Traffic Noise Modeling of Short Safety Barriers

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ABSTRACT

Solid safety barriers are commonly constructed along highways. These barriers improve highway safety by preventing collisions and providing separation from slopes or adjacent hazards such as deep water. For elevated and at-grade roadways, these shorter barriers have also been shown to noticeably reduce traffic noise. In this study, modeling methods were developed and evaluated for their ability to accurately calculate the performance of short barriers in reducing traffic noise at the wayside. Five real-world highway scenarios were selected for model validation, including four sites located behind short safety barriers and a site located behind a short berm. Theoretical modeling was conducted to systematically evaluate the effects of modeling parameters on the prediction of noise reduction provided by short barriers.

BACKGROUND

Highway traffic noise is ubiquitous in most communities and a persistent environmental concern for potential highway projects. Federal Highway Administration (FHWA) policies identify five approved highway traffic noise abatement options (*1*), with barriers currently being the primary method of abating traffic noise (*2*). In 2013 alone, the California Department of Transportation (Caltrans) spent more than $44 million on the construction of barriers throughout the state (*3*). However, in many situations, tall barriers are too expensive to be considered cost reasonable. In contrast, short (3- to 6-foot) barriers would be relatively inexpensive and easily constructed compared to typically taller (14- to 16-foot or more) barriers. These shorter barriers serve a dual purpose of preventing collisions and providing separation from slopes or adjacent hazards such as deep water, while also providing noise reduction to the community. However, short barriers are not currently a federally approved highway traffic noise abatement option.

Before shorter barriers can be considered for noise reduction, noise modeling techniques must be identified to ensure that modeling can accurately predict the noise reduction that will occur in the community. FHWA requires the use of its Traffic Noise Model (TNM 2.5) for all federally funded highway noise studies in the United States (*4*). Recent studies conducted by the Ohio Department of Transportation (ODOT) (*5*) and the California Department of Transportation (Caltrans) (*6*) found that measured insertion loss of short barriers was greater than the insertion loss that would be expected based on TNM 2.5 modeling results.

- ODOT conducted comprehensive in-state field research (*5*) that determined that short berms are effective at reducing highway noise levels. The study found “that many low height berms (3 to 6 feet) were providing a much higher level of noise reduction than would be expected … many of the small height earthen berms of less than six feet in height were providing a measured noise reduction of much greater than 5 dB.”
- Caltrans has measured a reduction of 10 to 12 dB at distances of 90 and 130 feet behind short, earthen berms. Further, the replacement of a 3-foot-tall solid concrete safety barrier at the edge of a highway bridge deck with a steel railing resulted in numerous noise complaints (*6*).

This research builds upon the Caltrans and ODOT studies by evaluating how to adapt TNM 2.5 modeling parameters to effectively predict sound levels at receptor locations behind short barriers.

VEHICLE NOISE SOURCE HEIGHTS

The algorithms for TNM 2.5 were developed based on field work conducted from 1993 to 1995 (*7*). Substantial data by vehicle type was acquired at 40 sites throughout the United States. Data collected included highway speeds, pavement types, and roadway grades. The measurement methodology included microphones positioned at a height of 1.5 meters (5 feet) relative to the roadway elevation, at distances of 7.5 and 15 meters (25 and 50 feet, respectively) from the centerline of the near lane of travel. This data was used to generate Reference Energy Mean Emission Levels (REMELs), which are used in the TNM 2.5 model.

Since the early 2000s, advancements have been made both in vehicle design and in traffic noise measurement methodologies. As an example of modernization of the truck force, diesel oxidation catalyst and diesel particulate filters have been used in all heavy-duty trucks since 2007; all heavy-duty trucks have had selective catalytic reduction systems and ammonia slip catalysts since 2013. Additionally, many modern trucks now use underfloor or horizontal exhaust systems. These modern aftertreatments reduce exhaust noise to the point of near inaudibility and further move the acoustic center of the noise source closer to the pavement surface.

Using beamforming and on-board sound intensity (OBSI) (*8*) measurement methodologies, recent Caltrans (*9*), National Academy of Sciences, and National Cooperative Highway Research Program (NCHRP) studies (*10, 11, 12*) have concluded that the primary vehicle subsource noise generators are now much closer to the pavement surface than those used in TNM 2.5. Beamforming results from these studies demonstrate that at highway speeds, most heavy vehicle noise is generated by the tire/pavement interaction or mechanical and exhaust sources located close to the pavement. Elevated traffic noise sources were found to have noise levels equal to or greater than ground-level sources for only 0.4% of trucks (5 out of 1,289). Only 56 (4.3%) of trucks had exhaust stack noise within 10 dB of the ground level source. Vertical profiles of trucks were unaffected by site, vehicle operating conditions, terrain, pavement, and region of the country. For light vehicles, beamforming found that almost all the energy is at or near ground level with tire noise being the predominant noise source. TNM 2.5 places 57% of low-frequency noise and 46 to 48% of high-frequency noise for heavy trucks at a height of 12 feet and uses an upper subsource height of 5 feet for light vehicles and motorcycles (*13*). **Figure 1** visually compares the upper subsource height of heavy trucks and light vehicles from TNM 2.5, the currently approved version of TNM, to the vehicle profile data developed for NCHRP Research Report 842 (10). The more recent version of TNM, TNM 3.0, utilizes the same subsource heights as TNM 2.5.

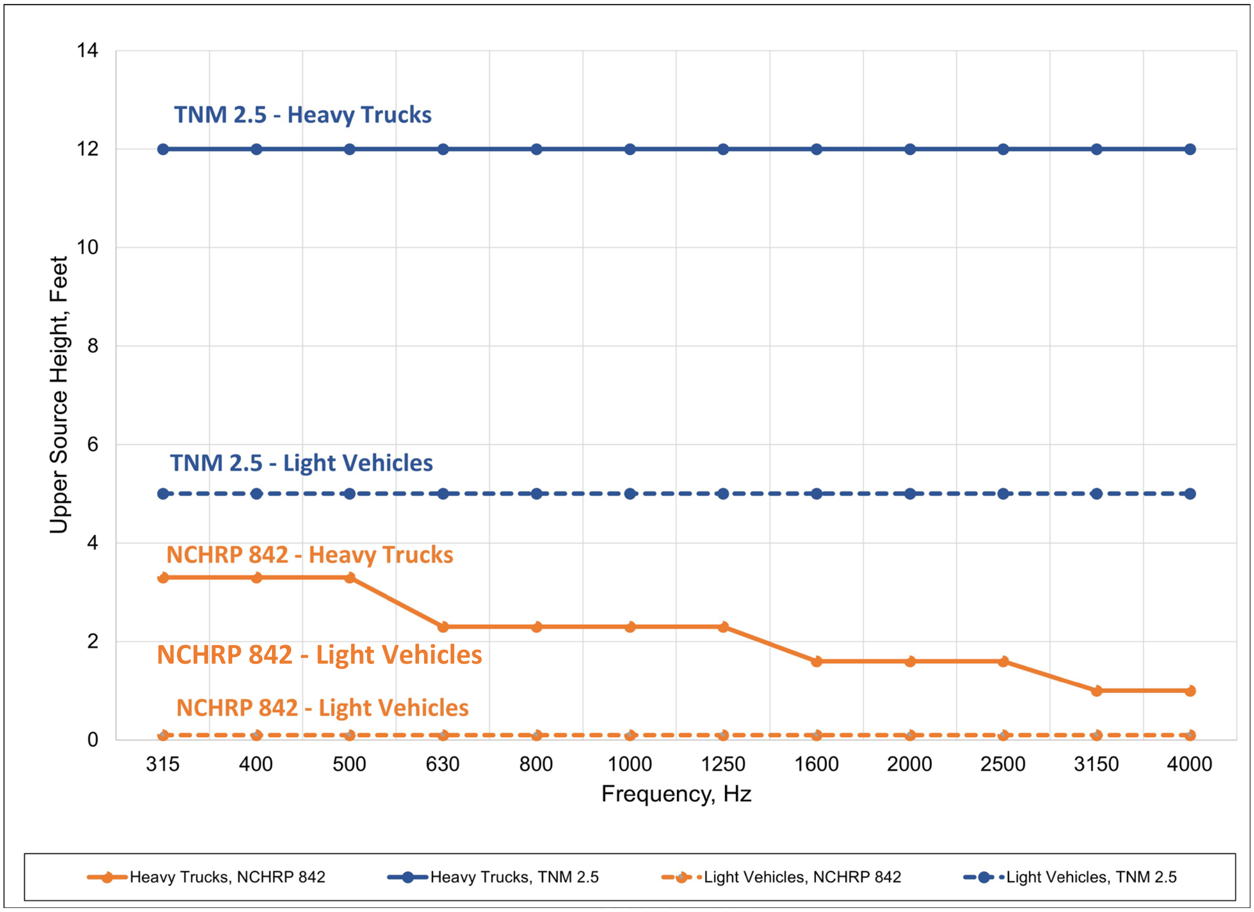


Figure 1 Upper subsource heights, TNM 2.5 and NCHRP Report 842 results

As indicated in **Figure 1**, the NCHRP Research Report 842 profiles have upper subsource heights for heavy trucks that are significantly closer to the pavement than those in TNM 2.5; 1.0 to 3.3 feet above ground level as compared to the 12-foot upper subsource height in TNM 2.5 (13). TNM 2.5 uses an upper subsource height of 5 feet for light vehicles and motorcycles, which would be above the top of most of these vehicles. The beamforming and OBSI results described above determined that for light vehicles, almost all the sound energy is at or near ground level—with tire noise being the predominant noise source.

Utilization of vehicle subsource heights and acoustic energy distributions that are closer to the pavement surface, as recommended in the beamforming studies described above, may not be crucial when calculating the insertion loss of traditional (14-foot or taller) noise barrier heights, where the noise source remains below the height of the barrier. However, noise source heights may become more important for correctly quantifying the insertion loss of shorter (30-inch to 6-foot high) noise barriers, where a falsely elevated noise source would look over the top of the barrier, rendering it ineffective from a modeling standpoint. This hypothesis is evaluated through the use of modeling methods that utilize the TNM 2.5 algorithms with subsource heights that approximate the NCHRP Research Report 842 results.

IDENTIFIED ERRORS IN TNM 2.5

In 2007, SoundPLAN developers identified five modeling errors in TNM 2.5; these include 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. Review of the top map in **Figure 2** and **Figure 3**, which will be described later in the paper, show the dimensional propagation error in the TNM 2.5 software, with the heavy vehicle noise extending unrealistically upward in the z-direction. Some of these identified errors, including the dimensional propagation error, have been corrected in the more recent version of the model (TNM 3.0). The second-from-the-top map in **Figure 2** and **Figure 3** show the modeling results with all five corrections, resulting in more realistic propagation in the z-direction. Both SoundPLAN and CadnaA sound models include optional corrections for these errors when TNM 2.5 is implemented within the SoundPLAN or CadnaA software packages.

MODEL DEVELOPMENT AND SELECTION

To identify modeling methods that might best predict the insertion loss of shorter barriers, modeling methods utilizing different noise source height positioning and distributions were implemented in the SoundPLAN software and validated with field data. These results were compared to TNM 2.5, the currently approved version of TNM under FHWA. The modeling methodology was facilitated through use of a code allowing for the alteration of TNM 2.5 source heights and energy distributions in TNM 2.5 implemented within the SoundPLAN software package. The code also allowed for the alteration of the Multiplier, m, that is used in TNM 2.5 to remove the effect of soft ground present during vehicle noise emission level measurements (adjusting to free-field condition) (*14*). This study used the three preexisting Multipliers that had been calculated for use in TNM 2.5.

Through preliminary testing of numerous combinations of source heights and multipliers, five modeling methods were selected for further evaluation. A summary of the selected modeling methods is shown in **Table 1**. The Multipliers are indicated with a capital letter (A, B, or C), which is used to indicate the Multiplier type throughout the remainder of the paper. Multipliers A, B, and C are the Multipliers used in TNM 2.5 for ground level, 5-foot high, and 12-foot high sources, respectively.

TABLE 1 Summary of Selected Modeling Methods

Model Number	Implemented in SoundPLAN?	Source Height			Multiplier for Source Height		
		Lower	Upper, Heavy Trucks	Upper, Other Vehicle Types	Lower	Upper, Heavy Trucks	Upper, Other Vehicle Types
1	No	0 feet	12 feet	5 feet	0 feet (A)	12 feet (C)	5 feet (B)
2	Yes	0 feet	12 feet	5 feet	0 feet (A)	12 feet (C)	5 feet (B)
3	Yes	0 feet	2.3 feet	0.33 feet	0 feet (A)	0 feet (A)	0 feet (A)
4	Yes	0 feet	3 feet	0.33 feet	0 feet (A)	0 feet (A)	0 feet (A)
5	Yes	0 feet	3 feet	0.33 feet	0 feet (A)	5 feet (B)	0 feet (A)

All of the selected modeling methods use TNM 2.5 as the base calculation module. Model 1 is a direct use of the TNM 2.5 software. Models 2, 3, 4, and 5 utilize the SoundPLAN implementation of TNM 2.5, including the SoundPLAN "Bug Fix," which corrects what it characterizes as five errors with TNM 2.5 that are described above. TNM 3.0 has corrected many of these errors; therefore, Model 2 approximates the results that would be anticipated with TNM 3.0. Models 3, 4, and 5 vary the upper subsource heights to match the NCHRP Research Report 842 results. Model 3 uses an upper subsource height of 2.3 feet for heavy trucks and places all light-vehicle energy near the pavement surface with Multiplier A. Models 4 and 5 both use an upper subsource height of 3 feet for heavy trucks and at ground level for light vehicles, with Model 4 utilizing Multiplier A for both heavy trucks and light vehicles and Model 5 utilizing Multiplier B for heavy trucks and Multiplier A for light vehicles. Further discussion of the development and selection of these modeling methods is available in the Project Memo (*15*).

CROSS-SECTION NOISE CONTOUR MAPPING

Cross-section noise contour maps can provide further visualization of the differences between the models. Cross-section noise contour maps of heavy trucks behind a 42-inch-high barrier scenario for models 1, 2, 3, 4, and 5 are shown in **Figure 2** for a single elevated traffic lane and in **Figure 3** for a single at-grade highway lane. Propagation to the left of the roadway is over a hard ground surface (pavement) and to the right of the roadway is over a soft ground surface (lawn). 'TNM Average' pavement is used in all cases and the barrier is made of traditional reflective material.

Review of Model 1 (top map) in **Figure 2** and **Figure 3** clearly shows the impact of the dimensional propagation error in the TNM 2.5 software, with the heavy vehicle noise extending unrealistically upward in the z-direction in both figures. With TNM implemented in SoundPLAN (Model 2), this error is corrected, resulting in more realistic propagation in the z-direction. Again, this may be representative of TNM 3.0. The noise source heights between TNM 2.5 and TNM implemented in SoundPLAN (Models 1 and 2) are identical. For heavy trucks, the upper subsource height is reduced from 12 feet to 2.3 feet in Model 3 (center map) and to 3 feet in models 4 and 5 (lower two maps), resulting in similarly lower noise levels at the receivers. In Model 5 (bottom map), Multiplier B was used for the upper source height, resulting in higher levels that are more similar to the TNM implemented in the SoundPLAN model (Model 2) in the elevated case and the highest noise levels overall in the at-grade case.

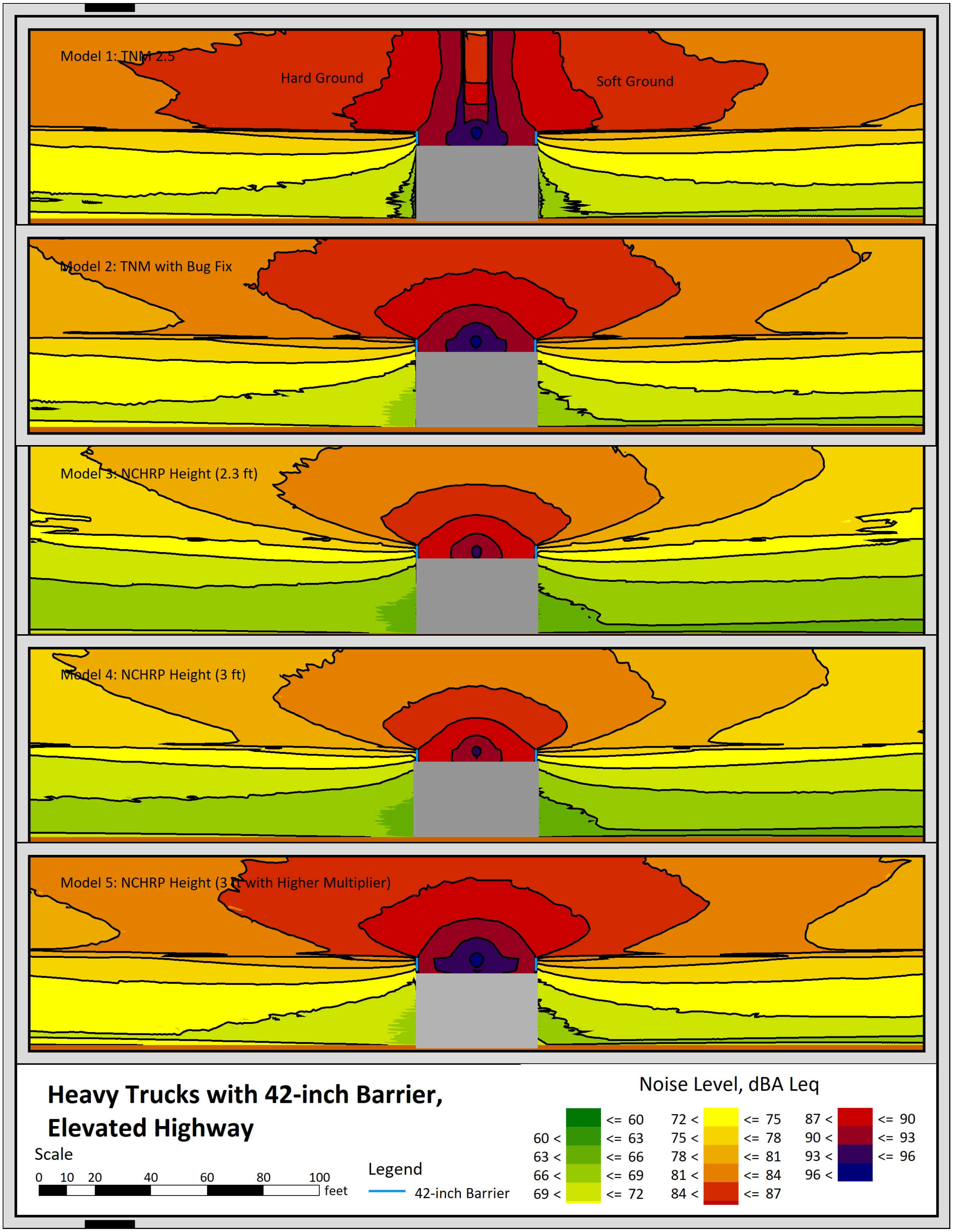


Figure 2 Noise contour map for heavy trucks with a 42-inch barrier, elevated case

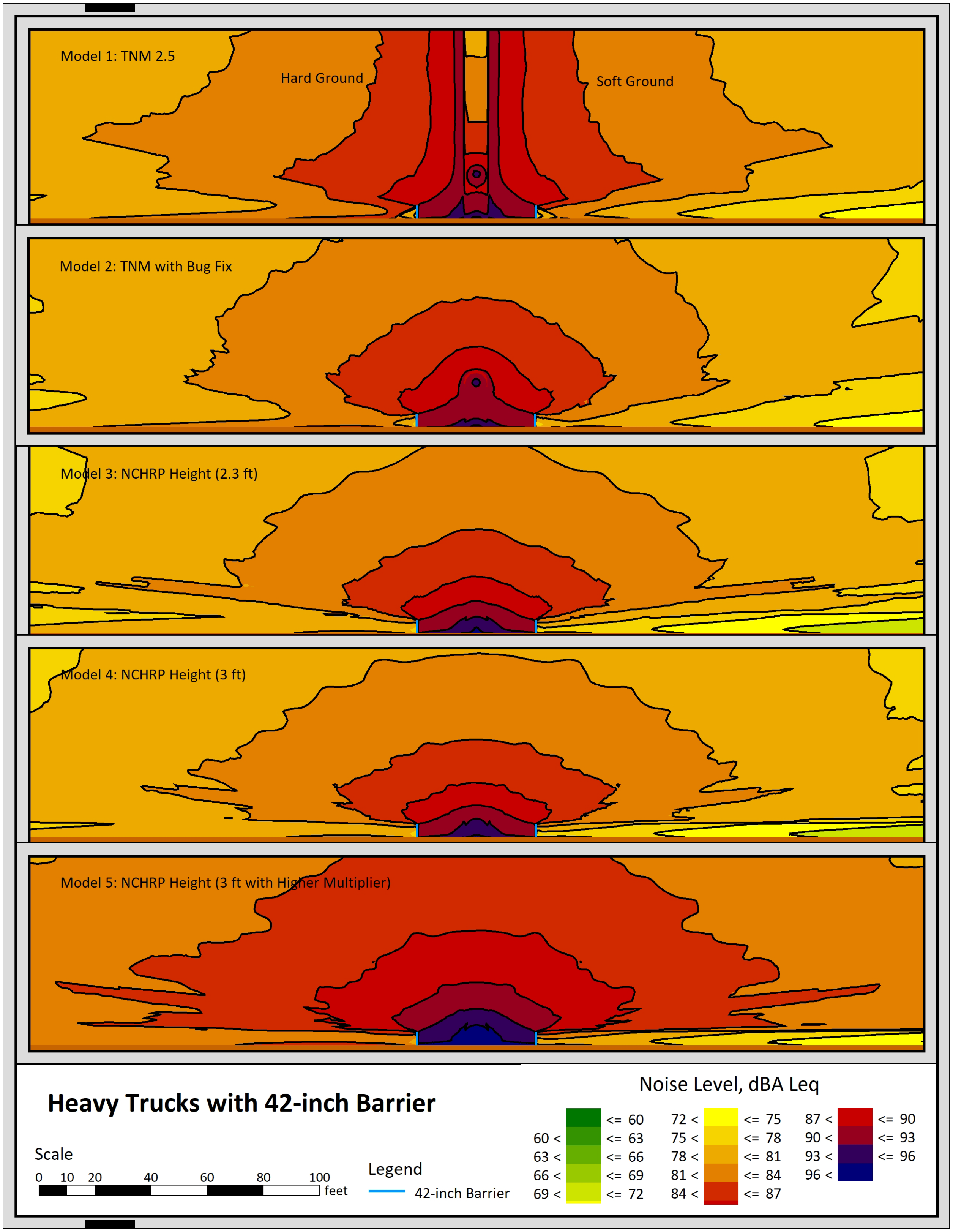


Figure 3 Noise contour map for heavy trucks with a 42-inch barrier, at-grade case

REAL-WORLD HIGHWAY CASE STUDY DESCRIPTIONS

Each of the selected modeling methods shown in **Table 1** was validated against five real-world highway noise measurement locations. Four of the five highway simulations were developed for highway noise study projects conducted under FHWA policy 23 CFR 772 (*16, 17, 18*). These include a measurement location behind an existing elevated short safety barrier. The fifth simulation is a short berm site used in recent Caltrans research (*19*). Aerial and street views of each location are shown in **Figure 4**.

<u>Site 1 (Vail, Colorado)</u>: First-row residential backyard located about 385 feet horizontally and depressed 50 feet below the edge of the near travel lane of I-70. The interstate is on structure in this area, with two lanes in each direction on separate bridge structures separated by 100 to 150 feet. Solid concrete safety barriers (32-inch tall) are constructed at the edge of the shoulder along both directions of I-70. The hourly equivalent traffic volume counted for the validation period was 1,520 vehicles. The traffic mix was approximately 82% light vehicles, 7% medium trucks, and 11% heavy trucks during the validation period. The pavement was a dense-graded asphalt concrete (DGAC) with some cracking due to heavy use of chains and studded tires in winter months (**Figure 4a**).

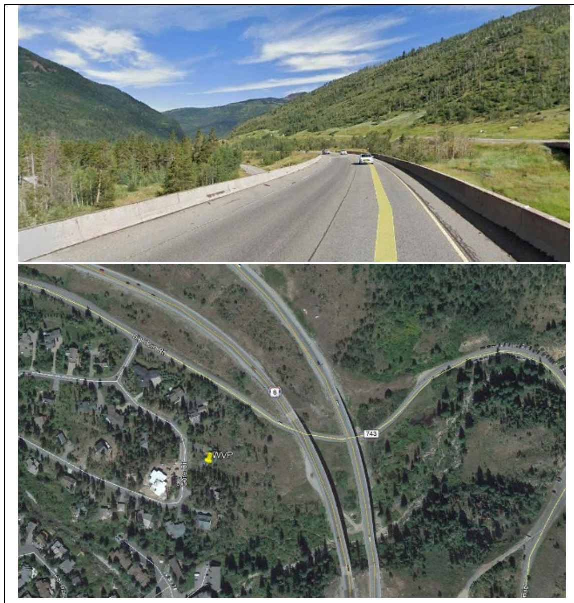
<u>Site 2 (Oakland, CA)</u>: Childcare center located about 90 feet horizontally from the edge of the highway off-ramp and about 175 feet from the edge of I-880. The project area is urban, with many structures and roadways, and the pavement in this area varies between lanes and along lanes. Both I-880 and the off-ramp are elevated on structure. A 32-inch high, solid concrete safety barrier is located at the edge of I-880 in this area. The hourly equivalent traffic volume counted for the validation period was 11,216 vehicles. The traffic mix was approximately 85% light vehicles, 5% medium trucks, and 10% heavy trucks during the validation period (**Figure 4b**).

<u>Site 3 (Oakland, CA)</u>: Recreational trail on a college campus located about 240 feet horizontally from the edge of I-880. Interstate consists of four westbound and five eastbound lanes elevated on structure with a 32-inch high solid concrete safety barrier constructed at the edge of the roadway shoulder. The traffic mix was approximately 85% light vehicles, 5% medium trucks, and 10% heavy trucks during the validation period, with an hourly equivalent traffic volume of 11,216 vehicles. The pavement on I-880 in this area is a concrete surface in good condition (**Figure 4c**).

<u>Site 4 (Norwalk, CA)</u>: Recreational use area located about 225 feet horizontally and depressed 30 feet below the edge of the near travel lane of I-605 and 150 feet horizontally and depressed 20 feet below the edge of the adjacent off-ramp. A 32-inch high, solid concrete safety barrier is constructed at the edge of the off-ramp at this location. No safety barrier exists along the highway edge of shoulder. The hourly equivalent traffic volume counted for the validation period was 11,142 vehicles. The traffic mix was approximately 84% light vehicles, 6% medium trucks, and 10% heavy trucks during the validation period (**Figure 4d**).

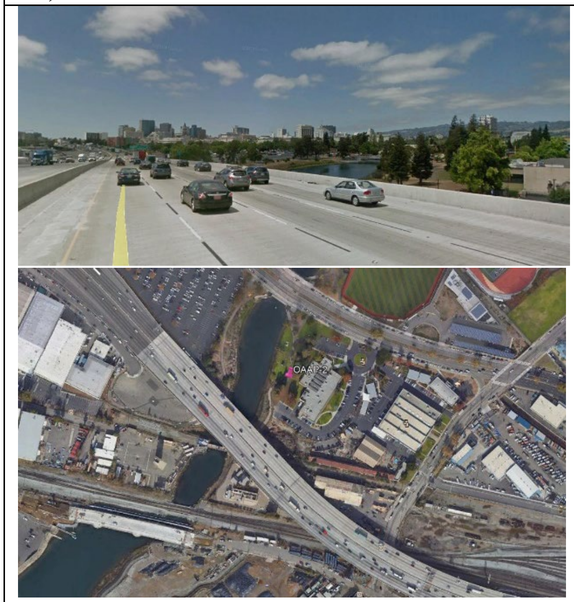
Site 5 (Short Berm): Research site located 37 feet behind a short berm along the southbound shoulder of US 101. Highway consists of two lanes of travel in each direction. The top of the berm is 5 feet, 5 inches above the pavement. The pavement along this segment is damaged DGAC, with an average OBSI level of 105.6 dBA. The hourly equivalent traffic volume counted for the validation period was 6,364 vehicles. The traffic mix was approximately 91% light vehicles, 4% medium trucks, and 5% heavy trucks during the validation period (**Figure 4e**).

'TNM Average' pavement was used in all simulations, for conformity with the procedure for studies under the FHWA policy. The highway noise simulations were not altered from the original TNM 2.5 simulations for this analysis.

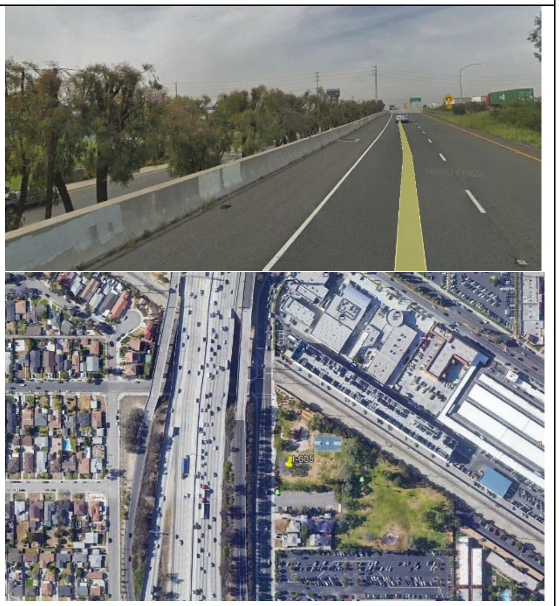


4a) Site 1

4b) Site 2



4c) Site 3



4d) Site 4

4e) Site 5

Figure 4 Aerial and street views of case study sites

REAL-WORLD HIGHWAY CASE STUDY MODEL VALIDATION

Comparing field measurements to the results of existing condition model simulations allows the user to check or "validate" that the variables in the simulation are representative of the real-world geometry. This allows the user to proceed with confidence in analyzing and comparing future condition alternatives. Differences of +/-3 dB or less between measured and simulated results are considered "validated" under FHWA highway noise study procedures. The smaller the difference, the better the validation of the model.

A summary of the differences between the modeled and measured results for each case study is shown in **Table 2** and **Figure 5**, along with the average differences between the modeled and measured results. For the short berm site (Site 5), results were normalized for pavement, following procedures recommended in NCHRP Research Report 738 (*20, 21*). Tire-pavement noise level data is not included in the procedure for studies under FHWA policy and was therefore not available for the four highway study simulations. As a result, pavement normalization was not possible for these sites.

TABLE 2 Summary of Case Study Results (Modeled vs. Measured)

	Site	Model Number				
		Model 1 (TNM 2.5)	**Model 2 (TNM in SP)**	**Model 3 ($H_{2.3\ ft}$, M_A)**	**Model 4 ($H_{3\ ft}$, M_A)**	**Model 5 ($H_{3\ ft}$, M_B)**
Difference from Measured (dB)	Site 1	5.8	4.3	0.2	0.2	1.2
	Site 2	3.1	1.7	-1.0	-0.7	1.6
	Site 3	1.2	-0.5	-2.7	-2.4	-0.2
	Site 4	4.7	1.1	-0.9	-0.9	0.8
	Site 5[1]	6.4	0.9	0.1	0.2	2.1
Average Difference		**4.2**	**1.5**	**-0.9**	**-0.7**	**1.1**

[1] Includes pavement effects.

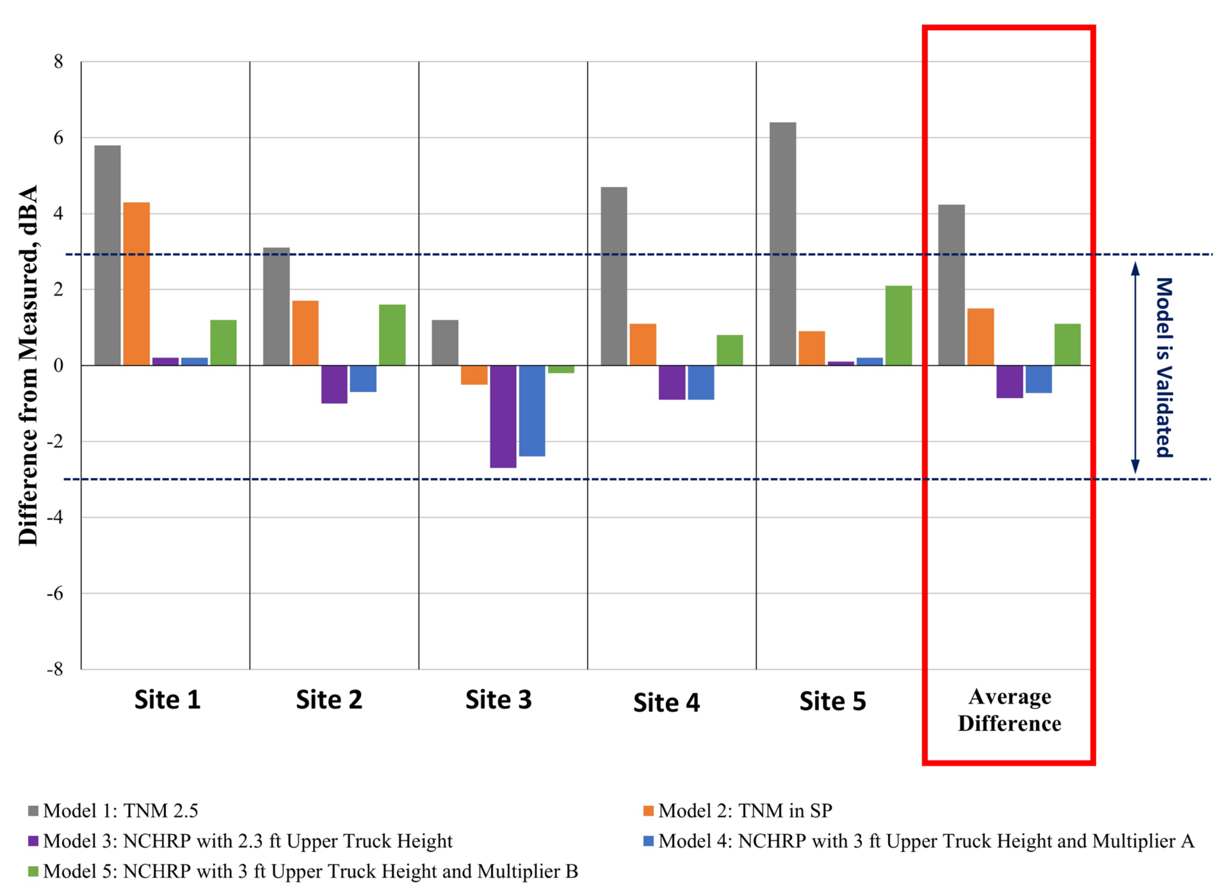


Figure 5 Summary of case study results (modeled minus measured) (dB)

As shown in **Table 2** and **Figure 5**, TNM 2.5 (Model 1, in gray) resulted in noise levels that differed the most from measured results, with the average difference from measured results being +4.2 dB. TNM 2.5 was validated at only one of the five sites (Site 3). TNM implemented in SoundPLAN (Model 2, in orange), resulted in modeled levels that were, on average, 1.5 dB greater than measured results. Four of the five sites were validated, with the exception being Site 1: the site with the greatest elevation difference between the roadway and the receiver. A comparison between TNM 2.5 and TNM implemented in SoundPLAN shows the influence of the TNM 2.5 bugs partially addressed in TNM 3.0. These fixes improved the validation for all five sites, with an average improvement of 2.7 dB.

All five sites were validated for the three NCHRP height-based models, shown in purple, blue, and green, with average differences for the NCHRP subsource height-based models ranging from -0.7 to +1.1 dB, an average improvement over the TNM 2.5 validation by 3.1 to 3.5 dB. The direct effect of the alteration of subsource heights can be seen through comparison of the three NCHRP height-based models (models 3, 4, and 5 in purple, blue, and green) to TNM implemented in SoundPLAN (Model 2, in orange), indicating that 0.4 to 0.8 dB of the improvement in validation can be attributed as a direct effect of the alteration of subsource heights. The model with the lowest subsource height, Model 3, shown in purple, resulted in the lowest sound level values overall. Raising the subsource height somewhat for Model 4, shown in blue, increased the values minimally, and the results showed the best validation with measured values. For Model 5, shown in green, a higher multiplier was used, elevating levels as compared to the other NCHRP height-based models and bringing the results closer to those of the TNM implementation in SoundPLAN results.

THEORETICAL MODELING

Field measurements ensure that computer simulations are representative of real-world conditions. However, theoretical modeling provides a method of systematically evaluating changes related to varying modeling parameters. A test matrix comprising of 132 preliminary test scenarios and cross-sectional contour mapping was developed to further evaluate the effects of modeling parameters on the prediction of noise reduction provided by barriers. The test matrix was intended to assess the sensitivity of the modeling methods to common highway design variables, including the following:

- At-grade roadway and 20-foot-high elevated bridge
- Four- and six-lane highway alignments
- 11 barrier height alternatives (0, 2.5, 3, 3.5, 4, 5, 6, 10, 12, 14, and 16 feet)
- Three truck percentage alternatives (5, 10, and 100% trucks)

Each scenario included 10-foot-wide roadway shoulders and a 22-foot-wide median. Receiver distances of 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 feet from the center of the near travel lanes were assessed. 'TNM Average' pavement and soft ground type (lawn) was used in all cases.

The insertion loss of a 42-inch barrier for the elevated and at-grade four-lane alignment, with 10% trucks and 90% light vehicles, is shown graphically in **Figure 6** and **Figure 7**, respectively.

The elevated alignment shown in **Figure 6** best approximates the four real-world short barrier highway simulations described above. Other examples are given in the in the Project Memo (15).

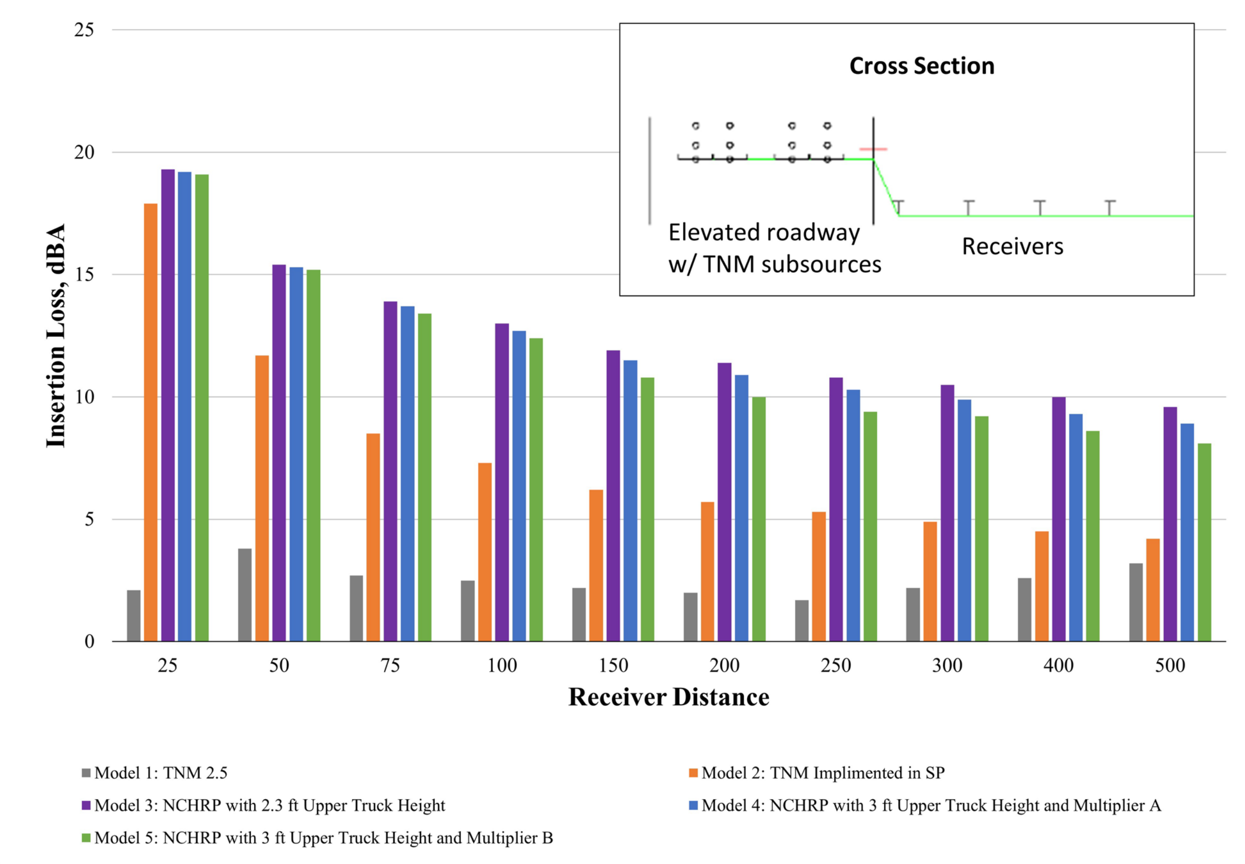


Figure 6 Insertion loss of elevated 4-lane highway with 42-inch barrier

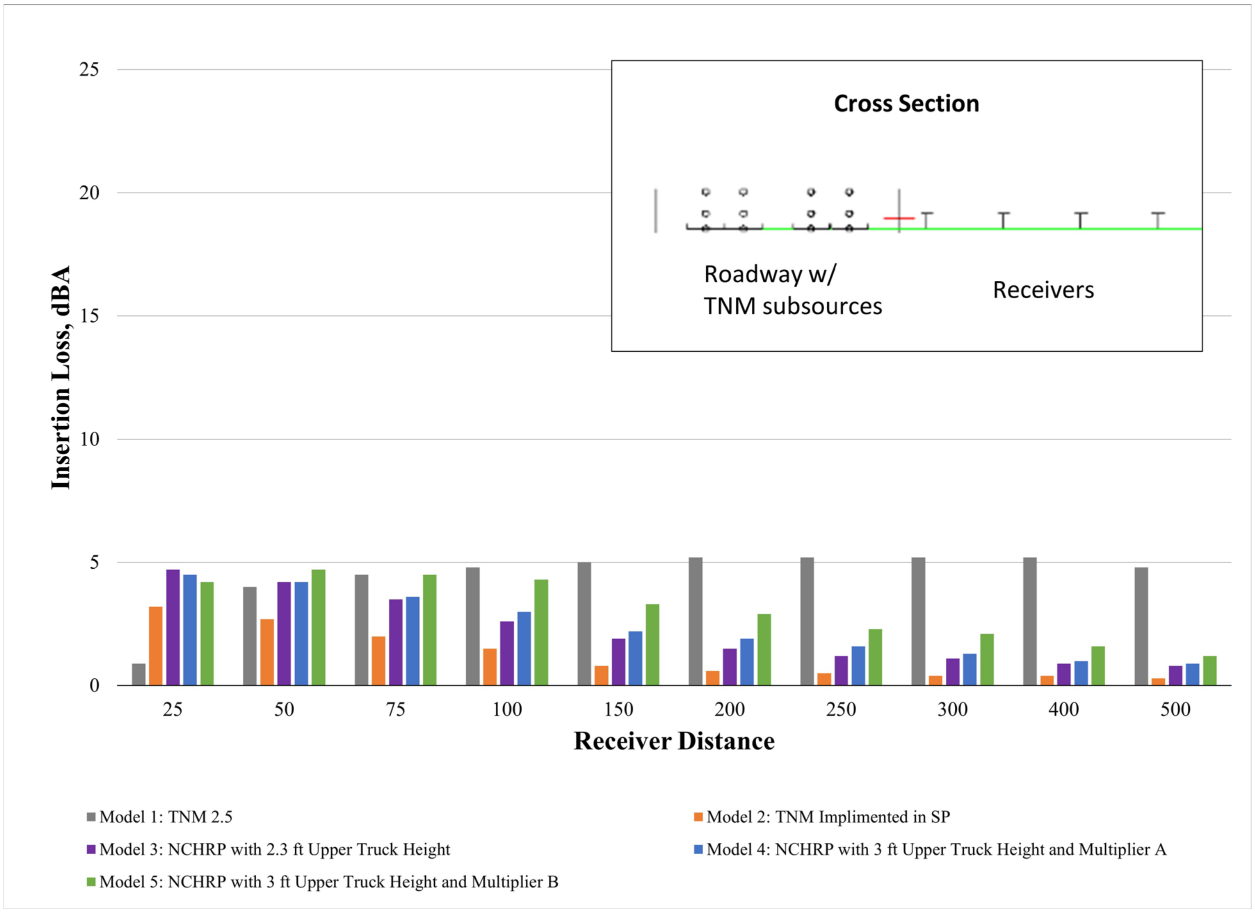


Figure 7 Insertion loss of at-grade 4-lane highway with 42-inch barrier

As indicated in **Figure 6** and **Figure 7**, TNM 2.5's (Model 1, in gray) calculated insertion losses are only minimally affected by distance from the barri[illegible] and at-grade barrier geometries. This contrasts with commonly accepted literature, which indicates that barrier insertion loss drops off with distance from the barrier (22,23). TNM implemented in SoundPLAN (Model 2, in orange) and NCHRP-result-based models (models 3, 4, and 5, in purple, blue, and green, respectively) show greater insertion loss at the closer receiver distances for both elevated and at-grade barriers. The insertion loss drops off with distance, as would be expected from the literature (22,23), indicating that this modeling improvement is due to the inclusion of the SoundPLAN 'Bug Fix' and may be corrected with the use of TNM 3.0.

Cross Section
Roadway w/
TNM subsources
Receivers

For the elevated case (**Figure 6**), TNM 2.5 (Model 1, in gray) resulted in insertion losses of less than 4 dB for all distances. The three NCHRP height-based models (models 3, 4, and 5, in purple, blue, and green, respectively), gave substantially greater insertion loss values than TNM 2.5, with 15 to 20 dB of insertion losses calculated for the 42-inch-tall barrier at the 25 and 50-foot positions. A 9 dB reduction was calculated using Model 3 at distances as far at 500 feet from the elevated 42-inch tall barrier. Again, a comparison between TNM 2.5 (Model 1, in gray) and TNM implemented in SoundPLAN (Model 2, in orange) shows the influence of the bugs that are partially addressed in TNM 3.0. The direct effect of the alteration of subsource heights can be seen through comparison of the three NCHRP height-based models (models 3, 4, and 5 in purple, blue, and green, respectively) to TNM implemented in SoundPLAN (Model 2, in orange). This comparison indicates that the alteration of the subsource heights resulted in an increase in insertion loss values of 3 to 5 dB as compared to the TNM 2.5 subsource heights.

These theoretical results are consistent with the case study results, with the largest differences between the Model 1 and Model 2 results occurring at the site closest to the roadway (Site 5). Models 2, 3, 4, and 5 show similar trends for all sites, with the largest differences between Model 2 and the NCHRP height-based models (models 3, 4, and 5) occurring at the site most set back from the highway (Site 1). Also, these findings are consistent with the case study validation being improved substantially by the bugs partially addressed in TNM 3.0 and further refined by the alteration in the subsource heights.

For the at-grade case (**Figure 7**), all five models resulted in insertion loss values that were 5 dB or less at all barrier heights and distances. TNM 2.5 resulted in insertion loss values that were 2 to 4 dB less than the NCHRP height-based models at the 25- and 50-foot positions, and 1 to 4 dB greater than the NCHRP height-based models for the distant positions. TNM implemented in SoundPLAN (Model 2) again resulted in insertion losses that trended with but were 1 to 3 dB less than the NCHRP height-based models.

Other test matrix scenarios resulted in similar trends to the example cases described here (see 15). In these other scenarios, higher truck percentages resulted in slightly less insertion loss in all scenarios, as anticipated. Moreover, the six-lane highway alignment results were generally within 1 dB of the four-lane highway alignment results.

CONCLUSIONS

In situations where taller (14- to 16-foot or more) sound walls are too expensive to be considered cost reasonable under FHWA policy, short (3- to 6-foot) sound walls may be an option to provide some noise reduction to communities. Short sound walls would be relatively inexpensive and easily constructed compared to taller sound walls and can serve a dual purpose of improving driving safety while providing noise reduction to the community. Improved modeling methods may enable state departments of transportation and other transportation agencies to accurately predict the noise reduction provided by these short barriers.

TNM 2.5 was shown to underpredict the insertion losses of short barriers along elevated highway alignments and behind a short berm. It may also overpredict the insertion losses of short barriers at distant locations along at-grade highway alignments. Use of the SoundPLAN "Bug Fix" improved results in both theoretical cases and in field validation studies; predictions were improved by 2.7 dB on average for five real-world highway simulations. Some of the corrections included in the SoundPLAN "Bug Fix" are integrated into TNM 3.0, indicating that this newer version may improve calculations of results behind short barriers. Further study is needed to confirm this hypothesis.

The alteration of TNM 2.5 to utilize upper subsource heights closer to the pavement surface further improved validation of the model with field studies at locations behind short barriers. Predictions, which also include the SoundPLAN "Bug Fix," are improved over TNM 2.5 results by 3.1 to 3.5 dB on average for five real-world highway simulations. Approximately 0.4 to 0.8 dB of this improvement in validation can be attributed as a direct effect of the alteration of subsource heights.

Based on the theoretical modeling, approximately 3 to 5 dB of noise reduction can be realized at traditional setbacks of residences to 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 (30-inch or taller) at distances of 25 and 50 feet from the barrier. A 9 dB reduction was calculated at distances as far at 500 feet from the elevated 42-inch tall barrier with use of the lower subsource heights and the SoundPLAN "Bug Fix". These noise reductions would be considered a halving of noise or better and, in many cases, would meet or exceed the feasibility and design goal criteria identified under a state's policy.

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 4 pounds per square foot. A solid concrete safety barrier easily meets this criterion. Metal-beam-guard-railing does not provide any noise reduction.

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AUTHOR CONTRIBUTION STATEMENT

The author confirms sole responsibility for the following: study conception and design, collection of studies to be included in analysis, analysis and interpretation of results, and manuscript preparation. Collaboration and review were provided by parties listed in acknowledgements, above.

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