

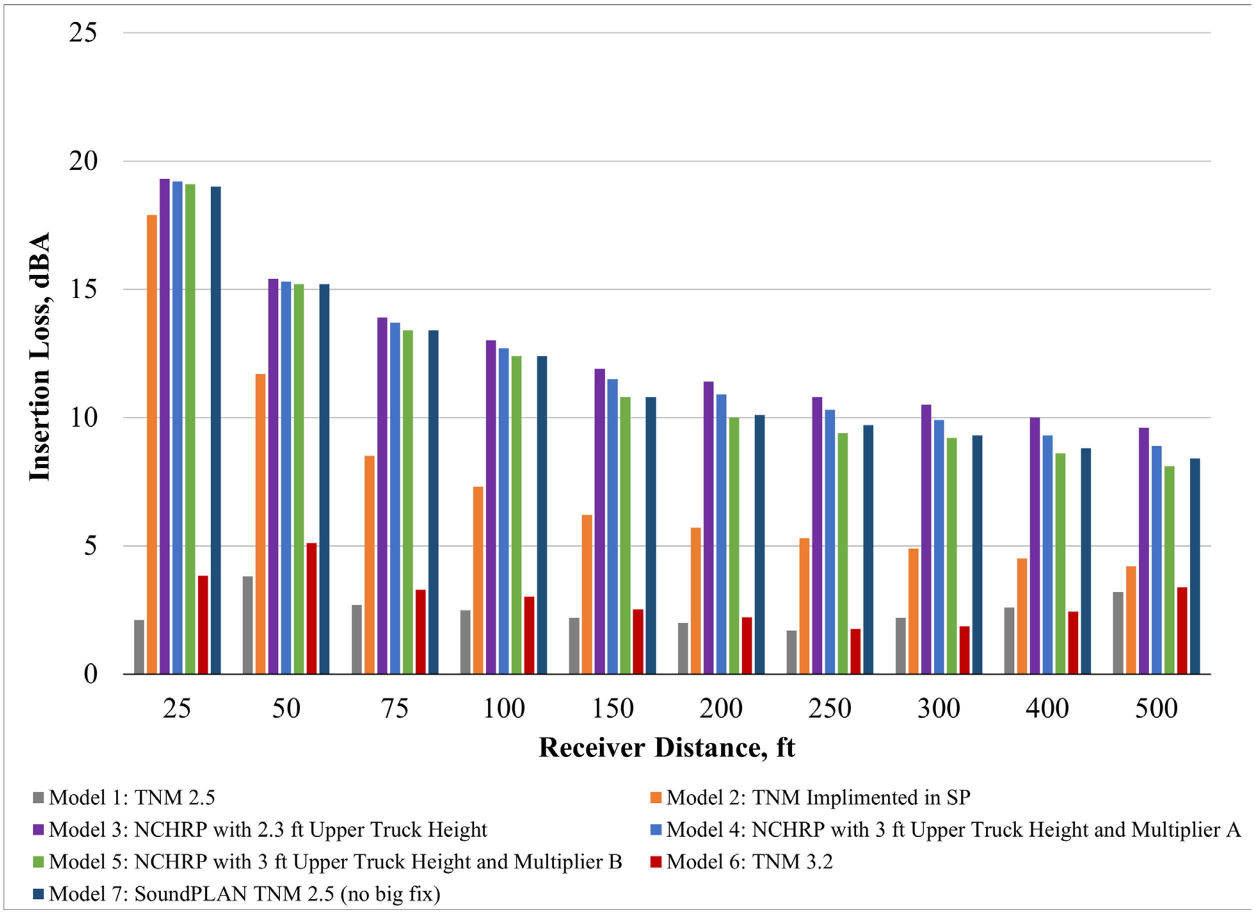

Figure 4.2: *Insertion Loss for Elevated 4-Lane Highway with 42-Inch Barrier*

4.2 Model Validation

The measured sound levels at the six sites were validated using TNM 2.5. The validated TNM 2.5 models were then input into TNM 3.2 and SoundPLAN to calculate the model sound level results under each modeling method. The geometry and traffic inputs are the same per site for all modeling methods.

The modeled sound pressure levels for each site can be found in Table 4.1 show the monitoring locations measured and modeled hourly L_{eq} from each of the models. The validation results (modeled – measured) per monitoring location for each model are shown in Appendix C. The model 7 is added with SoundPLAN in TNM 2.5 with no bug fix.

Figure 4.3 through Figure 4.7 show the modeled minus measured results (differences) for each of the measurement locations. The TNM 2.5 implemented in SoundPLAN (Model 2) and the NCHRP height-based models (**Models 3, 4, and 5**) models are underpredicting compared to the measured sound levels. The biggest difference between the measured and the modeled levels was 8 dB using the NCHRP height-based Model 3 and 4, as shown in Figure 4.7.

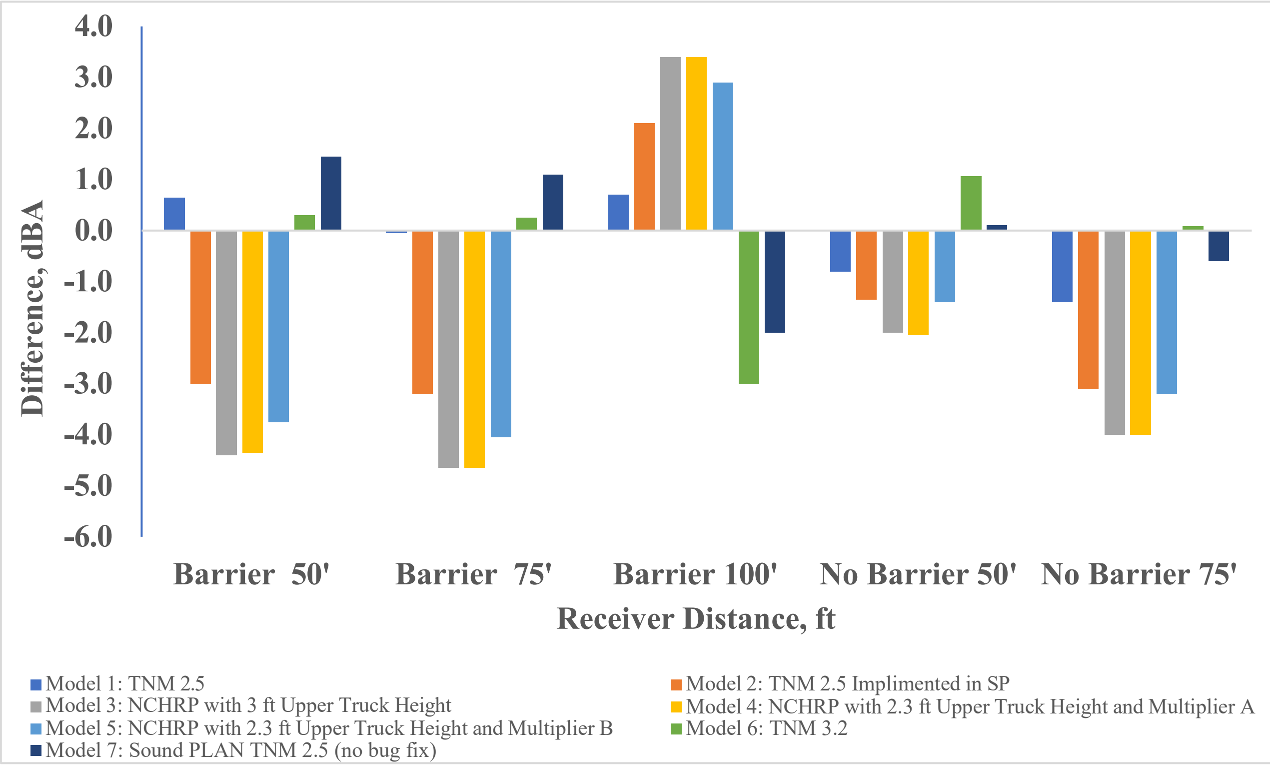

Figure 4.3: *Model Validation of Site 1*

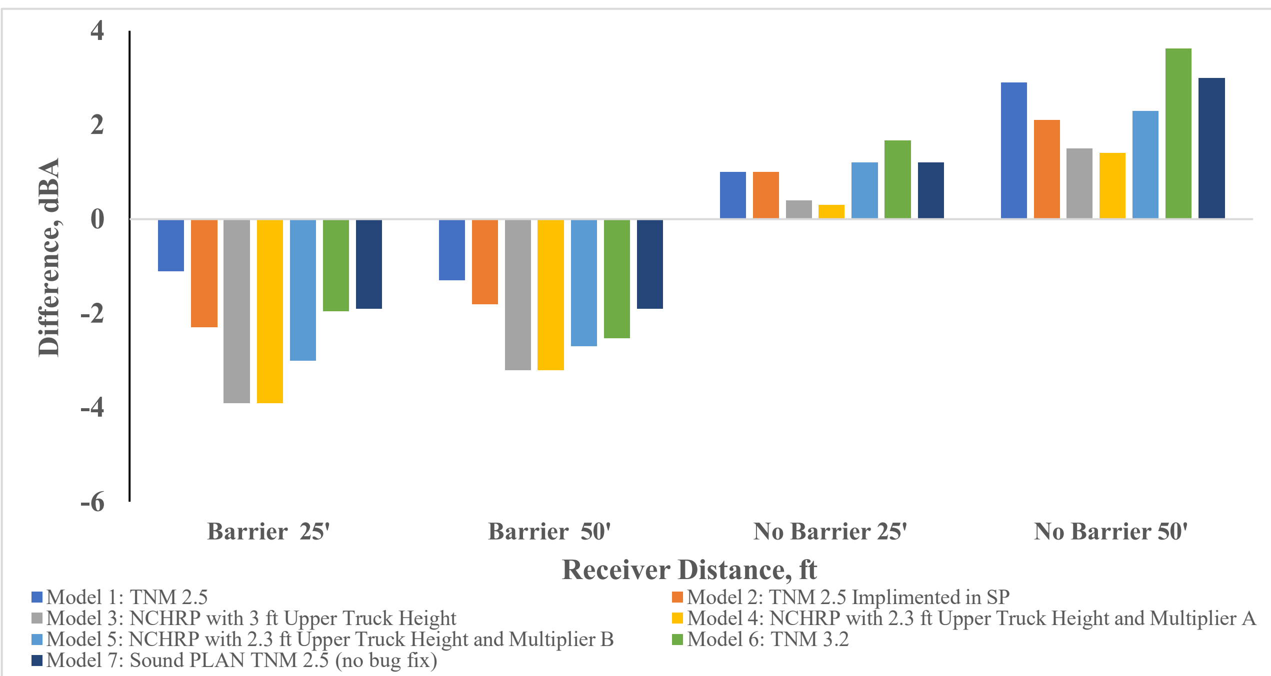

Figure 4.4: *Model Validation of Site 2*

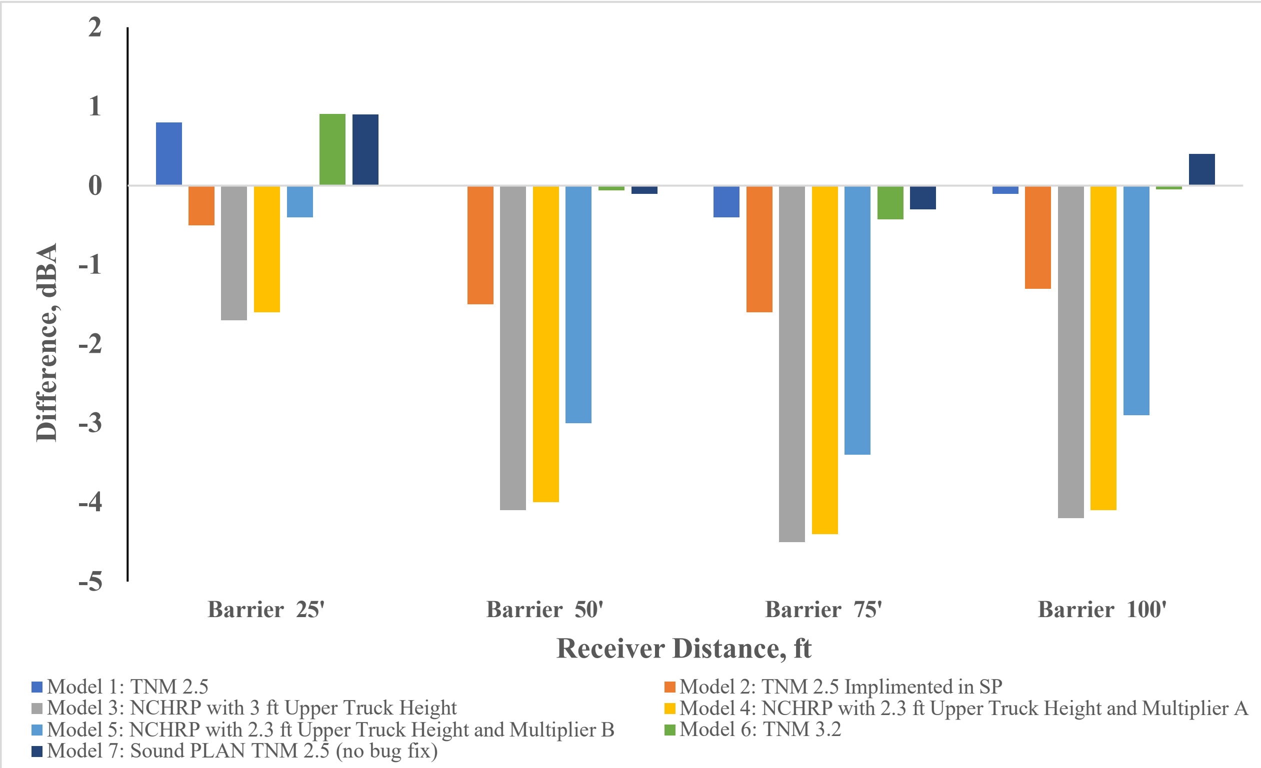

Figure 4.5: *Model Validation of Site 6*

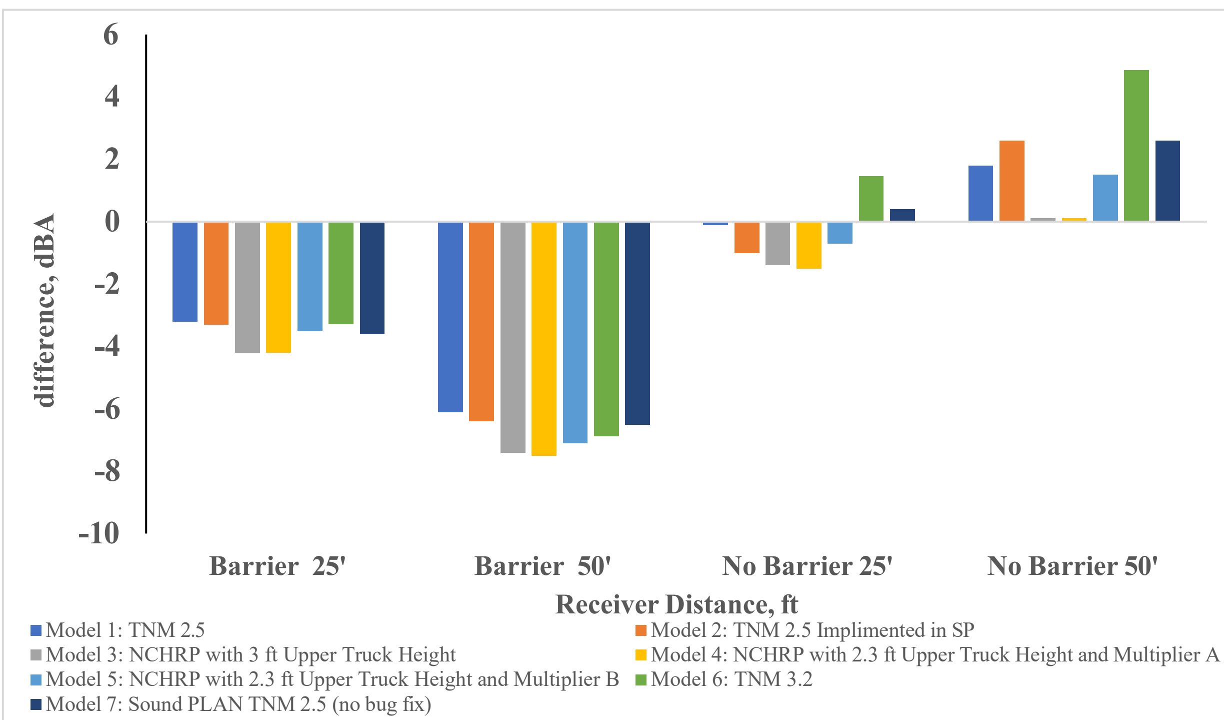

Figure 4.6: *Model Validation of Site 8*

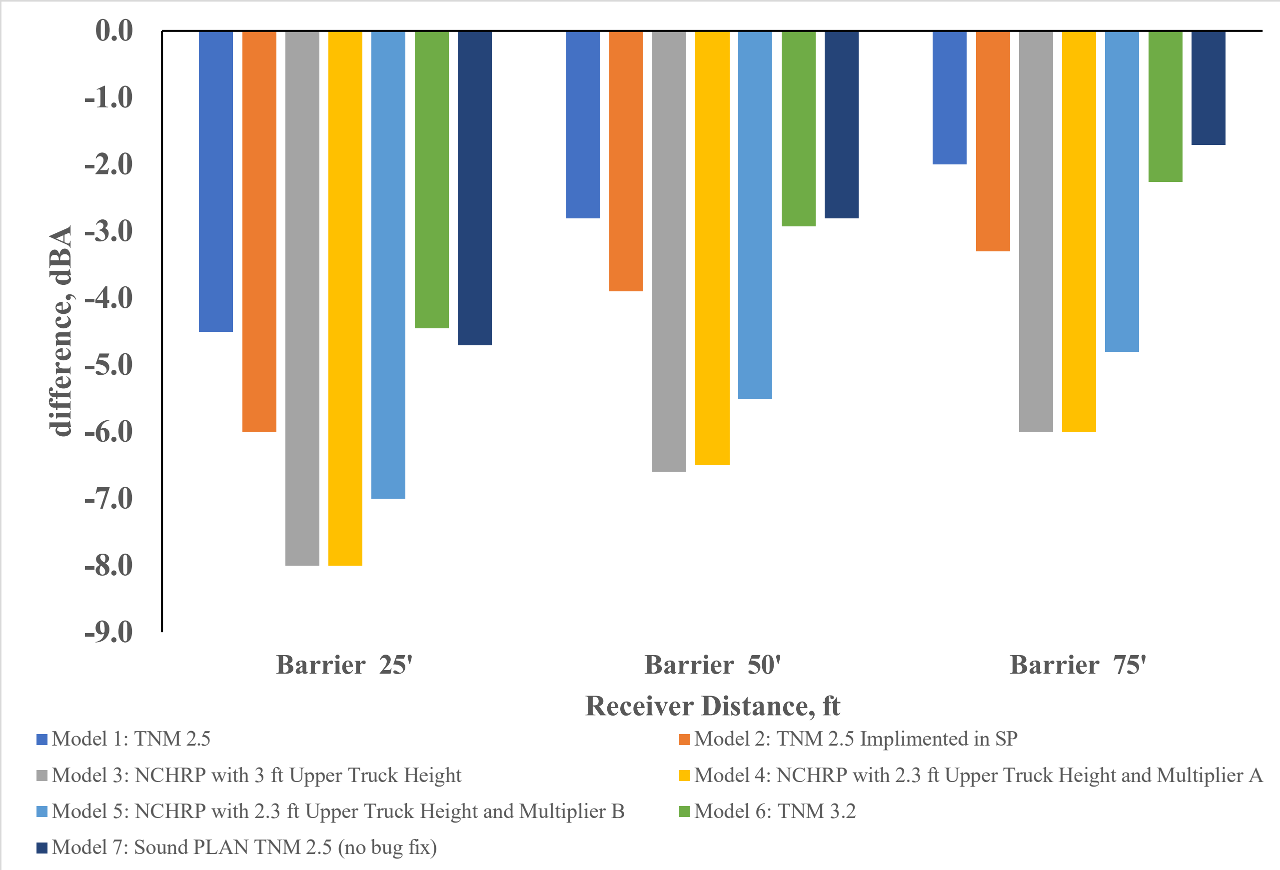

Figure 4.7: *Model Validation of Site 10*

Differences of ±3 dB between measured and modeled results are considered "validated"" under FHWA highway noise study procedures. TNM 2.5 and TNM 3.2 gave results that were most closely aligned with measured levels (Table 4.1). TNM 2.5 validated at 17 out of the 20 measurement locations (85% validation performance) and TNM 3.2 validated at 16 out of the 20 measurement locations (80% validation performance). Although, the sites that were validated in TNM 3.2 were not the same as the TNM 2.5 sites that were validated (Appendix D). The Caltrans modeling methods (Models 2 through 5) did not perform as well as TNM 2.5 or 3.2, resulting in five to twelve validated sites. This result is different from the outcome found in the Caltrans study, which found that the SoundPLAN implemented models performed better than TNM 2.5 or 3.1. Applying the model 7, no bug fix to TNM 2.5, implemented in SoundPLAN, 16 out of the 20 measurement sites validated (80% validation performance).

Table 4.1: *Model Performance*

Model	Number of Validated Sites (±3 dB)	Total Number of Sites	% Validation
Model 1: TNM 2.5	17	20	85
Model 2: TNM 2.5 Implemented in SP	12	20	60
Model 3: NCHRP with 3 feet Upper Truck Height	5	20	25
Model 4: NCHRP with 2.3 feet Upper Truck Height and Multiplier A	6	20	30
Model 5: NCHRP with 2.3 feet Upper Truck Height and Multiplier B	9	20	45
Model 6: TNM 3.2	16	20	80
Model 7: Sound PLAN TNM 2.5 (no bug fix)	16	20	80

4.3 Modeled Insertion Loss

The modeled insertion loss of the short barriers at each of the five monitoring sites was determined by comparing the modeled sound results and the modeled sound level results when the barrier height was reduced from 3 feet to 0 feet for each modelling method. The calculated insertion loss values for each monitoring site are detailed in Appendix D. Figures 4.8 through 4.12 shows the predicted insertion loss at each measurement location for the six models. These findings revealed the potential significance of short barrier in mitigating traffic noise and highlighted the variability in model predictions, which may have implications for future noise control strategies and urban planning policies. TNM 2.5 and 3.2 (Models 1 and 6) trended similarly by distance for all locations and all sites, with TNM 3.2 resulting in higher insertion loss values by 0 to 9 dB. The TNM implemented in SoundPLAN method (Model 2) and the NCHRP height-based models (Models 3, 4, and 5) trended similarly, with Model 2 generally resulting in slightly lower insertion loss than the others.

Both TNM 2.5 and 3.2 gave lower insertion loss values (by 1 to 5 dB) for the at-grade sites (Site 1 and the 25-foot position for Site 6) than the other modeling methods. This is consistent with the theoretical modeling results for the 25-foot distance, but inconsistent with the theoretical modeling at further distances. For the elevated sites, the trends are less apparent. Site 2 shows an insertion loss of 8 to 9 dB for all methods at 25-feet and little insertion loss at the 50-foot position except TNM 3.2, which had a 2 dB insertion loss at 50-feet. At Site 8 and the 25-foot distance for Site 10, TNM 2.5 gave insertion loss values that were 1 to 5 dB higher than the other models. However, at Site 6 and the distant locations for Site 10, the TNM 2.5 and 3.2 insertion loss levels were lower by 2 to 5 dB. The theoretical modeling found that TNM 2.5 and 3.2 gave lower insertion loss values for all distances.

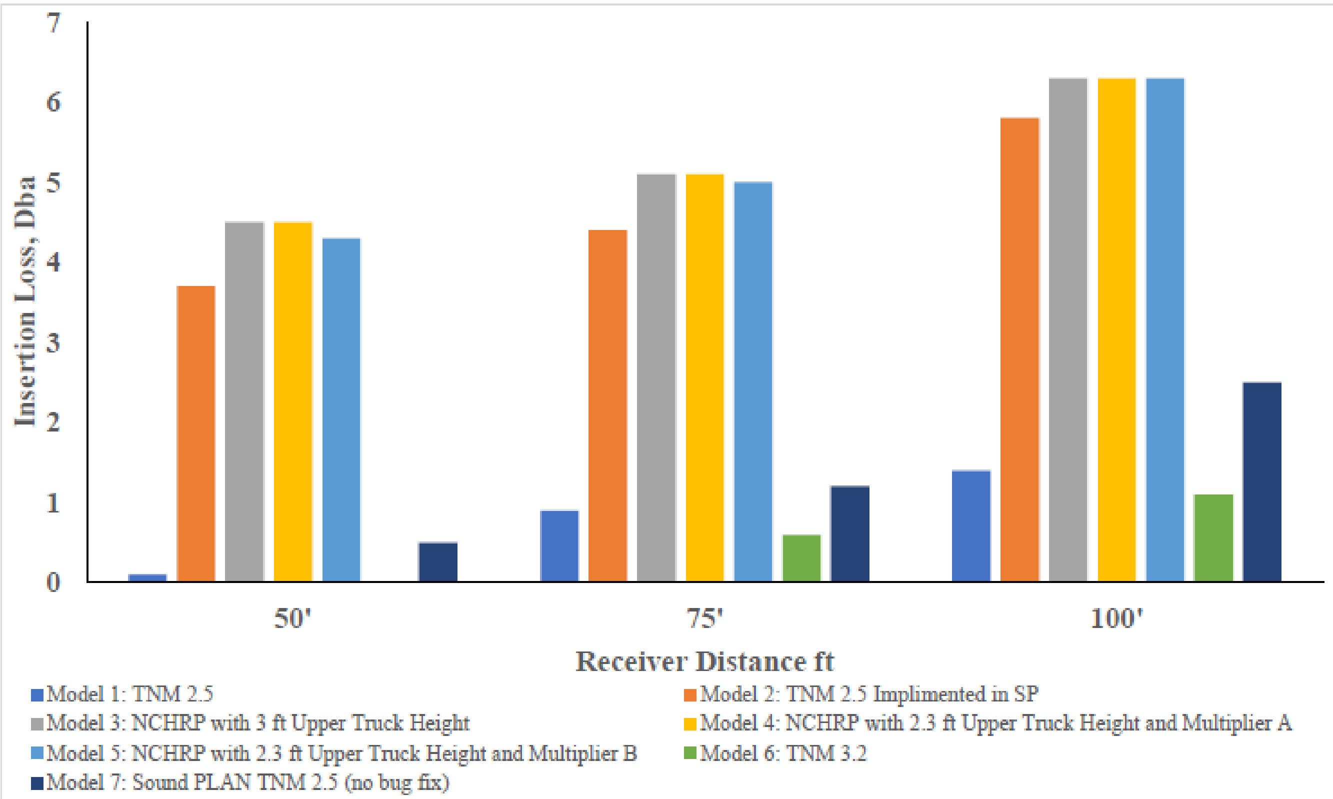

Figure 4.8: *Modeled Insertion Loss for Site 1 (At Grade)*

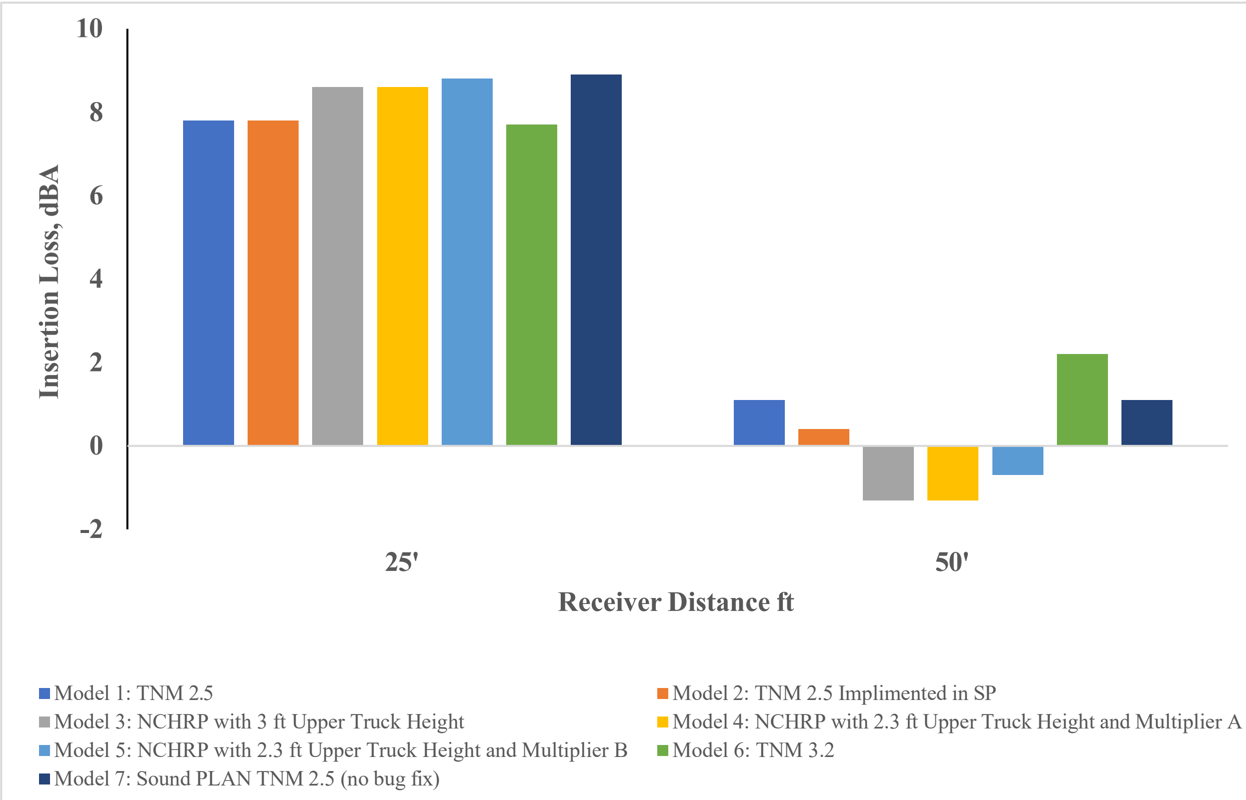

Figure 4.9: *Modeled Insertion Loss for Site 2 (Elevated)*

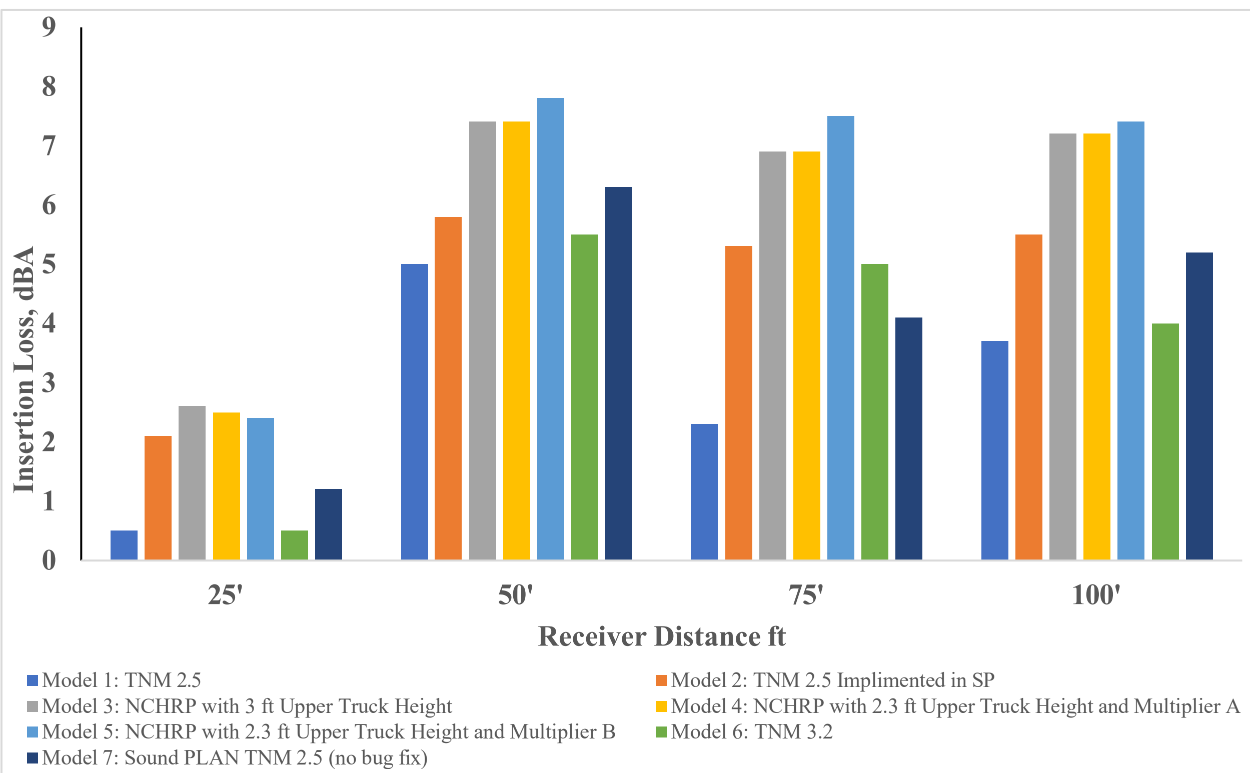

Figure 4.10: *Modeled Insertion Loss for Site 6 (At Grade)*

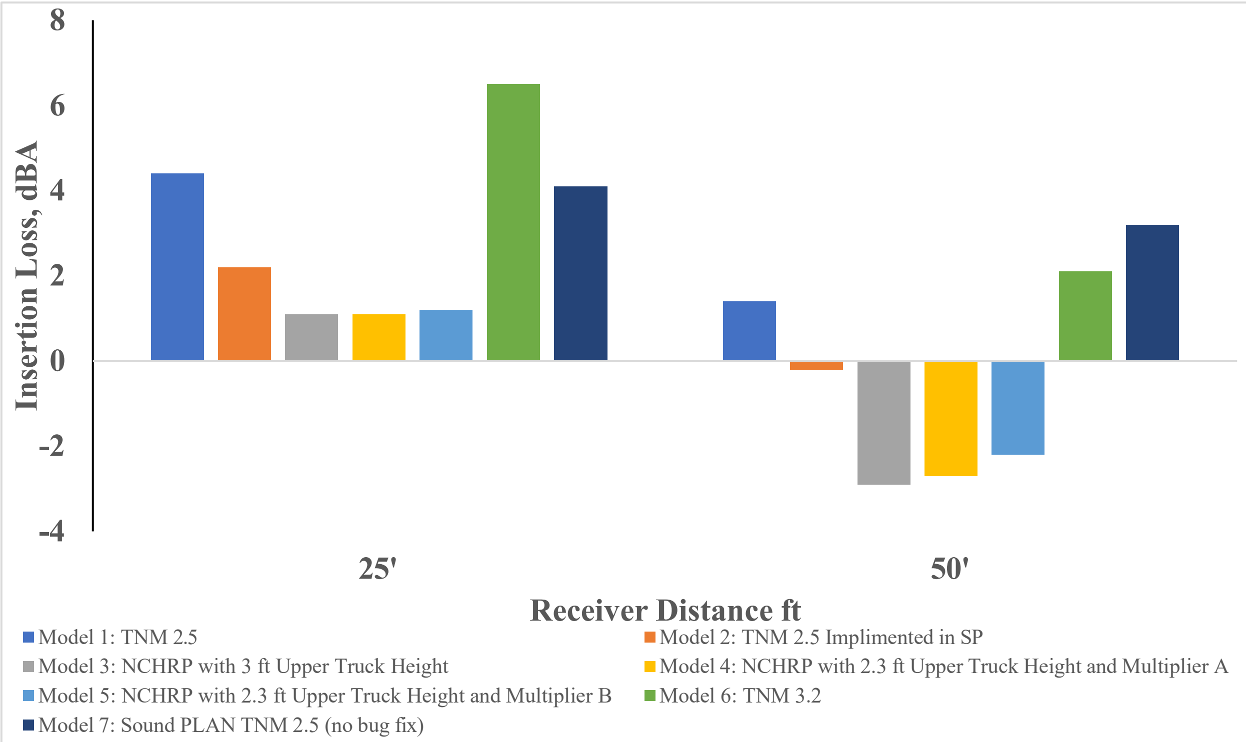

Figure 4.11: *Modeled Insertion Loss for Site 8 (Elevated)*

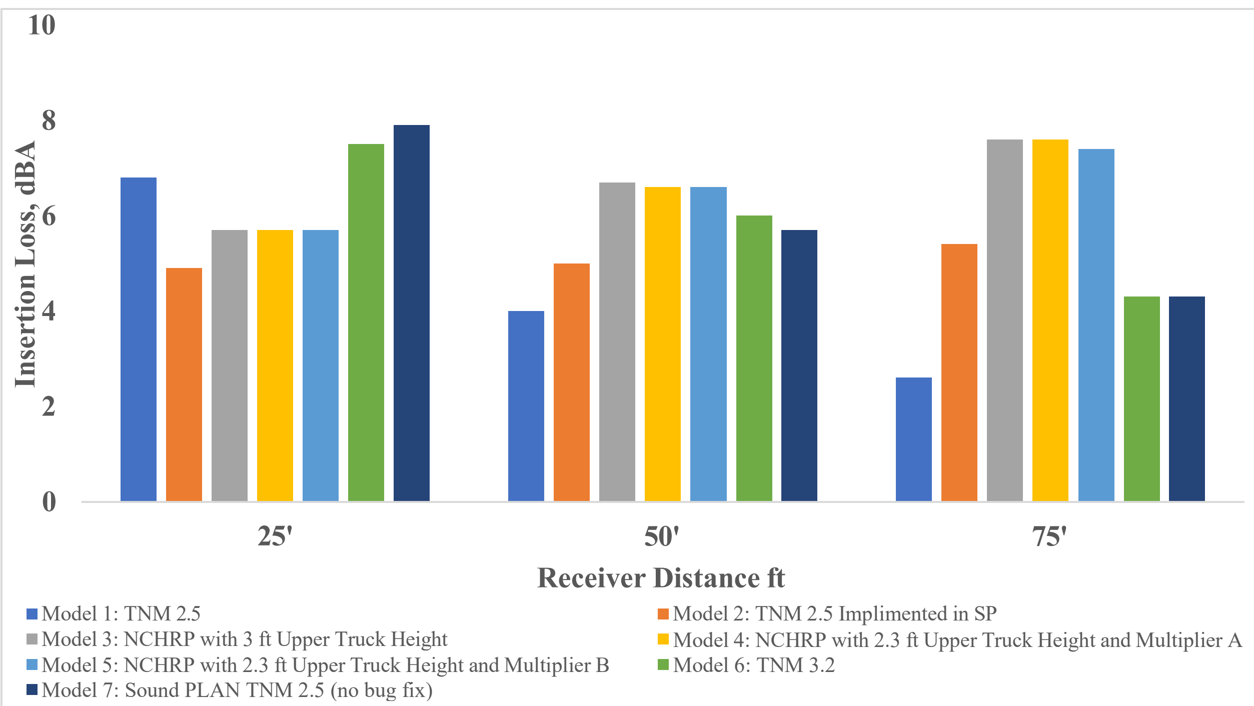

Figure 4.12: *Modeled Insertion Loss for Site 10 (Elevated)*

The difference between the source and the receiver elevation was also investigated and the result is as presented in Table 4.2. Positive elevation difference is revealed that the roadway is higher compared to the receiver (elevated). Initially designated sites as “at grade” were found to be within ±2.0 ft. The elevation differences greater than 10 ft were found at site 8 and site 2 at 50 ft receiver locations. These are also sites that were found not to be validated in our models as well as having negative insertion losses for TNM implemented in SoundPLAN with upper truck height adjustments. Hence, there is a likelihood of path influence on the models. Although 85% of the modeled noise results were validated when SoundPLAN was implemented in TNM 2.5 with no bug fixes (Model 7), but there was no general pattern for other models with distance to the roadway. This is expected because SoundPLAN with no bug fixes should be the same or close to the algorithms in TNM 2.5.

Table 4.2: *Elevation Difference in Comparison with Measured and Modeled Insertion Losses*

Site	Distance (ft)	Condition	Elevated	Diff in Elevation (ft)	Measured Insertion Loss (dB)	Modeled Insertion Loss (dB)						
						Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Site 1	50	Barrier	at grade	0	1.1	0.1	3.7	4.5	4.5	4.3	0	0.5
Site 1	75	Barrier	at grade	-1	1.5	0.9	4.4	5.1	5.1	5	0.5	1.2
Site 1	100	Barrier	at grade	-1		1.4	5.8	6.3	6.3	6.3	1.1	2.5
Site 2	25	Barrier	Elevated	4	6.1	7.8	7.8	8.6	8.6	8.8	7.7	8.9
Site 2	50	Barrier	Elevated	16	9.3	1.1	0.4	-1.3	-1.3	-0.7	2.3	1.1
Site 6	25	Barrier	at grade	0		0.5	2.1	2.6	2.5	2.4	0.4	1.2
Site 6	50	Barrier	Elevated	4		5	5.8	7.4	7.4	7.8	4.3	6.3
Site 6	75	Barrier	Elevated	6		2.3	5.3	6.9	6.9	7.5	3.8	4.1
Site 6	100	Barrier	Elevated	5		3.7	5.5	7.2	7.2	7.4	2.8	5.2
Site 8	25	Barrier	Elevated	9	9.5	4.4	2.2	1.1	1.1	1.2	5.3	4.1
Site 8	50	Barrier	Elevated	23	3.7	1.4	-0.2	-2.9	-2.7	-2.2	1.0	3.2
Site 10	25	Barrier	Elevated	4		6.8	4.9	5.7	5.7	5.7	6.6	7.9
Site 10	50	Barrier	elevated	4		4	5	6.7	6.6	6.6	4.5	5.7
Site 10	75	Barrier	elevated	4		2.6	5.4	7.6	7.6	7.4	3.2	4.3

4.4 Measured Insertion Loss

Since measured insertion loss was not able to be calculated from measurements conducted before and after short barrier installation, the measured insertion loss values in this study have some caveats. It was possible to find sites where a short solid barrier is located along a portion of the roadway with a comparable site with a solid barrier located along a portion of the roadway and a no barrier option nearby along the same roadway, but it was practically impossible to have comparable site conditions behind the barrier. Equally, site access and safety issues prevented utilization of more sites or further distances for the study.

Consequently, the result presented in Table 4.3 shows the results of the measured insertion loss obtained in the field by utilizing the above-described methodology. For site 1, the measured insertion losses were 1.1 dB and 1.5 dB for receivers' distances of 50 and 75 feet behind the center line of the near drive lane respectively. Although, there is not much significant difference between the difference in source height and receiver height (both sites were at grade), the sound path behind barrier site was on hard ground with building interference, and the no barrier condition was on soft ground in the wood. From the results, the measured insertion losses at Site 2 were 6.1 dB and 9.3 dB for 25 feet and 50 feet receiver locations, respectively. However, the roadway at the barrier location was elevated with height differences of 4 feet for the 25 feet distance and 16 feet for the 50 feet, while the roadway in the no barrier condition was at grade. For site 8, the measured insertion from field measurements were 9.5 dB at 25 feet and 3.7 dB at 50 feet, respectively. Although both roadway conditions at the barrier and no barrier sites were elevated, the barrier condition was more elevated than the no barrier condition. As revealed on Table 4.3, elevation difference was 9 feet for 25 feet barrier condition while for the no barrier condition was 4 feet at 25 feet. For 50 feet distance, the barrier condition was 23 feet, while for the no barrier condition, it was 9 feet. Ideally, the best method to calculate insertion loss would be to find multiple locations where barriers are in the process of getting built then conduct sound monitoring before and after construction. However, since this was not possible during the study, our recommendation for future studies is to utilize these best practices.

Table 4.3: *Measured Insertion Loss*

Site		Barrier		No Barrier		Measured Insertion Loss (dB)
	Distance (ft)	Sound Level Hourly L_{eq} (dB)	Elevation difference (ft)	Sound Level Hourly L_{eq} (dB)	Elevation (ft)	
1	50	76.7	0	77.8	3	1.1
1	75	74.5	-1	76.0	0	1.5
1	100	72.0	-1	-	-	
2	25	72.1	4	78.2	1	6.1
2	50	65.1	16	74.4	0	9.3
8	25	67.2	9	76.7	4	9.5
8	50	64.1	23	67.8	9	3.7

CHAPTER FIVE

FEASIBILITY AND REASONABLENESS

The United States Code of Federal Regulations Part 772 (23 CFR 772), "Procedures for Abatement of Highway Traffic Noise and Construction Noise," establishes standards for abatement of highway traffic noise. The Federal Highway Administration (FHWA) policies identify five approved highway traffic noise abatement options, with barriers currently being the primary method of abating traffic noise (America, 2010; USDOT FHWA, 2010). All highway agencies must adopt written statewide highway traffic noise policies approved by FHWA. To be considered as noise abatement under FHWA policies, barriers must be both feasible and reasonable, as defined by statewide highway noise policy.

The Maryland Department of Transportation State Highway Administration sets forth its traffic noise policy in the Highway Noise Abatement Planning and Engineering Guidelines (SHA, 2020). Under SHA policy, a noise barrier is considered feasible if it achieves a minimum noise reduction of 5 dB for at least 70% of the impacted residences (residences that exceed the loudest hour traffic noise limit of 66 dB) located behind the barrier. For the barrier to be considered reasonable, the barrier must achieve a noise abatement design goal of at least 7 dB for at least three impacted residences or 50% of impacted residences.

Review of modeled insertion losses presented in Appendix 4 indicates that short solid barriers may be able to achieve noise reductions exceeding 5 dB except Site 6 at 25-feet. The elevated sites (Sites 2, 6, and 10) achieve noise reductions exceeding 7 dB in some locations. If shorter barriers are found to meet Federal/State noise reduction criteria, more barriers would be considered cost reasonable; therefore, more areas would potentially qualify for noise abatement. Short barriers that provide 3 to 5 dB of reduction may be considered due to their low cost, even if Federal funding is not provided.

To be acoustically effective, a short sound wall must be constructed with a solid material with no gaps in the face of the wall or at the base. Openings or gaps between sound wall materials or the ground substantially decrease the effectiveness of the sound wall. Suitable materials for sound wall construction should have a minimum surface weight of four pounds per square foot. A solid concrete safety barrier easily meets this criterion. Metal-beam-guard-railing does not provide any noise reduction.

REFERENCES

4 Silence. (2020). *Reducing noise by diffraction innovative and proven solutions for reducing traffic noise*. brochure-4silence-2020-en-1.pdf

Alberola, J., Flindell, I. H., & Bullmore, A. J. (2005). Variability in road traffic noise levels. *Applied Acoustics*, *66*(10), 1180–1195. https://doi.org/10.1016/j.apacoust.2005.03.001

America, C. on T. for a Q. (2010). *Technology for a Quieter America*. National Academies Press.

Basner, M., & McGuire, S. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. *International Journal of Environmental Research and Public Health*, *15*(3), 519. https://doi.org/10.3390/ijerph15030519

Burton, K., Pinckney, J., Kubitza, J., Miller, J., Burris, M., & others. (2016). *Earthen berm noise reduction analysis.* Ohio. Department of Transportation. Office of Statewide Planning and Research.

Conter, M., & Haider, M. (2008). Austrian investigation on the influence of sound leakage in noise reducing devices. *Journal of the Acoustical Society of America*, *123*(5), 3138–3138.

Cubick, K., & Rochat, J. (2022). Solid safety barriers as a highway traffic noise reduction strategy. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, *264*(1), 836–846. https://doi.org/10.3397/NC-2022-824

Ding, L., Van Renterghem, T., & Botteldooren, D. (2011). Estimating the effect of semi-transparent low-height road traffic noise barriers with Ultra Weak Variational Formulation. *Acta Acustica United with Acustica*, *97*(3), 391–402.

FHWA. (2011). *Highway Traffic Noise: Analysis Abatement Guidance*. FHWA-HEP-10 025.

FHWA. (2018). *Noise Measurement Field Guide HandBook*. FHWA-HEP-18-066.

Fredianelli, L., Del Pizzo, L., & Licitra, G. (2019). Recent Developments in Sonic Crystals as Barriers for Road Traffic Noise Mitigation. *Environments*, *6*(2), 14. https://doi.org/10.3390/environments6020014

Garai, M., & Guidorzi, P. (2015). Sound reflection measurements on noise barriers in critical conditions. *Building and Environment*, *94*, 752–763. https://doi.org/10.1016/j.buildenv.2015.06.023

Ibili, F., Owolabi, A. O., Ackaah, W., & Massaquoi, A. B. (2022). Statistical modelling for urban roads traffic noise levels. *Scientific African*, *15*, e01131.

Jiang, L., & Kang, J. (2016). Combined acoustical and visual performance of noise barriers in mitigating the environmental impact of motorways. *Science of The Total Environment*, *543*, 52–60. https://doi.org/10.1016/j.scitotenv.2015.11.010

Jolibois, A., Defrance, J., Koreneff, H., Jean, P., Duhamel, D., & Sparrow, V. W. (2015). In situ measurement of the acoustic performance of a full scale tramway low height noise barrier prototype. *Applied Acoustics*, *94*, 57–68.

Karimi, M., & Younesian, D. (2014). Optimized T-shape and Y-shape inclined sound barriers for railway noise mitigation. *Journal of Low Frequency Noise, Vibration and Active Control*, *33*(3), 357–370.

Kesten, S., Umut, Ö., & Ayva, B. (2020). Acoustic and structural design of a highway noise barrier. *IOP Conference Series: Materials Science and Engineering*, *800*(1), 012029. https://doi.org/10.1088/1757-899X/800/1/012029

Kim, J. (2006). *Effects of median barriers in reducing highway noise levels*.

Koussa, F., Defrance, J., Jean, P., & Blanc-Benon, P. (2013). Acoustic performance of gabions noise barriers: Numerical and experimental approaches. *Applied Acoustics*, *74*(1), 189–197.

Laxmi, V., Thakre, C., & Vijay, R. (2022). Evaluation of noise barriers based on geometries and materials: A review. *Environmental Science and Pollution Research*, *29*(2), 1729–1745. https://doi.org/10.1007/s11356-021-16944-2

Lodico, D. M. (2020). Noise Modeling of Short Safety Barriers Using Realistic Vehicle Source Height Distributions. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, *262*(1), 581–591.

Lodico, D. M. (2023). Traffic noise modeling of short safety barriers. *Transportation Research Record*, *2677*(1), 1098–1107.

MD SHA. (2020). *Highway Noise Abatement Planning and Engineering Guidelines*.

MDOT SHA. (2020, April 16). *Highway Noise Abatement Planning and Engineering Guidelines, Maryland Department of Transportation State Highway Administration*.

NCHRP 25-57. (2022). *Breaking Barriers: Alternative Approaches to Avoiding and Reducing Highway Traffic Noise Impacts*.

Oldham, D. J., & Egan, C. A. (2015). A parametric investigation of the performance of multiple edge highway noise barriers and proposals for design guidance. *Applied Acoustics*, *96*, 139–152.

Oludare, O., Shokouhian, M., Efe, S., & Ikiriko, S. (2019). *Highway Geometrics and Noise Abatement Decision*. MD SHA Research Report.

Park, Y., & Koh, H.-I. (2020). Case study: Prediction and field tests of railway noise and effects of a low-height noise barrier. *Noise Control Engineering Journal*, *68*(4), 303–314.

Radsten-Ekman, M., Vincent, B., Anselme, C., Mandon, A., Rohr, R., Defrance, J., Van Maercke, D., Botteldooren, D., & Nilsson, M. E. (2011). Case-study evaluation of a low and vegetated noise barrier in an urban public space. *40th International Congress and Exposition on Noise Control Engineering (Inter-Noise-2011)*, *5*, 1–6.

Rymer, B. (2020). Breaking Tall Barriers, An Alternative Approach to Reducing Highway Traffic Noise Impacts With Inexpensive Short Noise Barriers. *Proc., 99th Annual Meeting of the Transportation Research Board, Washington, DC*.

Sipari, P., Jalkanen, T., & Siponen, D. (2017). Sound reflection from different noise barriers. *Liikenneviraston Tutkimuksia Ja Selvityksiä*.

Song, L., Gao, K., Liu, Q., Zhang, L., Feng, Q., & Guo, W. (2022). Acoustic performance of near-rail low-height noise barriers installed on suburban railway bridges. *Environmental Science and Pollution Research*, *29*(41), 62330–62346.

Sperry, B. R., Rochat, J. L., Cubick, K. L., & Khoury, I. (2023). Measured Effect of Low-Height Solid Safety Barriers on Heavy Truck Noise. *Transportation Research Record: Journal of the Transportation Research Board*, *2677*(1), 1753–1763. https://doi.org/10.1177/03611981221106175

USDOT FHWA. (2010). *Title 23: Highways – Part 772 Procedures for Abatement of Highway Traffic Noise and Construction Noise, U.S. Department of Transportation, Federal Highway Administration*. USDOT FHWA.

van der Eerden, F., Kurylek, R., Blaak, S., Salomons, E., Eisses, A., Van der Laan, T., & Vliet, W. J. van. (2021). Additional noise reduction with diffracting elements on barriers using numerical and standard calculation methods. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, *263*(3), 3118–3129.

Van Kempen, E., & Babisch, W. (2012). The quantitative relationship between road traffic noise and hypertension: A meta-analysis. *Journal of Hypertension*, *30*(6), 1075–1086. https://doi.org/10.1097/HJH.0b013e328352ac54

Watts, G. (2000). Factors affecting the performance of traffic noise barriers. *29th International Congress and Exhibition on Noise Control Engineering, Inter Noise, Nice, France*.

Wijnant, Y., Rochat, J. L., Willems, B., & Schwanen, W. (2021). A FEM/Kirchhoff-Helmholtz integral model for noise diffractors on low height noise barriers. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, *263*(5), 1455–1461.

World Health Organization & others. (2011). *Burden of disease from environmental noise: Quantification of healthy life years lost in Europe*. World Health Organization. Regional Office for Europe.

Zaets, V. (2021). Influence estimation of the inclination angle of the top of the noise protection barrier on its efficiency. *Technology Audit and Production Reserves*, *1*(1), 57.

APPENDIX A

Utilization of Short Solid Noise Barriers Survey

This survey is being conducted by Morgan State University to gather State practices on the utilization of short solid noise barriers as noise abatement.

Survey information submitted will not identify the name of the individual(s) completing the survey questionnaire. Your contact will be kept strictly confidential and will not be reused or disclosed.

The survey contains three sections:
Section 1 includes questions on responder's information
Section 2 asks about the utilization of short concrete barrier as noise abatement
Section 3 gathers additional comments.

Section 1. Participants Information

Please Note: Your personal information will be kept strictly confidential and will not be reused or otherwise disclosed.

1. Name
2. Title
3. Telephone
4. Name of Organization or Agency
5. Email
6. Select years of experience on Highway Noise Abatement Planning or Design
   Years of experience <1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, >10
7. Select years of experience in Noise or Acoustics
   Years of experience <1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, >10

Section 2 The utilization of short concrete barrier as a noise abatement strategy

1. Does your state/agency currently utilize short concrete barriers or Jersey barriers for safety? Yes or No

2. If yes, what are the determining factors in the selection of solid safety barriers as opposed to metal guard rails for safety?

3. Is your state/agency currently planning to utilize short concrete safety barriers (6 ft or shorter) as a noise abatement or mitigation strategy?
   Yes or No

4. Have you ever carried out any study/research to investigate the possibility of utilizing short concrete noise barriers for noise abatement or mitigation?

   Yes or No

5. If Yes what were your findings?

6. What are the factors do you foresee as impediments to the implementation of short solid barriers for noise abatement or mitigation?

7. Please share a link to your current noise guidelines of your state/agency below.

8. What modeling tools are you currently using to determine the feasibility of your abatement choices?

9. Please provide your level of satisfaction with the modeling tool(s).
   Not Satisfied, Somewhat Satisfied, Satisfied, Very Satisfied, Extremely Satisfied

10. What are the benefits and shortcomings of the modeling tool(s)?

11. How much is the typical construction cost per mile for the noise wall in your state/jurisdiction?

12. What is the average height of noise walls in your state/jurisdiction?

13. What other tall barrier alternatives have you sought to reduce the growing construction cost of noise abatement systems?

14. Do you think short concrete noise barriers will be a viable alternative that will effectively mitigate noise impacts? (Rate your answers)

    Not effective, Somewhat Effective, Effective, Very Effective, Extremely Effective

15. Do you think utilizing a short concrete barrier could equate to significant cost savings if it becomes a viable alternative to constructing a traditional concrete noise barrier? Yes, or No

16. If yes rank the level of cost effectiveness (1 to 5, with 5 being the most cost effective)

17. What other noise mitigating strategies have you implemented at locations where a traditional tall noise wall is not feasible to be constructed due to site constraints?

18. Has your state DOT/agency used any proprietary short noise barrier materials (e.g WHIS Wall)? Yes, or No?
    If yes, list any proprietary noise barrier materials used and describe your experience and findings.

19. Is your agency currently conducting research or studying the effectiveness of new noise reduction products, materials or technologies?
    Yes or No?

    If yes, list names of materials, products, and technologies and your experience and findings.

Section 3: Additional Comments

Please provide any other useful comments to assist with evaluation of the effectiveness of short solid barriers as a noise abatement strategy.

APPENDIX B

Results of Survey

The results presented in this appendix highlight the current practices among State DOTs and other agency experts who voluntarily participated in the survey. Figure S1 illustrates the years of experience in highway noise abatement planning or design among the experts involved in the study. Of these experts, 41.7% had over 10 years of experience, while approximately 25% had less than 1 year of experience. Figure S2 focuses on the participants' experience in acoustics, with 58.3% having more than 10 years of experience, and 8.3% having less than 1 year of experience in the field.

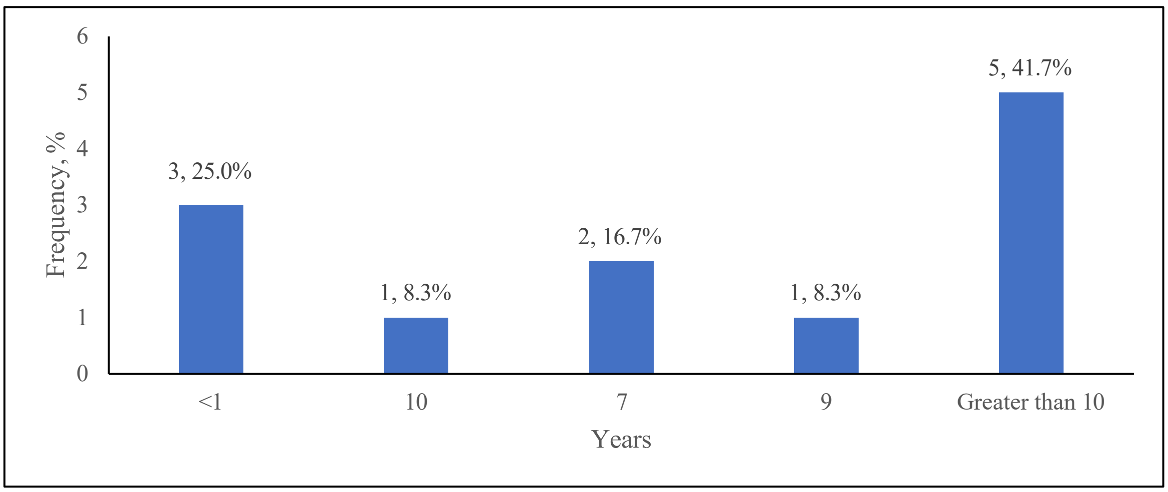

Figure S1: Years of experience on Highway Noise Abatement Planning or Design

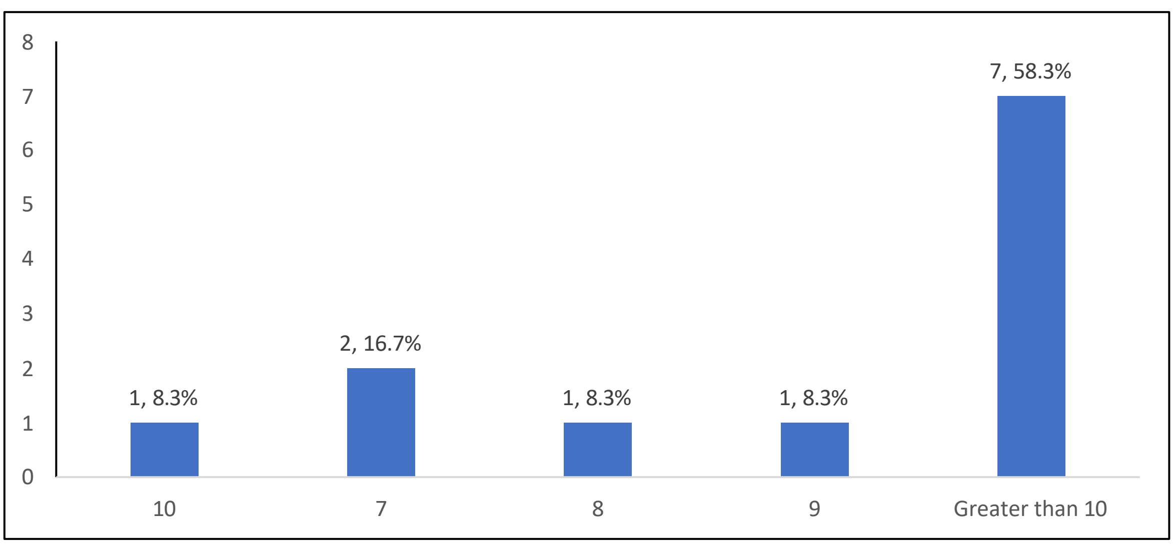

Figure S2: Years of experience in Noise or Acoustics

The result presented in Figure S3 showed the job title of the respondents. The result showed that the participants ranged from noise experts to abatement coordinator, research physicists, quality coordinator among others. Figure S4 showed the organizations that were present in the study. It can be observed that majority of participants were from State Department of Transportations.

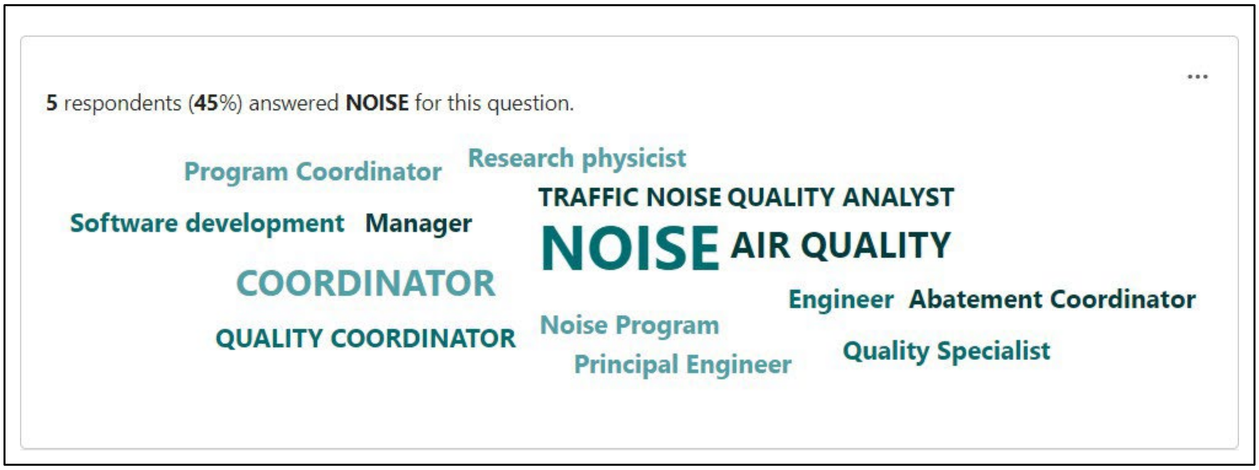

Figure S3: Job Title of Respondents

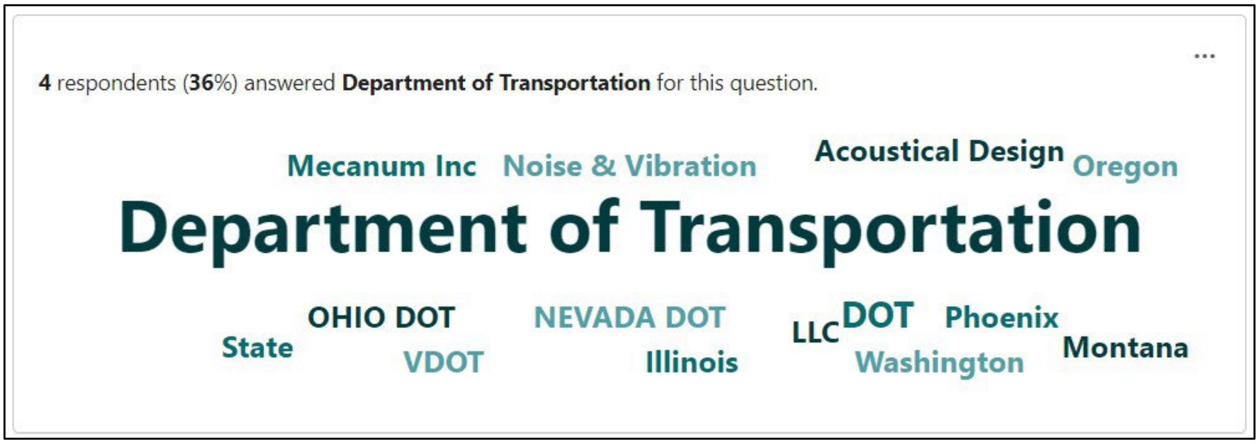

Figure S4: Organizations represented in the Study.

Responses of participant to the item that inquired about how state/agency currently utilize short concrete barriers or Jersey barriers for safety showed that 92.0% were utilizing short concrete barriers of jersey barriers for safety while 1.8% were not certain (Figure S5).

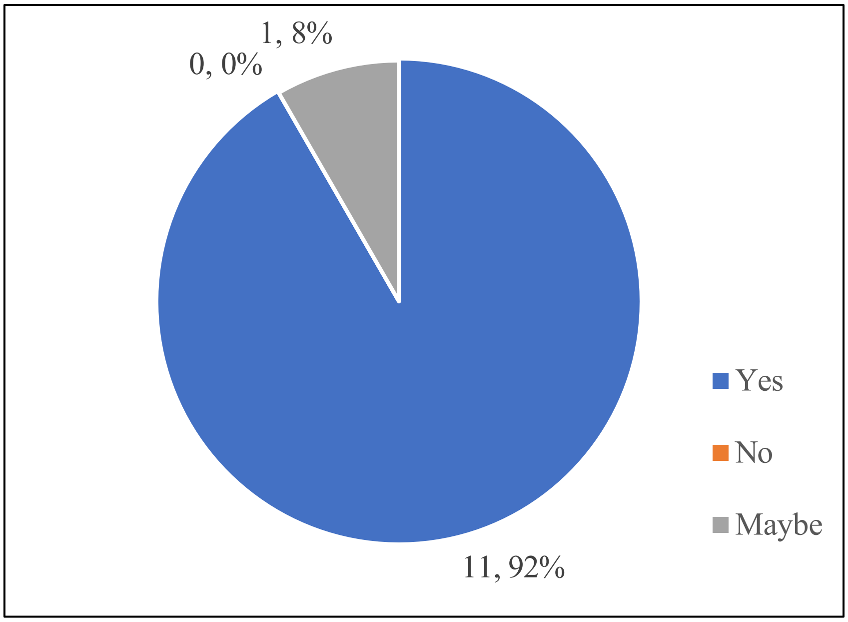

Figure S5: Use of Short Concrete Barrier/Jersey Barriers by DOTs

The survey response also showed the determining factors in the selection of solid safety barriers as opposed to metal guard rails for safety. The result indicated that factors such as temporary usage, existing roadway design and hydraulics, traffic related factors and deflection (Figure S6).

10 Responses

1	anonymous	Unknown
2	anonymous	Unknown
3	anonymous	unknown, determined by structures, hydraulics and roadway design
4	anonymous	Roadway designer makes the decision
5	anonymous	For temporary use
6	anonymous	The main factors for using solid safety barriers over guard rails is to re-direct traffic traveling in opposing directions at the median, re-direct traffic from steep slopes at the roadway edge and protect structures within the clear zone such as sign posts.
7	anonymous	There are a variety of factors in the decision that include speed, traffic volume, duration of work zones, presence of significant maintenance items (such as bridge piers or noise walls), crash data, available space, deflection space, etc.
8	anonymous	Low deflection of rail vs. g-rails on high volume roads with narrow median. Lower maintenance with ssb.
9	anonymous	I am not a safety expert or even in that field.
10	anonymous	insufficient clear zone space or object needing shielding

Figure S6: Factors Influencing the Utilization of Short Concrete Safety / Jersey Barriers

The survey also investigated plans of DOTs to utilize short concrete safety barriers (6 ft or shorter) as a noise abatement or mitigation strategy and the result (Figure S7) indicated that 58% plans to utilize short concrete safety barriers (6 ft or shorter) as a noise abatement or mitigation strategy.

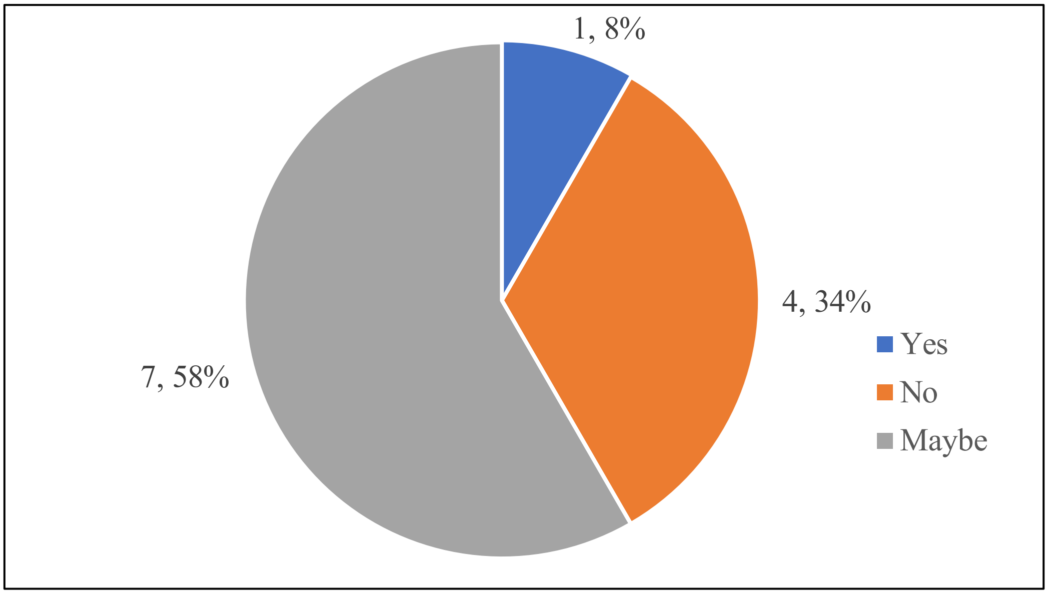

Figure S7: Utilization of short concrete safety barriers (6 ft or shorter) as a noise abatement or mitigation strategy

Figure S8 showed that 83% of the participants mentioned that their states have plans for utilizing short concrete noise barriers for noise abatement or mitigation.

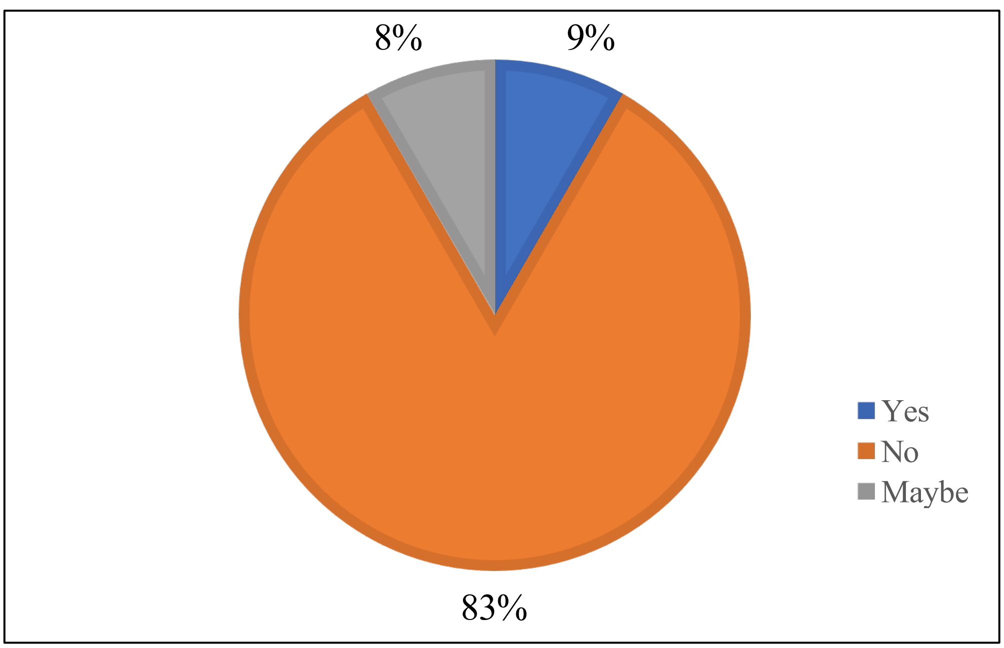

Figure S8: Plans for utilizing short concrete noise barriers for noise abatement or mitigation.

The findings of one agency that conducted the study indicated that short concrete barriers reduced noise by 3.0- 5.5 dB (Figure S9).

3 Responses

ID ↑	Name	Responses
1	anonymous	We put all barrier rail (SSB) in our model if it's 3' tall or greater. It helps in TNM
2	anonymous	Short concrete noise barriers reduced noise by 3.0-5.5 db
3	anonymous	N/A

Figure S9: Findings from agency investigation on short concrete barriers

The perception of participants on impediments to the implementation of short solid barriers for noise abatement or mitigation revealed variation in perception such as public perception, maintenance cost, insufficient noise reduction, unable to meet DoT noise wall criteria, and not meeting the feasibility and reasonable criteria.

12 Responses

ID ↑	Name	Responses
1	anonymous	Public perception
2	anonymous	Not as effective for noise abatement due to the height compared to barrier walls
3	anonymous	Maintenance, cost, unsightliness, clearing snow
4	anonymous	noise isn't sexy. Others make that descision.
5	anonymous	Insufficient noise reduction; unable to meet DOT noise wall criteria
6	anonymous	The way the traffic noise model underestimates performance of short barriers due to the way it treats heavy trucks
7	anonymous	Maybe limited efficiency due to lack of height and sound absorption
8	anonymous	They have been shown to not meet the feasibility and reasonableness criteria to be considered noise abatment although we have on a few occasions used them to appease the neighborhood when noise abatement did not meet the criteria.
9	anonymous	The biggest factor is dealing with the public as they are used to tall noise barriers that block the line of sight.
10	anonymous	Acceptance by FHWA given the current TNM modeling parameters in allowing shorter barriers.
11	anonymous	They will only mitigate tire noise, close the ground and then only for vehicles close to the barrier. They will not likely be effective for vehicles greater than 2 lane widths from the barrier.
12	anonymous	placement of SSB where not needed for safety will need to be addressed

Figure S10: Perception towards implementation of short solid barriers for noise abatement or mitigation

Figure S11 showed the links to the State DOTs current noise guidelines of your state/agency below.

12 Responses

ID ↑	Name	Responses
1	anonymous	
2	anonymous	Unknown
3	anonymous	Unknown
4	anonymous	https://www.dot.nv.gov/home/showpublisheddocument/14255/636637253326570
5	anonymous	https://www.transportation.ohio.gov/programs/noise/resources/noise-analysis-ma
6	anonymous	https://www.oregon.gov/ODOT/GeoEnvironmental/Docs_Environmental/Noise-ma
7	anonymous	https://laws-lois.justice.gc.ca/eng/regulations/C.R.C.%2C_c._1038/page-13.html
8	anonymous	https://wsdot.wa.gov/engineering-standards/environmental-guidance/noise
9	anonymous	https://www.virginiadot.org/projects/pr-noise-walls-about.asp
10	anonymous	https://www.mdt.mt.gov/publications/manuals.aspx
11	anonymous	https://roads.maryland.gov/mdotsha/pages/index.aspx?PageId=827
12	anonymous	https://public.powerdms.com/IDOT/documents/1944401/Highway%20Traffic%20N

S11: Links to Different State DOTs

Figure S12 showed the findings of common tools employed by experts in modelling the feasibility of abatement choices. Most common tools used for conducting feasibility of abatement strategies was TNM2.5 (66.7%). Other tools include Cadna software, Onsite measurement, noise mapping software, Excel, and others. It is important to note that some states/agency used more than 1. Figure S13 showed that 25.0% were very satisfied with their modeling tools while 16.7% were satisfied with their modeling tools.

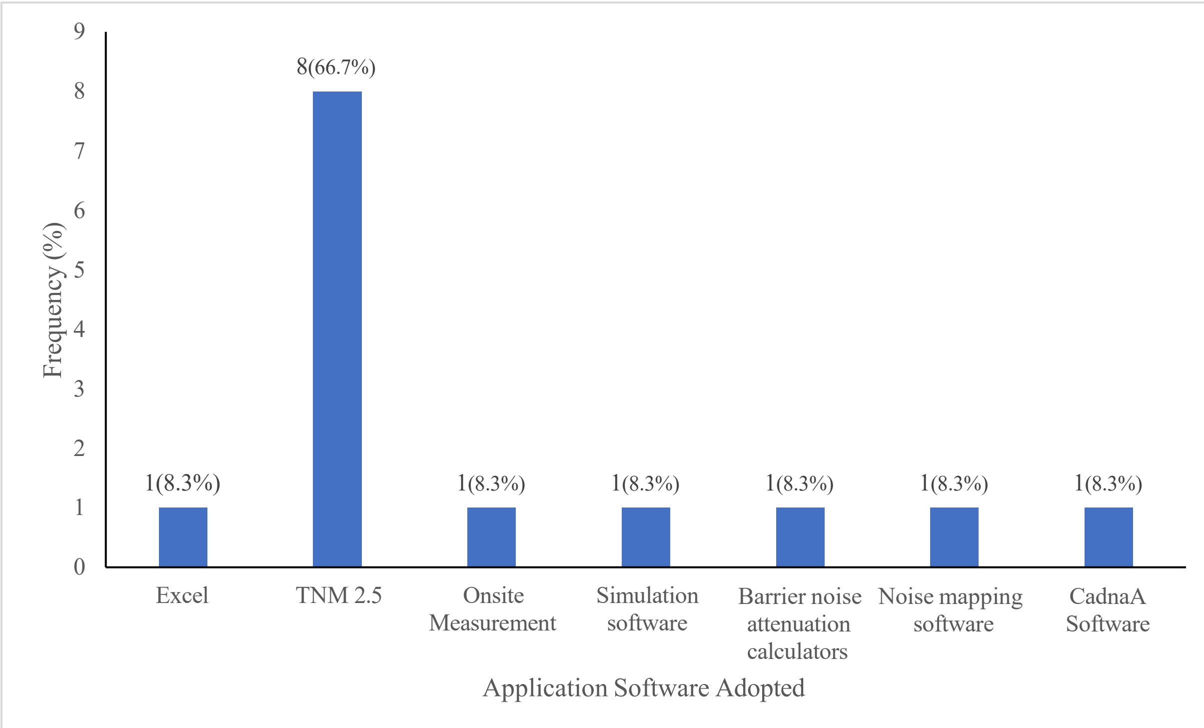

Figure S12: Modeling Tools for Feasibility of Abatement Choices

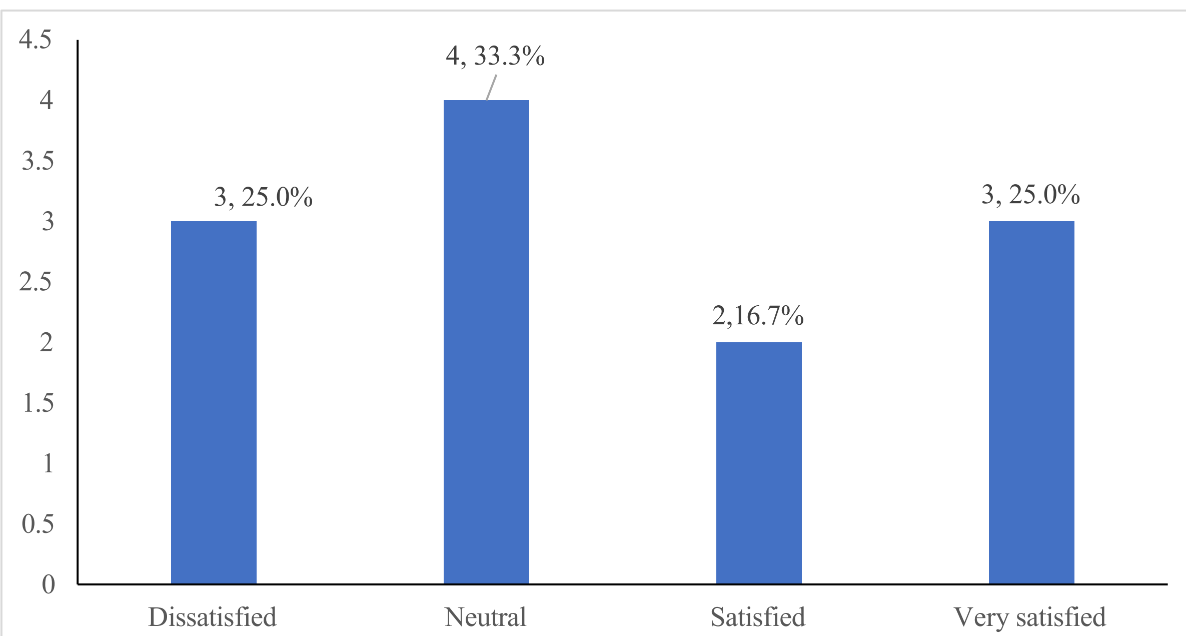

Figure S13: Level of Satisfaction with modeling tool

The respondents' perception of the modeling tools' merits and drawbacks is illustrated in Figure S14. Based on the findings, users of the tools have identified several shortcomings. These include the tools' failure to consider noise source heights and percentages, significant underrepresentation of reductions from short solid barriers, which leads to the construction of taller walls instead of shorter ones by DOTs. Additionally, the models' handling of heavy trucks results in an underestimation of the performance of short solid barriers. Lastly, the tools' simplicity makes it challenging to apply them to more complex scenarios. Perceived benefits encompass the advantages of simplicity in usage and implementation, allowing for noise impact assessment.

12 Responses

ID ↑	Name	Responses
1	anonymous	
2	anonymous	None
3	anonymous	Long run rimes
4	anonymous	does not accurately account for noise source heights and percentages
5	anonymous	Grossly underrepresents reductions from SSBs; Forces DOTs to build taller walls than needed
6	anonymous	The way the model treats heavy trucks means it underestimates the performance of shorter noise barriers
7	anonymous	Easy to implement, fast results, generally needs experimental validation
8	anonymous	Benefits are that we are familiar with the tool and it is relatively simple to use. Shortcomings are that the tool is more than 20 years old with no updates, the internal vehicle data used to calculate noise is outdated and the model can be too simplistic to address more complex issues that come up on projects such as reflected noise.

9	anonymous	TNM is the approved software for federally funded projects. The biggest shortcoming is that the software it isn't updated on a regular basis to make sure it stays current and relevant. The recent updates (TNM 3.X) dont appear to have been successful as there are several performance issues that have be pointed out by the various users.
10	anonymous	Allows for the prediction of noise impacts. The current noise model needs to be updated and has take too long to implement.
11	anonymous	Calibration is necessary with measured data.
12	anonymous	TNM 2.5 interface is out of date. TNM 3.0 is an improvement but has proprietary elements.

Figure S14: Benefits and Drawbacks of Models for Noise Abatement Strategy

According to the participants, the construction cost per mile for the noise walls is less than $2 million (25.0%), while 33.3% mentioned that its about $2 million (Figure S15).

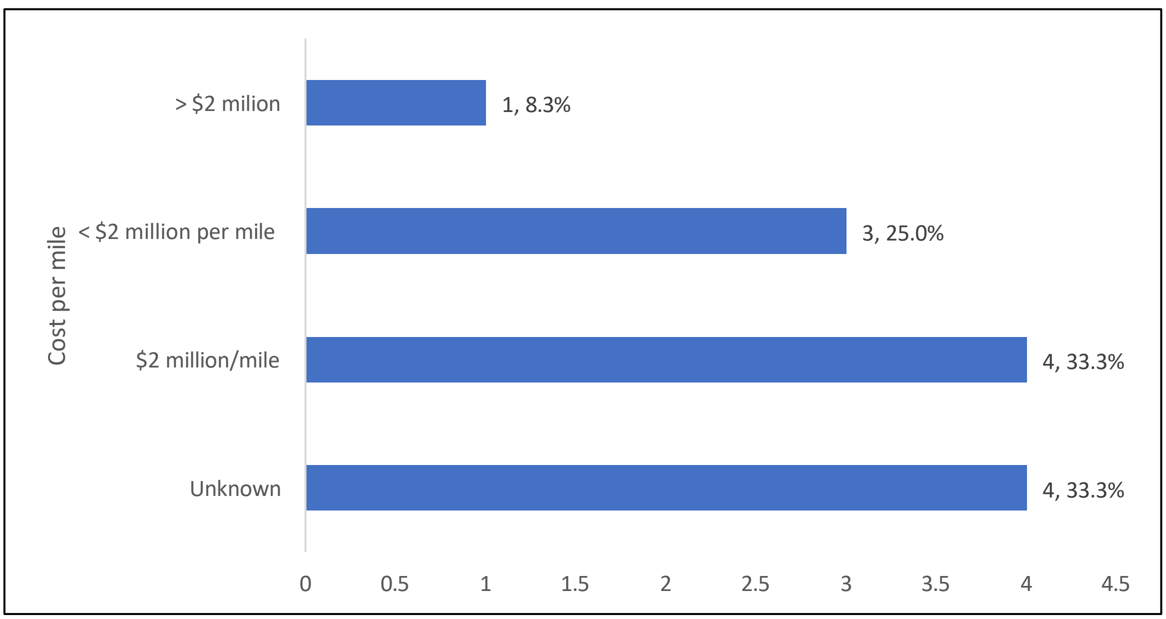

Figure S15: construction cost per mile for the noise wall in your state/jurisdiction?

The average height of noise walls in the state/jurisdiction of respondent is presented in Figure S16. The result showed that 33.3% affirmed it was between 12-13ft while 33.0% also affirmed it was above 13ft.

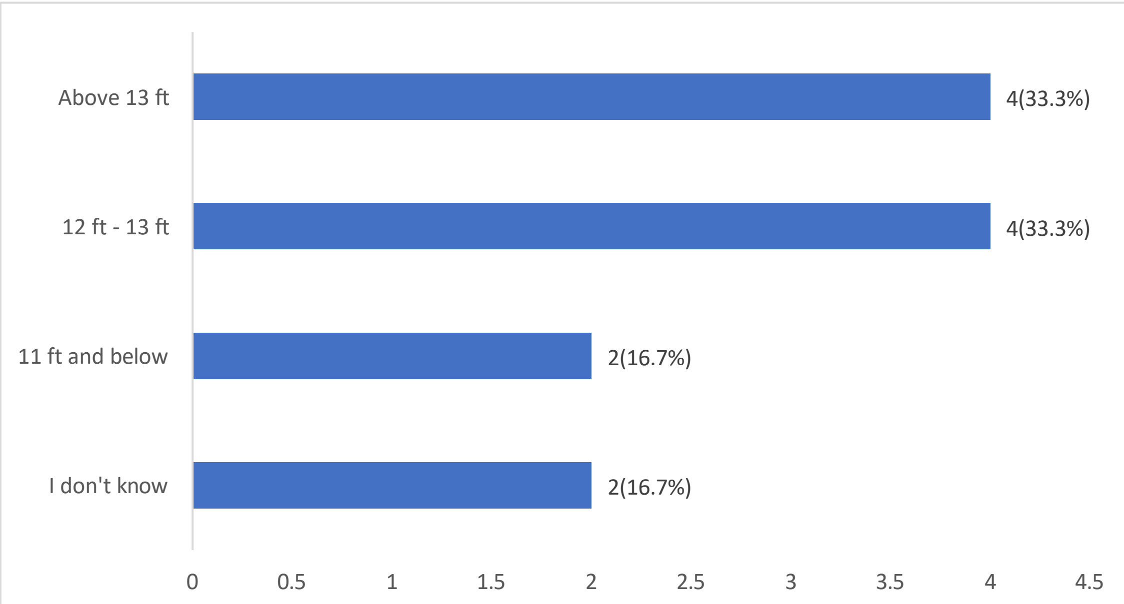

Figure S16: Average Height of Noise Walls in State/Jurisdiction of Respondent

Figure S17 presents alternatives to tall barriers materials employed by agencies/State DOTs to reduce the growing construction cost of noise abatement systems. The result revealed that two distinct choices which are not common among the participants were vinyl noise wall options and design considerations. Other responses showed that there are no better alternatives that can reduce costs.

12 Responses

2	anonymous	No other alternatives
3	anonymous	Not applicable
4	anonymous	n/a
5	anonymous	We researched a vinyl noise wall option
6	anonymous	N/A
7	anonymous	I don't know
8	anonymous	Looking at alternative noise wall materials they are typically the same or more than our standard concrete materials. Other barrier altlernatives do not meet the feasible and reasonable criteria and so cannot be considered for noise abatement.
9	anonymous	NA
10	anonymous	None to date.
11	anonymous	Modified building components.
12	anonymous	none, all alternatives are expensive, best way to reduce cost is to have better designs

Figure S17: Tall barrier alternatives have you sought to reduce the growing construction cost of noise abatement systems.

A high proportion (75.0%) of the participants as shown on Figure S18 indicated that short concrete barrier is somewhat effective in mitigating noise impact. 58..3% of the respondents somewhat agreed that short concrete barrier could equate significant cost savings if it becomes a viable alternative to constructing a traditional concrete noise barrier (Figure S19). As presented in Figure S20, in a rating of 0-4, 25.0% rated 3 (effective) as level of agreement that short solid barriers can be a significant cost saving alternative to tall barriers (Figure S20)

As responses to the survey, other strategies that agencies/State DOTs have employed where tall noise walls were not feasible include vegetation/plantings and low berms (Figure S21).

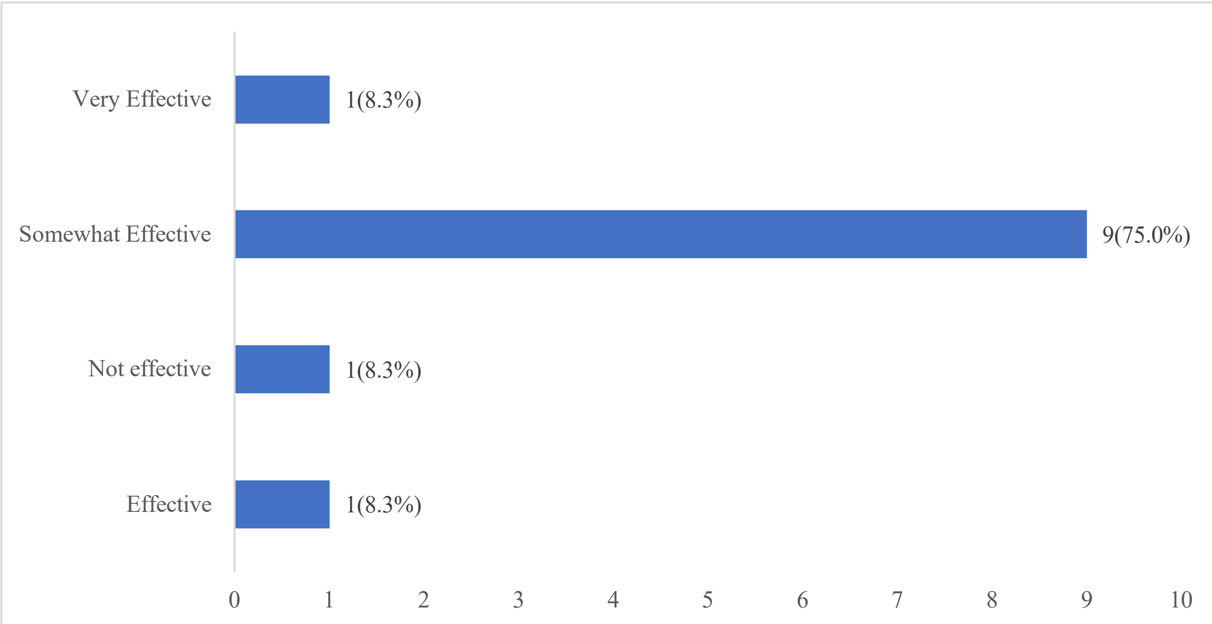

Figure S18: Perception on Short concrete noise barriers as a viable alternative that will effectively mitigate noise impacts.

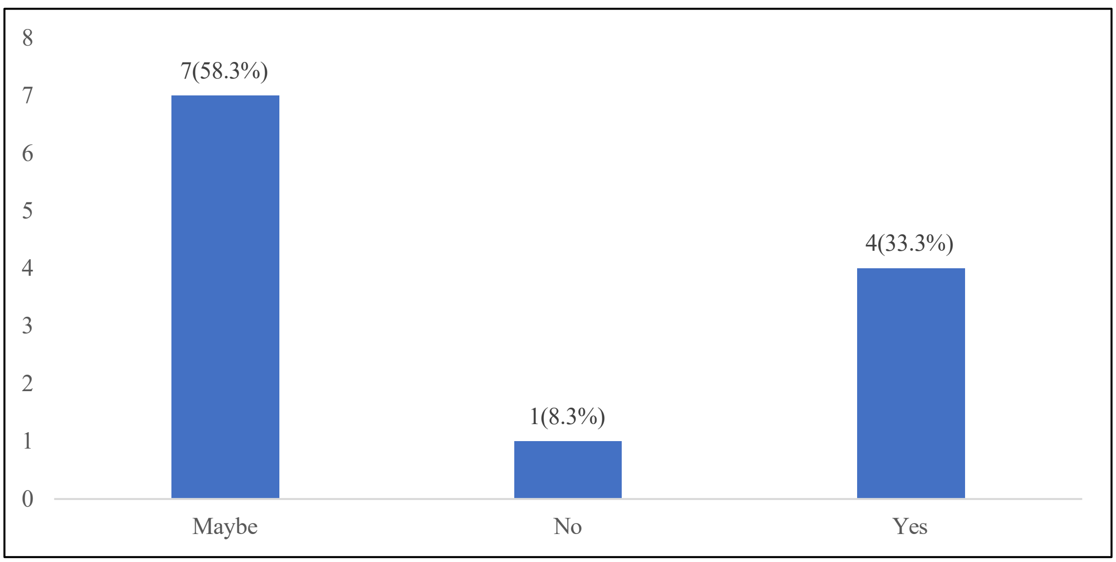

Figure S19: Cost Saving Potential of Short Concrete Barriers

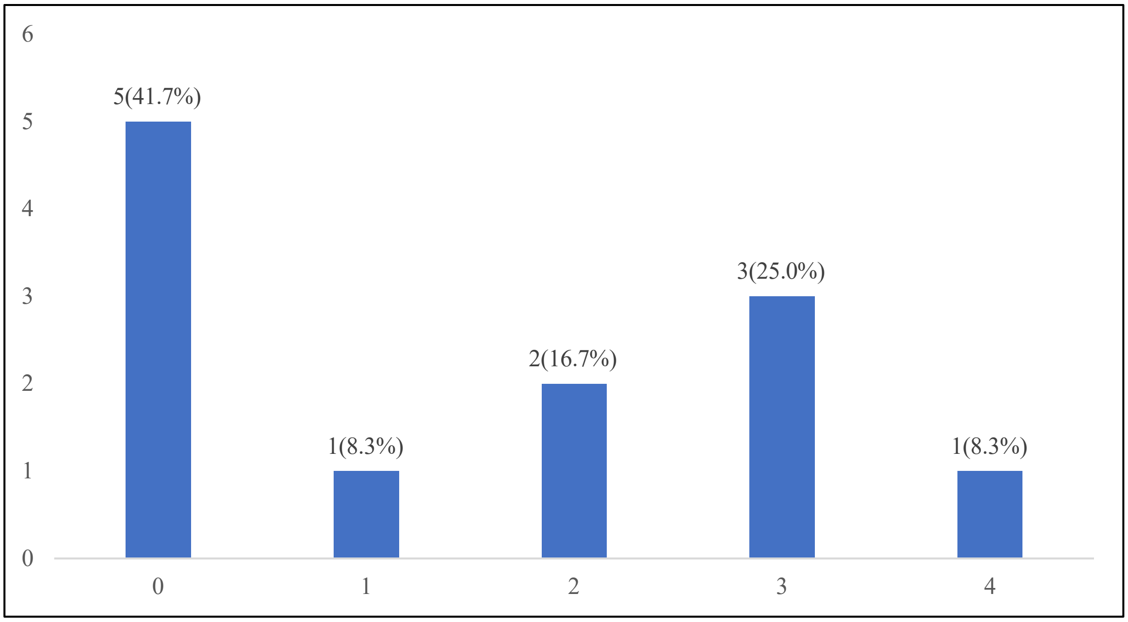

Figure S20: Rating of Perception of Effectiveness of Short Solid Barriers as Effective Cost Saving Technology against traditional tall barriers.

12 Responses

2	anonymous	None but speed limits can be lowered
3	anonymous	Vegetation, low berms
4	anonymous	for AC B, none. Schools have added AC to keep windows closed many years ago
5	anonymous	n/a
6	anonymous	some locations have berms where space allows, but otherwise, N/A
7	anonymous	Never installed such walls
8	anonymous	We have other strategies as part of our noise policy that we can impliment such as plantings but they are not effective at reducing noise levels, only the perception that they are being reduced.
9	anonymous	NA
10	anonymous	None.
11	anonymous	Site planning. Locate parking decks between impacted occupied buildings and roadways.
12	anonymous	none, we just don't build a wall

Figure S21: Other noise mitigating strategies where Tall Noise Walls is not feasible.

As presented in Figure S22, 25.0% of the respondents indicated that the DOT/agency have maybe used a proprietary short noise barrier material. Only 8.3% of the respondents identified that their agency/DOT is conducting research into new product/materials/technologies to reduce noise (Figure S23). Some of the materials/products/technologies include berms, steel and fiberglass (Figure S24).

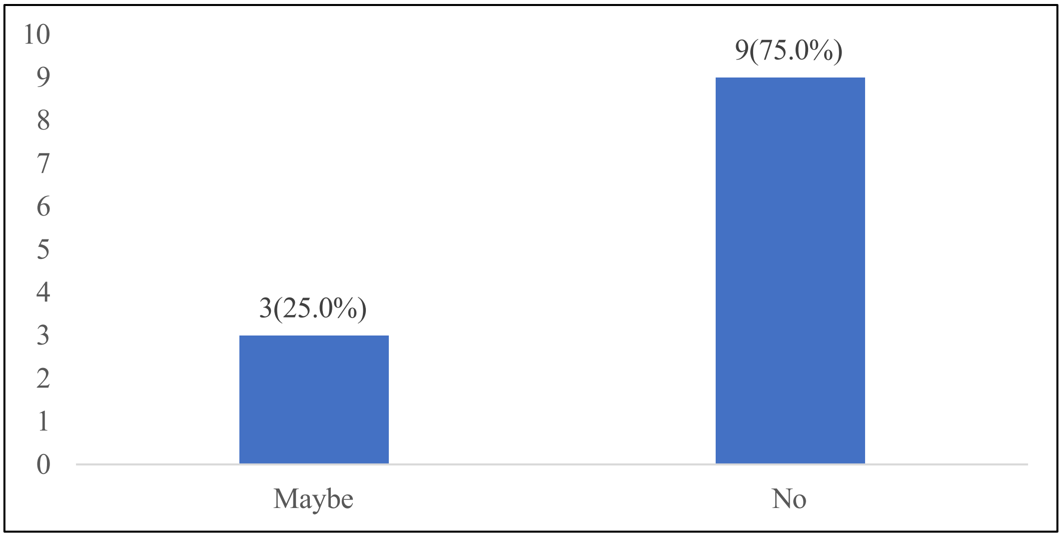

Figure S22: Use of Proprietary Short noise barrier materials

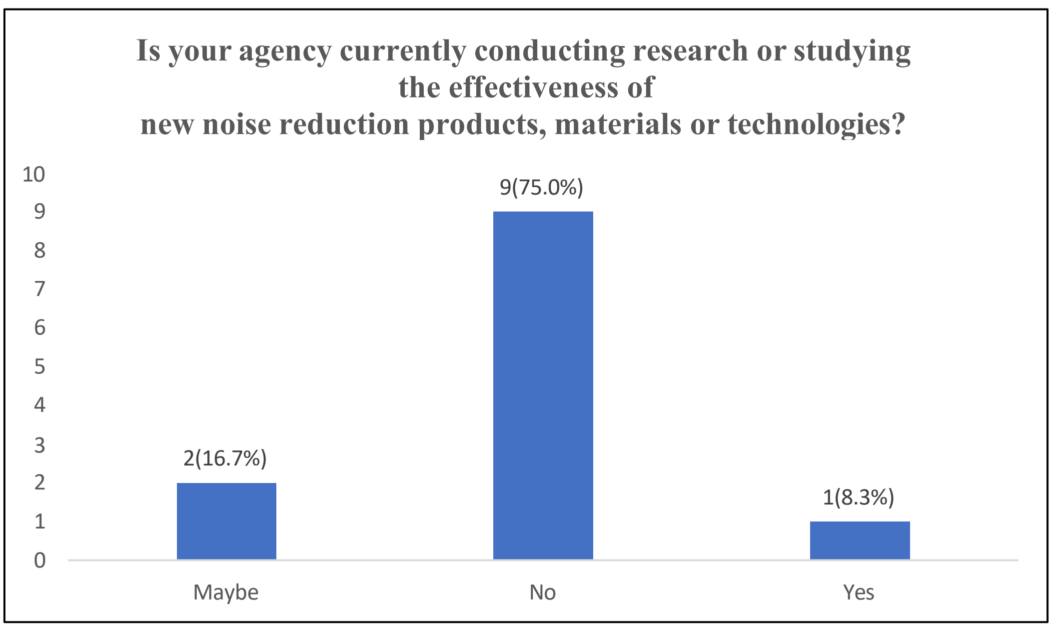

Figure S23: DOT/Agency Research into Effectiveness of New Noise Reduction Products/Materials/Technologies

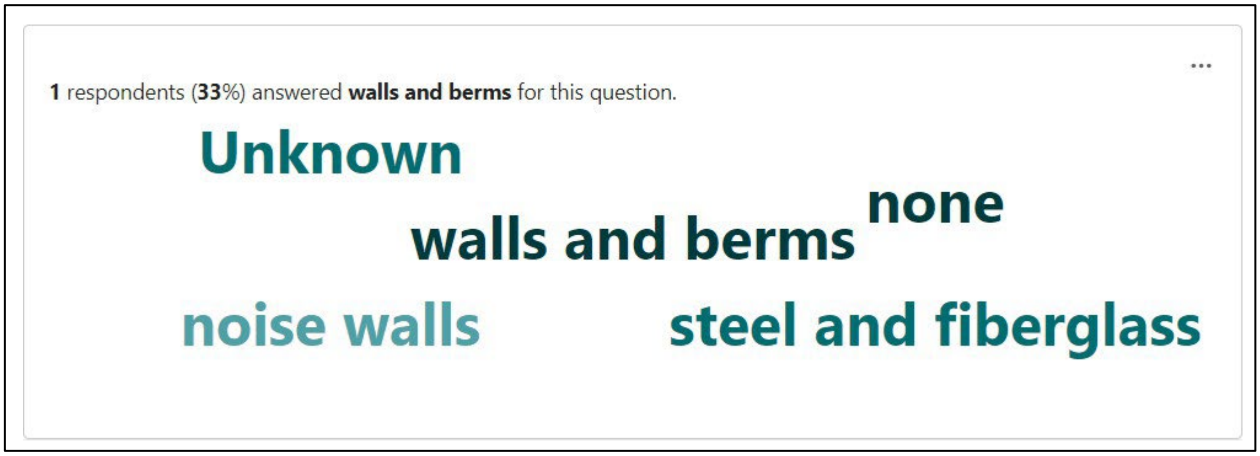

Figure S24: Materials/Product/Technologies currently studied by Agency/DOT.

7 Responses

ID ↑	Name	Responses
1	anonymous	Noise abatement with barriers is controlled by height. Short barriers are just not as effective.
2	anonymous	based off limited modeling with them in TNM, they can reduce noise by at least 0.5 dBA when included
3	anonymous	n/a
4	anonymous	Short solid barriers could potentially be used to slightly reduce traffic noise levels but they would not be considered noise abatement because they do not meet the criteria. Public perception can also be an issue if one community gets a tall noise wall and another gets a short solid barrier and whether they are being treated equitably.
5	anonymous	VDOT currently doesn't have an opinion on questions #21 thru 23, as this depends on research findings.
6	anonymous	Montana is still a fairly rural state with widespread population and doesn't face the some of the larger traffic noise issues as other larger more populous states but we like to learn about the challenges the larger states have.

Figure S25: Useful comments to assist with evaluation of the effectiveness of short solid barriers as a noise abatement strategy.

APPENDIX C

Measured and Modeled Sound Pressure Levels

Site	Distance, ft	Condition	Measured Hourly L*eq*	Barrier						
				TNM 2.5	TNM 2.5 Implemented in SP	NCHRP with 3 ft Upper Truck Height	NCHRP with 2.3 ft Upper Truck Height and Multiplier A	NCHRP with 2.3 ft Upper Truck Height and Multiplier B	TNM 3.2	Sound PLAN TNM 2.5 (no bug fix)
Site 1 - Average	50	Barrier	76.7	77.4	73.7	72.3	72.4	73.0	77.0	78.2
Site 1 - Average	75	Barrier	74.5	74.5	71.3	69.9	69.9	70.5	74.8	75.6
Site 1 - Average	100	Barrier	72.0	72.7	69.9	68.6	68.6	69.1	75.0	74.0
Site 1 - Average	50	No Barrier	77.8	77.0	76.5	75.8	75.8	76.4	78.9	77.9
Site 1 - Average	75	No Barrier	76.0	74.6	72.9	72.0	72.0	72.8	76.1	75.4
Site 2	25	Barrier	72.1	71.0	69.8	68.2	68.2	69.1	70.2	70.2
Site 2	50	Barrier	65.1	63.8	63.3	61.9	61.9	62.4	62.6	63.2
Site 2	25	No Barrier	78.2	79.2	79.2	78.6	78.5	79.4	79.9	79.4
Site 2	50	No Barrier	74.4	77.3	76.5	75.9	75.8	76.7	78.0	77.4
Site 6	25	Barrier	79.0	79.8	78.5	77.3	77.4	78.6	79.9	79.9
Site 6	50	Barrier	71.8	71.8	70.3	67.7	67.8	68.8	71.7	71.7
Site 6	75	Barrier	70.3	69.9	68.7	65.8	65.9	66.9	69.9	70.0
Site 6	100	Barrier	69.6	69.5	68.3	65.4	65.5	66.7	69.6	70.0
Site 8	25	Barrier	67.2	64.0	63.9	63.0	63.0	63.7	63.9	63.6
Site 8	50	Barrier	64.1	59.0	58.7	57.7	57.6	58.0	58.2	58.6
Site 8	25	No Barrier	76.7	76.6	75.7	75.3	75.2	76.0	78.2	77.1
Site 8	50	No Barrier	67.8	69.6	70.4	67.9	67.9	69.3	72.7	70.4
Site 10	25	Barrier	75.5	71.0	69.5	67.5	67.5	68.5	71.1	70.8
Site 10	50	Barrier	73.2	70.4	69.3	66.6	66.7	67.7	70.3	70.4
Site 10	75	Barrier	71.6	69.6	68.3	65.6	65.6	66.8	69.3	69.9

APPENDIX D

Model Insertion Loss for Validated Sites (Barrier Only)

Site	TNM2.5	TNM2.5 SoundPLAN	Modeled 3' Barrier NCHRP with Upper Truck height	Modeled Barrier NCHRP with 2.3' Upper Truck height and multiplier A	Modeled Barrier NCHRP with 2.3' Upper Truck height and multiplier B	TNM 3.2	SoundPLAN with TNM box checked (no bug fixes)
Site 1 50ft	0.1	3.7					0.5
Site 1 75ft	0.9						1.2
Site 1 100ft	1.4	5.8			6.3		2.5
Site 2 25ft	7.8					8.3	8.9
Site 2 50ft	1.1				-0.7	2.6	1.1
Site 6 25ft	5					0.5	1.2
Site 6 50ft	0.5	5.8			7.8	5.5	6.3
Site 6 75ft	2.3	5.3	6.9	6.9	7.5	5	4.1
Site 6 100ft	3.7	3.7					5.2
Site 8 25ft		2.2				6.5	4.1
Site 8 50ft		-0.2			-2.2	2.1	3.1
Site 10 25ft			5.7	5.7	5.7	7.5	7.9
Site 10 50ft	4	5			6.6	6	5.7

Site 10 75ft		5.4				4.3	

Not Validated
Validated (Less than 5dB)
Validated (5-7 dB)
Validated (greater than 7dB)